PROCEEDINGS
OF THE
SYMPOSIUM ON SOLAR SCIENCE AND TECHNOLOGY

25 November-4 December 1980
Bangkok, Thailand

VOLUME TWO

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PROCEEDINGS OF THE SYMPOSIUM ON SOLAR SCIENCE AND TECHNOLOGY

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organized jointly by the

UNITED NATIONS ECONOMIC AND SOCIAL COMMISSION FOR ASIA AND THE PACIFIC

and the

REGIONAL CENTRE FOR TECHNOLOGY TRANSFER

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FOREWORD

In pursuit of the goal of acquiring new and renewable energy supplies for their development needs, many Asian and Pacific countries have initiated a series of policy measures leading to possible future self-sufficiency in energy. Since 1978, ESCAP in accordance with resolution 33/148 of the United Nations General Assembly, has undertaken several important programmes and projects for the development of alternative sources of energy in the region. New policies, plans and priorities have been set in motion towards achieving a well co-ordinated relationship between energy and development, including the management of their inherent and over-all impact on society.

As a major input to the field of solar energy for the United Nations Conference on New and Renewable Sources of Energy held in August 1981 at Nairobi, the Symposium on Solar Science and Technology was convened at ESCAP headquarters and at the Asian Institute of Technology, Bangkok, during November and December 1980 and attracted experts from various United Nations and other international and national organizations.

In the wake of this Symposium, and in order to emphasize its own commitment to the development of energy resources throughout Asia and the Pacific, ESCAP highlighted energy as the main theme at its thirty-seventh session which recommended, among other things, that ESCAP play an active role as the regional focal point for further work in the field of energy. In fulfilment of this role, and also to reinforce its already existing programmes concerned with energy, ESCAP has established a special unit on energy to cope with the increased demand for information and expertise on conventional as well as new and renewable sources of energy.

In particular, ESCAP will continue to place special emphasis on solar energy and to co-ordinate activities in member countries designed to meet immediate energy needs. Reflecting the priorities of the region, ESCAP will stress low-cost technologies applicable to small-scale farmers and rural communities so that its efforts in the field of energy will have the widest possible impact and will be of direct benefit to the peoples of Asia and the Pacific.

S.A.M.S. Kibria
Executive Secretary

PREFACE

The present Symposium on Solar Science and Technology was organized to serve as a major regional input in the field of solar energy to the United Nations Conference on New and Renewable Sources of Energy held in August 1981 at Nairobi. Recognizing the developments in highly sophisticated solar technology by many industrialized nations, the Symposium reminded the participating scientists, technologists and industrialists from Asia and the Pacific of the need to remain fully abreast of this rapid technological progress and vigorously to continue to work towards the greater use of solar energy in the region.

The primary objectives of the Symposium were to provide an exchange of scientific and technological knowledge concerning solar energy; to introduce programmes related to solar energy in university and college curricula; to promote the transfer of technology related to solar energy; and to encourage the incorporation of solar energy programmes into national energy policies and plans throughout the Asian and Pacific region. These primary objectives met with the unanimous support of the Symposium.

The Symposium had four components: (a) a general session for the presentation of keynote addresses; (b) a meeting of solar scientists; (c) a meeting of solar technologists and (d) a workshop to provide interaction between the two groups. After a comprehensive review of the status of solar science and technology in the region, the meeting of scientists broke up into four groups on photothermal conversion, photoelectric conversion, photosynthetic conversion and the storage of thermal energy. The meeting of technologists, divided into five groups, to study solar applications in drying, heating, cooling, pumping and cooking. Each group then returned to the plenary and presented sets of recommendations with regard to their respective disciplines. On the whole, the most notable recommendation emphasized by the Symposium was the need for the evolution of clear-cut national policies for the utilization of solar energy.

To substantiate the discussions at the Symposium, an exhibition of solar equipment (SOLEX'80) was displayed at the Asian Institute of Technology as part of the Symposium. This equipment has been retained at the existing site and maintained by AIT as its Energy Park.

The Symposium was supported by the United Nations and other international and national organizations. The United Nations Interim Fund for Science and Technology for Development provided financial support for the Symposium, while, UNCTAD, UNEP, UNIDO, FAO, UNESCO and WIPO actively participated and also lent their names in co-sponsoring it. This was in fact the first Symposium of its kind on energy, supported by the various United Nations bodies, the International Solar Energy Society and the Asian Institute of Technology.

The secretariat would like to express its sincere gratitude to those individuals who helped ESCAP and the Regional Centre for Technology Transfer in organizing this Symposium, particularly Dr. Prida Wibulswas (Dean, King Mongkut Institute of Technology), Dr. Robert Exell (Associate Professor, Associate Chairman, Division of Energy Technology, AIT) and Dr. G.Y. Saunier (Chairman, Division of Energy Technology, AIT).

Volume Two

I. INVITED PAPERS

STRATEGIES OF SOLAR ENERGY DEVELOPMENT AND USES IN DEVELOPING COUNTRIES

by

DR. R.L. DATTA

1.0 *Man, Surroundings and Energy:*

Basic needs of life center round food, housing, clothing medical aid and education, and energy plays a major role in meeting these needs. Inadequacy of man's muscle power for such energy made him look to his surroundings, and discovered animals, and then, wood, wind, water-falls, and the sun as the natural sources of energy for power and thereafter, in succession, more concentrated forms of energy in coal, oil and natural gas for obtaining higher rates of material achievements by way of agricultural and industrial developments, the technologies of these later ones being developed by the presently known developed countries, enabling the peoples therein to substantially meet the basic needs of life, improve its quality and increase the standard of living. The developing countries, on the other hand, characterised by low income (per capita GNP less than US$ 500), highly dispersed high percentage of rural population, vast semiarid and arid regions, surplus labour, absence of transport and communication facilities, aversion of transport and communication facilities, aversion of people towards sophisticated technologies for developments (but endowed with higher intensity of solar radiation) mainly relied on the early-known non-fossil energy sources (muscle power, animal, wood, wind, water falls and sun and also agricultural waste and dung) and labour-intensive hand-made technologies and consequently, had been struggling to meet the basic needs of life, and remained underdeveloped and undeveloped. In a developing country like India, - even as of to-day, at least, one-third of the energy consumed, is in animate form. In the rural areas of the developing countries, firewood constitutes about 80 - 90 percent of the total energy used, essentially for cooking. It was considered, that - one of the main yardsticks of assessing the material progress of a country is by the ratio of commercial (fossil/hydro/nuclear) to non-commercial (wood/agricultural waste/dung) forms of energy used, such ratios in cases of India, and Mexico are about 1.5 : 1, and 4 : 1 respectively, whereas in many other developing countries including Ethiopea, Tanzania, this is varying between 1:4 and 1:48, implying the use of huge quantity of non-commercial energy, evidently in a wasteful way. However, in the recent scenario of energy shortage, both the advanced and developing countries with plans of rapid developments in their own ways, have been severely affected by such shortage, especially, of fossil fuels. An advanced country like U.S.A. imports every year oil to the tune of more than 45 percent of her oil requirement, and India, a developing country, imports more than 17 million tons of oil. Moreover, if the developing countries' aspiration, according to Lima declaration, to achieve the target of 25 percent of world's industrial production (as against hardly 10 percent at present), is to be fulfilled by the year 2000, all the forms of energy will have to play significant role. In the wake of severe shortage of fossil fuels, and the search for other viable sources of energy, the hitherto uncared for shortcommings for their usage have come to the surface, namely, (a) these pollute environment (b) these are unevenly distributed on earth's surface resulting in unequal opportunities and political tension (c) it has taken million of years for these to be formed but will be used up in a few hundred years (d) these are to be used mainly for high temperature uses and chemicals recovery. These newer awakenings have led the peoples of both the advanced and developing countries to look back to the earlier usage of energy in sun, wood, wind and water-fall which continue to shine, grow, blow and fall respectively as before, to modernise these by development of the technologies for their uses, and to discover other sun-based sources of energy like ocean-thermal gradient, tide, wave, photosynthetic biomass in the newer context. The currently known sources of energy are shown in table 1. These can essential be grouped as:

(i) fossil fuels (coal, oil peat, natural gas)

(ii) photosynthetic (wood, vegetable wastes human and animal energy)

(iii) solar radiation, environmental heat, wind, wave, tide and hydro energy)

(iv) geothermal energy

(v) nuclear energy.

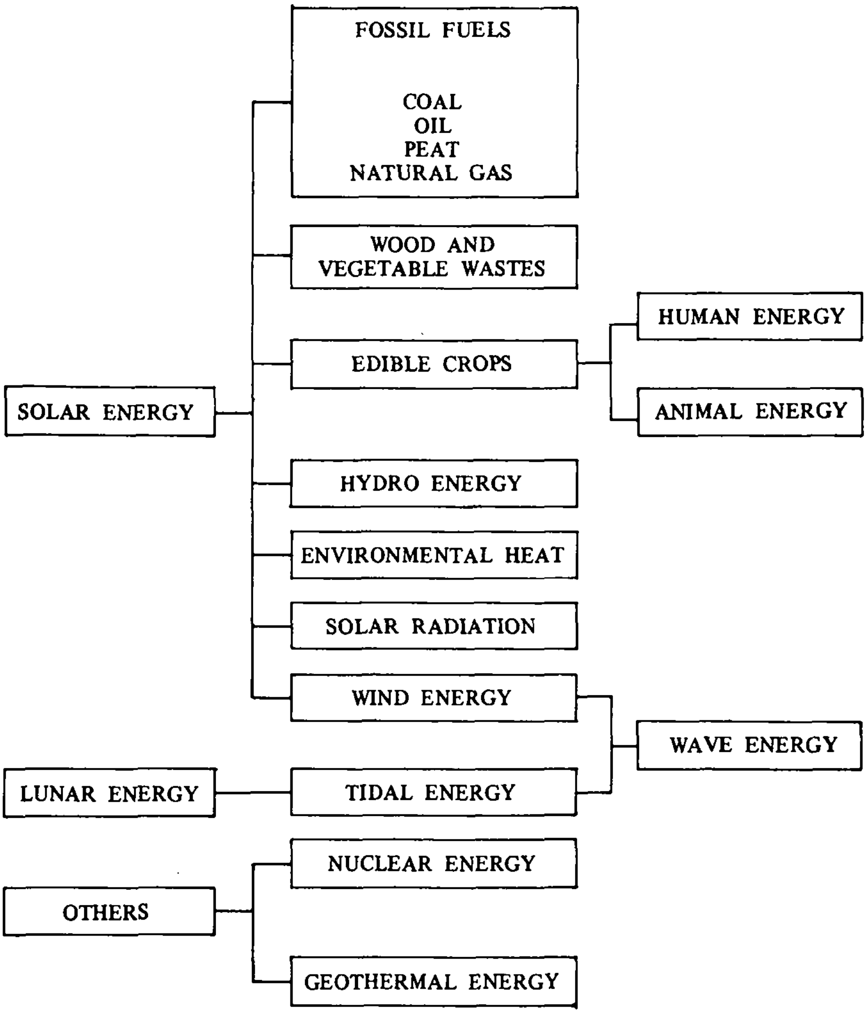
It can be seen that all the sources of energy except geothermal and nuclear are sun-based sources. Among the sun-based energy sources, fossil fuels are in concentrated forms; whereas others are in dilute or diffuse forms and hence thermo-dynamically less efficient; in addition, some of the latter are intermittent in nature, (e.g. solar, wind) and others may require transportation. These, therefore, would require huge-sized trapping devices unless these forms of energy are concentrated and stored with the use of materials of desirable radiative properties.

It is relevant to mention that a combination of such energies for use may be more suitable for certain given purposes eg. sun + wind + biomass. In recent years feasibility studies are being made for combination system, say, renewable and non-renewable sources like mix of sweage methane (biogas) + coal gas, with promising result, by Southern California Edison Co., U.S.A.

1.2 *Rural areas of the world:*

Most of the developing countries have (i) a high percent (80 percent or more) people living in rural areas, as given in table 2, for some typical countries. These are further characterised by (ii) high dispersion of people (iii) vast arid and semiarid regions (iv) absence of suitable transport facilities (v) surplus labour (vi) aversion of people to sophisticated technological developments and their utilisation (vii) high intensity of solar radiation over a longer period of the year. with the developing countries constituting

Table 1. WORLD SOURCES OF ENERGY



two-third of the world population, and at least three-fourth of which are rural dwellers, - the overall picture is that atleast, half of the world population live in villages. Any national and international developmental activities therefore must be to give utmost attention to this vast populace to meet their basic needs of life and improve the quality of life in order to avoid future catastrophic consequences. Solar energy and sun-based sources of energy can play a great role in these respects. Table 3 gives the possible use of solar and sun-based sources of energy in rural communities for domestic, agriculture and community development, - avoiding as far as possible human drugedy and deforestation with consequent adverse effect on agricultural land. It is pertinent to mention that in meeting the energy demands of the rural communities of the developing countries, there will be need to combine solar with wind and biogas in order to increase the usefulness of each of these. The elaborated version of such a system wherein a man will obtain energy on a continuous basis encompasses integrated bio-aqua-culture techniques with solar + wind + biogas supplies - has good possibilities in rural areas of the developing countries.

1.3 *Energy distribution in different regions of the earth:*

The present use rate of energy in the world is close to 7 x 10^{13} kWh per year which is estimated to go up to 6 x 10^{14} kWh by the year 2000. Table 4 gives the distribution of the energy sources on different regions of the world in percent of the total energy reserve except the last column which gives the yearly intensity of solar radiation in kWh per square meter. Petroleum reserves are mainly situated in the middle east (55 percent) which has no coal deposit and not much of hydroelectric potential. USA has only 6 percent of the world oil reserve. Many of the higher energy consuming countries (as in Oceania) have practically no oil. Quite a substantial amount of coal deposits are shared by China (14 percent), USA (31 percent), USSR and Eastern Europe (23 percent) and western Europe (21 percent). Hydroelectric potential exists in regions of Africa (20 percent), Asia (13 percent), China (13 percent), Latin America (16 percent), mostly in countries nearer to equatorial zone and elevated areas of temperate zone). In contrast to such uneven distribution, the solar energy is more evenly distributed throughout all the regions (between 0.6 x 1000 to 2.5 x 1000 kWh per square meter yearly). As a matter of fact, no life can exist and no vegetable can grow and thrive without sun's energy. It is potinent to mention that there is a good relationship between the energy consumption and the standard of living expressed in terms of average yearly income per head. Material achievements have to be energy based. It is also relevant to mention that there are more than a billion people, living mostly between 30°N-0-30°S latitude, in the world without electric power. Sunshine in many of these areas is the most available natural energy source. This sunbelt (30° N-0-30°S) is therefore the poverty belt. With an average sunshine intensity of 500 cal/cm^2/day and conversion efficiency of 10 percent, such intensity over an area of 300 square meters will give energy equivalent to 150 kWh, a man is capable of performing in a year on an average. The use of solar energy during early fifties in the exploration of outer surface was a welcome surprise and had given hope to mankind for its terrestrial applications. Solar radiation reaching the land surface of the earth annually is 0.26 x 10^{18} kWh against the present world consumption of close to 7 x 10^{13}

Table 2. Distribution of population in rural areas in some typical developing countries.
(Source: UN Statistical Year Book)
(1 ton of coal = 8000 kWh)

	Burma	*India*	*Indonesia*	*Thailand*
Area ($10^3 . Km^2$)	678	3,280	1,904	514
Population (10^6)	28.9	550.4	125.8	35.3
Percentage rural (%)	81	80	83	85
Population density 1/Km2	42.6	167.8	66.1	68.7
Total Energy Consumption (coal equivalent per year) 10^6 ton	1.9	102.5	15.4	10.5

Table 4. Distribution of World Energy Reserves.
(Percent of World Total) (1 to 4)
(Solar Electricity: By W. Plaz. Butterworth - 1978).

	Coal (1)	*Petroleum (2)*	*Natural gas (3)*	*Hydro Elec. Potential (4)*	*Yearly Solar Radiation (1000 kWh for m^2).*
Africa	3	14	9	20	1-2.5
Asia	3	2	2	13	1-2.3
China	14	2	2	13	1.2-1.7
Canada	1	1	5	6	0.7-1.2
Latin America	-	8	3	16	0.8-2.0
Middle East	-	55	16	-	2.0-2.5
Oceania	4	-	11	2	1.2-2.0
U.S.A.	31	6	-	-	0.8-2.3
USSR & Eastern-Europe	23	8	28	11	0.7-1.7
Western Europe	21	3	7	7	0.6-1.8

Table 3. Energy Demands of Rural Communities and their Potential Supply with Renewable Energy Sources. (Sources: Procds. Expert Group Meeting on Uses of Solar and Wind Energy, March 1976, ESCAP Bangkok)

Energy Use	*Time requirements.*	*Energy Supply*		*Solar-Wind-Methane Energy, Storage.*
		Traditional	*Solar-Wind Methane Potential.*	
Domestic				
Water heating	Daily	Wood cowdung	Solar	Insulated tank.
Cooking	Precise daily	Wood, cowdung	Solar, methane	No gas holder.
Lighting	Precise nightly	-	Wind (electric) methane.	Battery; gas holder
Water Supply	Constant	Human	Wind, solar.	Tank
Agriculture				
Ploughing	Precise, seasonal	Human, animal -	Wind -	No -
Sowing	"	Human	-	-
Cultivation	"	Human, animal	-	-
Harvesting	"	Human	-	-
Threshing	"	Human, animal	Wind	No
Winnowing	"	Human	Wind	No
Drying	"	Solar	Solar, Wind.	No
Grinding	Random, daily	Human, animal wind, water.	Wind	No
Crushing	Precise, seasonal	Human, animal Wind	Wind	No
Water pumping	"	Human, animal wind, water.	Wind, Solar.	Reservoir
Agriculture	Constant	Human	Wind, Solar.	Reservoir
Community Development				
Communication and Education	Precise, daily	-	Wind-solar (electric)	Battery
Transport	"	Human, animal	-	-
Housing	Seasonal	Human	Solar	Solar wall
Refrigeration	Constant	-	Wind, solar (electric)	Battery
Salt production	Random	Solar, wind	Solar, wind	No reservoir.
Entertainment (Radio, TV cinema)	Precise	Human	Wind, solar (electric)	Battery

kWh. As mentioned earlier, intermittent and diffuse nature of solar energy on the earth's surface have been the greatest obstacles for its effective uses.

1.4 *Pre-technology Problems of Solar Energy Applications:*

As indicated earlier, the total solar energy reaching earth's surface is much greater than required by world population and technically can replace entirely the conventional sources of energy. The two major shortcomings of this energy are (i) it's diffuse in nature and (ii) it's intermittent and of changing direction nature. In order to overcome these shortcomings, and evolve economically viable gadgets, substantial scientific/technological inputs are required to solve problems connected with:

1. Solar collector (flat plate collector, concentrators, selective surface).
2. Storage of energy (chemicals, mechanical electrical, physico-chemical).
3. Materials (radiative properties, mechanical stability, availability and cheapness).
4. Measurement of solar radiation (radiation station and cheaper and portable solarimeter).

Solution of each of these problems will make the solar gadget efficient and economically more viable.

1.5 *Present State of Technology of Applications of Solar Energy:*

In summarising the commercial status of solar energy applications, it can be stated that apart from production of solar common salt, and other marine chemicals like potash, bromine, magnesium salts, - solar water heating and house heating are now competitive in countries with moderate climate. Designs for solar distillers and crop driers are available for small scale applications but can be extended for larger scale uses with more engineering inputs. Designs for solar green houses are available. In regions where water and fire wood are not abundant, solar pumps and cookers can be used with the present state of development. For small and medium wind power production commercial designs are available.

1.6 *Advanced and Developing Countries' Approach for Solar Energy Uses:*

Good amount of informations of the principles and scientific data are available for solar energy conversion processes from some more than 80 countries of the world with funding from Governments and/or UN agencies and/or individual efforts but more exhaustive technological and engineering data are required in many of these processes for commercialisation. For developed economy, the emphasis on the uses of solar energy is from the point of view of supplementing the energy requirements and need of large scale power production, unless the countries of such developed economy can usher in a newer concept of smaller scale energy usage and can afford with lesser energy with consequent change of life style. Consequently, at present, in many of the western countries, Japan USA and other advanced countries, heating and cooling of houses and commercial buildings, and thermal electric and photovoltaic power production are being actively pursued. Judicious mixture of conventional and non-conventional energy sources may lead to more efficient utilisation of these. In developing countries dominated by rural areas, on the other hand, emphasis is on production of small-scale power in scattered rural areas for agricultural water pumping, crop drying, water purification for drinking, cooking and lighting and also other uses as given in table 3. For power production, - in addition to wind and ocean thermal, both photovoltaics and thermodynamic system with flat plate or concentrating collectors can be used; in both cases, economy of solar gadgets is to be improved. The imaginative Satellite Solar Power System (S.S.P.S.) is being examined more closely for large scale power production.

2.0 *Basic needs of life and Solar Energy Conversion Technologies:*

Of the commonly useable forms of energy, electrical form is the highest quality energy, followed by mechanical and thermal forms. Selection of one or more technologies of solar conversion will depend on the amount of energy requirement and the end uses, for example, if warm/hot water is required for domestic/industrial purposes, solar collector technology will play the most significant part in the solar device; thermally operated Rankine cycle-engine pump can be used for lift irrigation. Climate of a location may determine such selection, for example, in arid and semiarid regions, - during summer months cooler places of stay are required for comfort conditions and there is need for reflecting away solar heat from dwellings by passive system or taking resort to solar air-conditioning. Selection of technology will also be guided by sector-wise needs of energy in rural and in urban and in metropolitan areas in each of which emphasis will be on different needs, for example, in rural areas energy is required for lift irrigation cooking/lighting/drying; with better socio-economic conditons, as in urban areas, emphasis on energy uses will be more for community developments, transport system, education and cultural activities, whereas, in metropolitan cities, - in addition to those above, energy uses will be emphasised more for industrial developments.

Solar energy uses must, therefore, be related to the needs of life, and the best approach for selection of the technologies of solar conversion should be from the point of view of (A) meeting the basic needs of life, namely, food/housing/clothing/medical aid/education. (B) Improving the quality of life, by way of community development, cultural activities, transport and other allied developments. (C) increasing the standard of living with additional ammenities like transportation, communication, organisation and managerial proficiency for higher scale agricultural and industrial developments. The aspects which are significantly relevant to those above, center round. (a) Agriculture (including food, irrigation pumping, storage, drying, fertiliser, plant growth and afforestation). (b) Industry (including salt and marine chemicals, heating and cooling, process heat, power, renewable fuels). (c) architecture (passive system and active system and retrofiting), and (d) medical uses (including solar biology, curing of diseases).

2.1 *Technologies of solar energy conversion:*

There are three basic approaches to the uses of solar energy, namely, (a) low grade solar heating, (b) direct conversion to electric energy, and (c) photosynthesis and biological conversion processes. The gadgets which have been proved useful are water heater, solar still, cooker, refrigerator and pump. It is advisable to reassess the possible applications of these devices in rural and other areas taking into account the technological, economical and social constrains and further potential uses. Most of these devices use collector or concentrator to collect solar energy to heat a working fluid; they operate on varying degrees of efficiency. In indicating the immediate uses and present status of these technologies and R & D needs, the classification given below essentially is that given in item 2 above.

(a) *Agriculture:*

(i) *Pump:*

The technologies which can be used for pumping, are Solar Rankine, and Sterling engine, solar cells, biogas engine, and wind mills. Solar pumps run by thermal energy of the sun as in Rankine cycle have been constructed in a few countries. Solar cells pump is expensive at present and its economy is tied up with the cost of direct conversion electricity of the cell. Wind mill pumps are in use in many countries, and quite a number of biogas pumps have been constructed and experimented.

Problems still to be solved in these are concerned with fluid selection of engine cycles, collector/concentrator efficiency; (e.g. freon for 25 kWh pump at New Mexico; 150 kW at Arizona) materials of solar cells including amorphous semi-conductors, conductor-insulator-semiconductor, rice-husk silicon, E.F.G. growth, ribbon, polycrystalline wafers, thin film C_dS, concentrator with cells and use of extracted heat; optimisation of biogas plants; materials and optimised design of wind mills.

(ii) *Dryers:*

Convective dryers have separate areas for collection of solar energy and for drying of product, whereas radiation dryers have a common space for collection of solar energy and for drying of the product.

With suitably developed solar collector/chamber, larger scale experimentation (demonstration plants) is necessary for applications in quite a number of fields e.g. drying of food grains, timber, tobacco etc., and heating livestock shelter.

(iii) *Refrigeration and Storage of food:*

In many of the tropical and developing countries, a substantial quantity of foodstuffs cannot be preserved and are spoilt. At a number of international meetings, it was pointed out that famine could be prevented in many of these countries if the food which is raised during certain parts of the year could be preserved for use during the rest of the year. This requires refrigeration, and for remote area or areas without electricity solar refrigeration may well be the answer. In many of the tropical countries milk and meat are not traditionally used partly because they cannot be preserved. In some hot countries, perhaps a quarter of the vegetable crop spoils because of lack of cooling facilities.

In ammonia + water system of solar heat engine refrigeration, the weight proportions of ammonia and water are in the ratio of 1:1.3, and the maximum heating temperature is about $130^{\circ}C$, with a special valve separating the water from the liquified ammonia; the overall coefficient of performance (COP) is about 0.10. Flat plate collectors also can be used for the system, in which case the COP will be still reduced. Ammonia and water system has the disadvantage of some of the water vaporising with ammonia (requiring a rectifying arrangement for separation). Ammonia + sodium thiocyanate solutions have suitable thermodynamic/properties with high solubilities, low vapour pressures, and high heats of vaporisation: they are chemically stable and inert, comparatively inexpensive and can be used in iron vessels; they have high heat conductivities and low viscosities. The COP of this system is approximately three times of that of the ammonia + water system. Ordinary parabolic concentrators, and overnight lower temperature can be used. It is to be emphasised at this stage, for the purposes of refrigeration and production of ice, the temperature of regeneration of the refrigerant is usually above $100^{\circ}C$, and for such a temperature, one has normally to take resort to moveable focussing collector.

Many absorption refrigeration systems have been tried mostly using ammonia as the refrigerant. These include ammonia-water, ammonia-lithium nitrate, ammonia-calcium chloride and other systems like lithium bromide-water, Freon 21 - tetraethylene glycol dimethylether etc. Ammonia-water system can be compared fairly well with other systems, it gives more or less equal performance, more refrigeration per kg. of solution. In case of ammonia-water system, we require a rectifier-analyzer column to prevent water vapour to condense with ammonia. Ammonia-sodium thiocyanate system is similar to ammonia-water system, except sodium thiocyanate being non-volatile and having favourable properties like high heats of vaporization, high solubility, low vapour pressure, low viscosity and is stable, safe and noncorrosive. Hence either of these two combinations can be used.

Nevertheless studies of systems, ammonia + water, ammonia + thiocyanate for refrigeration with increased COP, of system lithium bromide + water for low temperature, and further development of biogas engine for the purpose are necessary.

(iv) *Fertilizer/fuel:*

Bioconversion of organic materials including cowdung, under anaerobic conditions to transportable fuel like methane, methanol etc. with residues having manurial value (good N-K-P content) has already taken root in countries like China (with 7 million units in existence) India (with 80,000 units) and Philippines and other developing countries. Solar energy by being captured by plants, is converted into chemical energy through photosynthesis, and such plants on being eaten or decayed transfer this energy to the living, - such plant matters are, therefore, also called biomass, and the energy from such mass after its being eaten, burned or converted into fuel is known as biomass energy. Vegetable/animal and farm wastes, sewage/solid refuse, waste hyacinth and kelp are examples of biomass. It has been estimated by the Biomass Institute, Winnipeg, Canada that the annual formation of renewable biomass (dry basis), on an average, is 200 billion tons whereas utilisation is hardly 2 billion tons (for food, fibre and building materials), whereas the corresponding values for non-renewable biomass (coal, oil, gas and petro-chemicals) is nil and 5 billion tons, respectively, giving an annual deficit of 5 billion tons.

Depending on the composition of the primary biomass, the type of conversion plants, temperature and time of decomposition in the chamber of the plant and other variables, some variation in the biogas composition would be noticed, but the approximate gas composition will be: methane = 55 to 65, (percent by volume), carbon dioxide % = 35-45, the others being nitrogen, hydrogen, oxygen, sulphurated hydrogen. The caloritic value of a biogas composition of 60 percent methane is 5130 k.cal/m^3. It is relevant to mention that one litre each of petrol, diesel oil and kerosene are approximately equivalent to 1.4 m^3, 1.6 m^3 and 2.5 m^3 of biogas respectively. The value of the biogas will increase by increasing the methane percent which can be used more efficiently to operate biogas engine for various purposes. Certain basic studies including carbon-nitrogen ratio of biomass mix, increased N-K-P value of residual fertiliser, optimisation of biogas plant and standardisation, and technolo-economic aspects of biogas engine have become necessary.

(v) *Plant growth:*

Photosynthesis is basic to plant growth and solar energy conversion efficiency in this to chemical energy is known to be not more than 2 percent. Environment controlled green house has been a boon to many of the arid and semiarid regions of the world for growing vegetables, greens and fruit; control essentially of water vapour and carbon dioxide in plastic-covered green house in sandy soil is effected by proper dosing of the constituents and suitable fertilisers are used. High protein containing algae can be cultured in polythene lined pond for use by cattle, poultry and silkworm.

Many of the basic problems in this field of study which are required to be solved relate to (a) attainment of higher (than 2%) photosynthetic conversion efficiency (although, theoretically 10 percent efficiency is known), (b) crop productivity and solar energy i.e. trapping solar radiation more by C_4 (sugarcane) than by C_3 (cow pea) in tropical wet climate (c) larger scale demonstration green house for growing vegetable in arid/semiarid region (the concept originated at the Arizona University's Environment-controlled green house Experimental Station, experimented on larger scale at Peurto Pinasco and applied at the Shaikdom of Abu Dhabi), (d) solar spectra of different wave length and plant growth.

(vi) *Afforestation:*

Afforestation (countering denudation of forest by indiscriminate cutting of fire wood) is very much linked up with agricultural development. For ecological balance and healthy development of a country, it must have substantial piece of its land area under forest. For example, in the case of India, the aim is to maintain one-third of its total area under forest as against the present 22 percent forest area; such an effort would constitute conversion of about 30 million hectares of land. With a break through in photosynthetic efficiency coupled with forest technology, planned forestry production is a challenging opportunity. Social forestry is being looked into more scientifically. Short-rotation (4 to 8 years) forestry (e.g. CASUARINA, green feathery conifer and others like ECALYPTUS, WILLOW) - energy plantation and efficiency of conversion and fuel-wood (calorific value: 5000 k.cal. per kg. or so) for generation of power (estimated area of plantation as 1 square km/MW) are some of the pertinent problems requiring substantial input of research and development. In recent years, interest has been revived on investigation of fuel trees. Certain types of plants e.g. *EUPHORBIA LATHYRIS* secrets lower molecular weight (range of molecular weight 2000 and higher) liquid hydrocarbons, black in colour, which can be grown in tropical climate. Melvin Calvin and others are carrying out investigation on pilot scale, and the techno-economic studies indicate that in climatic conditions of say, Morocco/Ethiopia, such fuel trees can be grown such that these are equivalent to about 18 barrels of oil/acre with growth rate of plant of 3 inches to 24 inches in one year, and cost of such oil will be US$ 40/barrel. Such hydrocarbon can substitute crude oil.

(b) *Industry:*

(i) *Salt and Marine Chemicals & Solar Pond:*

For every ton of common salt produced, 4500 litres sea water are to be evaporated by solar energy; optimised designs of salt farm known, are to be adopted and extended for more effective use of solar energy to obtain higher yield of quality product; certain green dyes/chemicals are known to enhance the rate of solar evaporation with increased yield of common salt; more extensive investigations in these respects will go a long way for advancement of technology of salt-winning from sea water. The mother liquor of common salt crystallization (bittern) is the store house of many of the marine chemicals of industrial importance, for example, potash fertiliser, bromine and magnesium chloride and sulphate, mixed-salt, the starting raw material for potash manufacture and other marine chemicals is obtained by further solar evaporation of the mother liquor (bittern), and here also, optimised design conditions are to be established for effective use of solar energy.

"Solar pond" in principle, is a good collecting and storage device of solar energy. The bottom most layers of a solar pond can have a temperature of as high as 90°C or more. Despite low Carnot's efficiency, a low temperature turbine can be used to produce small power. According to one estimate, 1 km^2 of sunny climate = 10^6 kWh = 6000 kW installation at 58 percent load factor. With more technological data obtained relating to size, shape, density-gradients and corresponding temperatures control, such a device can be used for smaller capacity power production in isolated regions.

(ii) *Heating and Cooling:*

Solar energy collector/concentrator/selective surface together with materials of construction, energy storage and intensity of solar radiation are significantly important aspects of "Heating and cooling" in industry. Development of higher temperature (more than 60° C and 110° C, and more than 110° C) collectors, pressurised collectors based on evacuated tubes and honey-combo principle (convection loss reduced by at least 30 percent), concentrating collectors using refractive optics and mirrors will have direct impact on the technology of heating and cooling. Techno-economic gaps are to be filled up in respect of allied other collectors, namely, collectors of different geometrics, parabolic collectors in series, mirror strips and refractive optics collectors, compounding parabolic concentrators, Fresnel lens-mirror combination, stationery spherical collector, total internal reflection prismatic panel, Winston collector, sealed optical module (containing say, solar cells) for power and co-generation application.

Materials development with high visible-absorption and low emmission surface, stable selectivity and resistant to humidity and corrosion with low fabrication cost, iron-oxide with silicon resin (known to be stable upto 180° C), metal carbide-silicide and silver silicon, will go a long way in the use of selective surfaces for obtaining very higher temperature.

(iii) *Process heat:*

Quite a number of industries require comparatively lower temperature process heat upto, say 80° C, hot air system of 70-80° C, and low pressure steam of 130-140° C. For example, textile industry, diary industry (preheating air for spray drying), laundry, milk pasturisation (62.5° C for 1½ hrs.) and sterilisation (72.5° C for 15 mins) and many of the pharmaceutical chemicals and other industries require such low temperature process heat. It is, therefore, essential that survey should be emphasised for such requirement in industries, and every country is to be made conscious of such possibilities. Collectors with selective surface and concentrators will play important role in such applications. It is estimated that in USA solar energy will be able to replace one percent of the current usage of energy in another five year's time, and with the present rate of development of collecting/concentrating devices therein about 20 percent of the industrial energy could be met by solar energy. One of the main conclusions of US studies in this respect in that, 35 percent of the industrial process heat could be supplied by solar energy by the turn of this century. In the studies carried out in food processing industries in Australia, it was concluded that over 50 percent of the annual heat requirements can be met by solar energy. In a country like U.K. with about 40 percent of the total energy used is for industry (and with substantially more diffused solar energy), the solar energy has the potential of replacing at least 3.5 percent of the energy used in industry (except Iron & Steel Industries) which is equivalent to one percent of the total energy used in U.K. In a country like India where also industry consumes about 40 percent of the total energy used in country, in some partial studies the regions of lower-temperature energy uses in certain industries (e.g. . . Chemical, textile, pharmaceutical, glass and ceramics and engineering), have been identified, for example, 50/60°C (Green-House Drying) 60/110°C (baking), 130/140°C (sterilisation, fractional distillation): in such thermal systems, solar energy can be used, of course, for temperature range of about 60°C, use of selective surface/solar concentrators are to be taken resort to for higher ranges of temperature.

(iv) *Renewable fuels:*

As indicated earlier, wood and other forest cellulosic materials are important biomass, - these being produced by photosynthetic process. Production of liquid fuels, such as solar - ethanol by conversion of cellulose into ethanol in chemical processing plants will constitute definite advancement in the field of renewable fuels.

(v) *Power Production:*

The technologies concerned with the solar power production are solar thermal and biogas, wind power and photovoltaic power. Solar thermal power unit is similar to any conventional external heat engine except that the heat is provided by the solar collectors. Higher temperature collectors will be more convenient but expensive. A field of mirrors, each of which is to concentrate sunshine on a stationery elevated boiler obtaining high temperature for producing power. SOFRETES solar engine uses flat-plate collector to boil low-boiling liquids like methyl chloride. Low emmissivity selective surfaces in evacuated glass envelopes have been used to obtain higher temperature. In power production, energy storage will play important part. In photovoltaic power production, although silicon cells (with efficiency of 10 to 12 percent) are used, there is better possibility of use of silicon for the purpose by increasing its purity further and its processing for the purpose. Cadium sulphide is considered as a good photovoltaic material with its weight per unit power more, although the efficiency of solar energy conversion to direct electricity is not more than 7 percent at present. To make photovoltaic power competitive with conventional power, the cost per watt has to be brought down, generally, at least to one US dollar. Nevertheless, even with the present higher cost of photovoltaic power, the solar cells are being used for specialised applications, e.g. unattended light houses, remote communications, TV in rural areas. The concept of Sattelite Solar Power System (S.S.P.S.) is being investigated.

The areas in which more research and developmental investigations are to be made involve: total energy system (as iso-butane turbine generator, also for heating and cooling), wood thermo-power plant, collector based solar thermal power production of (a) 10-50 kW (using say, screw expander engine) (b) higher capacity power by solar farm and "tower power" concept, techno-economic study of solar cells, wind generator, combined solar/bio-gas/wind for rural power, solar furnace-based power, heliohydro-power generation, tide, ocean thermal gradient, wave. Hydrogen is one of the important future clean sources of energy. Investigations are in progress for obtaining this by potentially cheaper methods like photobiological and photoelectrochemicals methods.

(c) *Medical Uses:*

In the life-cycle of human beings and of other forms of life and of vegetable kingdom, sun plays a very significant role. Solar radiation in many instances has been responsible for curing some diseases and improvement of health. Synthesis of vitamin D with ultraviolet radiation is known. Herpis (a skin disease) and jaundice are known to be controlled and cured by solar radiation. Many solariums (slowly moving houses with coloured glasses) are known in some countries. Solar energy as means of curing diseases is under study in certain countries; a number of interesting papers of such study were presented in the 1973 - UNESCO - Solar Energy Congress at Paris. Certain wave lengths of the solar spectrum are found to enhance vegetable growth.

Research and development investigation in the field should emphasis on (i) solar biology involving the effect of different wave lengths of the solar spectrum on human system, growth, resistance to diseases (ii) solarium; vitamin and other body chemicals, solar radiation as germicide, solar radiation and natural behavior of human beings and animals and vegetable kingdom.

(d) *Architecture:*

(i) *Passive System:*

Protection from extremes of nature and of environment is needed for man (as well as for any living being) and or vegetable kingdom. In the passive system of architectural design of houses, community and industrial buildings, optimised design is aimed at for judicious utilisation of solar energy, surrounding air and environment. With the newer technologies of materials at the disposal of man, his concept of more judicious use of solar energy has come to the forefront. Modified and optimised design conditions of the dwellings have to undergo change.

(ii) *Active System:*

Incorporation of solar devices, e.g. heating and cooling, power for lighting and for other uses, can be made in the design of new houses, or can be retrofitted in the existing ones. Experiments are being made with solar houses in different parts of the world under various climatic and environmental conditions. Here again, solar collectors and storage, and materials play critical roles, - the economy of the houses depending on these.

2.2 *Problems of Technology Development (Pre-technology aspects):*

(i) *Measurement:*

Instrumentation and solar mapping are the two most important aspects on which emphasis has to be laid. Although World Meteorological Organisation has laid down certain standard for instruments for recording of data in Solar Radiation Stations, there are not sufficient number of such stations in the world to make use of such instruments. Increasing the number of stations is both expensive and time consuming. At the same time, there are many difficult regions like rural and mountainous ones where in 'direct solar data cannot be obtained. Cheaper/potable solarimeters for such isolated regions will be welcome. Solar mapping including solar, wind, turbidity coefficient data and other allied informations will be extremely useful for solar energy applications. A chain work of radiation stations will be permanent assets of a country for solar energy applications.

(ii) *Collection of solar energy:*

Research and development needs for efficient collection of solar energy have been given details under item "Industry: Heating and Cooling", in which, as much in any other solar devices, collection of solar energy plays important role. Standard testing methods are to be applied for each collector development.

(iii) *Storage:*

Solar energy can be stored as sensible heat, latent heat, biomass, electrochemically, in chemical reactions, mechanical devices, hyurogen, and as potential energy.

The areas of research and development cover: inventories of materials and their physico-chemical and other properties including system stability, corrosion and other effects; for sensible heat water, oil, iron, stoneconcrete; for latent heat, salt hydrates in low thermal grade storage with suitable nucleating agent for recrystalisation guide lines of faster heat absorption and slower rate of release and of thermodynamic, kinetic and chemical criteria which may meet with developments of heating, cooling and pumping; use of white paraffin (b.p. 50-60°C) and also lauric acid and sodium hydrogen phosphate; introduction of metal conductor in paraffin; sodium thiosulphate (mol. of crys. water 5); chemical bond storage amoniated iron-calcium chloride; thermocrete tiles storage; reversible chemical reactions e.g. SO_3 SO_2 + O_2; polymerisation-depolymerisation e.g. system formaldehyde + Alumina; sodium floride (NaF)/water system for refrigeration; eutectic floride salt (melting at 400-800°C) for high level heat supply; fly-wheels for mechanical storage; steam accumulators; solar pond for collection and storage; for power storage, - nickel/cadmium batteries; lead acid batteries; cost per watt (stored); improvement of life cycle.

3.0 *Development of rural:*

It has been indicated before that at least half of the world population live in villages. Any developmental activities under taken nationally or internationally must have a dent on this economically weaker section of the world population. The needs of the people in these areas relate to:

(i) Small-scale/localised needs for domestic purposes. These involve cooking; passive system simple architecture, water desalting and purification; hot water; entertainment. The study needed is the survey of usage of energy both commercial and non-commercial; adoption of cooker, biogas, solar distillation, water heating, solar cells for TV/radio; heat pump with cooker.

(ii) Community developments. These involve wind-solar electric (community education), refrigeration (thermal-wind-solar-electric). Areas of research and development are wind generator/Solar cells/biogas/fertiliser in combination. Improvement in design of animal-driven transport system.

(iii) Agriculture and small-scale industry. These involve solar thermal/wind/-biogas power for small-scale industry, and for ploughing, threshing/-drying/grinding/crushing/pumping/spinning/sawing. Developmental investigation should include small-scale (10-50 kW) electric power from solar/wind/biogas. Feasibility study of the integrated system of solar + wind + biogas along with algae and fish culture and vegetable growing) against the background of supply of food/water/power; rural energy centres.

4.0 *Cost consideration and need for Standardisation of Costing Procedure.*

In many of the applications of various known solar technologies through the solar gadgets, cost has become one of the serious inhibiting factors. Solar intensity, materials, collecting/concentrating device and storage of energy play significant roles in this respect; in addition, geography, labour, transport, climatic condition, technology transfer, and national energy planning also play part. In many instances, it was and is difficult to know the cost of a solar gadget based on a solar technology in a given situation until all the above stated pertinent scientific and technological informations and allied relevant data are known, for example, the cost of solar collector for use in solar water heating device varies (as reported by various authors) from US\$ 12/m^2 to ten times this value. Different investigators had given the cost of solar cookers (say, for 3 m^2 area) ranging from US\$ 20 to 35. Cost of electricity from silicon solar cells has been reported by various scientists and manufacturers as US\$ 5 to 15 per peak watt. Many more examples can be cited in these respects. In the techno-economic study of a solar technology and the device thereof, under a given situation in a region, it is very difficult to arrive at a definite conclusion as regards the suitability of a device with existing informations. It is, therefore, emphasised that some kind of standard costing procedure has to be evolved, not only for the above stated purpose but also for a comparison of techno-economic viability of a solar device developed by various scientists under different overall conditions. Any organisation of United Nations System (e.g. ESCAP) can take initiative in setting up such standardised costing procedure.

5.0 *Organisational/Operational:*

Harmonious co-ordination of the peoples, resources, technologies and organisation for effective development and use of technologies must be effected with bilateral/-regional/international collaboration. The important aspects of this respect are: sector-wise energy survey and data analysis, including traditional and socio-economic aspects; environmental impact; data bank; technology transfer centres country-wise and region-wise; technology, R & D, and scientific man-power directories; standardisation of methods of testing of devices singly and in combination and in integrated systems; training; rural energy centres; setting up demonstration units; National Solar Energy Commission; International Solar Energy Commission.

6.0 *Strategies, and a plan of action:*

(i) *Strategies*

In the light of those enumerated above, it is now possible to state more concretely the strategies to be adopted by the developing countries under conditions of deteriorating energy scenario. These are:

(a) Energy developments must be related to the basic needs of life.

(b) Emphasis is to be laid on the all round development of the rural areas, and rural energy centers must be established as part of the national planning of a country.

(c) Modernisation of the usage of the renewable sources of energy is to be carried out with faster rate.

(d) Development of materials must go ahead and their radiative properties must be known for use in solar gadgets.

(e) Solar technological developments must incorporate developments of collecting and storage devices in concrete way.

(f) Integrated systems of energy usage must be experimented and emphasised, and combined use of conventional and renewable-based energy must be encouraged (e.g. coalgas+biogas).

(g) Research and development investigations are to be carried out in fields relating to small capacity power developments, solar ethanol, energy plantation, solar biology, and hydrogen production.

(h) Establishment of National Commissions and International Commission on Solar Energy, including in their scope all direct and solar - based sources of energy (given in table 1).

(ii) *A plan of action:*

Such a plan of action comprises of the activities both R & D, and organisational in nature, and other allied activities which will lend to further utilisation of this natural source of energy. These activities have been categorised under the main approaches of conversion for use of solar energy, and the organisational/operational aspects.

(a) *THERMAL CONVERSION:*

(A) Collector technology and fluid systems for higher temperature ranges, and use of selective surface, different geometrics, pressurised and evacuated tubes and honeycomb principle.

(B) Materials inventories and development with desirable radiative thermodynamic, physico-chemical, chemical and mechanical properties for solar devices including storage of energy as heat (sensible and latent), mechanical (e.g. flywheel) and electrical power.

(C) Small capacity (10-50 kW) engine development and total energy system.

(D) Solar pond development as combined collector/storage and for small capacity power.

(E) Development of cheaper and portable solarimeters.

(b) *DIRECT ELECTRIC CONVERSION:*

(A) Development of materials for semiconductors and comparison of performance of different solar cells e.g. polycrys-silicon and monocrys-silicon cells, thin film cadium sulphide and amorphous silicon cells, Schotky Barrier (S-B) silicon cells, EFG-cells, higher concentrator-coupled cells and use of extracted heat, the ultimate object being to bring down the cost.

(B) Wide-scale demonstration units of solar cells with battery for TV/radio/light houses/distant communications.

(c) *PHOTOSYNTHESIS & BIOCONVERSION AND ALLIED METHODS:*

(A) Short-rotation forestry and Energy plantation, Fuel trees secreting hydrocarbon and power generation.

(B) Modernisation of non-commercial energy sources (e.g. firewood, vegetable wastes).

(C) Green-house for vegetables in arid/semi arid regions.

(D) Optimisation and standardisation of biogas plant/fertiliser production.

(E) Solar ethanol production.

(F) Hydrogen by photobiological and photoelectrochemical methods.

(G) Solar radiation as germicide.

(d) *ORGANISATIONAL AND OPERATIONAL:*

(A) Sector-wide (rural/urban) energy usage survey and environment.

(B) Feasibility studies of integrated systems including combined energy uses in rural areas.

(C) Technology transfer centres country-wise and region-wise.

(D) Rural Energy Centres.

(E) Demonstration Units.

(F) Training of personnel: Existing fabrication facilities and creation of new ones.

(G) Standardisation of methods of testing of devices and cost estimates.

(H) Directory of technology, R & D and scientific man-power, information system.

(I) National Commissions of Solar Energy.

(J) International Commission of Solar Energy.

With harmonious co-ordination of the peoples, technology, resources and the organisations, the developments obtained with the applications of solar energy will have take off stage for having definite socio-economic impact.

DEVELOPMENTS IN SOLAR COOLING:

A REVIEW

by

J.C.V. CHINNAPPA

1. INTRODUCTION

Refrigeration cycles can be operated by heat sources at relatively low temperatures (around 100° C) and as such as have been considered as applications for solar energy. In recent years there has been considerable activity in this field of research more so in air conditoning than in applications requiring sub zero temperatures.

Most types of air conditioning systems using solar energy as heat source for their operation have been proposed and include:

(i) LiBr-water single and multistage absorption systems,

(ii) organic working fluid Rankine cycle systems coupled to vapour compression units,

(iii) ammonia-water single stage and multistage absorption systems, and

(iv) adsorption and absorption dehumidification.

Two of these schemes, namely the LiBr single stage absorption and the Rankine cycle systems, have progressed well beyond the proposal stage and are now in the process of full scale testing. Others are at various stages of development from feasibility studies through the design and testing of components to the testing of experimental prototypes. Examples of these systems will be reviewed.

2. AQUEOUS LITHIUM BROMIDE SYSTEMS

The pioneer work on the solar operation of the aqueous LiBr cycle was due at the University of Wisconsin Solar Energy Laboratory (Chung et al, 1959, 1963) and the first house to be cooled by a prototype system was the solar house at Brisbane at the University of Queensland (Sheridan, 1972). Since then a considerable amount of work has been done on all aspects - thermodynamic, plant design, and full scale performance testing.

The simple absorption cycle is shown in Figure 1. The coefficient of performance of this cycle

$$COP = Q_S / Q_A$$

where Q_S is the heat supplied to the generator from the high temperature heat source. This heat boils off refrigerant which condenses in the condensor and then evaporates in the evaporator abstracting heat from a low temperature (Q_A). Heat is rejected (Q_R) from the condensor and absorber to the cooling medium.

The ideal thermodynamic vapour absorption cycle can be represented on the p-t-x diagram (Fig. 2). On the abscissa scale we can read off values for evaporator temperature, condenser temperature, the temperature ranges during absorption and generation, on the ordinate scale the associated pressures and from the graph the solution concentrations.

Allen, Morse et al (1974, 1976) have performed a systematic analysis of the thermodynamic cycle. They have investigated the basic cycle, and thereafter the effect of off-design operation on the coefficient of performance, heat exchanger size, solution circulation rate etc. Miller (1976) has computed the effect of variations in cooling water and chilled water temperatures on heat supply temperatures.

Multistage LiBr systems have been theoretically investigated in computer studies by Allen, Morse et al (1976) and by Wilbur and Mitchell (1975). In addition Wilbur and Mitchell have enquired into the effect of a heat rejection buffer and of refrigerant storage. Interesting developments are foreshadowed by these enquiries.

In addition to the theoretical studies just mentioned full scale testing of air-conditioning plant incorporating single-stage aqueous LiBr coolers are in progress in many countries, including the U.S.A., Japan and Australia. The Ishibashi solar house in Japan (Ishibashi, 1979) has the following specifications:

Floor area:	138 m^2
Collector:	flat plate, single glass cover, selective surface, 56.7 m^2
Hot store:	56.4 l/m^2
Chiller:	1.3 ref. tons (4.6 kW)
Aux. boiler:	kerosene

The results of two years of testing are presented in Table 1. The solar fractions reported are satisfactory but it is not clear whether the auxiliary energy includes parasitic power consumption - i.e. the power required to drive the pumps in the solar system.

Among the earliest full scale plants installed in the U.S.A. were the three Colorado State University Houses, and performance data has been forthcoming on the basis of systematic testing.

CSU House III has the following plant:

Collectors:	flat plate (Chamberlain), single cover selective surface, 53.3 m^2
Hot store:	4.54 m^3
Chiller:	2 ref. tons (7 kW) LiBr
Cold store:	1.89 m^3

The performance over the period July 1978 to March 1979 has been reported by Ward and Oberoi (1980). The electrical solar COP (ESCOP), the controlled useful heat supplied to the heating/cooling load divided by the total electrical consumption of the solar system excluding auxillary power was about 7.5. With improvements in plant layout it was expected that this ratio would improve to 15.

Information on the design and performance of components, namely storage tanks, chillers etc are being collected (e.g. Szokolay, 1980). The heat losses from hot storage tanks have been found to be significant. Ward et al (1978) have proposed a 3 tank storage system for a heating/cooling installation. Yazaki have quite recently recommended that a chilled water store is not necessary.

The fact that LiBr water chillers operated by steam or gas were already in commercial production enabled these devices to be readily modified for operation by hot water from solar collectors at temperatures below 100°C. Consequently a number of these plants have been installed. In addition to the performance data described above, the capital cost of plant is available, and is of importance.

Booth and Saunders (1980) have compared the costs of several installations in Australia (Table 2, Figures 3 and 4). These costs, in relation to the predicted performance of the plant and the savings that can be expected therefrom, are uneconomic according to Langridge and McCormick (1980).

It has to be borne in mind that these installations are experimental, and reductions in cost can be expected as designs and control strategies improve and construction costs decrease. Moreover actual performance figures will become available and soon we should be able more realistically to appraise economic viability.

However there seems little doubt that quite substantial decreases in capital and installation costs need to be achieved if aqueous LiBr plant is to become cost-effective for applications where only cooling is required. In the case of combined heating and cooling applications Ward (1979) has demonstrated economic viability.

Methods of assessing economic viability using discounting procedures are available in the literature, and are fully described in Kreith and Kreider (1978). These methods are dependent upon a number of uncertain factors e.g. inflation rate, increase in cost of auxillary energy. But clearly economic viability is a crucial matter, and an estimate, as reasonable as possible, needs to be made.

Where r = interest rate (as a fraction)

f = inflation rate

y = increase in cost of fuel,

the effective interest rate, $r^1 = \frac{(1+r)}{(1+f)} - 1$, and

effective increase in fuel cost, $y^1 = \frac{(1+y)}{(1+f)} - 1$

If C = (initial capital investment on solar plant) - (capital cost of equivalent conventional plant)

S_1 = Savings in operating cost in first year (which will include energy and maintenance costs)

p = payback period in years,

then
$$\frac{C}{S_1} = \frac{1}{r^1 - y^1}\left[1 - \frac{(1+y^1)^P}{(1+r^1)}\right]$$

A plot of this equation for various probable values of r, f and y, and estimated values for p and S, for the particular application would provide a range of values of C which indicate economic viability. These values indicate a ceiling for capital investment on solar plant for that application. It is advisable that a preliminary assessment such as this is made at the design stage.

3. AQUA AMMONIA SYSTEMS

Pioneer work in the aqua-ammonia absorption system for air conditioning was done at the University of Florida by Farber and his associates (1966). In spite of this early start development of these systems has been slow.

One of the reasons for this slow development was perhaps that NH_3 was toxic whereas the aqueous LiBr combination was not toxic at all. The other and perhaps the major reason was that generator in the commercial aqua-ammonia air conditioning unit operates at much higher generator temperatures (in excess of 150° C) - temperatures well in excess of those attainable with flat plate collectors. The generator had therefore to be completely redesigned to accommodate temperatures around 100° C.

This work has been taken in hand, and at the University of California Berkeley, Simmons and his coworkers (1975) have modified an Arkla ACB 60 5 ref ton machine by designing and building a new generator to be heated by hot water (Figures 5 and 6). Tests on this unit have been published (Dao, 1979): see Figure 7.

At the University of Sydney A.M. Johnston (1980) has developed a compact form of heat exchanger by photo-etching flow passages into stainless steel plates which are then diffusion bonded together (Figure 8). This enable a close temperature approach in the counter current heat exchangers with the possibility of values of COP of 0.75 to 0.85 for sink temperatures of 30 to 50°C. An extremely compact design results: Figure 9 shows a 1 kW refrigerator.

The NH_3-H_2O system lends itself more easily to air cooled operation - as shown by the work at Berkeley and Sydney - than the LiBr system where there is the danger of crystallisation. (Charters and Chen (1979) have suggested an air cooled design for H_2O-LiBr).

While plant design and experimental work is proceeding studies of the thermodynamics of the cycle and modelling of the solar collector - absorption refrigerator combination are also under way (Allen et al, 1976). The NH_3-H_2O combination can be used with facility in a variety of cycles, single and two-stage. Chinnappa (1974, 1976), Dao (1978, 1979), Johnston (1980) and others have proposed more efficient cycles which could reduce the overall cost of solar plant.

An experimental program is now under way at James Cook University to build and test a pilot plant working in dual-mode on the double effect cycle (Figure 10).

The intermittent cycle has also been proposed for air conditioning (Swartman, 1976), and the performance of an experimental plant working on this cycle reported at the University of Florida by Farber et al (1978).

A considerable amount of theoretical and experimental work is still left to be done before the aqua-ammonia absorption system both single and two-stage can be adequately assessed. There certainly appear to be quite promising possibilities in this area.

4. RANKINE CYCLE SYSTEMS

The third method of utilising solar energy to produce cooling is by operation of a vapour cycle the ideal form of which is the Rankine cycle (Fig. 11). The arrangement consists essentially of 3 loops. The solar loop consists of solar collectors heating up water which can be stored as hot water. This hot water is used to boil the working fluid in the vapour cycle. The vapour is expanded in a turbine, condensed in a feed pump and returned to the boiler. The turbine drives the compressor of a conventional vapour compression refrigerator.

Plant development is being vigorously pursued (Prigmore and Barber, 1975; Barber, 1976; Eckard and Bond, 1976; Biancardi and Meader, 1976).

One of several organic fluids may be used in the vapour cycle loop. The ideal coefficient of performance is the cooling effect produced in the evaporator divided by the heat supplied in the boiler and this is shown in Figure 12 for an evaporator temperature of 7°C against the COP of an absorption system. It will be observed that at lower condensing temperatures the Rankine cycle-vapour compression conbination has significantly higher values of coefficient of performance.

Research in this field is being conducted by come of the outstanding technical firms in the U.S.A. e.g. G.E.C., Carrier, and has been reviewed by Rooks (1979).

5. DEHUMIDIFICATION BY ABSORPTION AND ADSORPTION

Essentially the procedure for producing comfort conditions using a dehumidification process with a solid desiccant packed into a wheel is as shown in Figure 13. Ambient air which is hot and humid is passed through the matrix of the dehumidifying wheel packed with desiccant (e.g. silicagel or molecular sieve). The air is both heated and dried as it passes through this wheel. It is then cooled and finally humidified to achieve comfort conditions. The earliest proposal regarding the use of solar energy for dehumidification was due to Lof (1955). He proposed the use of tetraethylene glycol as a dehydrating agent (Fig. 14).

Since then work has been done on several absorbents both liquid and solid and on absorbents, the investigations at the C.S.I.R.O. Division of Mechanical Engineering Melbourne by Dunkle (1965) and co-workers being notable.

Dunkle's proposal for cooling has not yet, as far as the writer is aware, been experimentally tested but testing of components and studies on absorption - desorption have been in progress (Hollands, 1963; Dunkle et al, 1976; Close and Pryor, 1976; Close and Dunkle, 1976). A recent award of a U.S.A. Department of Energy contract to the University of Wisconsin, Madison with a subcontract to the C.S.I.R.O. Division of Mechanical Engineering, Melbourne ensures progress in this research (Close, 1980).

At the 1975 ERDA Los Angeles Solar Cooling Workshop systems operating on the same principle but differing in detail were described by Rush (1976) and Lunde (1976). Lunde described a feasibility study using silicagel and Rush a prototype unit in which a gas burner was provided to supply auxiliary heat (when solar heating is inadequate) to regenerate the 50% molecular sieve-impregnated asbestos dehumidifying wheel (Figure 15). The solar collectors were evacuated glass tube collectors and the hot water storage consisted of two 500 gallon tanks (Figure 16). Three of these units, each of approximately 3 ton capacity have been tested in the U.S.A. since 1976 and more recently in West Asia.

Tehernev (1976) has described a system using zeolite as an absorbent. He claims that the properties of zeolite are superior to silicagel when solar operation is considered. This work has been developed further by Meunier (1979).

Of interest in these several investigations were various absorbents proposed and the manner in which solar regeration was accomplished. Dunkle has suggested silicagel and its regeneration by hot air directly from solar air heaters or indirectly from a rock pile thermal store. Lunde and Rush have proposed zeolite and molecular sieve respectively with hot water from collectors being used to heat the air required for regeneration. On the other hand Tchernev and Meunier have proposed that the absorbent zeolite be heated directly by the sun.

Meanwhile Mullick and Gupta (1974) and Gandhidasan et al (1979) have systematically investigated $CaCl_2$ as an absorbent. The first phase of the investigation has been the design and testing of a free flow solar heater for the refrigeration of the brine with one glass cover, open at top and bottom to the atmosphere. A similar investigation using LiCl has been reported from the U.S.S.R. (Baum et al, 1973).

6. REFRIGERATION

In contrast to air conditioning research in recent years, research in solar refrigeration (sub-zero evaporator temperatures) has been pursued in only a few places. This is perhaps due to the opinion that solar refrigeration may not be widely applicable - indeed may only be relevant to regions where there is a lack of a reticulated power supply and an abundance of solar radiation. There are sociological and economic factors also to be considered as shown by Gururaja and Ramachandran (1979) and Sloop and Gordon (1979).

The main thrust has been in the development of the intermittent absorption system (Fig. 17). Such devices have used concentrating collectors (Trombe and Foex, 1957; Williams et al, 1957; de Sa, 1964) and flat plate collectors (Chinnappa, 1961, 1962; Swartman, 1970; Exell et al, 1978; Venkatesh et al, 1979). The Asian Institute of Technology plant is shown in Figure 18. All the intermittent refrigerators tested have been small devices with collector areas of less than 2 m^2 using ammonia-water and ammonia-sodium thiocyanate as refrigerant absorbent combinations. The properties of the NH_3-NaSCN combination was determined by experiment and its potential for use in an absorption cycle theoretically assessed by Sargent and Bechman (1968).

Larger capacity plants have been proposed by research workers e.g. the NH_3CaCl_2 plant described by Eggers-Lura (1975), and the plant, shown in Figure 19, at the A.I.T. Bangkok. The continuous aqua-ammonia cycle is also being investigated for solar operation, and plants to maintain sub zero cold room temperatures are being built and tested at the Indian Institutes of Technology in Bombay and Madras. These plants use electricity to drive the solution circulation pumps.

A modification of this design whereby solution circulation is achieved by a hydraulically operated transfer tank (not an externally driven pump) is being tested at James Cook University. If this arrangement works then the iceplant will be entirely solar operated. The plant being tested has a collector area of 8.6 m^2.

7. CONCLUSION

Gartside (1977) has stated "electricity is widely used for domestic water heating and room heating. Each kWh of heat from electricity requires 3 kWh of coal, but if the same amount of coal was used to construct solar collectors 15 kWh of heat would be obtained." Solar cooling would be energetically less efficient: the ratio is more likely to be about 3:1 instead of 15:1. Still the energy saving is significant and justifies continued research and development in solar cooling.

The technology has been demonstrated in most applications. There remains the problem of making solar cooling cost-effective, and that is the major challenge facing us today.

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TABLE 1. OPERATION OF ISHIBASHI SOLAR HOUSE, JAPAN

FROM AUG 1976 TO JULY 1978

Operation	*Solar Radiation*	*Solar Energy Collected*	*Total Load*	*Energy Used*	*Energy Lost*	*Aux. Energy*	*Chiller COP*	*Solar Fraction*
Cooling		55566	25458	18420	23020	7031	0.48	0.724
	(3649)	(980)	(449)	(325)	(406)	(124)		
Heating		103307	47798	37876	33962	9923		0.792
	(6264)	(1822)	(843)	(668)	(599)	(175)		
Hot Water			52334	45587		6747		0.871
			(923)	(804)		(119)		
Total		158873	125590	101891	56982	23701		
	(9913)	(2802)	(2215)	(1797)	(1005)	(418)		0.811

Note: Columns 2 to 6 Upper row: Total energy for two years, MJ
Lower row: (Energy per unit collecting area, MJ/m^2.

TABLE 2. SUMMARY OF DEMONSTRATION PROJECTS

Symbol	*A*	*B*	*C*	*D*	*E*	*F*	*G*	*F*
Cooling Capacity (kW)	32	88	17.5	35	7	10.6	10.6	140
Collector Type	Flat Plate Selective Surface	Flat Plate Selective Surface	Evacuated Tube	Tracking Concentrating	Flat Plate Selective Surface	Flat Plate Selective Surface	Flat Plate Selective Surface	Flat Plate Selective Surface
Year of Installation	1979/80	1978/79	1979/80	1980	1979/80	1979/80	1979	1980/81
Location	W.A.	W.A.	W.A.	W.A.	N.S.W.	VIC.	VIC.	VIC.
Total Installed Cost ($)*	139 550	100 623	75 400	44 191	24 587	23 293	21 808	289 000
$/kW of Cooling Capacity	4 361	1 143	4 309	1 263	3 512	2 197	2 057	2 064

* $ DECEMBER 79.

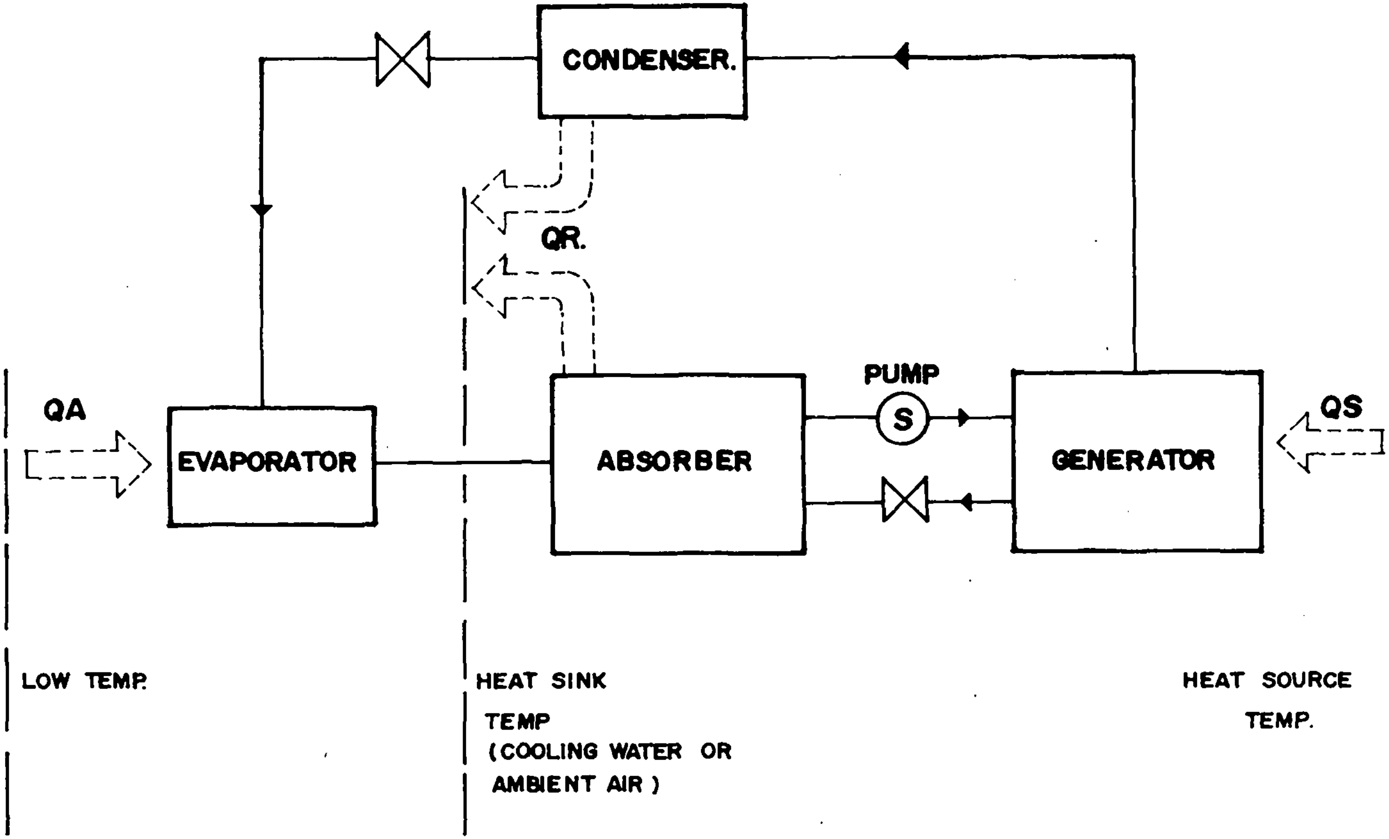


FIG. I SIMPLE ABSORPTION CYCLE.

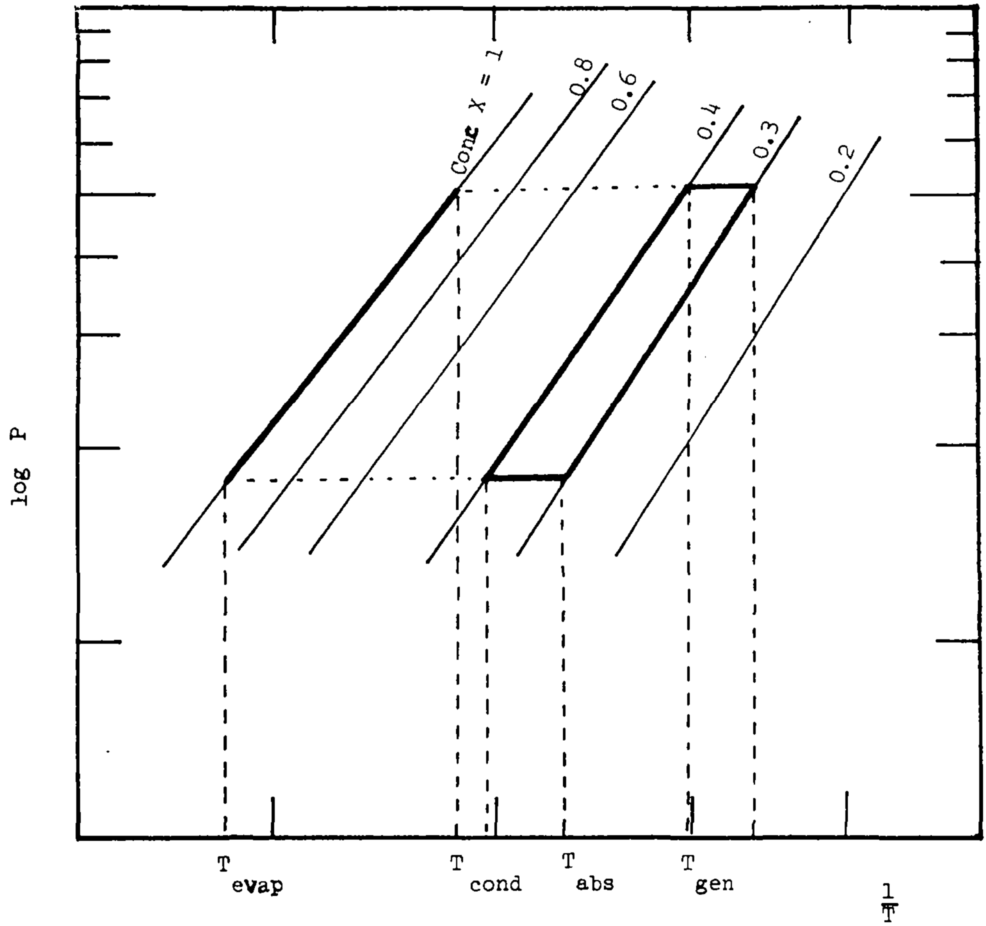


Fig. 2. Simple vapour absorption cycle.

Fig. 3. AIR CONDITIONING PLANT COSTS COMPARISON
Note: Width of column indicates plant size

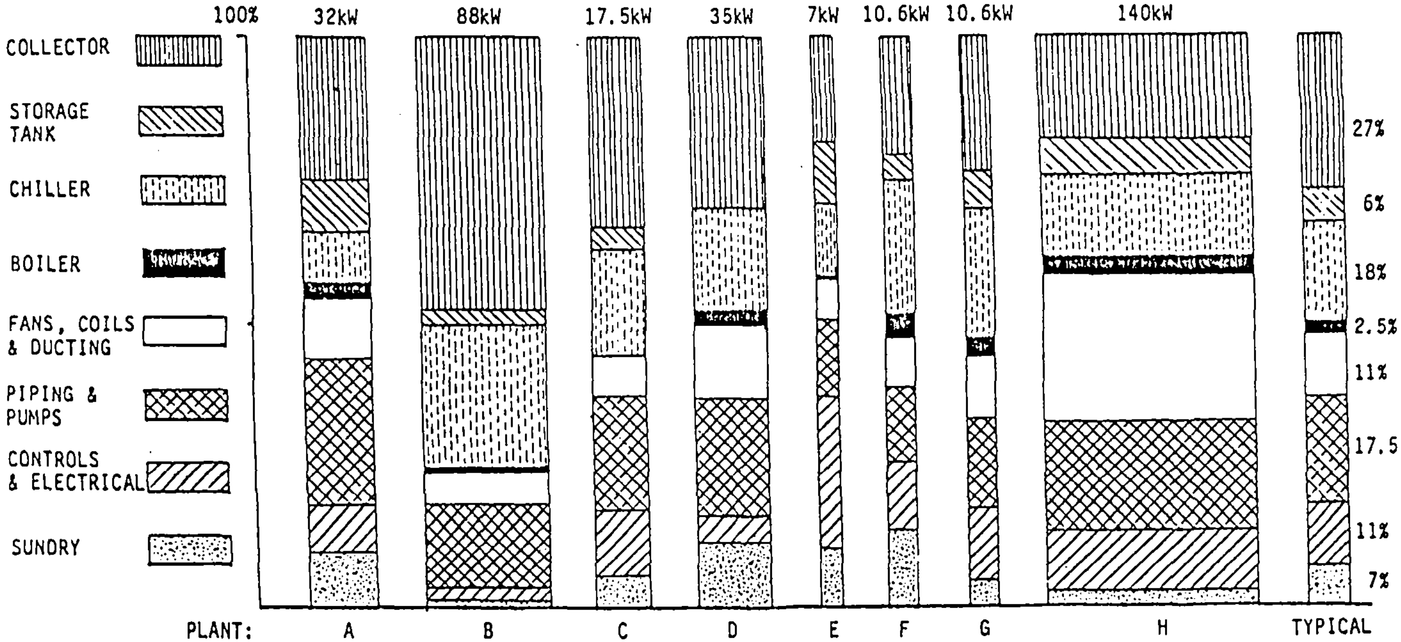
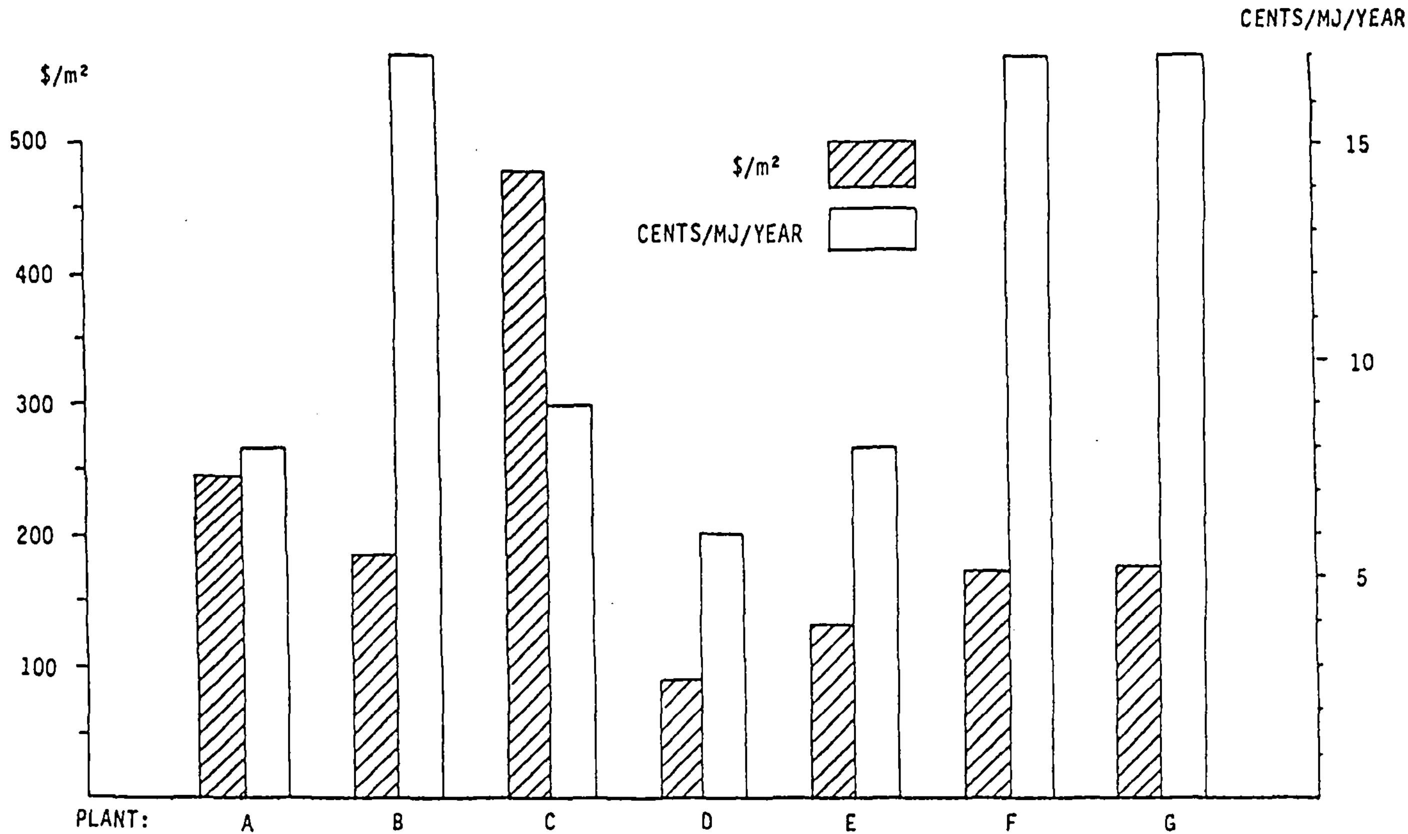


Fig. 4. CALCULATED SOLAR COLLECTION COSTS (PERTH)



Note: No information was available on collector performance for Plant H.

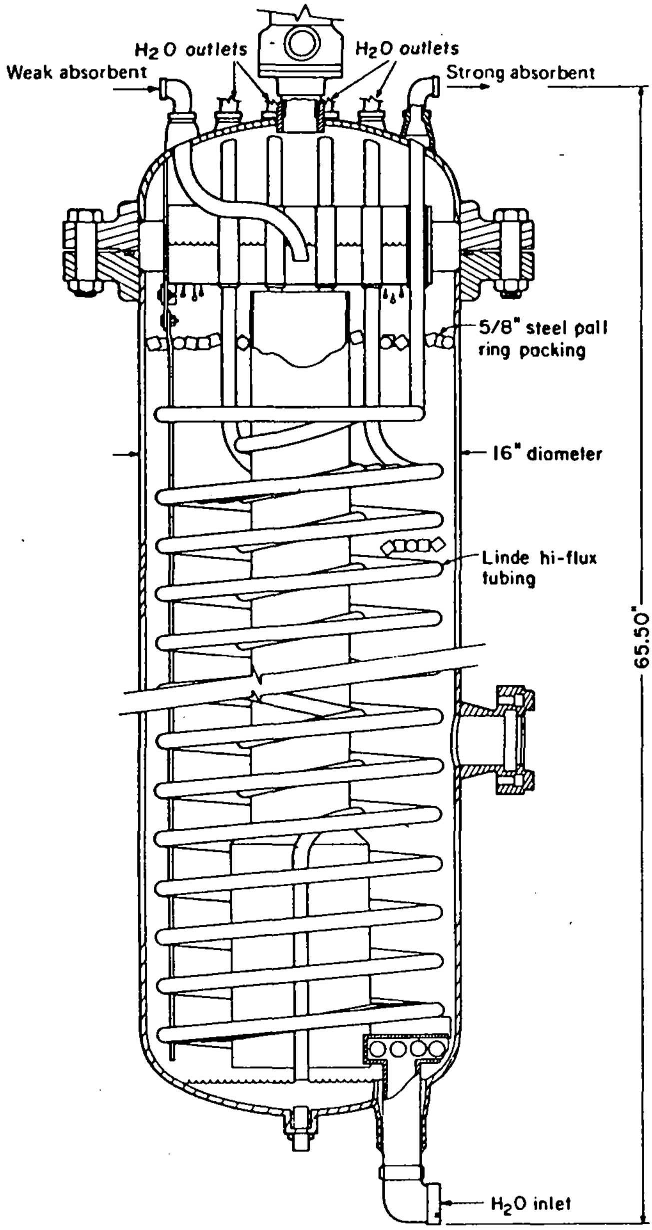
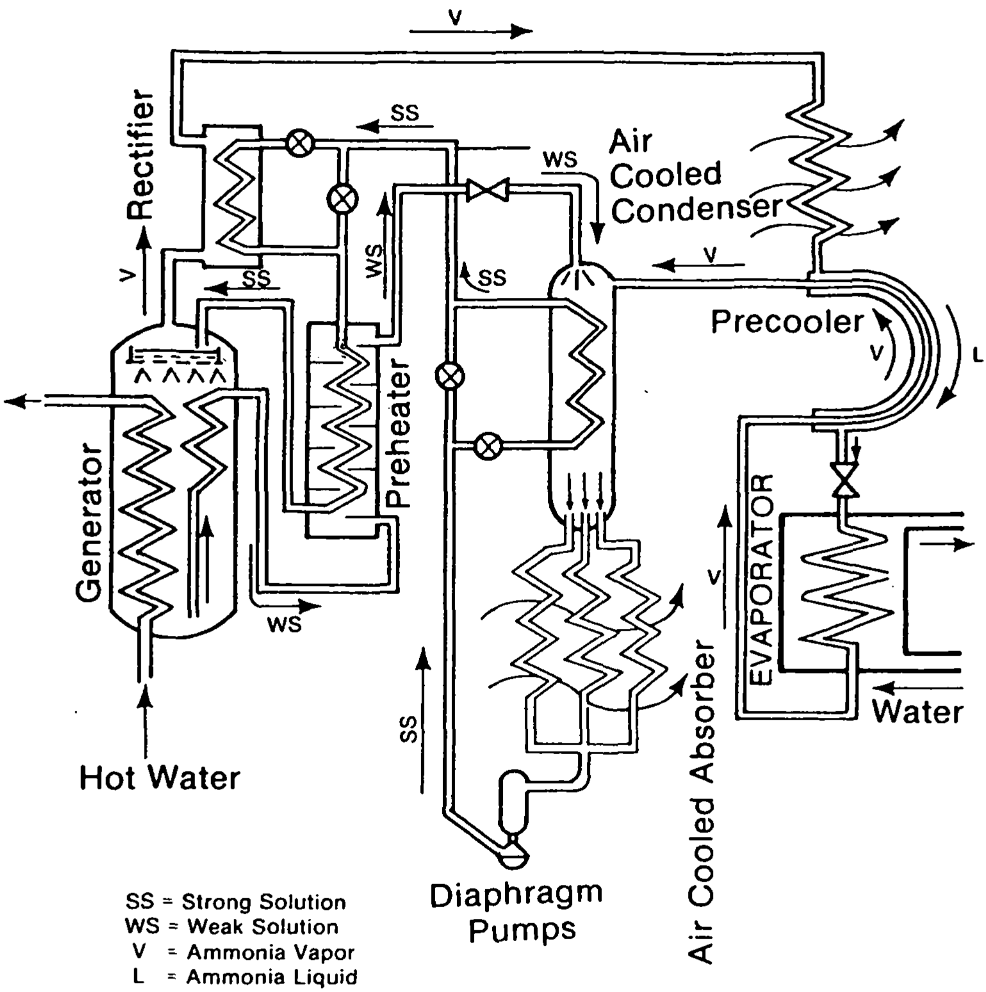


Fig. 5. The generator designed for operation with solar heated water. The Pall ring packing extends from the liquid distribution pan to the bottom layer of coils.



XBL 771-140

Fig. 6. Schematic diagram of the absorption air conditioner as modified for solar operation.

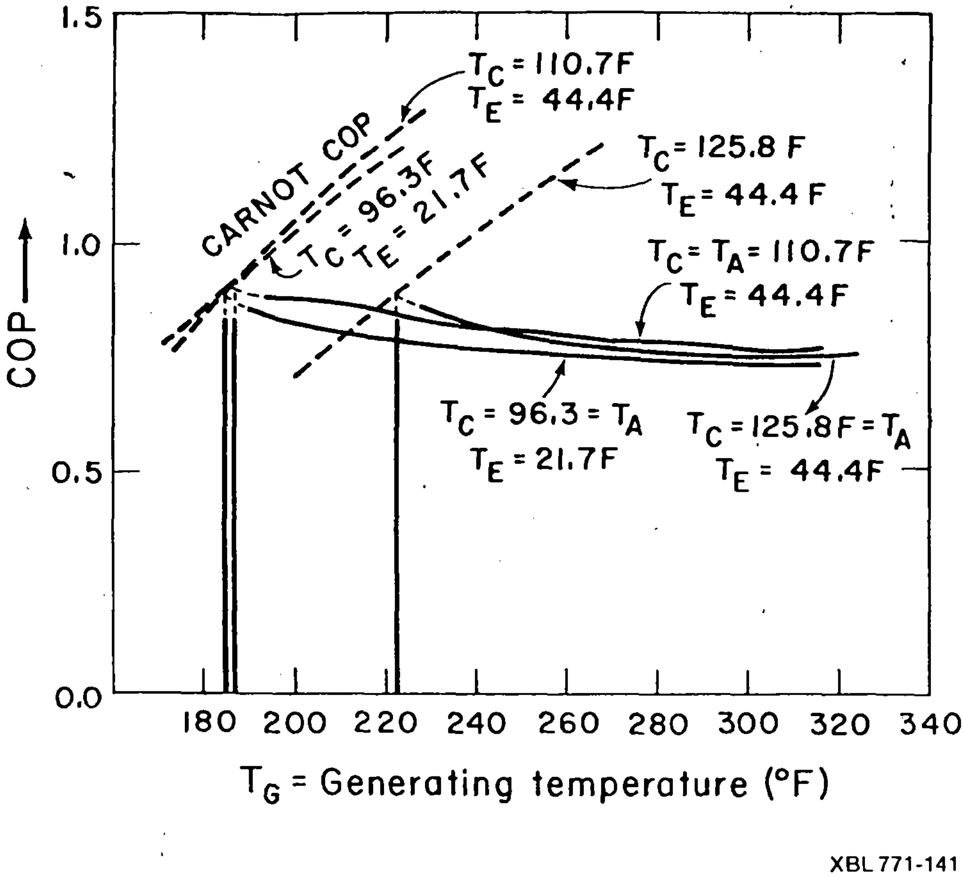


Fig. 7. Theoretical max COP for NH_3-H_2O absorption cycle (single stage) at different operating temperatures (equation 9).

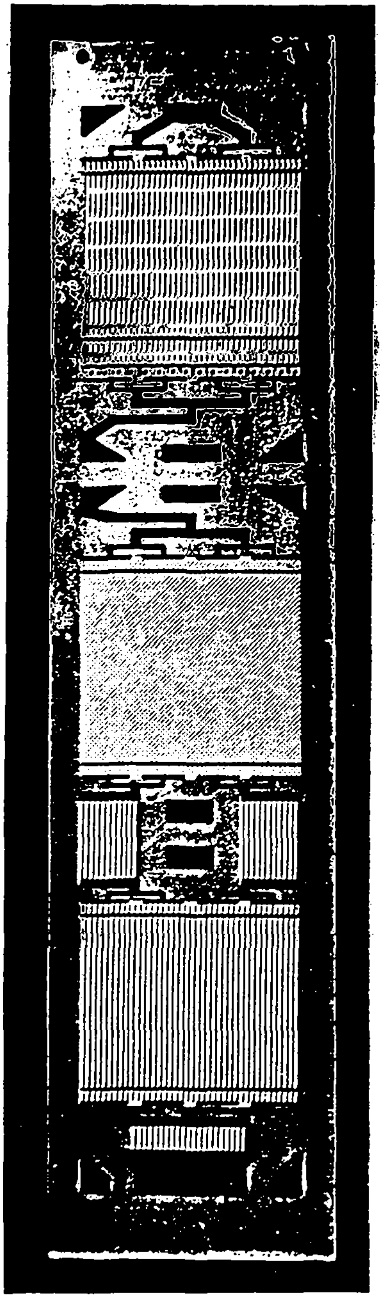


Fig. 8. Photo-etched heat exchanger plate for $NH_3 \cdot H_2O$ plant

Fig. 9. Experimental 1 kW NH_3-H_2O refrigerator (Johnston, 1980)

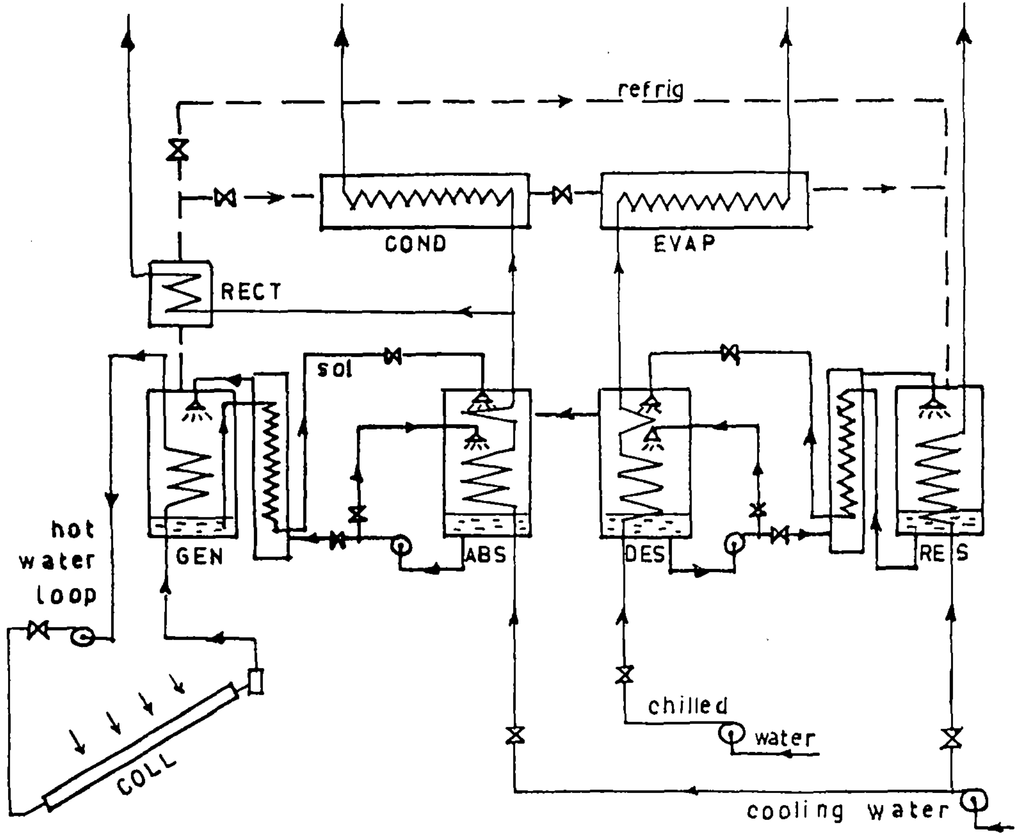


Fig. 10. Flow diagram for NH_3-H_2O two stage plant (Chinnappa, Martin 1976)

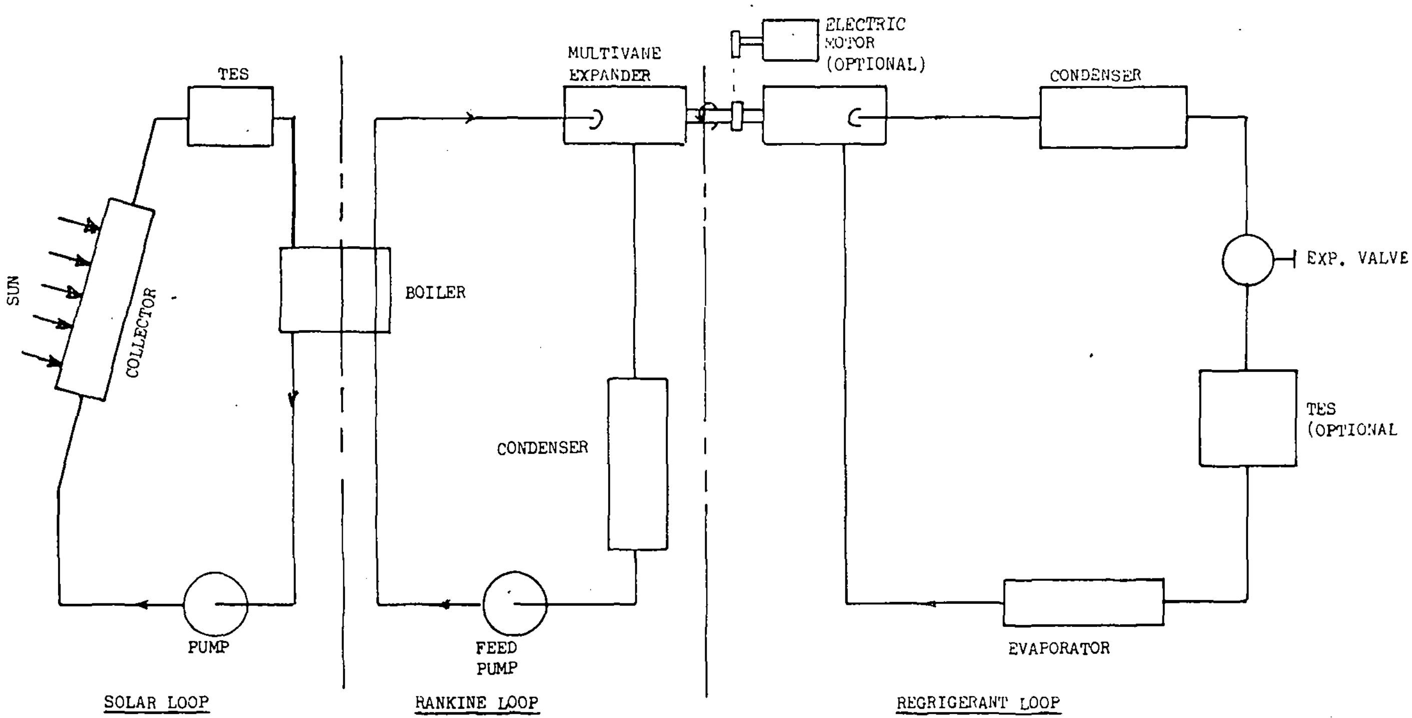


Fig. 11. Rankine cycle system

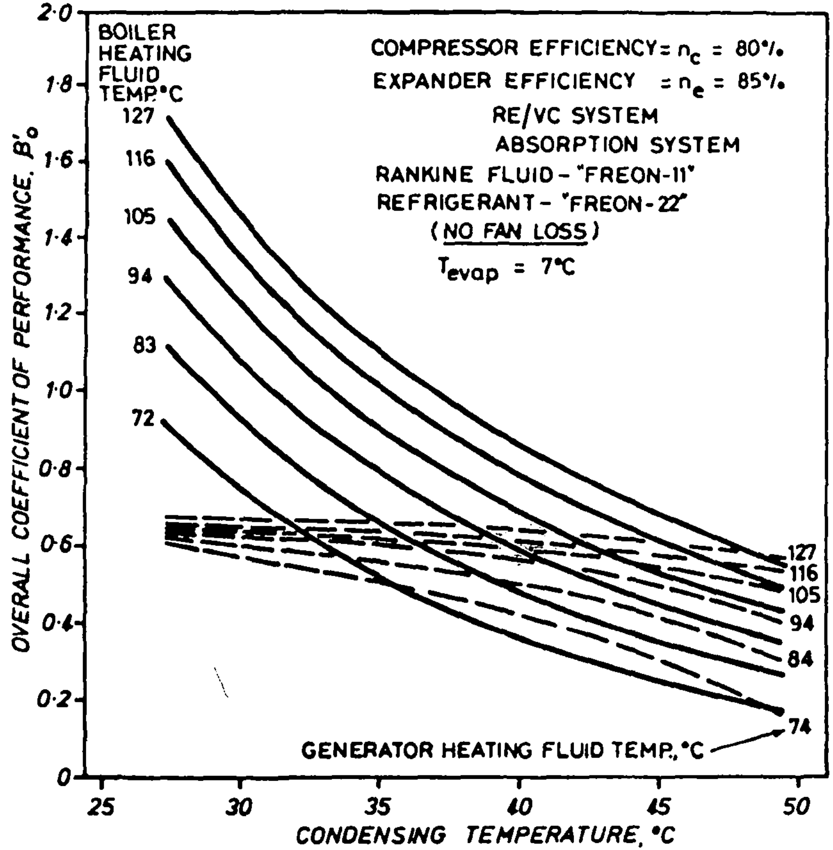


Fig. 12. RANKINE CYCLE AND ABSORPTION CYCLE PERFORMANCE RANGES

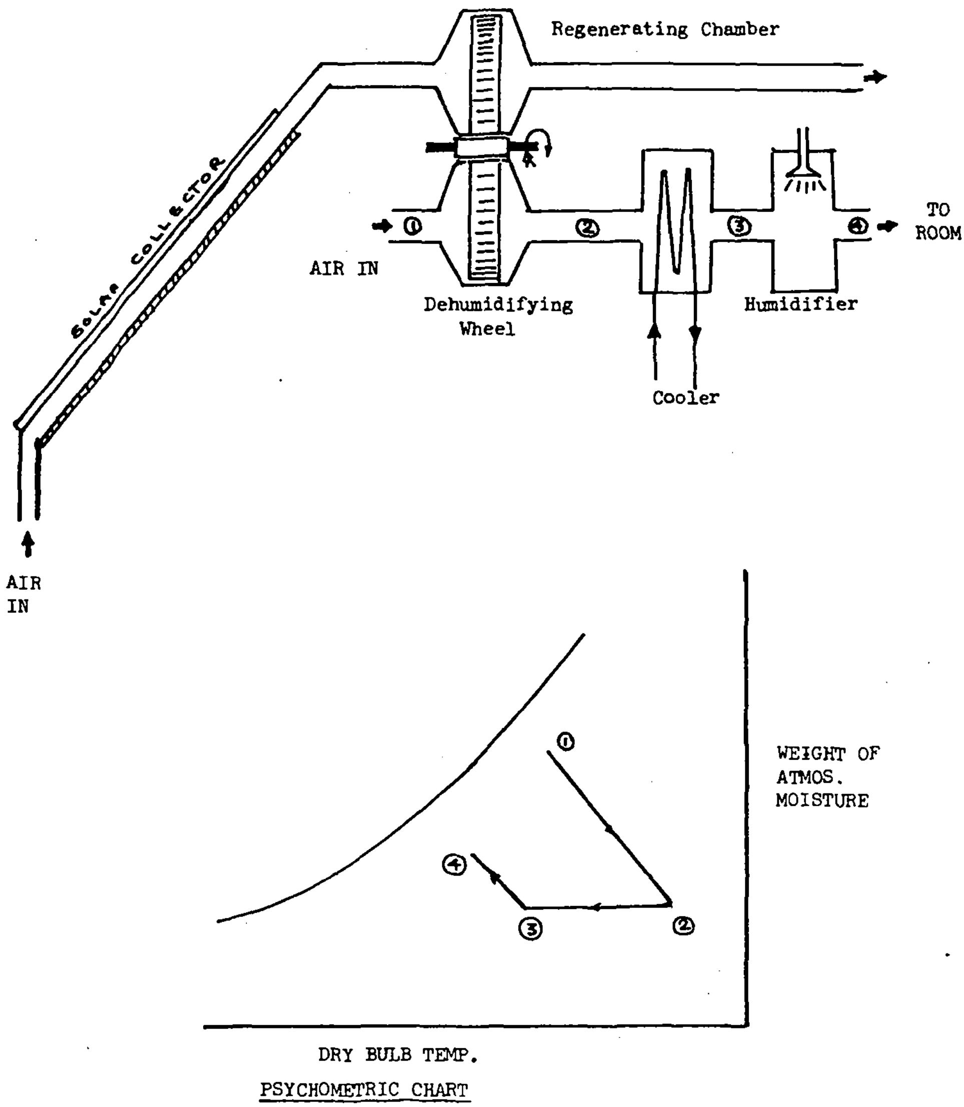


Fig. 13. Principle of Air Conditioning by Dehumidification.

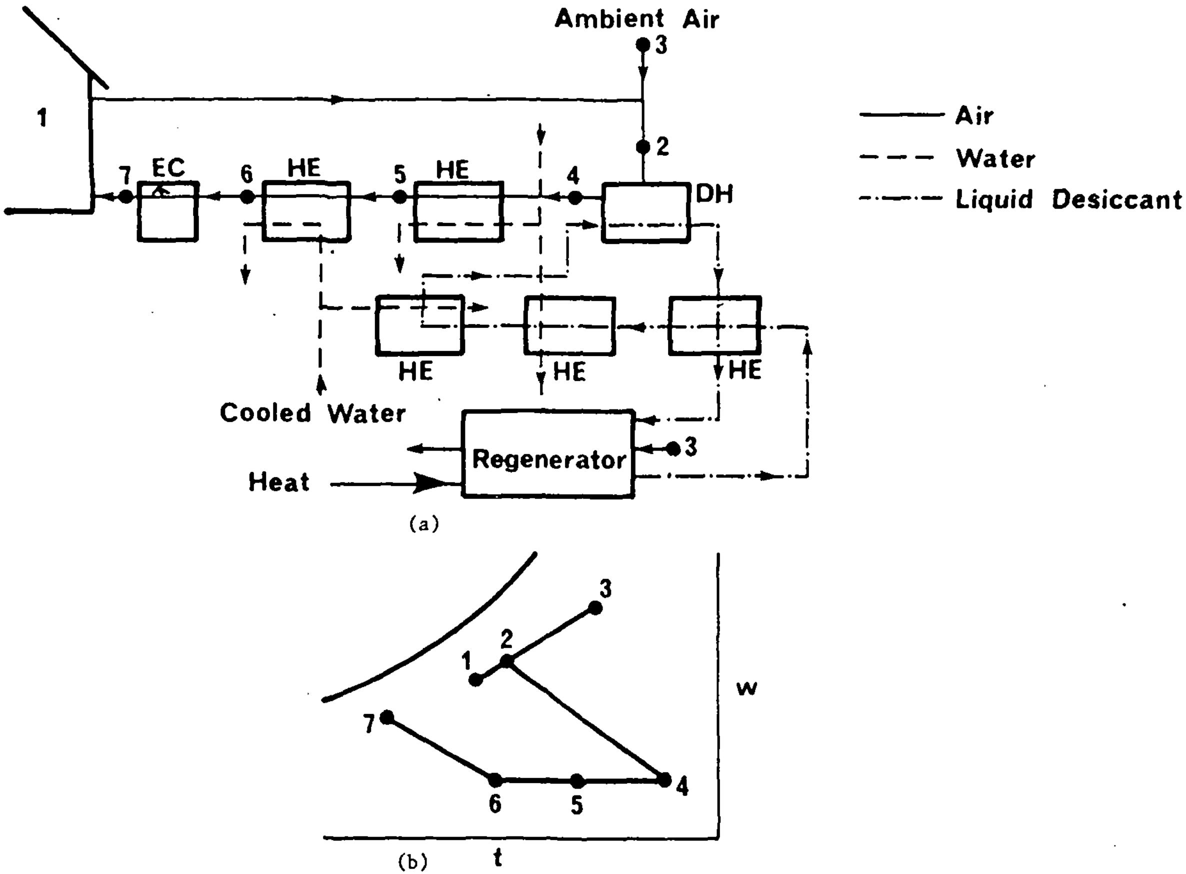


Fig. 14. Diagrams Illustrating the Behaviour of Open Cycle Cooling System with Liquid Desiccant. EC – evaporative cooler, HE – heat exchanger, DH – dehumidifier.

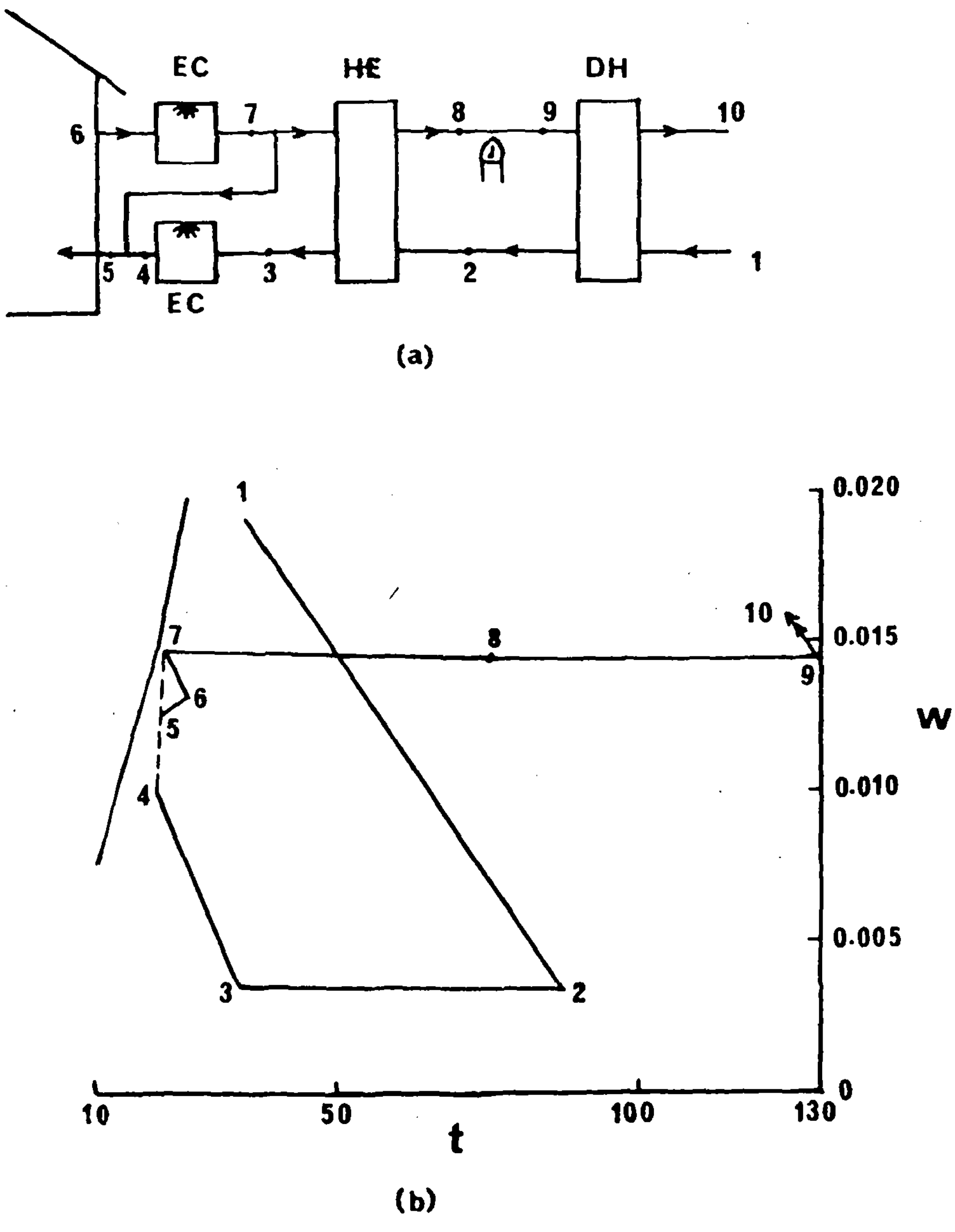


Fig. 15. Diagrams Illustrating the Behaviour of the Solar MEC Vent System.
EC – evaporative cooler, HE – heat exchanger, DH – dehumidifier.

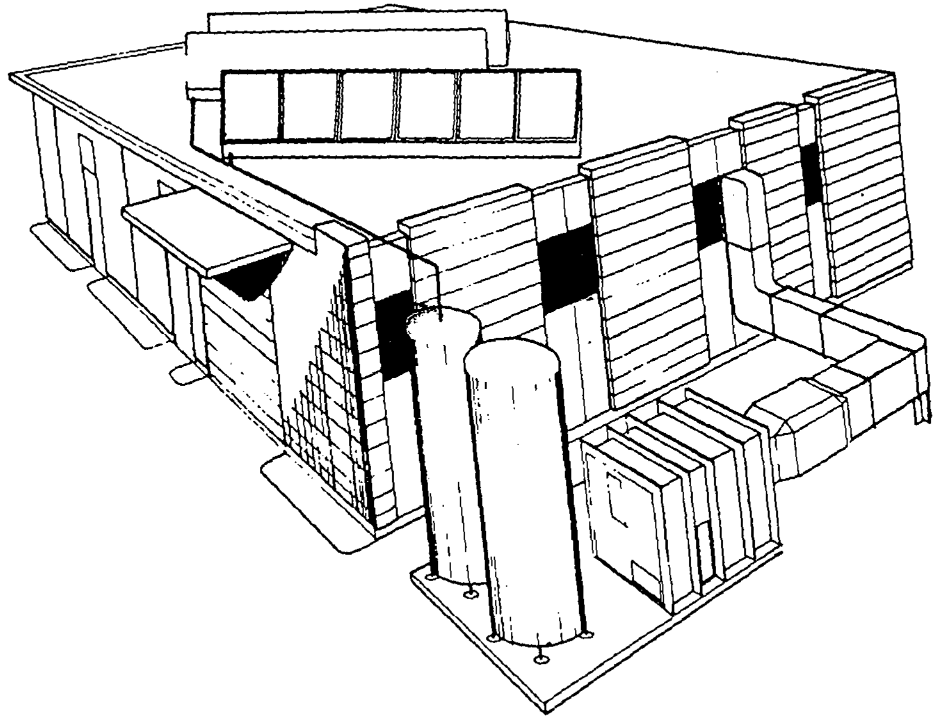
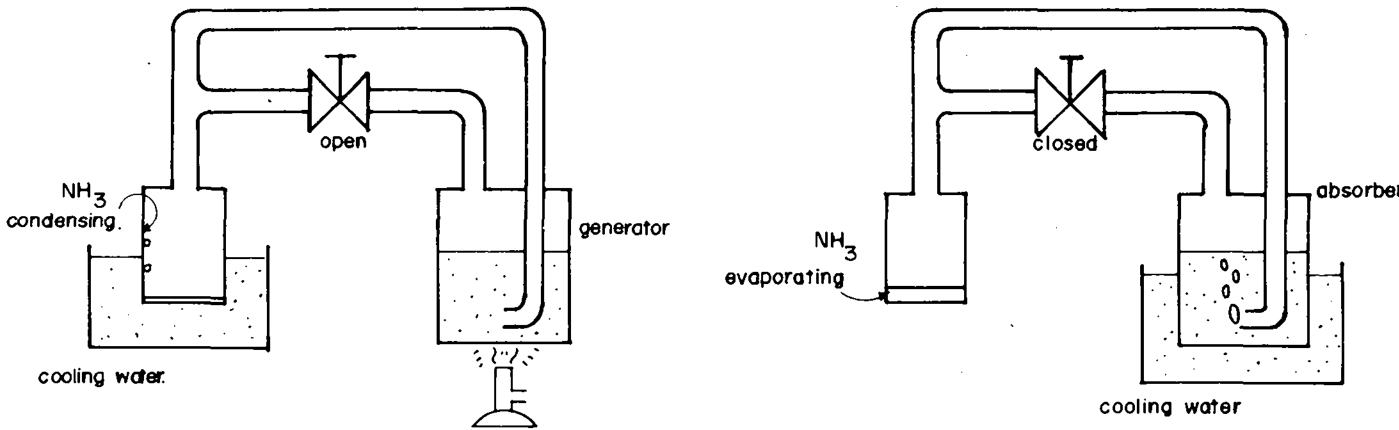


Fig. 16

SOUTHERN CALIFORNIA GAS CO. SOLAR INSTALLATION

IGT - SOLAR MEC - HEATING
AND AIR - CONDITIONING
UNIT

OWENS - ILLINOIS EVACUATED TUBE
SOLAR ENERGY COLLECTOR
MODEL SEC 100-5.



REGENERATION.   REFRIGERATION

FIG.17 $NH_3 - H_2O$ INTERMITTENT CYCLE OPERATION

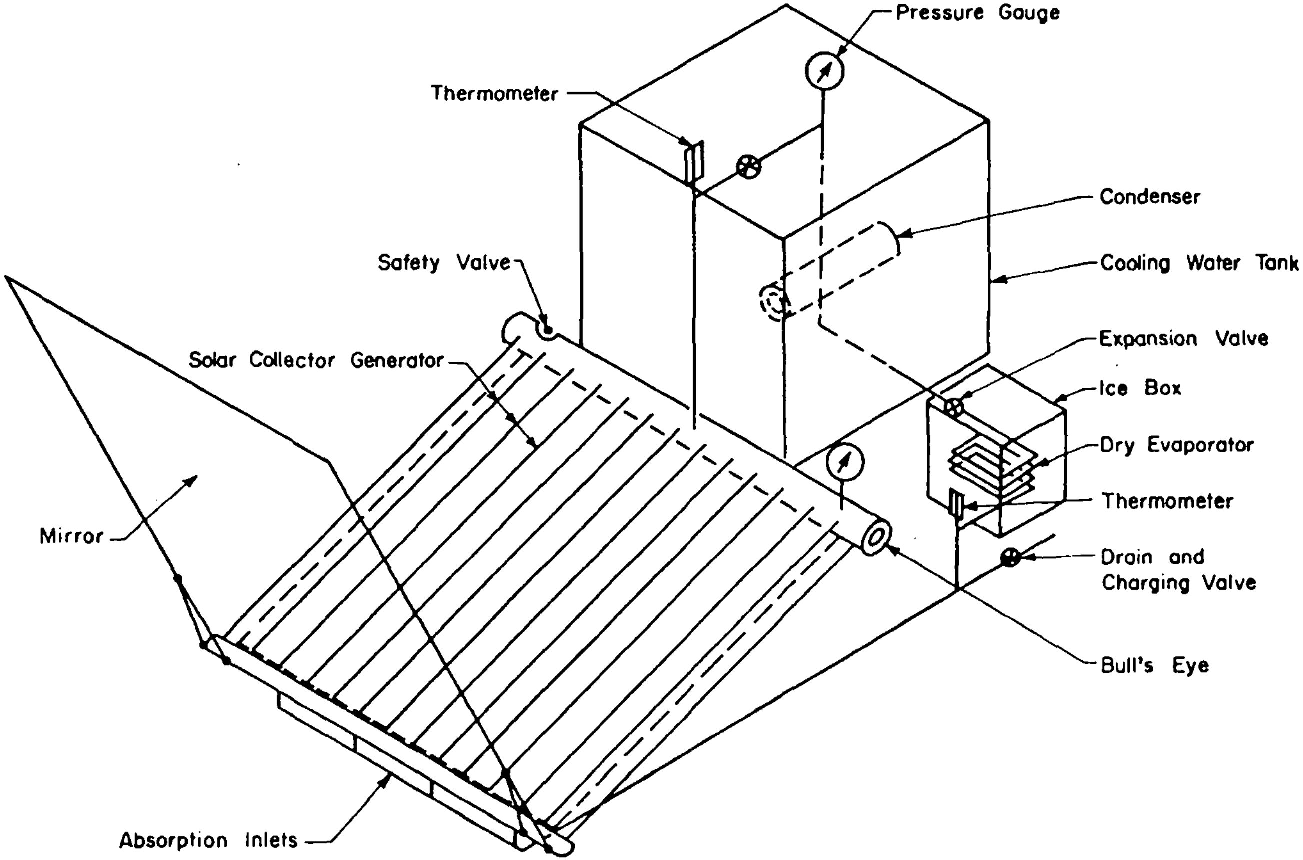


Fig. 18. The Small Solar Ice-Maker

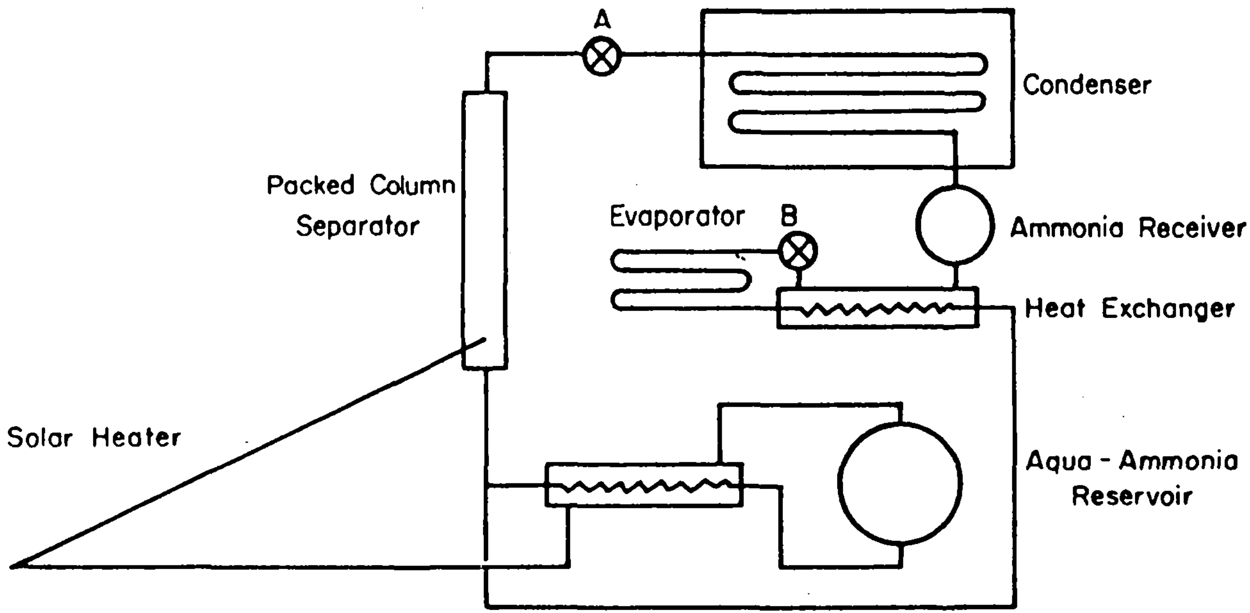


Fig. 19. Proposed New Solar Powered Ice-Making System

PROSPECTS AND PROBLEMS OF THE SOLAR ENERGY INDUSTRY IN THAILAND

by

RICHARD J. FRANKEL, TAWEESIN KUMPENGSATH

and

MANIT THONGPRASERT

1. *Introduction*

Solar energy systems are gaining in importance as other sources of fuel are becoming more expensive. In contrast the costs of solar energy installations are becoming less expensive due to improved system components and lower manufacturing costs as a result of advancements in research and in recent years an expanding market. Solar energy is being recognized as having the potential to supply a small but significant portion of future energy needs, and as more effective ways are found to economically and efficiently convert solar energy into heat, power, and electricity, both professionals and the general public are gradually considering the idea of solar energy as an alternative energy source. One application - solar water heaters - is already contributing to energy conservation in several countries. Heating water with solar energy is a particularly attractive business because of the year around need for hot water in residences, schools, hospitals, hotels and in some industrial processes, such as textile dyeing and finishing and food processing. This paper addresses the involvement of the private sector in the promotion of solar energy use in Thailand, in particular, the prospects, marketing, manufacturing, and improvement of solar hot-water heating systems. Lastly, recommendations are made as to appropriate government actions to further enhance this development.

2. *History of Involvement of SIAMTEC in Solar Energy*

Siam Technology Co., Ltd. (SIAMTEC) was started as an environmental engineering company in 1973. The main activities of the company dealt with the water cycle, that is, treatment, utilization, and reuse of water resources. Basically, the more water reused the less the cost of water development and subsequently, the lower the quantity of wastewater to treat. SIAMTEC worked also with industrial boiler water treatment, recirculating cooling water systems, and hence disposing of waste heat. As the cost of fuel increased, the value of this thrown away heat product appreciated. It became apparent that reuse of heat was equally important to industry as reuse of water. An era of energy conservation as well as water conservation had evolved in the company's thinking, and SIAMTEC began its deeper involvement with energy preservation.

As early as 1978 at a pineapple canning factory in the South, SIAMTEC designed and built a successful energy saving system reclaiming heat and hot water from a multiple effect evaporator used to concentrate pineapple juice to a thick 72° Brix concentrate. The reclaimed hot water was first used to preheat the incoming juice (through a plate type heat exchanger) then recycled back to the boiler as feed water. The cooling water was recycled separately to conserve on limited water supplies. Before the energy saving program was initiated, there was no attempt to recapture some 17 tons/hr of available hot condensate at 70°-75°C for reuse. The boilers of the factory operated on fuel oil heating water of 25°C up to steam at a rate of 30 - 40 tons per hour. Conserving both condensate return and cooling water in separate recycled systems cost the factory almost B 800,000 in capital (US$ 40,000), but it saved the factory about 8,600,000 mega joules/year (8,200 million BTU) or equivalent to B 756,000 per year in fuel costs. In addition, instead of throwing the very soft condensate water away, the condensate was a valuable high quality boiler feed water permitting the factory to cut down on its water softening requirements, thereby saving chemicals, operating time of pumps, and further fuel. Following this successful energy conservation application, SIAMTEC began to look for more ways to conserve energy and to utilize renewable energy resources. Abundant sunshine seemed to be one of Thailand's biggest assets. Each day the sun delivers an average of 16,800 kilo joules[1] per square meter of surface area in Thailand. An area of 1 rai or 1,600 m^2 thus receives solar energy of about 26,800 mega joules per day (25.5 million BTU) or equivalent to the energy from 690 liters of fuel oil per day! With this much free energy, the company asked itself why not try to utilize this energy economically?

At this same time a newly formed company in Thailand approached SIAMTEC to discuss a possible sales agreement to promote its new product called ENERSOL - a locally made solar water heater. The company, Solar Research (Thailand) Ltd. (SRTL), is a joint venture between Thai industry and Israeli technology. The company was actually formed in 1972 at which time it imported the first solar heaters into Thailand. These units were from Israel and have been operating efficiently since 1973. Local production of ENERSOL started in mid-1979 at the time agreement was signed between SIAMTEC and SRTL to market their locally manufactured solar water heaters for private homes, apartments, townhouses, and small commercial establishments.

3. *Marketing*

When SIAMTEC began marketing of the solar heater in 1979, the residential market was considered the primary target. The residential sector was chosen to gain experience and consumer acceptance of the first ENERSOL models which were designed for household use. Experience in solar energy collection and utilization was needed also before SIAMTEC could venture into the industrial markets.

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[1] One kilo joule is equivalent to 0.948 BTU (British thermal units). One mega joule is 10^3 kilo joules.

In Thailand, very few people use hot water in their homes, and these are mainly the upper middle and upper classes. When the solar heater was first introducted into the market, SIAMTEC began a public education and awareness campaign to make known the economic benefits of solar heating. The public disbelieved the earlier advertisements promoting the performance and capability of the solar heaters although a great deal of interest and curiousity was expressed. SIAMTEC took the solar heaters to where the public could see the results for themselves - to Moo Baan Seri near Ramkamhaeng University, to Chulalongkorn University energy exhibition, and to other townhouse developments for demonstration purposes. Newspaper advertisements, general articles, posters, catalogs and contact with government officials were used as means to increase public awareness. Initial response was slow and sales were considerably less than targets.

Another problem to be faced was one of pricing. The first cost or investment cost in a solar water heater appears high to the buyer (about B 18,500 installed) compared to a gas or electric heater (about B 5,000-B 7,000 per unit). A fact sheet on economic analysis of the solar heater was prepared to show that given 1979-1980 costs of electricity or gas, the solar water heater, when compared to two units of gas or electric heaters in a home could pay for itself in less than three years. A typical comparison of total annual costs as shown in Table 1, indicates solar heating is less costly than either gas or electric. However, initial purchasers regarded the solar heater as a new technology, a "prestige item" rather than an investment opportunity which gave favorable economics over gas or electric heaters.

The public attitude towards solar heating appears to be changing now as more units are installed. They are beginning to understand about solar energy in terms of fuel savings, performance, and durability of the equipment. Architects and engineers are considering solar heating in their new designs as an alternative energy source for hot water. The solar heater is finally gaining acceptance as an energy saving device and a development that aids the country. It is expected that as the Bangkok market expands, the provincial market will begin to follow its pattern, especially in the north of Thailand where the weather is colder than in other parts. However, it is estimated that 1-2 years are still needed before the solar water heater will be widely accepted by the general public.

From SIAMTEC's point of view the residential market will remain a small one and by far the more attractive target is solar heating applications in industry and institutions (hotel, hospitals, etc.). A year ago, an industry or institution was reluctant to go along with the idea of depending upon "free energy from the sun" to supply its needs because of the high initial investment and disbelief in the system. Now, after several successful small projects and better acceptance in the residential market, industries are beginning to show an interest in considering solar energy systems, particularly in conjunction with standard equipment using other energy sources. At present more than 10 solar systems have been sold to hotels, hospitals and industries. Not all of these are as yet operable to draw upon and attract further public interest, but by early 1981, Thailand will have a larger pool of experience. Solar heating is of course just the beginning of the solar industry in Thailand. The huge market in the future will be solar cooling and to some extent solar electricity.

4. *Manufacturing of Solar Collectors*

The ENERSOL solar water heaters are completely manufactured in Thailand. To be competitive, the solar heater was made of inexpensive local materials (galvanized steel pipe, fiber glass insulation, glass cover) and production technology was set up to maximize local labour inputs. The resulting production costs appear competitive with other brands offerred abroad at their f.o.b. factory costs. The selling price of ENERSOL is definitely less expensive than equivalent imported brands. The unit as shown in Figure 1, is a standardized compact residential size solar heater. It consists of two "flat plates" or panel type solar collectors and a 155 liter double insulated hot water storage tank, all manufactured locally. Only the selective black paint is imported from abroad. The solar collector absorbs energy from the sun and transfers the heat directly to water, thus producing hot water without any expenditure of gas, electricity or other fuels. With Thailand's stable and sunny climate, the solar heater produces water temperatures averaging 55°C with a flow rate of 70 litres per hour, and under optimum conditions can be designed to achieve hot water temperatures of up to 90°C. A typical residential installation is depicted in Figure 2. Configurations of solar collectors with interconnecting piping, etc. are available with several sizes of insulated hot water storage tanks to make up larger systems for industries and institutions (hotels, hospitals, etc.). An example of a multiple collector system is shown in Figures 3 and 4 for a small 60 room hotel.

Fortunately from a manufacturing point of view, the technology of solar systems is not complicated and private entrepreneurs in the third world countries can keep abreast of developments without the need to import new or sophisticated equipment from abroad. There appears to be sufficient experience and knowhow also in the private sector to take off from the present stage of development and manufacture a second generation of "closed system" solar energy collectors. The industrial systems planned for the future will utilize a closed system recirculating a "pure fluid" like demineralized water, high grade fuel oil, freon or ammonia in the solar collectors, then transfer or exchange the collected heat energy to a second body of water through an efficient heat exchanger. Thus the solar system would remain "closed" and would require a separate heat exchange unit to remove the absorbed solar heat from the recirculating fluid. At the same time the purity of the fluid (in the solar system) would be preserved; no contamination due to corrosion or deposition of solids would occur in the solar collectors (such as calcium carbonate hardness deposits due to heating of the water in the tubes and precipitation of the dissolved solids), and the heat transfer efficiency of the system would be maintained over the service life of the equipment. The collectors for the closed solar heating system are currently being manufactured (and improved) by ACR Industries, Rangsit, in cooperation with SIAMTEC engineers in their research and development program.

5. *Competition*

There are approximately 13 companies marketing solar heaters in Thailand. These are listed below:

1.	Siam Technology Co., Ltd.	- Enersol and ACR solar collectors
2.	Solar Industrial Co., Ltd.	- Sunpack
3.	American Appliance & Engineering	- Solarstream
4.	Diethelm & Co., Ltd.	- Enersol
5.	Gemini Co., Ltd.	- Gemini
6.	S.P.P. 57 Limited Partnership	- Sunpower
7.	Siam Darby (Thailand) Limited	- Siam Darby
8.	Sol Co., Ltd.	- Sol
9.	Yazaki (Japan)	- Blue panel
10.	Louis T. Leonowens	- Solar King
11.	Loxley Limited	- Lordan
12.	Building Materials Trading Co., Ltd.	- Smalls Solar Heeta
13.	Solartech International Co., Ltd.	- Solartech

Most of the solar marketing companies are importing their equipment from the USA, Australia, Israel or Japan. SIAMTEC and Sunpack make their solar heaters locally (and in fact Sunpack makes units for other companies using different trade names. The cost of the imported equipment usually exceeds the cost of locally made units by about 50% or more. Each company has a small share of the market with Sunpack appearing to have the largest number of units sold to date because of its longer existance in the business. They reported sales of about 150 solar collectors in 1978 and over 200 units in 1979. Sunpack has installed these units on the roofs of several small hotels, hospitals, private clinics, and private houses. SIAMTEC, by comparison, has sold 60 ENERSOL units to date or 120 solar collectors.

6. *Research and Development*

SIAMTEC is involved in a modest research and development program, including development of a low cost but high efficiency solar collectors, a closed circuit solar water system, and improved installation techniques.

SIAMTEC realizes that the cost of the solar collector is a key item in the marketability of solar systems. SIAMTEC has set a goal to develop more efficient solar collectors for industrial applications where higher heat absorption and transfer are worth the added cost of better conductive materials. By cooperation with ACR Industries, a leading manufacturer in fan-coil units, SIAMTEC is testing a solar collector that utilizes an absorber plate made of very thin aluminum fins spaced a few millimeters apart and arranged around and mechanically bonded to a thin walled copper tube. By this concept, most of solar radiation flux will be trapped in a narrow gap between the fins and transferred through the copper tubes to the collecting fluid. This newly developed solar collector works more efficiently than the flat plate solar collector. Furthermore, SIAMTEC is testing the use of a Tedlar film (a sturdy plastic transparent cover made by Dupont) as a collector top cover instead of using glass. The collector weight will be trimmed down by at least 3 kilos/m^2 and solar reflection will be less.

The closed circuit solar water system being developed by SIAMTEC appears to have promise in areas where water hardness is high and pre-treatment (to soften the water) impractical. The major components of the system are collector, storage tank, and heat exchanger. The high quality working fluid, such as fuel oil or demineralized water, would flow from storage through the collector to pick up thermal energy than back into storage. When hot water is needed, thermal energy from storage can be transferred to the supply water to be consumed through a heat exchanger. The working fluid from storage would not mix with the water supply. Thus, high hardness waters would not deposit scale inside the collectors and service life and efficiency of the units could be maintained for a longer period.

Lastly, emphasis is being placed on reducing installation costs and improving operation of solar heating systems. For a solar water system, installation can cost up to 30% of the total system cost. Improper installation can reduce the heat absorption efficiency of the collectors. SIAMTEC has developed a computer program to be used to calculate the optimum titled angle of the collector towards the sun throughout the year and the suitable number of collectors to provide the heat absorption (Energy) requirements. In this way, the tilt angle can be adjusted (manually) from winter to summer periods to maximum heat absorption. SIAMTEC also has employed a technique to keep heat loss to a minimum by double insulation using fiberglass and PVC pipe to cover hot water lines.

7. *Solar Economics*

To justify the investment in solar heating, the economic advantages over electric, gas or fuel heaters must be clearly defined even in the short run. Solar heaters bought from Israel 7 years ago by Solar Research (Thailand) Ltd. are still working very well, thus service life of the units appears satisfactory. With the present cost of fuel, the residential solar heater clearly has an economic advantage over electric or gas water heating as shown in Table 1.

For an industry, a solar water heating system can be used to pre-heat water before entering a boiler. Instead of utilizing fuel oil to heat the water from 25°C up to boiling temperature, the ambient water can be first fed into the solar collectors to raise its temperature up to 60°C or 70°C.

As an example, suppose a factory requires 20 cubic meters a day of steam for its processing needs. A solar water heating system for pre-heating 20 m^3 of water would cost about B1,000,000 (US$ 50,000) installed. To compare the cost of solar versus fuel sayings the "life-cycle costing" method was used to estimate the total costs to be incurred over the predicted lifetime of 10 years of the system. Annual capital costs were calculated at 15% interest rate as follows:

Annual capital costs		= (P - L) (CRF,i,N) + Li
Where	P	= investment cost = B 1,000,000
	L	= salvage value = B 100,000 (10% of the investment cost)
	i	= interest rate = 15%
	N	= expected service life = 10 years
	CRF,i,N	= capital recovery factor = 0.199

∴ = (1,000,000 - 100,000) (0.199) + 100,000 (.15) = B 194,100.

The annual operating and maintenance costs of the system are low and were taken at only 1% of the investment cost or B 10,000. Each year a 6% inflation rate was added to the cost of operation and maintenance.

To heat 20 m^3 of water from 25-60°C, the factory would need 2,700,000 kJ per day (2.5 million BTU). This energy would be equivalent to consuming 82 liters of bunker oil grade C per day, which costs B 3.78 per liter. The present fuel cost would amount to B 130,000 per year. It is assumed, however, that an annual increase of fuel prices will occur at 20% per annum. Figure 5 shows the cost comparison of supplementary solar water pre-heating to heat 20 m^3/day of process water versus paying for more fuel. The curve shows that the total annual cost of the solar heating system would increase very little each year compared to the estimated total annual cost increase of fuel. The break even point would be in about 3.8 years. The shaded area in the figure shows the value of savings after the break even point over the service life of the solar heating equipment.

8. *Encouragement from the Government*

Given Thailand's dependence on imported oil, the public and private sectors should be encouraged by government regulation and tax incentives to develop new and local sources of energy, namely, natural gas, solar, wind, lignite, and biogas energy. The only way Thailand can become less dependent upon OPEC is by full cooperation between the government and the private sector. As a private enterprise dealing with energy conservation and promotion of solar energy usage, SIAMTEC looks to the government for policy directions to judge its extent of involvement in these issues.

In the United States, for example, the government has enacted an energy credit program encouraging energy conservation (such as installing insulation, better furnace ignition systems to replace gas pilot lights, etc.). For persons who use renewable energy systems (such as solar collectors, rockbeds, etc.), there is tax relief to encourage public support and involvement in energy conservation. In Israel, the government pays 30 percent of installation costs to factories that switch from fuel to solar energy as a means to encourage the use of solar power. A similar type of energy credit program in Thailand would encourage the public of utilize more solar energy equipment.

The government also has many ways to support research and development of renewable energy sources. At the moment, the most widely available solar equipment in the market is the solar water heater. Government regulations and incentives could be passed to support the solar business, such as the following:

1. A new building code stating that use must be made of solar heating, if needed and applicable.
2. Provision of low interest government loans for those who use solar water heating systems.
3. Import duty/tax relief for local manufacturers of solar energy equipment.
4. On specialized solar equipment that is not available locally (for example, selective black paint, light weight transparent cover material, etc.), reduced import duty (write offs) for importation or lower business taxes for sale of such items.

Legislation should be enacted to permit tax privileges for all users importing energy saving industrial machinery. This would hopefully be a first step in an overall government energy conservation program.

9. *Conclusions*

SIAMTEC, as an example of private industry involvement in the solar energy business in Thailand, has already made a firm beginning and has progressed satisfactorily in both the areas of manufacturing and marketing. However, public awareness of solar energy potentials is still lagging and more public education is needed to insure a promising future market. Most encouraging is that architects and engineers are now considering solar energy as an alternative to conventional heating/hot water systems in their designs. Whether Thailand can benefit from the development and utilization of solar energy systems will depend largely on whether the government will work seriously towards defining some realistic goal, assist financially in a modest research and development program, and lastly support a broader public education program on the benefits from improved energy self-sufficiency.

ACKNOWLEDGEMENTS

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TABLE 1: ANNUAL COST COMPARISON AMONG SOLAR, ELECTRIC AND GAS HEATERS TO PRODUCE HOT WATER
(in Baht)

Year	Annual Cost of Investment[1]			Operating Cost[5]			Total Annual Cost[6]			Savings[7]		Accumulated Savings	
	Solar[2]	Electric[3]	Gas[4]	Solar	Electric	Gas	Solar	Electric	Gas	Solar vs Electric	Solar vs Gas	Solar vs Electric	Solar vs Gas
1	3,600	1,360	970	90	4,530	2,850	3,690	5,890	3,820	2,200	130	2,200	130
2	3,600	1,360	970	100	5,440	3,420	3,700	6,800	4,390	3,100	690	5,300	820
3	3,600	1,360	970	130	6,530	4,100	3,730	7,890	5,070	4,160	1,340	9,460	2,160
4	3,600	1,360	970	150	7,840	4,930	3,750	9,200	5,900	5,450	2,150	14,910	4,310
5	3,600	1,360	970	180	9,400	5,910	3,780	10,760	6,880	6,980	3,100	21,890	7,410

[1] Calculated by using life-cycle costing method with the formula:

Annual investment cost = (P-L) (CRF,i,N) + Li

Where
- P = Investment cost (unit price)
- L = Salvage Value (10% of investment cost)
- i = Interest (15%)
- N = Service life (10 years)
- CRF,i,N = Capital recovery factor = 0.199

[2] Unit price = B 18,500.- installed (equivalent in output to two units of either gas or electric heaters). Operating cost of solar heater is very low. The system works by thermosyphon effect, needs no pump and control unit.

[3] Unit price = B 7,000.- installed.

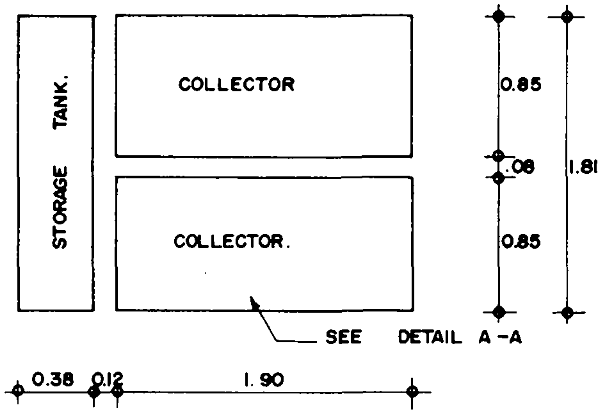
[4] Unit price = B 5,000.- installed.

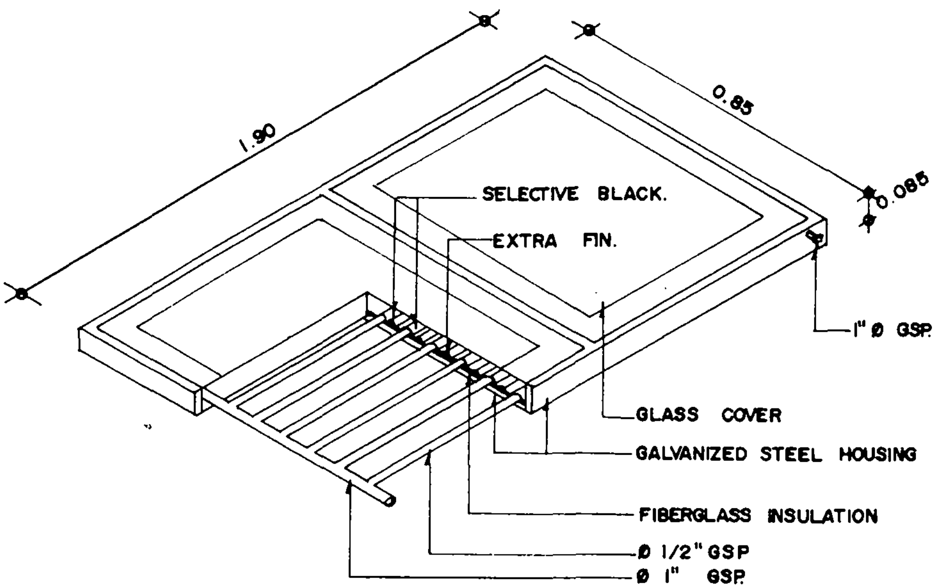
[5] Energy consumption is calculated base on 200 liters of water/day, 365 days a year (output capacity of solar heater is 200 liters, with 3 m^2 of heat collecting area) heated from 28°C to 60°C. An annual increase of fuel cost is assumed at 20% per year. 1 kWh costs B 1.50. Heating efficiency of electric heater is about 90%. 1 kg of LPG cost B 9.50. Heating efficiency of gas heater is about 70%. For the solar unit, auxilliary 1500 w electric heater used (average about 7 days a year) to supply needed hot water on very cloudy or heavy rainy days.

[6] Annual investment cost plus operating cost.

[7] Total annual cost of electric or gas heated hot water minus total annual cost of solar heater.

FIGURE 1. TYPICAL RESIDENTIAL SIZE SOLAR WATER HEATER (MODEL "ENERSOL")





DETAIL A-A

FIGURE 2. PERSPECTIVE OF RESIDENTIAL SOLAR WATER HEATER

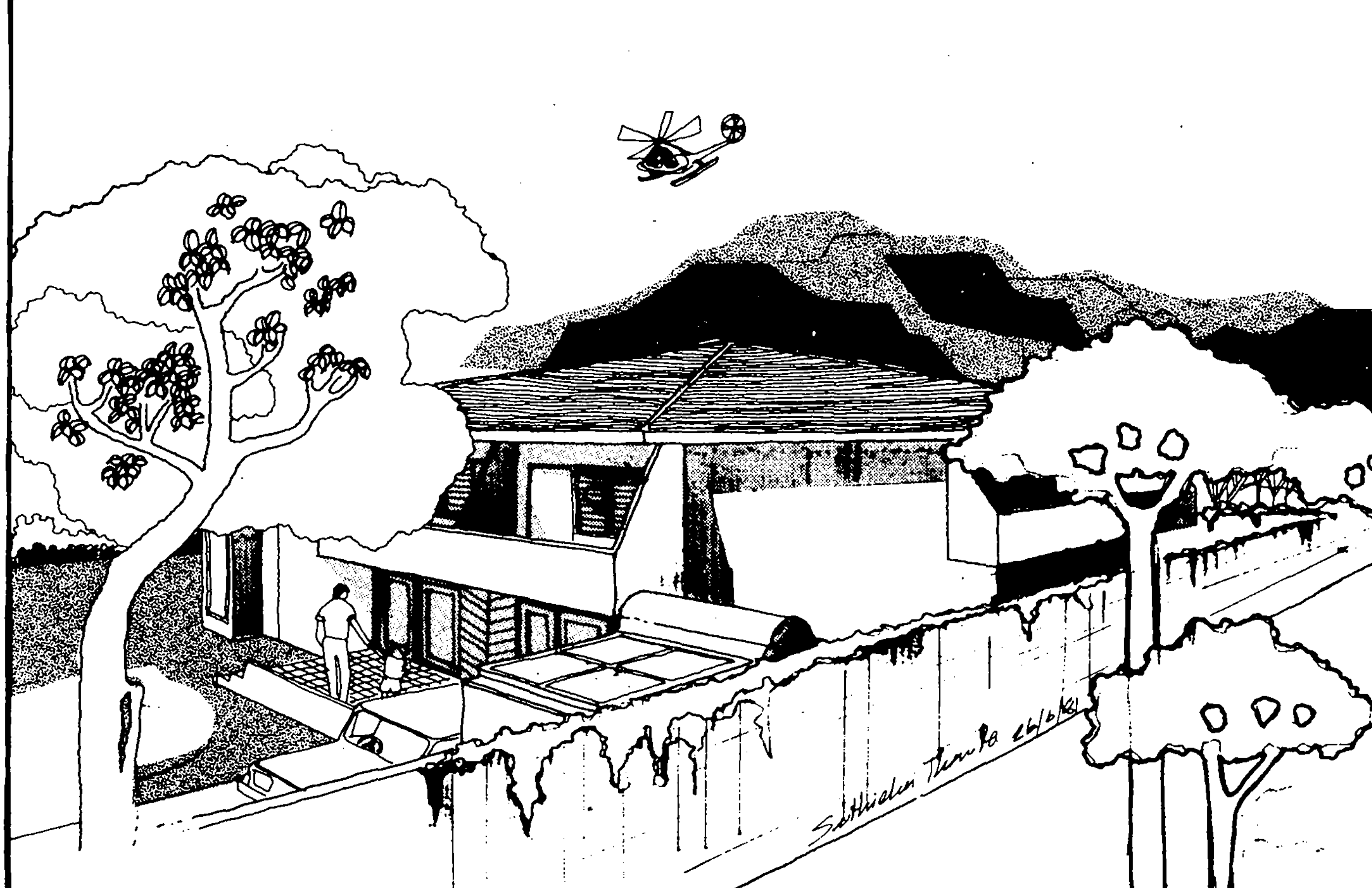


FIGURE 3. SCHEMATIC DIAGRAM OF MULTIPLE SOLAR COLLECTOR SYSTEM

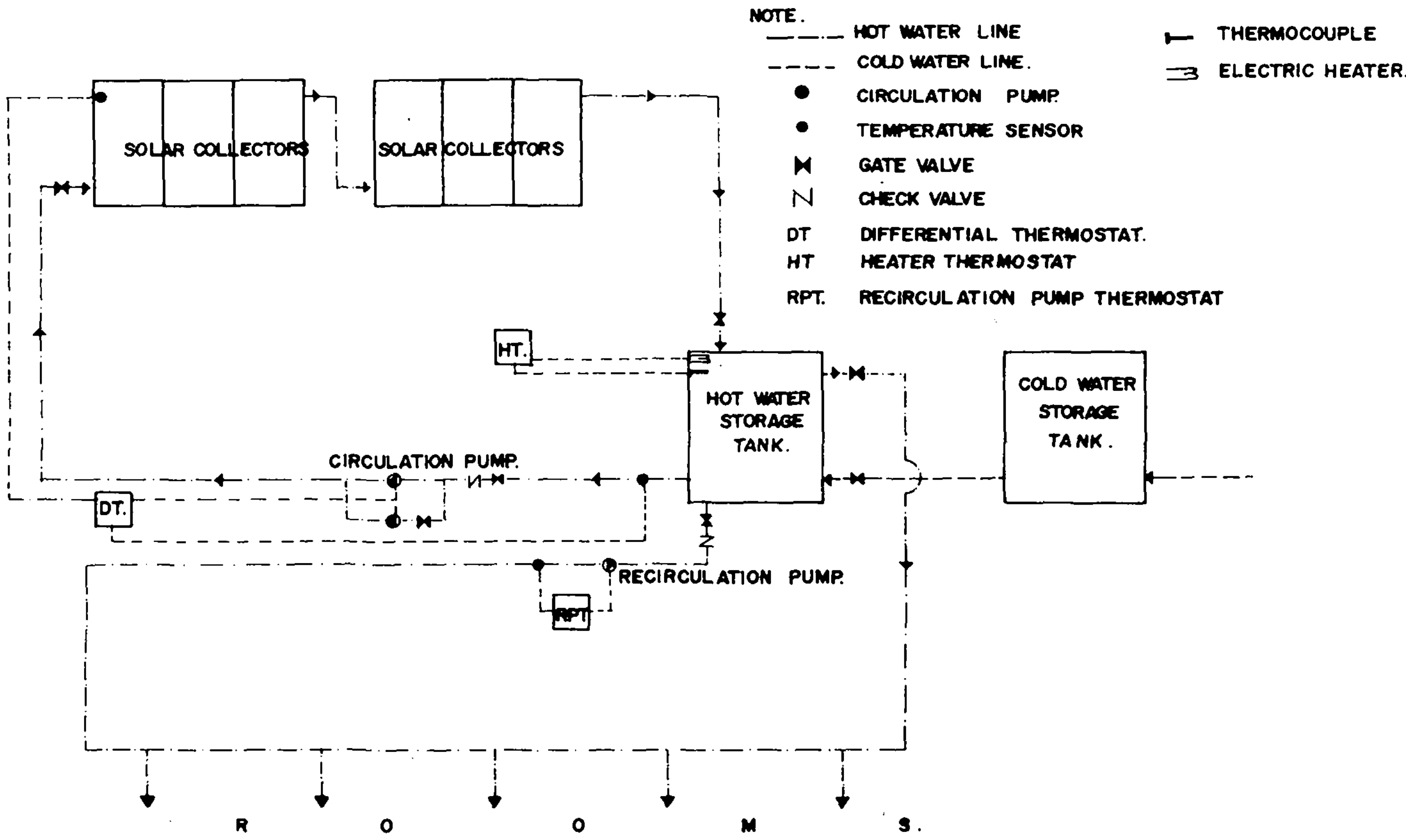
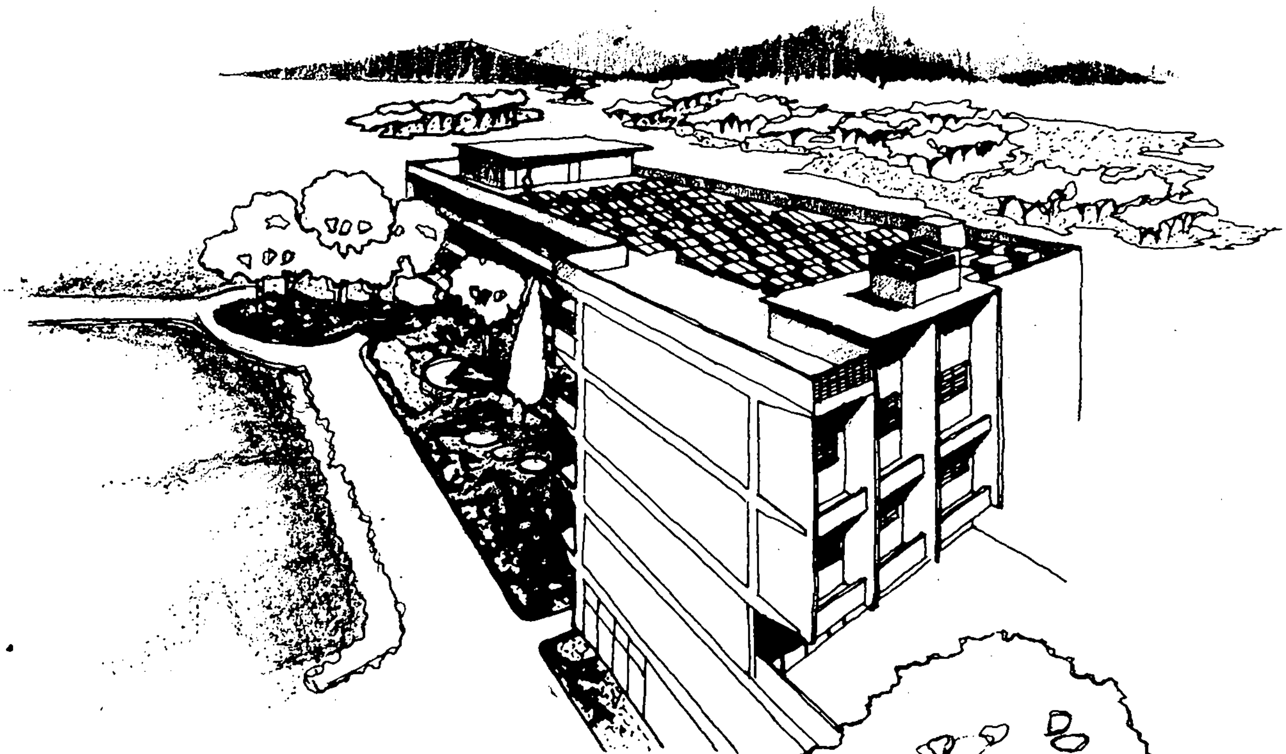


FIGURE 4. PERSPECTIVE OF MULTIPLE SOLAR COLLECTOR SYSTEM.



SIAMTEC SIAM TECHNOLOGY CO.,LTD.	JOB Food Processing Industries			TITLE Solar Economics of Industrial Water Preheating
	MADE BY T.K.		DATE Nov 1980	

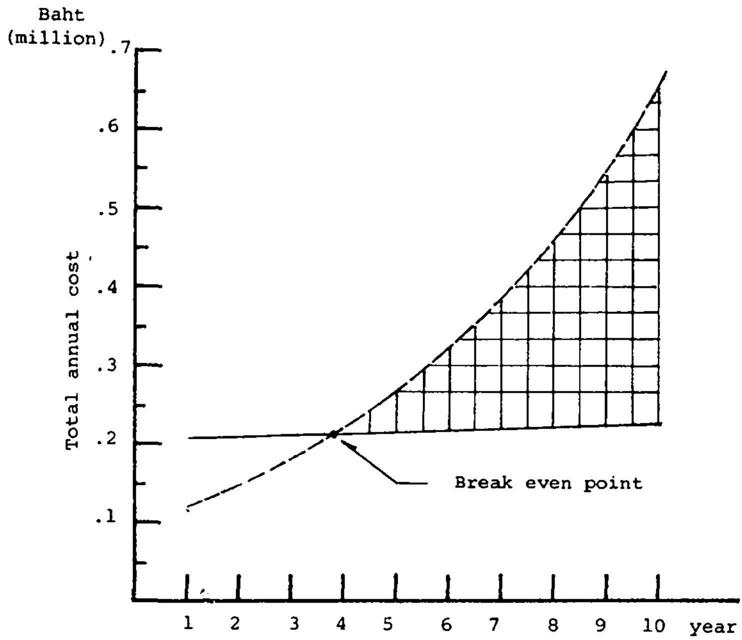


Figure 5: COST COMPARISON OF SUPPLEMENTARY SOLAR WATER PRE-HEATING SYSTEM TO HEAT 20 M^3/DAY OF PROCESS WATER

————————	Annual cost of solar heating system
- - - - - - - - -	Annual cost of fuel oil

Note: (1) Capacity of boiler assumed the same with or without the solar heating system as an auxiliary energy source

(2) Fuel cost assumed to increase 20% annually.

II. RESEARCH PAPERS

PERFORMANCE EVALUATION OF INEXPENSIVE TUBULAR SOLAR COLLECTORS FOR AIR HEATING APPLICATIONS

by

V.K. JINDAL and K.C. ROY

ABSTRACT

Two inexpensive tubular solar collectors were tested for their performance characteristics under various solar intensities and with different air flow rates. The experimental collectors, 12.2 m long with cross-sectic.. ?f 0.305 m, were constructed of black-painted tin sheet and of black plastic film and tested in various lengths and geometric confrigurations.

The thermal performance of both tubular collectors was determined to be similar for all practical purposes. However, the plastic film collector showed distinct merit, being very low in cost as compared to the tin sheet collector. The heat collection efficiency of bare collectors improved when a transparent eccentric tubular cover was provided. The collection efficiency strongly depended on the air flow rates. The net heat gain by the air and the collection efficiency both decreased with an increase in the air temperature rise.

The collector performance in terms of net heat gain improved greatly when a particular air flow was divided into a parallel arrangement of multiple tubular collectors of smaller length rather than using a single long collector. The results of comparison of drying of paddy with solar heated air and ambient air were strongly in favor of solar heated air drying.

INTRODUCTION

Increased interest in the application of solar energy for improving the drying operation of foodstuffs has led to the use of inexpensive plastic materials. The experimental use of black plastic films has shown their potential for use in solar collectors for air heating applications.

Supplemental heating of air in temperature range of 5 to 10°C above ambient is considered a definite advantage before passing it through the material to be dried. The low temperature rises are recommended because of low heat losses from heater surface and low construction costs. A given rate of energy input increases the temperature of larger volume of air to small degrees more effectively instead of smaller quantities of air to higher temperatures.

Many factors should be considered in the design and selection of solar collectors for heating air. These include principles of heat transfer, fluid mechanics and as well as economics and practicality. No matter how well a solar system operates, it will not be accepted unless it is an economically feasible alternative to the other sources of energy. The heat collection efficiency of solar collectors depends on a number of factors such as their geometric configuration, air flow rate, presence of a cover, solar insolation and heat transfer characteristics between the absorber surface and the air stream. In addition, the choice of a particular air heating system would be dictated by its initial investment and effective use.

The objective of this study was to test and compare the performance characteristics of two types of inexpensive tubular solar collectors for air heating applications.

RELATED STUDIES

The use of solar heated air for the drying of grains and foodstuffs has been reported in a number of studies (Akyurt and Selcuk, 1973; Buelow and Boyd, 1957; Converse et al., 1978; Foster and Peart, 1976; Lipper and Davis, 1960; Peterson and Hellickson, 1976; Phillips, 1965; Roa and Macedo, 1976; and Niles, 1976). Different types of collectors were utilized in these studies. However, flat plate type collectors have been widely used.

The efficiency of solar collection is usually defined as the ratio of useful power delivered by the collector to the insolation falling on the collector. Collector efficiency is useful for the purpose of comparing different types of collectors but is not of much value in determining how collector performance varies with certain operating variables. Collector performance is an important parameter but not the deciding one since most efficient collector may be most costly.

Buelow and Boyd (1957) used a metal plate as collector with an air space and one sheet of glass above the plate. Sobel and Buelow (1963) reported that efficiencies of upto 70 percent were possible for low cost, low temperature rise solar collectors. Bevil and Brandt (1968) used an absorber plate consisting of alumium fins to heat air from 12 to 20°C with collection efficiency of more than 80 percent. Akyurt and Selcuk (1973) used steel chips, painted black and encased in a chicken wire, as collector with a single layer of glass cover.

Close (1963) investigated the various configurations of duct-type inexpensive air heaters and reported that solar heating of air could compete with other forms of air heating. Foster and Peart (1976) tested black plastic tubular collectors (0.91 m in diameter and 35.5 m long) for heating air. They reported that half of the air temperature rise occurred in the first 12.2 m length and little temperature rise occurred in the last 6.1 m. The efficiencies among different tests varied from 14 to 46 percent. The use of a transparent plastic cover on tube type collector increased the energy collection by 50 percent.

Parker (1978) tested and compared the performance of two types of vee-corrugated and one plane surface solar plate for heating air. The vee-currugated plates using triangular ducts gave 9.6 to 15 percent greater efficiency than the plane surface collector plate with rèctangular duct for air flow.

Experimental studies on eccentric tubular solar collectors, made of plastic sheets, were made by Converse et al., (1978). The black absorbing tubes were 0.43 m and 0.96 m in diameter while the clear outer tubes were 0.51 m and 0.99 m. Collector length was 30.5 m and air flow was approximately 0.59 m^3/s for both collectors.

A economical and practical evaluation of plastic film solar collectors for heating air for grain drying applications has been carried out by Keener et al., (1977).

EXPERIMENTAL SET-UP

Two types of tubular collectors made of thin sheets of plastic and tin were fabricated for this study. Tin pipes, 0.305 m in diameter and 1.22 m long, were made from 0.79 m thick black-painted tin sheets. Ten such pipes were joined together by duct-tape to form 12.2 m long pipe. A transparent polyethylene tube, 0.39 m in diameter, was used as eccentric cover leaving a maximum spacing of about 8.3 cm above the pipe surface. The plastic pipe, 0.305 m in diameter and 12.2 m long, was made from a continuous black polyethylene sheet obtained locally. A similar transparent cover was used having a diameter of 0.39 m.

The collectors were laid on the ground horizontally. A thin rope was wrapped around the plastic pipe and fastened to the cement blocks placed on two sides of the pipe to keep it straight and in position. A one hp A.C. fan unit was used to force the air through the collectors. Air flow rate could be regulated by covering the fan inlet with adjustable PVC plates and measured with a vane type anemometer at the exit end.

Mercury thermometers were used to record the temperatures. A bimetallic type pyranometer recorded the daily solar insolation at the experimental site.

TEST PROCEDURE AND INSTRUMENTATION

The collectors were laid on the ground in east-west direction. The procedure consisted of forcing the air into collector from the blower end. After steady-state conditions were attained, air temperatures at the inlet and outlet of the collector and in the surrounding were recorded. The temperature rise in air was monitored at points spaced 2.44 m apart along the collector length. The whole procedure was repeated with different air flow rates. Sheet metal reducers were used at the collector end in order to measure the air flow with the vane type anemometer.

In the beginning, plastic pipe and tin pipe were tested separately without any cover. In later tests, plastic and tin pipe were joined and used as 24.4 m long single collector with a transparent plastic cover. The position of plastic and tin pipe was interchanged to check if it influenced the collector performance.

Two plastic film and one tin sheet collectors were also tested by placing them parallel to each other on the ground 0.8 m apart and in east-west orientation. The air flow from the fan-motor unit was divided approximately equally into each collector in parallel arrangement through an indigenous arrangement.

The air temperature at any cross-section of the duct was not uniform. It was maximum near the top surface of the pipe and minimum near the bottom. Since the temperatures recorded at different sections of the collector length were the maximum, a temperature rise factor was evaluated to estimate the average air temperature for a given cross-section. The temperature rise factor was calculated by dividing the average temperature at outlet section by the maximum temperature over a wide range of air flow rates. Since the temperature rise factor depended on the maximum temperature being recorded, it was evaluated for arbitrarily selected temperature ranges.

The collector efficiency, η, was computed from the relationship

$$\eta = m\, C_p\, (T_o - T_i)/I \qquad \ldots(1)$$

where, m = mass flow rate of air, gm/min-cm^2

C_p = specific heat of air, cal/gm-$^\circ$C

T_o = air temperature at the collector outlet, $^\circ$C

T_i = air temperature at the collector inlet, $^\circ$C

I = rate of solar isolation, cal/min-cm^2.

The solar flux used in the efficiency calculation does not include the reduction due to absorptance of the collector surface and the transmittance of the cover. The derivation of equation 1 is based on the assumptions of steady-state conditions, constant solar flux at all points during the test period, collector area equivalent to tube diameter times the length, and negligible heat conduction in the absorber plate.

The 24.4 m long tubular collector, made of tin and plastic pipes, was used to heat the air for drying of paddy in a model bin of 0.57 m diameter. The depth of grain was 0.305 m and the air flow rate was 22.54 $m^3/min\text{-}m^2$ in both the natural and solar drying tests. Three samples from the middle of grain bed were taken each hour for determining the moisture removal rate. Grain moisture content was determined by the standard oven method.

RESULTS

Performance of Individual Collectors

In all experimental tests, the collectors were laid on the loose gravel already placed on the ground surface. In view of the higher temperature of loose gravel layer than the ambient temperature, no insulation was provided underneath the collectors. Also, an increase in the air temperature was noticed in the range of 0.5 to 2.5 °C as a result of air being drawn by the blower. Consequently, the collector inlet air temperature was higher than the ambient temperature.

First series of tests consisted of evaluating the performance of 12.2 m long plastic film and tin sheet tubular collectors, without any cover. Figs. 1 and 2 show the temperature rise in air and the heat collection efficiency as a function of collector length at four different air flow rates for plastic film and tin pipe, respectively. The temperature rise in air took place at a faster rate initially and was followed by gradual increase. In general, the temperature rise decreased with an increase in the air flow for uniform solar intensities. The curves tend to flatten quickly at lower solar intensities and higher air flow rates. The efficiency is highest near the starting end of the collectors and is decreased with an increase in the tube length. The drop in the efficiency is more apparent in the beginning of pipe length and at higher air flow rates.

Comparison of results of Figs. 1 and 2 shows that the thermal performance of plastic pipe is slightly better than that of tin pipe. However, in view of different solar intensities, no definite conclusions can be drawn.

Assuming that the plastic and tin pipes performed equally well, tests were carried out by joining them together and providing a transparent cover. In the first test, tin pipe was followed by the plastic pipe and in the second, plastic pipe was followed by the tin pipe. Figs. 3 and 4 show the variation of air temperature rise and efficiency with collector length. Identical patterns emerged in Figs. 3 and 4 and in both cases, maximum temperature rise occurred in the first 15 m length of the collectors. For similar air flow rates and insolation intensities, the thermal performance of the two collector arrangements was very close to each other. Based on the results of Figs. 1 to 4, it may be concluded that plastic film collector is at least as good as the tin pipe collector or slightly better for air heating applications.

Fig. 5 shows the effect of air flow rate on the heat gain and efficiency. The relationship shows a rapid increase in efficiency and energy gain at lower air flow rates.

The relationship of heat gain and efficiency with air temperature rise is shown in Fig. 6. Results of Figs. 5 and 6 clearly depict the interdependence of temperature rise and the volume flow rate of air. At higher flow rates, the heat gain and efficiency approached a steady high level but with a marked drop in the temperature rise.

In case of high temperature rise, the heat losses from the collector surface to ambient are also high and thus resulting into decreased efficiency. Therefore, additional layers of cover should be provided to minimize the heat losses and thus to increase the collection efficiency. Results of Fig. 7 show the performance of collector with and without a single transparent cover under identical conditions of solar insolation (1.08 cal/min-cm^2), wind velocity ($<$ 1 m/s) and air flow rate (11.73 m^3/min). There was a marked increase in collection efficiency as a result of providing one cover on the bare collector. Also, the efficiency increased steadily with an increase in the air temperature rise.

Conventionally, collector performance data are expressed in terms of the collector efficiency as a function of the air temperature rise divided by the insolation falling on the collector surface. Fig. 8 shows such a plot obtained by pooling the experimental data for a 12.2 m long collector, made of either plastic film or tin sheet, for various air flow rates. The data points shown are mostly within 2 hours of solar noon. The insolation during the test periods was between 0.9 to 1.5 cal/min-cm^2 and the wind velocities were generally well below 1 m/sec. A curve passing through the scattered data points would indicate the thermal performance of the collector on average. The strong influence of air flow rates on thermal performance is clearly evident.

Performance of Collectors Joined in Parallel

The performance data on tubular collectors when joined in parallel are given in Table 1. Each collector was 0.305 m in diameter and 12.2 m long. Since the air flow in three collectors was a little different, corresponding temperature rise and efficiency also varied. Despite the fact that the metal pipe had least air flow in both cases shown in Table 1, it did not show either the highest temperature rise or the efficiency. Based on this information, it can be concluded that the thermal performance plastic pipes equal to or somewhat superior to that of tin pipe.

Table 2 presents the direct comparison of series and parallel arrangements of collectors. It is noticed that for same intensity of radiation and air flow, the two parallel pipes extracted 47.78 Kcal/min heat energy against the 24.85 Kcal/min heat gain for series arrangement. Similarly, the heat gain was approximately three times more in parallel arrangement as compared to series arrangement using three pipe lengths, each 12.2 m long.

These results clearly demonstrated the advantage of using the tubular collectors of smaller length in parallel configuration as compared to a single long collector.

Table 1. Performance of Tubular Solar Collectors when arranged in Parallel

Date	*Collector Arrangement*	*Collection Area (m^2)*	*Air Flow Rate (m^3/min)*	*Insolation ($cal/min\text{-}cm^2$)*	*Temperature Rise (^oC)*	*Collection Efficiency (%)*
June 8, 1978	Plastic pipe I	3.7	7.32	0.58	6.4	58.9
	Plastic pipe II	3.7	6.86	0.58	7.4	65.0
	Metal pipe	3.7	6.20	0.58	6.8	53.7
June 9, 1978	Plastic pipe I	3.7	7.32	1.20	10.2	43.3
	Plastic pipe II	3.7	6.86	1.20	13.2	52.3
	Metal pipe	3.7	6.20	1.20	11.7	41.0

Note: Each collector 11.2 m long and 0.305 m in diameter.

Table 2. Comparison of Collectors Performance in Parallel and Series Arrangements

Date	*Collector Arrangement*		*Insolation ($cal/min\text{-}cm^2$)*	*Air Flow Rate (m^3/min)*		*Temperature Rise (^oC)*	*Heat Gain (K cal/min)*	
				Individual Pipe	*Total*		*Individual Pipe*	*Total*
June 9, 1978	Plastic I	Parallel	1.25	7.89	14.34	11.4	24.57	47.78
	Metal			6.45		13.2	23.21	
June 14, 1978	Plastic I, Metal	Series	1.22	14.42	14.42	6.1	24.07	24.07
June 9, 1978	Plastic I	Parallel	1.20	7.95	22.61	10.1	21.99	72.90
	Metal			7.09		12.2	23.57	
	Plastic II			7.57		13.2	27.34	
June 14, 1978	Plastic I, Metal, Plastic II	Series	1.19	26.49	26.49	3.4	24.86	24.86

Note: Each Collector 11.2 m long and 0.305 m in diameter.

Effectiveness of Solar Heated Air for Grain Drying

The solar heated air dried the grain at a faster rate than the natural air (Fig. 9). It was possible to achieve lower moisture content of grain with solar heated air as compared to the natural air for the similar test duration. As is clear from Fig.9, the moisture content of paddy was reduced from 22.9 to 13.5 percent w.b. with solar heated air and from 24.5 to 20.4 percent w.b. with natural air in approximately six hours.

Cost Comparisons

The net cost of black plastic film collectors including the labor and clear polyethylene cover was about US $ 3.16 per square meter of collector area. The comparable cost of black-painted tin sheet collector was US $ 20.78 per square meter of collector area, more than six times the cost of plastic collector.

CONCLUSIONS

This study describes the results of some preliminary investigations of the performance of two types of inexpensive tubular solar collectors for heating air. The main conclusions of the study are:

(i) Black plastic pipes give at least comparable or a little better thermal performance than the black-painted tin pipes when used as tubular solar collectors under similar operating conditions.

(ii) Tubular solar collectors can be effectively used to heat air upto 10°C above the ambient temperature in single-pass operation.

(iii) Heat collection efficiency is strongly dependent on the air flow rates. The net heat gain by the air and the efficiency both decrease with an increase in the air temperature rise.

(iv) The efficiency of bare collectors is greatly improved when a transparent cover is used.

(v) Collector performance in terms of heat gain is improved when a particular air flow is divided into a parallel arrangement of multiple tubular collectors of smaller length than using a long collector alone.

(vi) Solar heated air increases the moisture removal rate in the drying of paddy as compared to the natural air.

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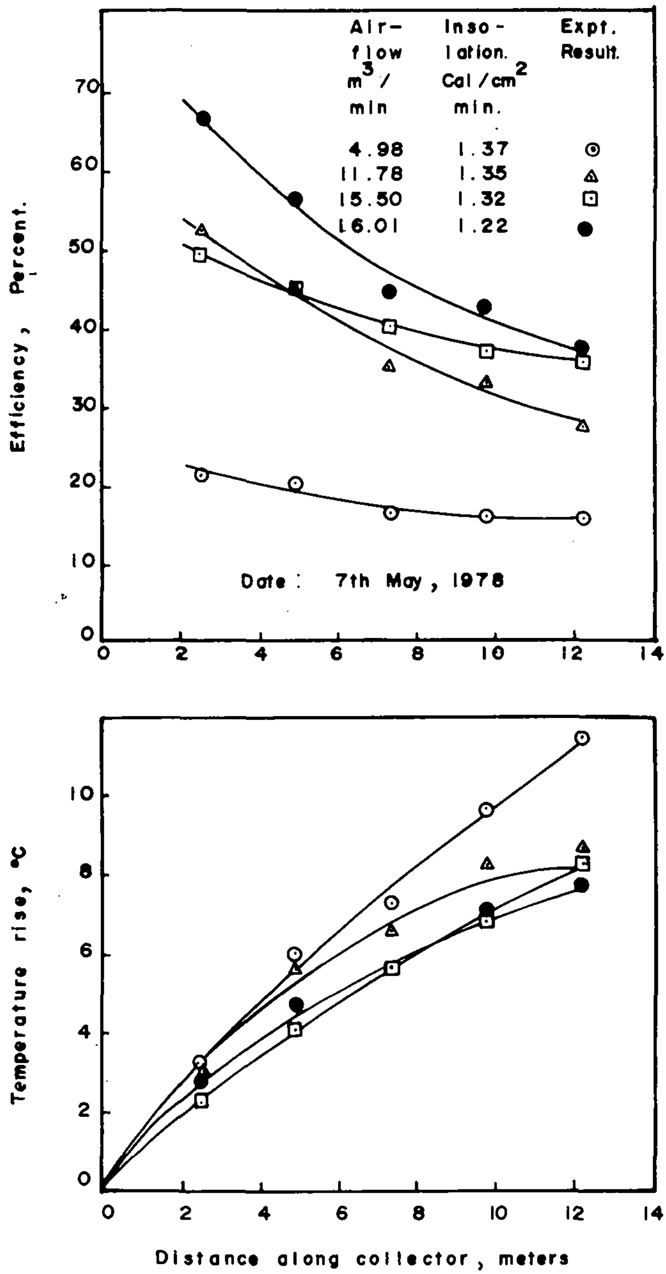


Fig. I – Temperature rise and efficiency as a function of collector length at different air — flow rates (black pipe without cover)

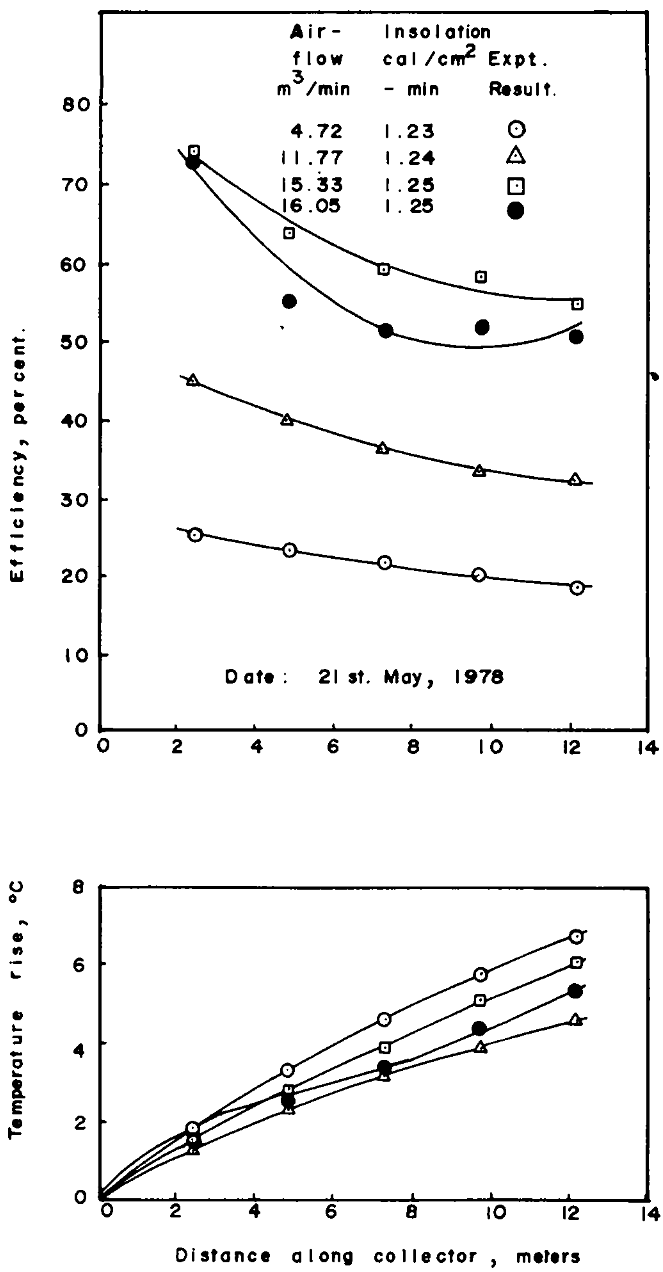


Fig. 2. Temperature rise and efficiency as a function of collector length at different air-flow rates (blackened metal pipe without cover)

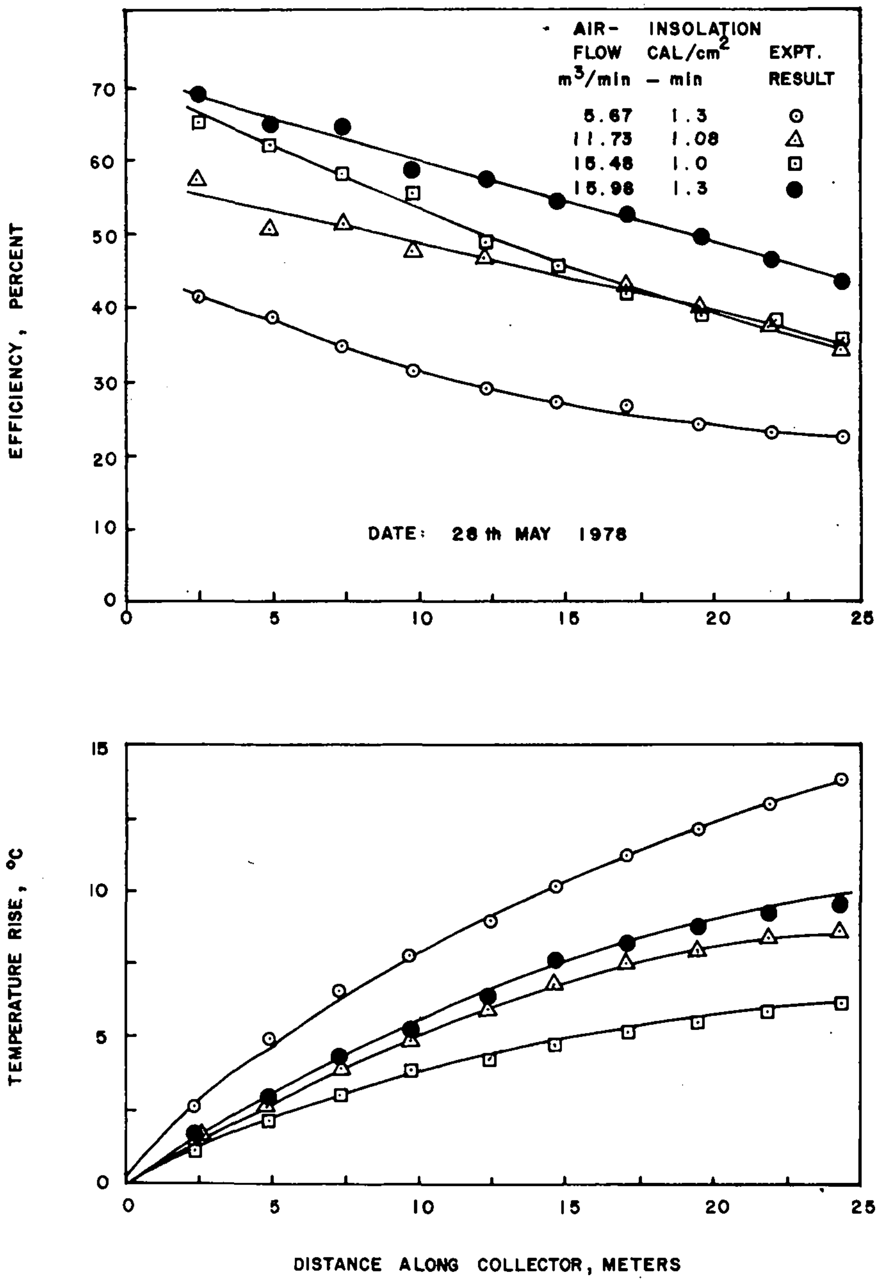


FIG. 3. TEMPERATURE RISE AND EFFICIENCY AS A FUNCTION OF COLLECTOR LENGTH AT DIFFERENT AIR–FLOW RATES (12.19 METERS BLACKENED METAL PIPE AND 12.19 METERS BLACK PLASTIC PIPE, BOTH COVERED)

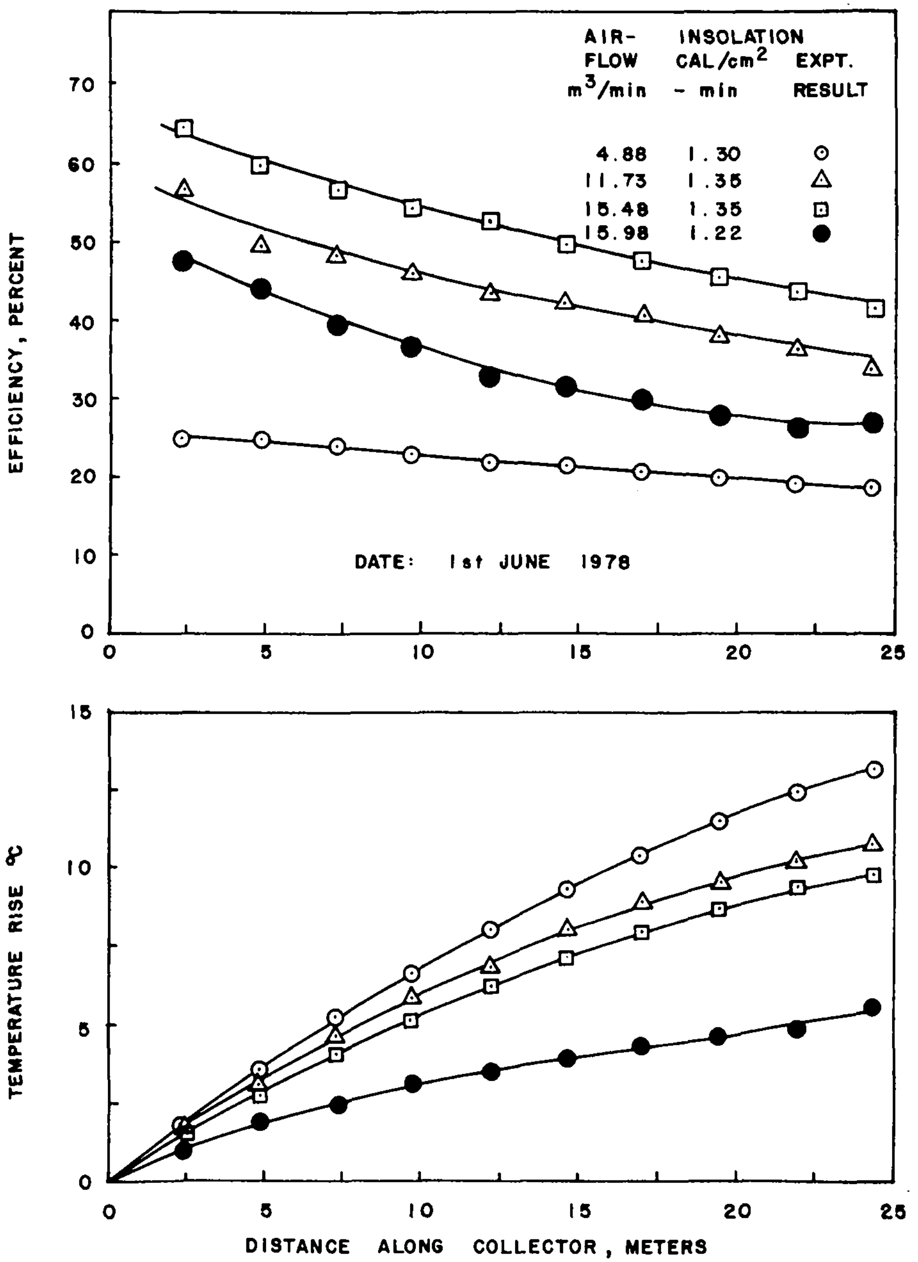


FIG. 4 TEMPERATURE RISE AND EFFICIENCY AS A FUNCTION OF COLLECTOR LENGTH AT DIFFERENT AIR-FLOW RATES (12.19 METERS BLACK PLASTIC PIPE AND 12.19 METERS BLACK ENED METAL PIPE, BOTH COVERED)

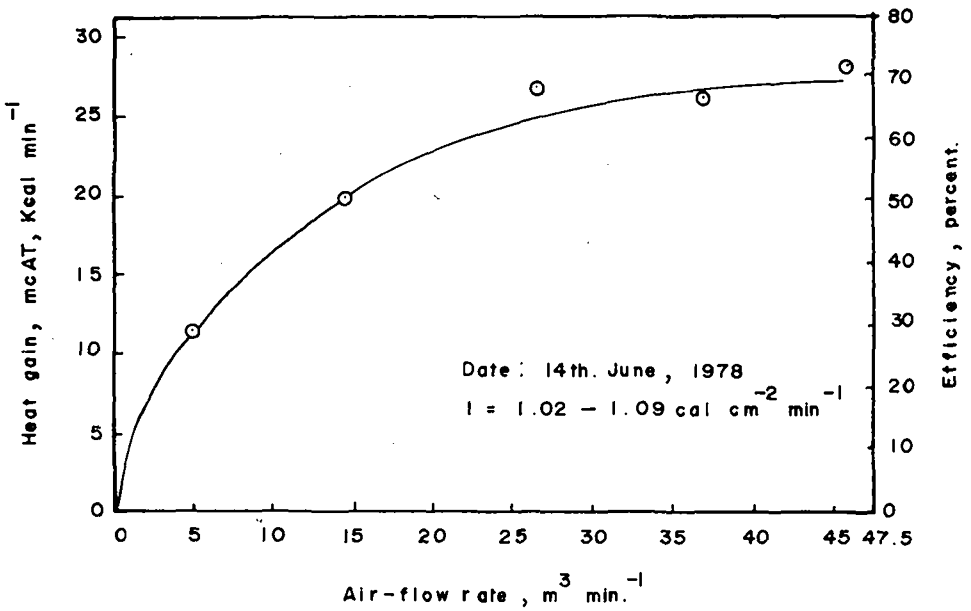


Fig. 5 Collector heat gain and efficiency as a function of air-flow (blackened matal pipe with cover 12.2 meters in length)

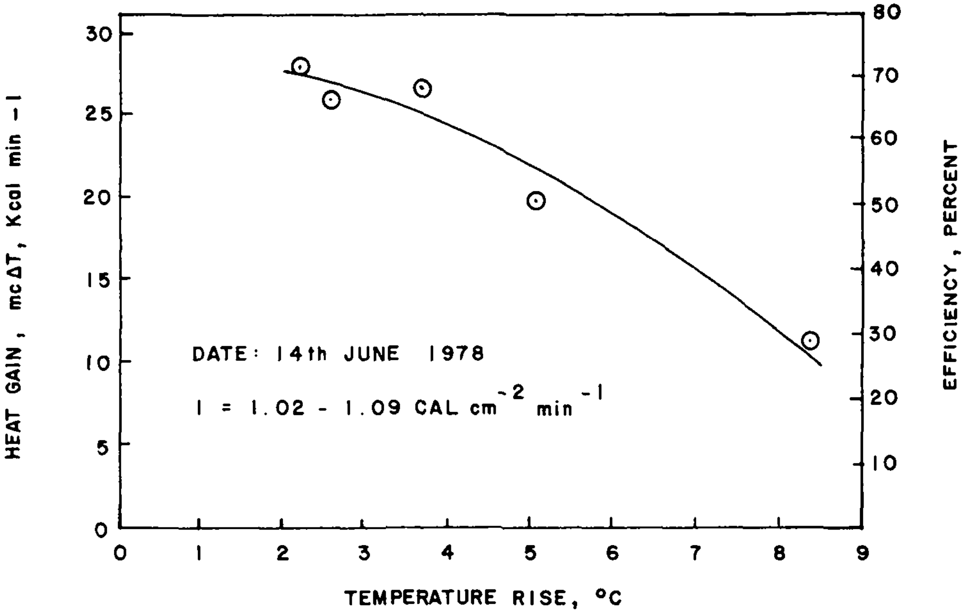


FIG. 6 COLLECTOR HEAT GAIN AND THE EFFICIENCY AS A FUNCTION OF TEMPERATURE RISE (BLACKENED METAL PIPE WITH COVER, 12.2 METERS IN LENGTH)

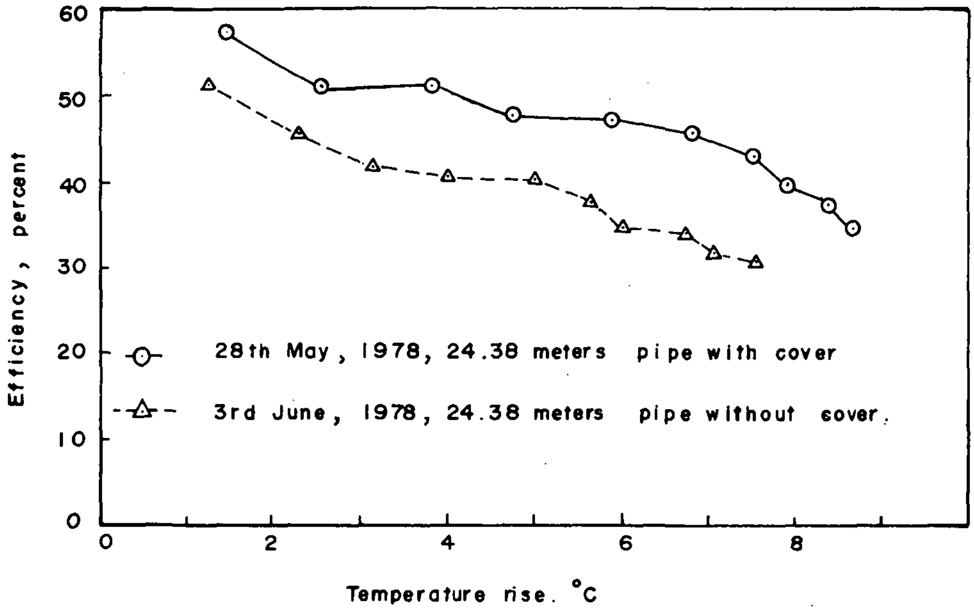
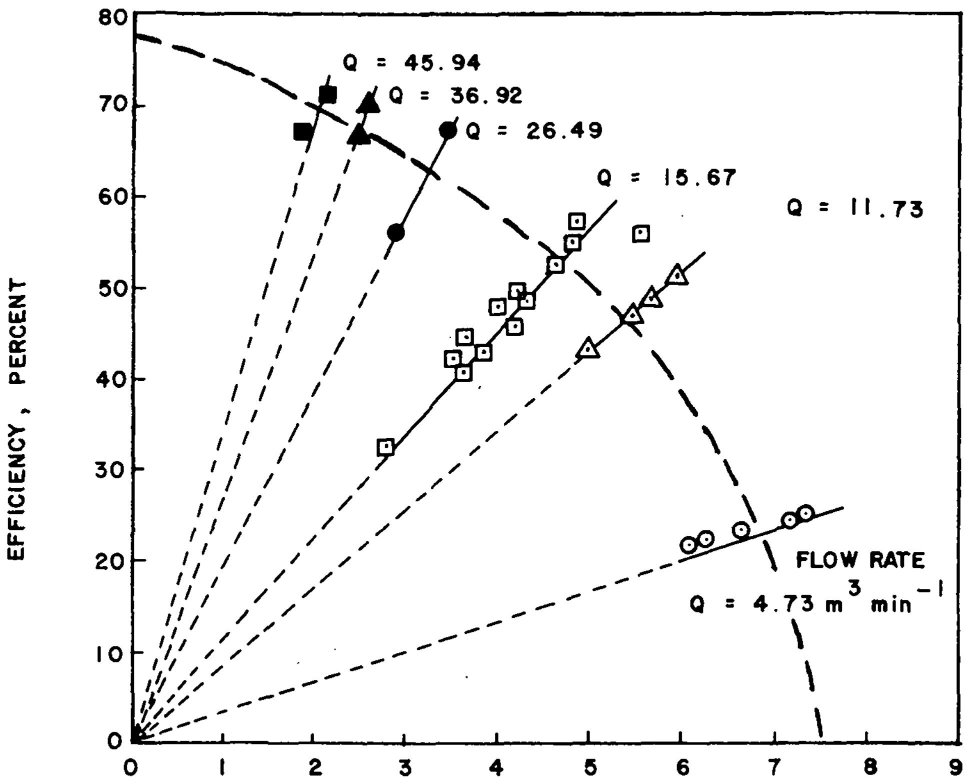


Fig. 7. Relationship between collector efficiency and temperature rise as influenced by the presence of transparent cover.



RATIO OF TEMPERATURE RISE TO INSOLATION, $\Delta T/I$, $^{\circ}C\ cm^2\ min\ cal^{-1}$

FIG. 8 PERFORMANCE CHARACTERISTICS OF 12.2 METERS LONG COVERED COLLECTOR FOR DIFFERENT AIR-FLOW RATE

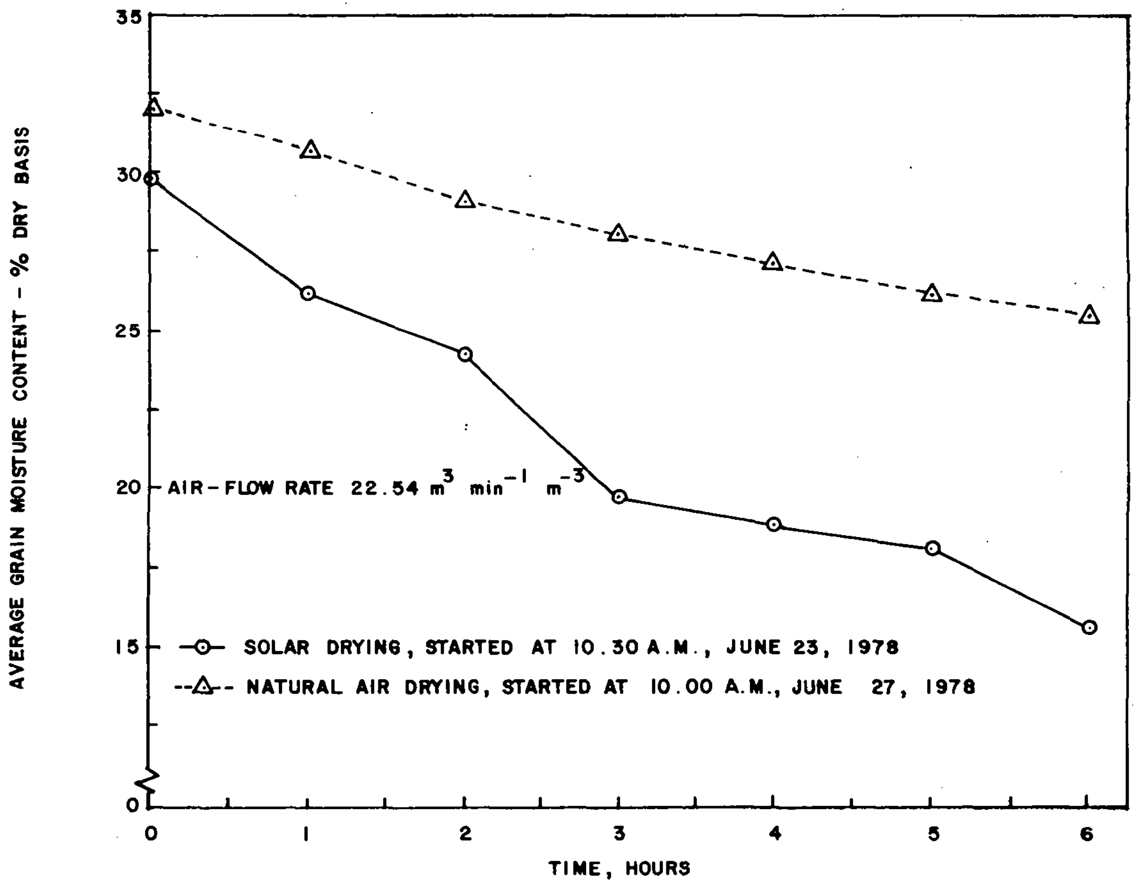


FIG. 9 EXPERIMENTAL DRYING CURVES FOR PADDY USING SOLAR BEATED AND NATURAL AIR

PERFORMANCE OF THE AIT SOLAR RICE DRYER DURING THE WET SEASON

by

SOMPONG BOONTHUMJINDA

ABSTRACT

Three experiments tested on the AIT solar rice dryer during the wet season in 1979 were a study of moisture and temperature profiles of 125 mm. rice bed in the solar dryer with chimney, a determination of moisture profiles for various depths of rice bed in the solar dryer as well as on mat drying using humidified paddy, and a determination of moisture profiles for various depths of rice bed dried in the solar rice dryer and on mat drying using fresh-harvested paddy. Their results show that drying in the solar chamber starts at the top and the bottom layers first while the middle layer dries the slowest, the optimum bed depth is 100 mm., the use of the chimney reduces the drying time of paddy in a 125 mm. bed by about ten percent, furthermore, stirring in a 100 mm. rice bed in a chamber with chimney reduces the drying time by about one half.

I. INTRODUCTION

This research work is a part of the Solar Rice Drying Project (Thailand) which is financially supported by the International Development Research Centre and it is under the supervision of Dr. R.H.B. Exell. The objectives of this project is to develop a low-cost method of drying rice paddy from the second harvest, which takes place during the wet season. The drying system will be constructed from materials available locally, and will be powered by natural energy sources including the sun and wind.

II. THE AIT SOLAR RICE DRYER

2.1 *Detailed Description of the AIT Dryer*

The AIT dryer is located in front of the AIT research centre in the open air. It was constructed in November 1978 with the help of Physical Plant Staff. The dryer has a capacity of one tonne of threshed paddy and consists of a drying chamber and a solar air heater as well as chimneys.

2.2 *Rice Drying Chamber and Chimneys*

The bed of paddy is contained in a hardboard box, 6 mm. thick, 9.6 m. long, 1.2 m. wide and 0.4 m. deep having eight similar compartments (Fig. 1 and Fig. 2). The bottom of the chamber is made of woven bamboo covered by No. 18 nylon netting to prevent the rice grains falling through. The box is supported one meter above the ground on a wooden frame with foundations in the ground. All the air spaces above and below the rice bed are fully covered by clear PVC sheet 0.15 mm. thick except for the outlets of the air. Each compartment, which is separated from its neighbours by clear PVC sheet, can be used with or without chimney by sliding a panel below the chimney. The chimney consists of black plastic sheet 0.15 mm. thick covering a triangular bamboo frame two meters high and having a rain protective cover on the top. The chambers without chimney have covers over their outlet as well for rain protection.

2.3 *Solar Air Heater*

The solar air heater having an area of ground 9.6 meter long and 3.6 meter wide (its area is three times of the rice bed) is in front of the rice bed. It faces towards the South; so that the prevailing wind can blow into the air inlet. A layer of burnt rice husks 30 mm. thick is spread on the ground to make a black absorber for solar radiation. The whole area is covered by clear PVC sheet 0.15 mm. thick supported by framework of bamboo poles and wrires. The plastic is made about 10° sloping downward, towards the opening, so that the heated air is guided up into the drying chamber and the rain water does not stay. The collector area is made convex and a drain cut around the solar dryer helps the water to escape. The solar air heater is separated by clear PVC sheet into sections such that each compartment has its own air heater.

2.4 *How the Dryer Works*

Fig. 3 shows the Principle of the Dryer as well as its important components. Sunlight passes through the clear PVC sheet and warms the air inside with the help of a layer of burnt rice husks covering the ground below to absorb the radiation. The warm air passes up through the bed of paddy and dries it. The chimney provides a tall column of warm air to increase the air flow through the bed by natural convection.

III. EXPERIMENTS

Three experiments were done during the wet season in 1979 on the AIT Campus.

3.1 *Experiment A*

This experiment was a study of moisture and temperature profiles in 125 mm. bed depth using solar rice dryer with chimney. One drying chamber of the dryer (No. 4) was chosen and filled with humidified paddy to a depth of 125 mm. The rice bed was divided horizontally into nine-equivalent sections (Fig. 4a) and each section was again divided into four equivalent layers (Fig. 4b). Measurements of temperature and moisture content were done about the centres of each layer. A mercury-in-glass thermometer was inserted in the rice bed at the centre point of each layer to measure the temperature. Ninety cylinders 45 mm. inside diameter having the same height as the rice bed were prepared with one end covered with nylon net No. 18 and the other end opened. They were filled with the paddy and placed vertically within the bed. One cylinder at a time from each section was taken out for moisture measurement. A computerized electrical resistance grain moisture meter was used to determine the moisture contents. The RICETER 3 having an accuracy of ± 0.5% wb. (12-20 wb.) was chosen. The average moisture contents were calculated from 3 sample sizes. The paddy was left unstirred in this experiment.

This experiment started at 9.30 a.m. on August 16, 1979 and ended at 9.30 a.m. on August 18, 1979. Measurements were taken about every two hours during the period of sunshine.

3.2 *Experiment B*

This experiment was a determination and comparison of moisture profiles for various depths of rice bed in the solar drying chamber as well as on mat drying using humidified paddy. To determine the average moisture contents of each rice bed, the rice beds were divided into layers. At a time of moisture sampling, 3 samples from the centres of each layer were taken out and measured by the RICETER 3. The number of layers for beds of depth 40, 100, 125 and 150 mm. were 1, 3, 4 and 4 respectively (see Fig. 5a, 5b, 5c and 5d). The temperatures of each layer are also measured by mercury-in-glass thermometers. The measurements had been taken every two hours at 8.00, 10.00, 12.00, 14.00 and 16.00 hrs. before the paddy was stirred.

3.3 *Experiment C*

This experiment was a determination and comparison of moisture profiles for various depths of rice bed in the solar drying chamber and on mat drying using fresh-harvested paddy. Process and measuring procedures were the same as in the experiment B except that fresh-harvested paddy was used instead of humidified paddy.

In the three experiments above each drying chamber has two more thermometers, one above the rice bed having a shield on its bulb to cut down the direct solar radiation to measure the upper air space temperature and the other thermometer under the rice bed to measure the heated air temperature. Air relative humidity was determined from dry bulb and wet bulb thermometers, solar radiation was recorded by a bimetallic recorder; furthermore, wind velocity and direction as well as weather conditions were also observed.

After the experiments had been finished, the samples of paddy of the experiment B and C were sent to the Rice Division, Department of Agriculture and cooperatives, in Kasetsart University for germination and milling tests.

IV. EXPERIMENTAL RESULTS AND DISCUSSION

4.1 *Experiment A*

Fig. 6 shows typical moisture contents at about the centres of each divided four layers of the nine sections in the 125 mm. unstirred bed tested on August 16-17, 1979.

The shaded layers having moisture content equal to or less than 20% wb. gradually extend from the top and the bottom into the middle of the rice bed. Fig. 7 shows typical temperatures at the centres where the moisture contents are measured. The top and bottom of the rice bed have higher temperature than the middle. This phenomenon can be described by using a psychometric chart (Fig. 8). The ambient air, point A on the chart fixed by wet and dry bulb temperatures, is gradually heated while passing through the solar air heater with constant humidity ratio (assumed no water vapour from the ground is added) to point B determined by temperature under the rice bed. When the heated air moves up into the rice bed the drying process starts. The latent heat of vaporization of the water in the grains is exchanged; this causes the air to cool and its relative humidity increases in successive layers till minimum drying rate, point C which is the minimum temperature in the rice bed, is obtained; then the air temperature increases again while its relative humidity decreases because of sun heating from the top of the bed. The drying process finishes at point D which is defined by a temperature of the rice bed at the top surface. Finally, before leaving the chamber the warm air temperature has been increased again with constant humidity ratio by sunlight passing through the clear roof and the chimney effect. This is point E in the chart and it is the maximum temperature of the air space over the rice bed. It is cleary seen that drying process starts from the top and the bottom into the middle layer. The maximum temperature in the bed is never over 45°C, the grain cracking temperature, in this experiment.

4.2 *Experiment B*

The average moisture profiles for various depths of rice bed both in the dryer and on mat drying using humidified paddy as well as maximum temperatures in their beds and global solar radiation are shown in Fig. 9. From the Figure the drying rates represented by slopes of the curves are greatly dependent upon the global solar radiation, the more the solar radiation the steeper the curves. The 40 mm. bed depth mat drying in the sun and the 100 mm. bed depth in the dryer with chimney reached the required moisture content of 14% wb. in one and a half days starting with the moisture content of 23% wb. The 125 mm. bed depth in the solar dryer reach the required condition in about two and a half days; however, the drying time of the dryer with chimney is only 23 daylight hours while the one without chimney is 26 daylight hours. That is the one with chimney of the 125 mm. bed depth dries faster than the one without chimney by about 12 percent. The 150 mm. bed depth in solar dryer with chimney and the 40 mm. bed depth mat drying in shade takes about three and a half days to arrive the preferred condition. The grain cracking temperature of over 45°C never occurs during the period between the beginning to the required condition of 14% wb. but it occurs when the moisture content is less than 13% wb. and the maximum temperature of 50°C observed is in the bottom layer of the 125 mm. bed. The weather was generally partly cloudly having no rain during this experiment.

Table 1 shows the moisture content, germination, milling quality, occurance of temperature over 45°C and drying period of down to 14% wb. of samples of the paddy after drying under the condition shown in Fig. 9 using the paddy before humidifying as a control sample. The moisture contents measured by the oven method have no significant difference from the ones measured by the Dole moisture tester. The sample of the 100 mm. bed depth in the dryer with chimney has the greatest percentage of head yield rice while the one from the mat drying in the sun has the lowest. All of the samples have germination over eighty percent, which is good germination.

4.3 *Experiment C*

Fig. 10 shows the average moisture profiles for various depths of rice bed in the dryer and on mat drying using freshy-harvested paddy as well as maximum temperature in their beds and global solar radiation. Again, the drying rates are greatly dependent upon the solar radiation. The 100 mm. rice bed in the dryer with chimney and the 40 mm. bed on mat drying in the sun reach the required condition of 14% wb. in two days. The unstirred 100 mm. bed depth in the dryer with chimney and the 125 mm. in the dryer with chimney reach the preferred moisture content in three and a half days. The 125 mm. bed without chimney and the 150 mm. bed with chimney arrive at required condition in four days; nevertheless, the 40 mm. bed mat drying in shade reaches the safety condition more than four days. Having chimney in the 125 mm. bed reduces the drying time from 37 daylight hours to 34 daylight hours or about eight percent. The stirring effect of the 100 mm. rice bed in the dryer with chimney reduces the drying period from 33 daylight hours to 17 daylight hours, i.e. about 49 percent. No temperature over 45°C occurs during the period between the beginning to the moisture content of 14% wb. The maximum temperature of 48°C was observed in the bottom layer of the stirred 100 mm. bed with chimney when its moisture content is about 12% wb. The average weather condition is cloudy *having heavy rain in the evening of the twenty-second and the twenty-third of September 1979* and the open mats was covered by plastic sheet during the rain.

Table 2 shows the moisture content, germination, milling quality, occurance of temperature over 45°C and drying period down to 14% wb. of samples of paddy after drying under the condition shown in Fig. 10 using freshy-harvested paddy. The moisture contents measured by both the oven method and the Dole moisture tester, the same as in the experiment B, have no significant difference. The head yields in the stirred and unstirred 100 mm. bed with chimney and in the stirred 125 mm. bed with chimney are the same but the drying period of the stirred 100 mm. is the fastest. Although the drying time of both the stirred 100 mm. bed and the 40 mm. of mat drying in the sun are the same, the head yield of the latter is lower; moreover, it is the lowest of all.

V. CONCLUSION

The first experiment (A) indicates that drying starts at the top and the bottom layers first and that the middle layer dries the lowest. The temperature in the top and the bottom layers is higher than in the middle; over heating in the rice bed does not occur since the observed temperatures are only rarely above 45°C.

The second and the third experiments (B and C) show that the optimum bed depth for the dryer in the west season is 100 mm. The use of the chimney reduces the drying time of paddy in a 125 mm. bed by about 10 percent. In the third experiment, stirring a 100 mm. rice bed in a dryer with chimney reduced the drying time by about one half. The 40 mm. bed open mat drying takes about the same drying time as in the stirred 100 mm. bed in the dryer with chimney, but rice from the dryer had a head yield 3 to 10 percent greater. However, mat drying of large quantities of rice is impractical in wet weather.

ACKNOWLEDGEMENT

I am indebted to the International Development Research Centre, for funds supporting the Solar Rice Drying Project (Thailand), to Dr. R.H.B. Exell, Project Supervisor, who encourage me to write and check this paper; to the Rice Division, Department of Agriculture, Ministry of Agriculture and Cooperatives for doing the germination and milling test; to AIT students Mr. Bharata Kunjara and Mr. Suwit Bunyawanichkul who worked as student assistants and Miss Ratrie Suppipat and Mrs. Nantha Thongkomwongse for typing.

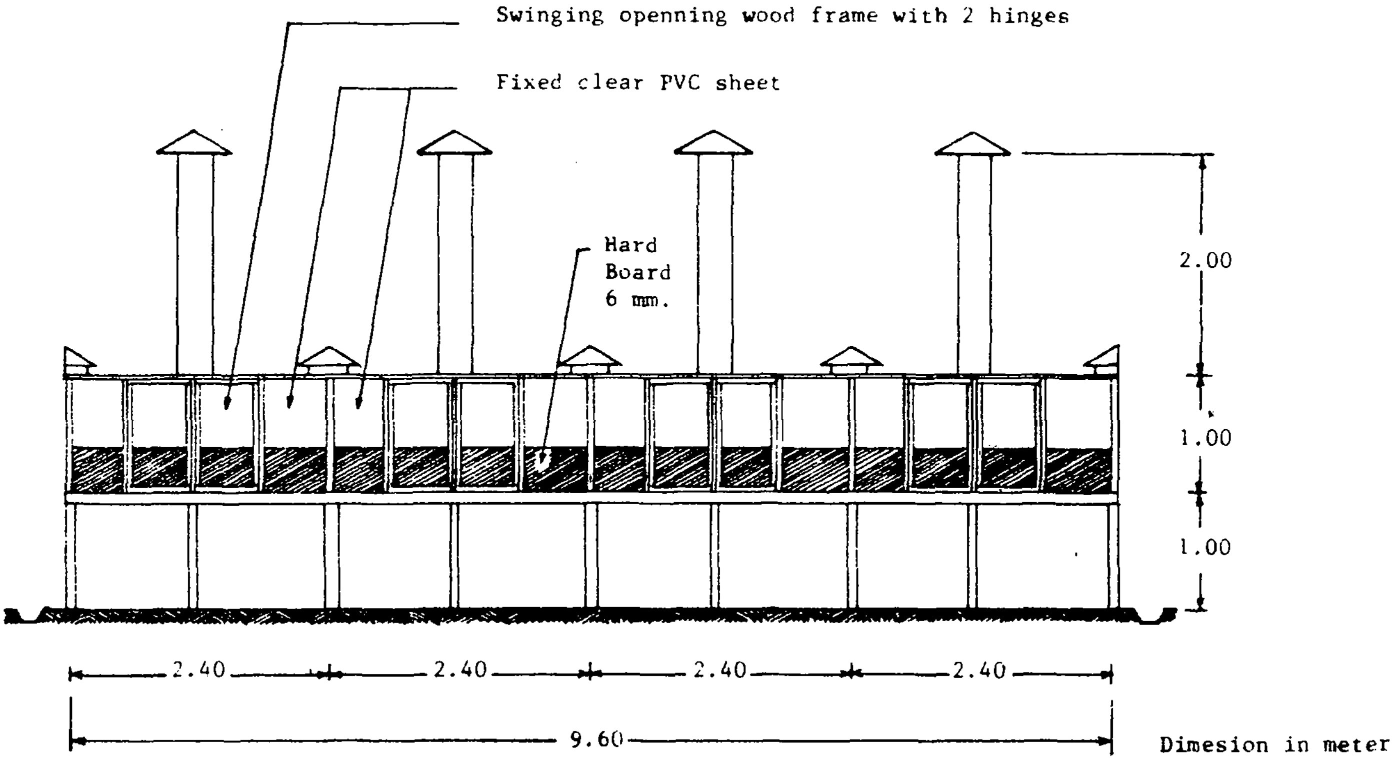


Fig. 1. Back Elevation of the AIT Solar Rice Dryer

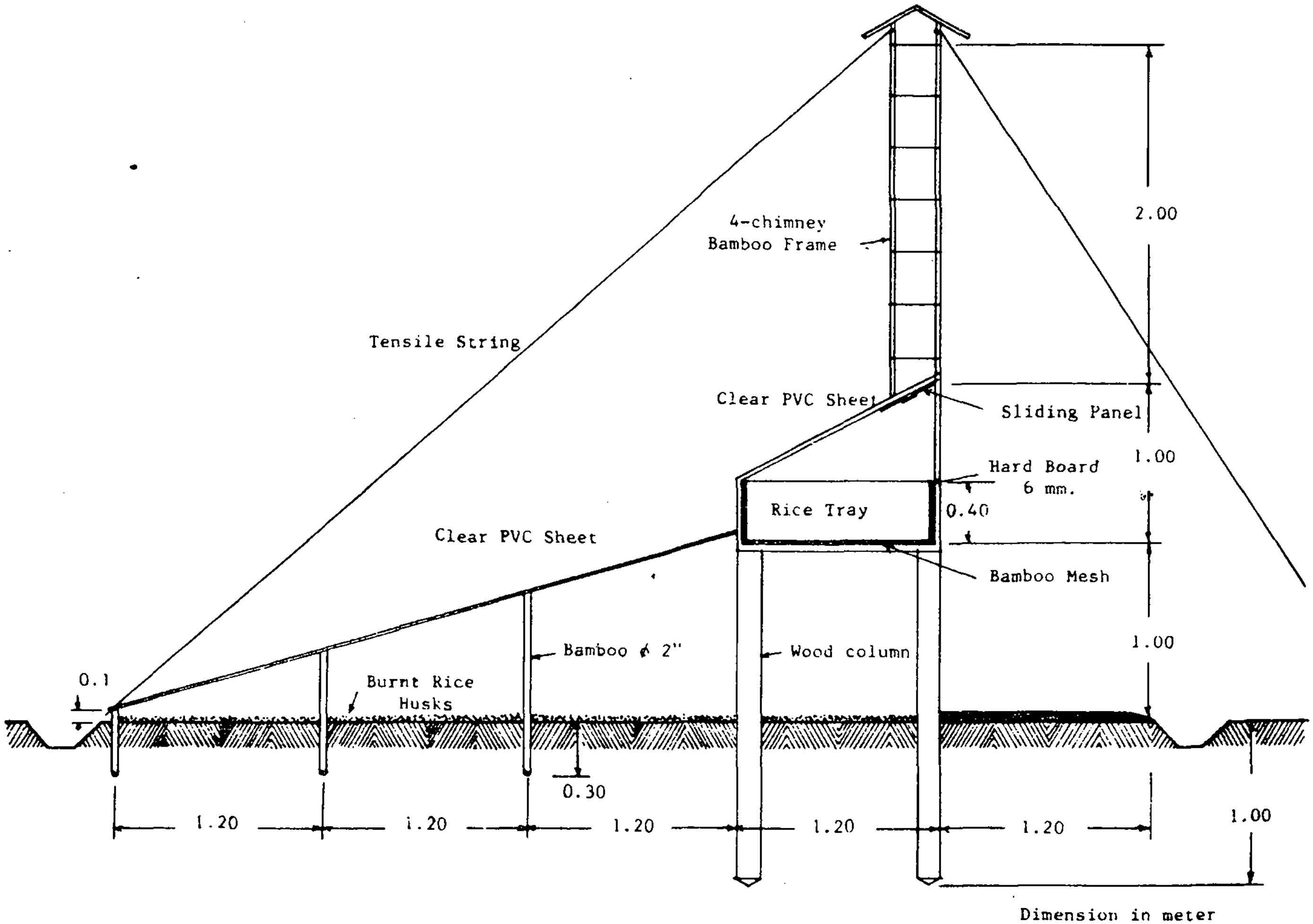


Fig. 2. Cross Section of the AIT solar Rice Dryer

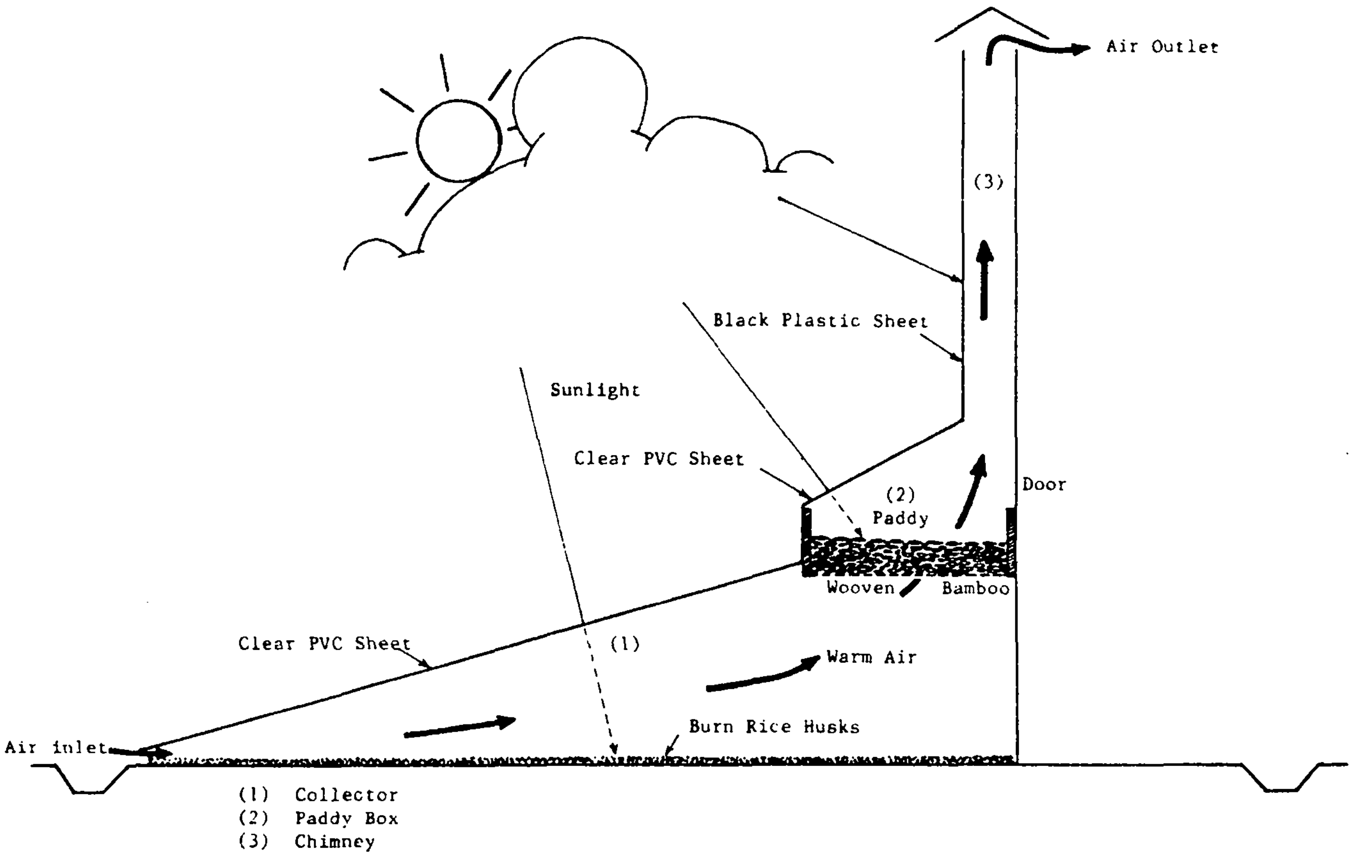


Fig. 3. The Important Components and Principle of the AIT Dryer

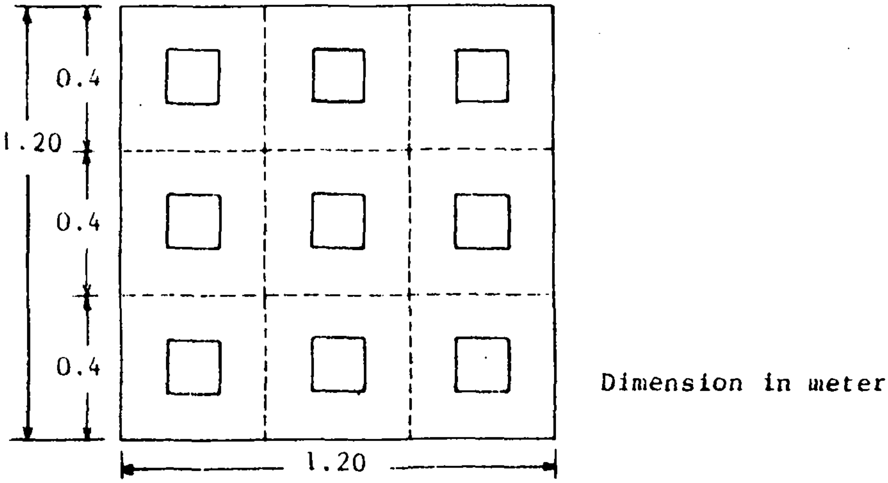


Fig. 4a. Top View of the 125 mm. Rice Bed

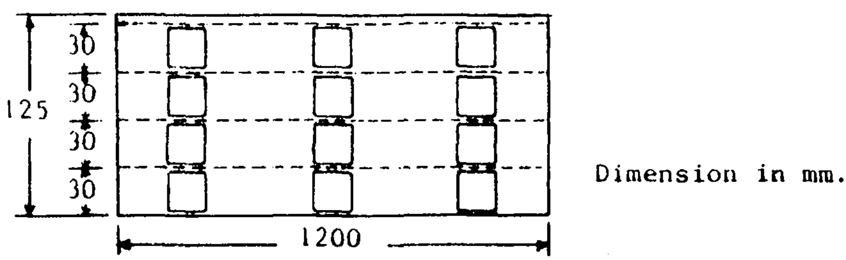


Fig. 4b. Cross Section of the 125 mm. Rice Bed

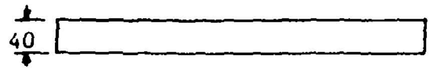


Fig. 5a. Cross Section of the 40 mm. Rice Bed

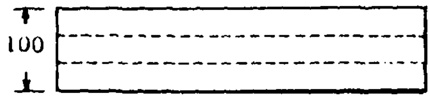


Fig. 5b. Cross Section of the 100 mm. Rice Bed

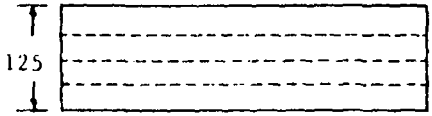


Fig. 5c. Cross Section of the 125 mm. Rice Bed

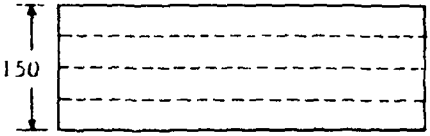


Fig. 5d. Cross Section of the 150 mm. Rice Bed

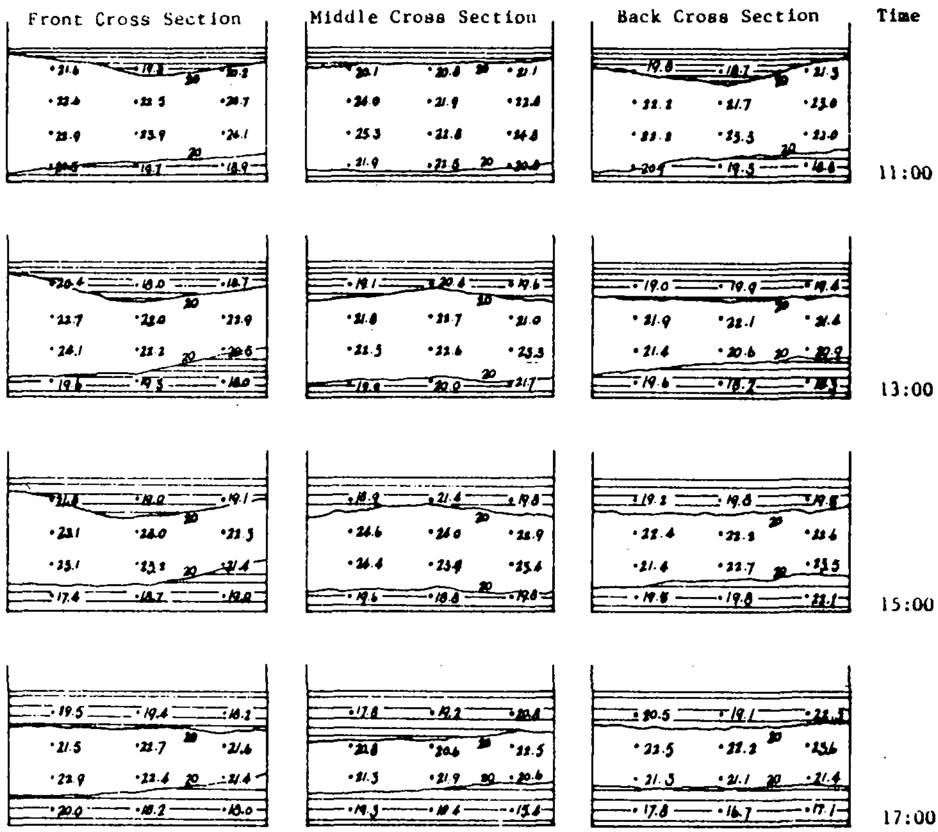


Fig. 6. Moisture Contents in the Unstirred Bed (%Wb)

Average Initial Moisture Content 24.3% Wb.
Measured at 9:30 August 16, 1979.
Tested on the 16th August 1979.
Depth of Rice Bed 125 mm.

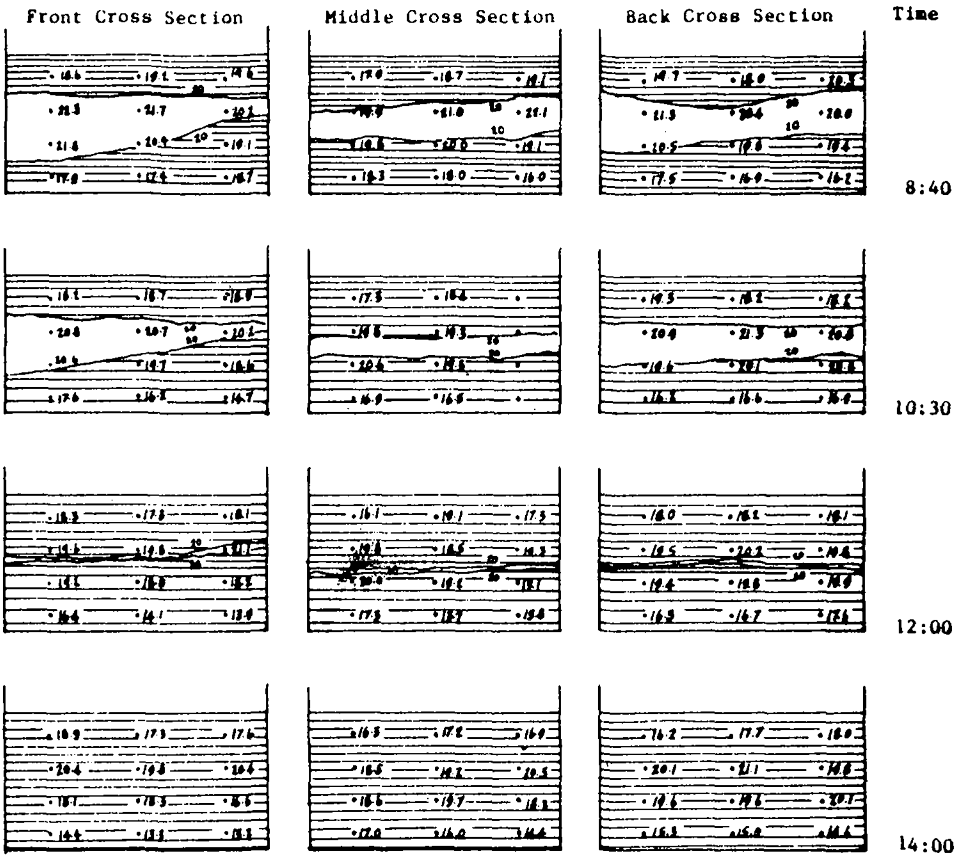


Fig. 6. (*continued*)

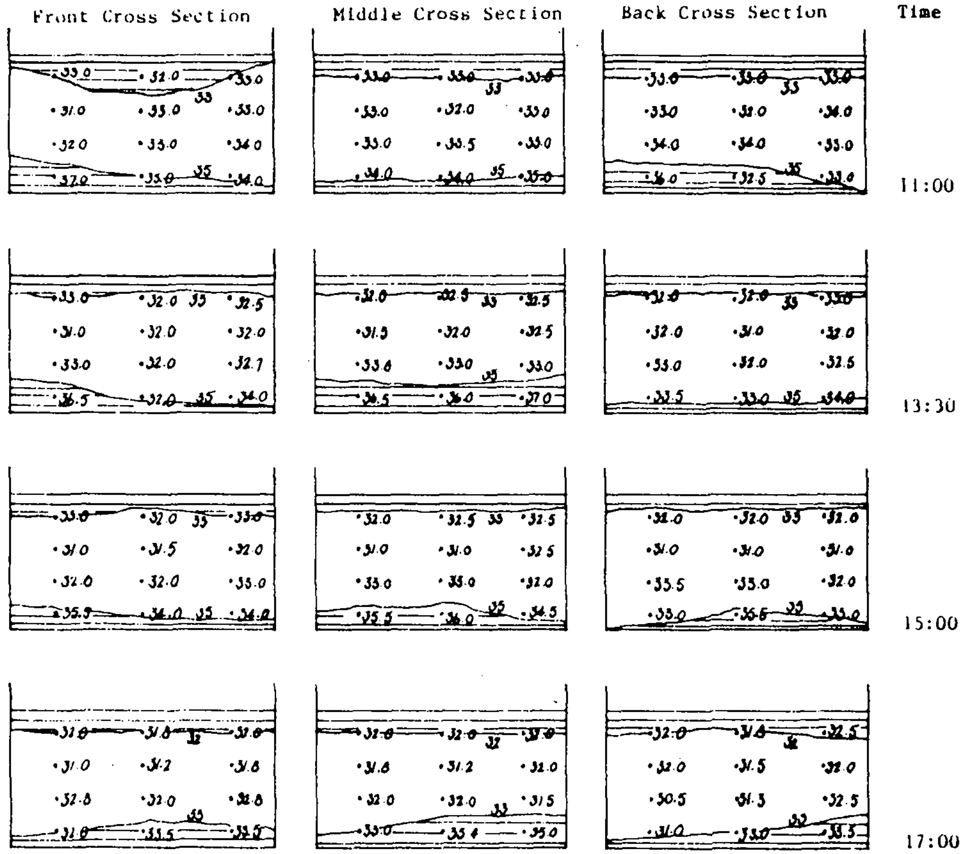


Fig. 7. Temperatures in the Unstirred Bed (°C)
Tested on the 16th August 1979
Depth of Rice Bed 125 mm.

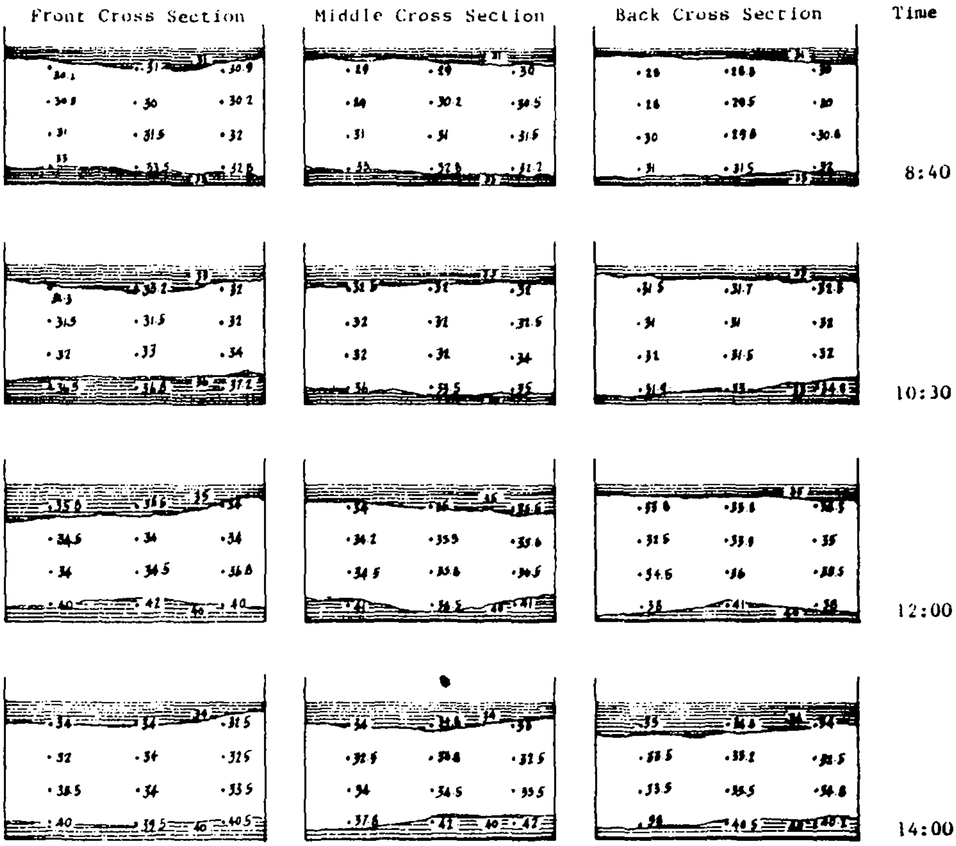


Fig. 7. *(continued)*

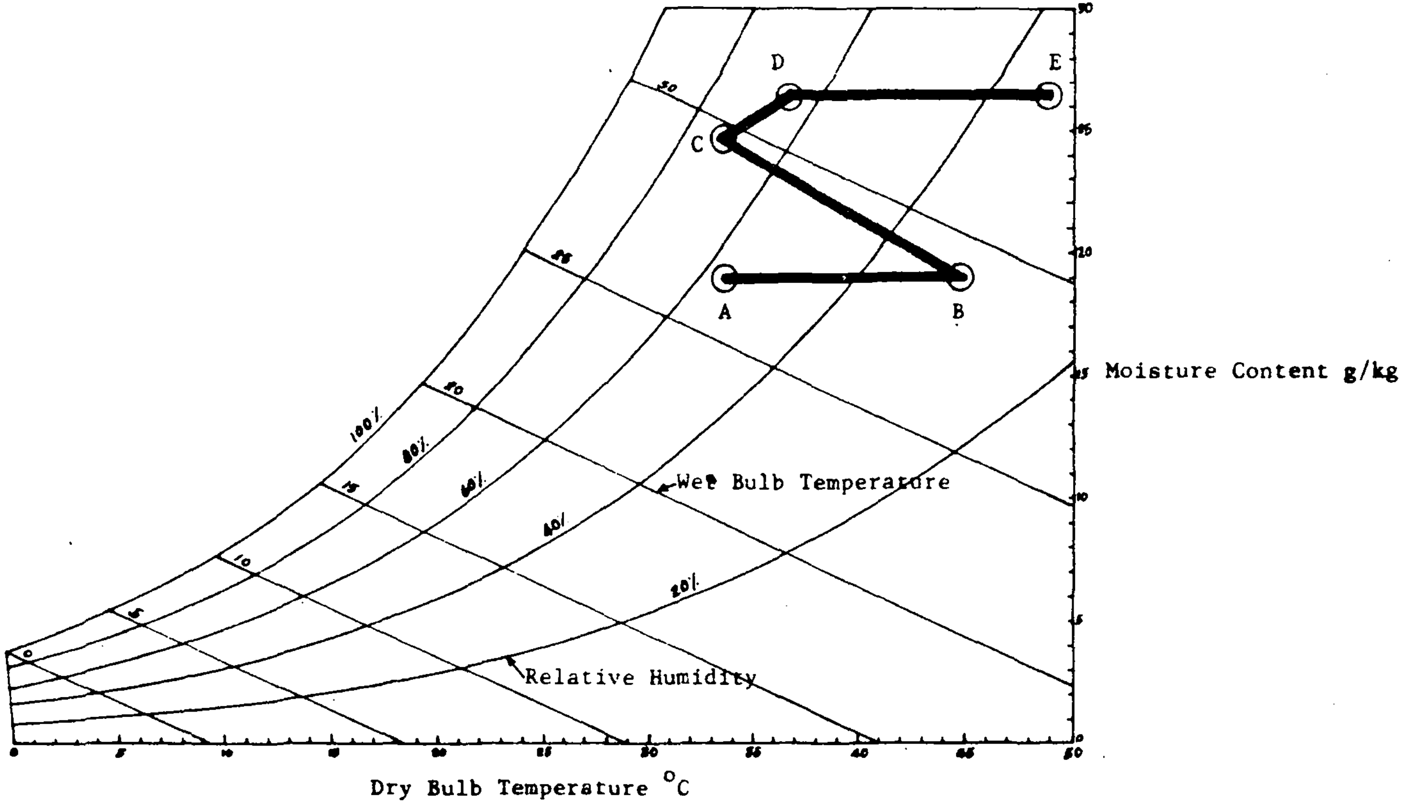


Fig. 8. Psychometric Chart Shows a Typical Drying Process in the AIT Solar Rice Dryer.

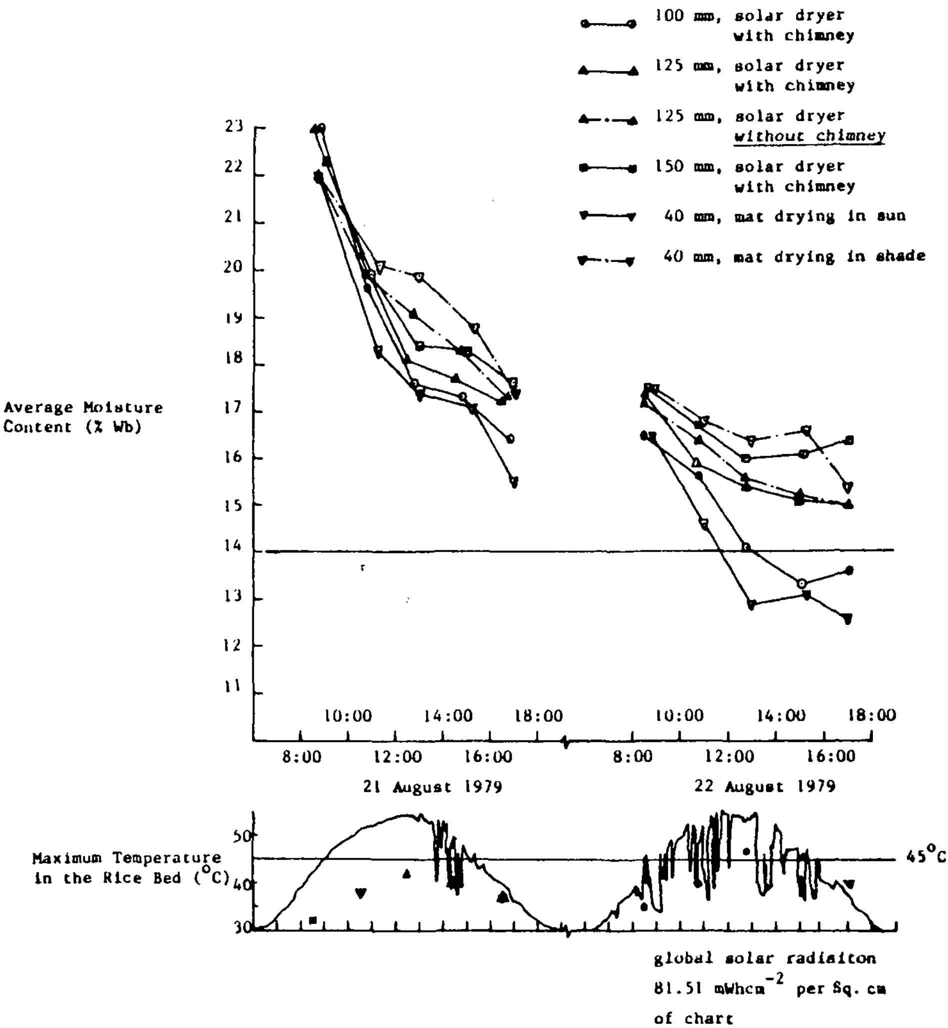


Fig. 9. Drying Curves in Stirred Beds of Hemidified Paddy

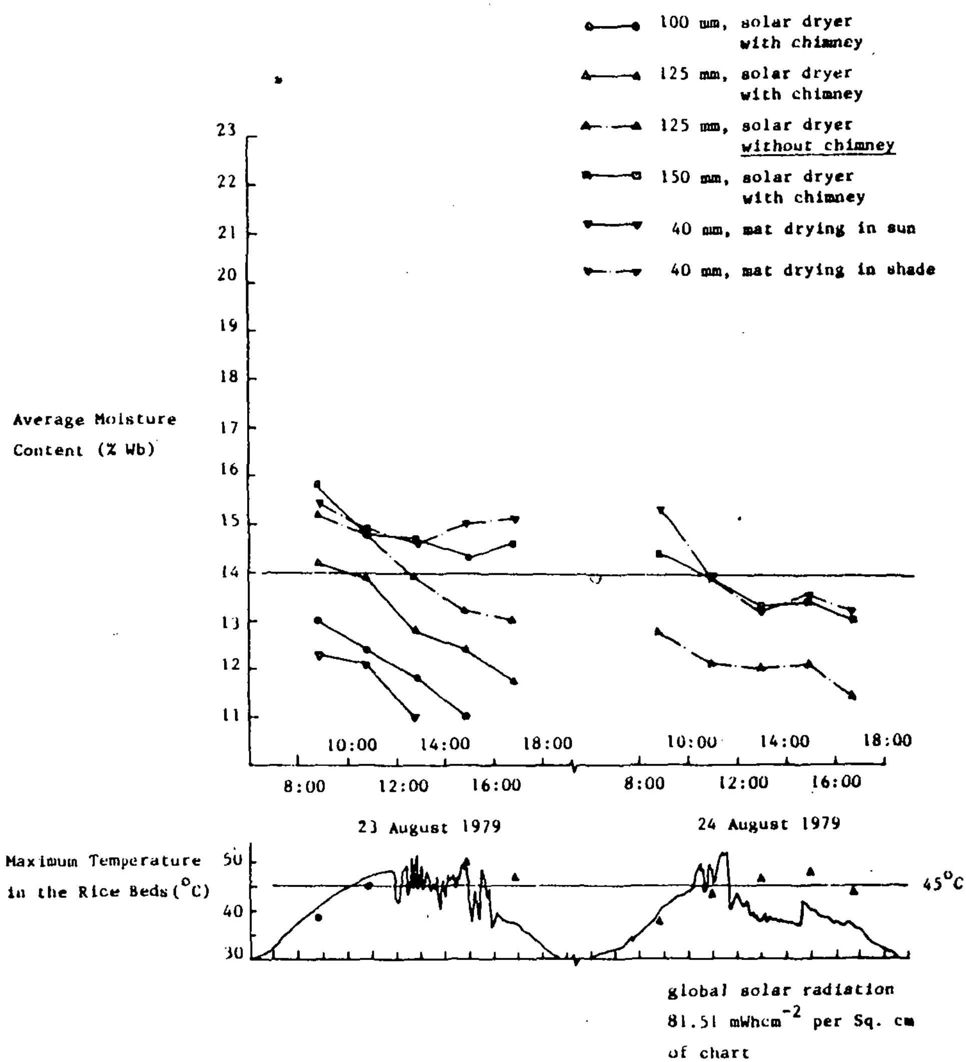


Fig. 9. *(continued)*

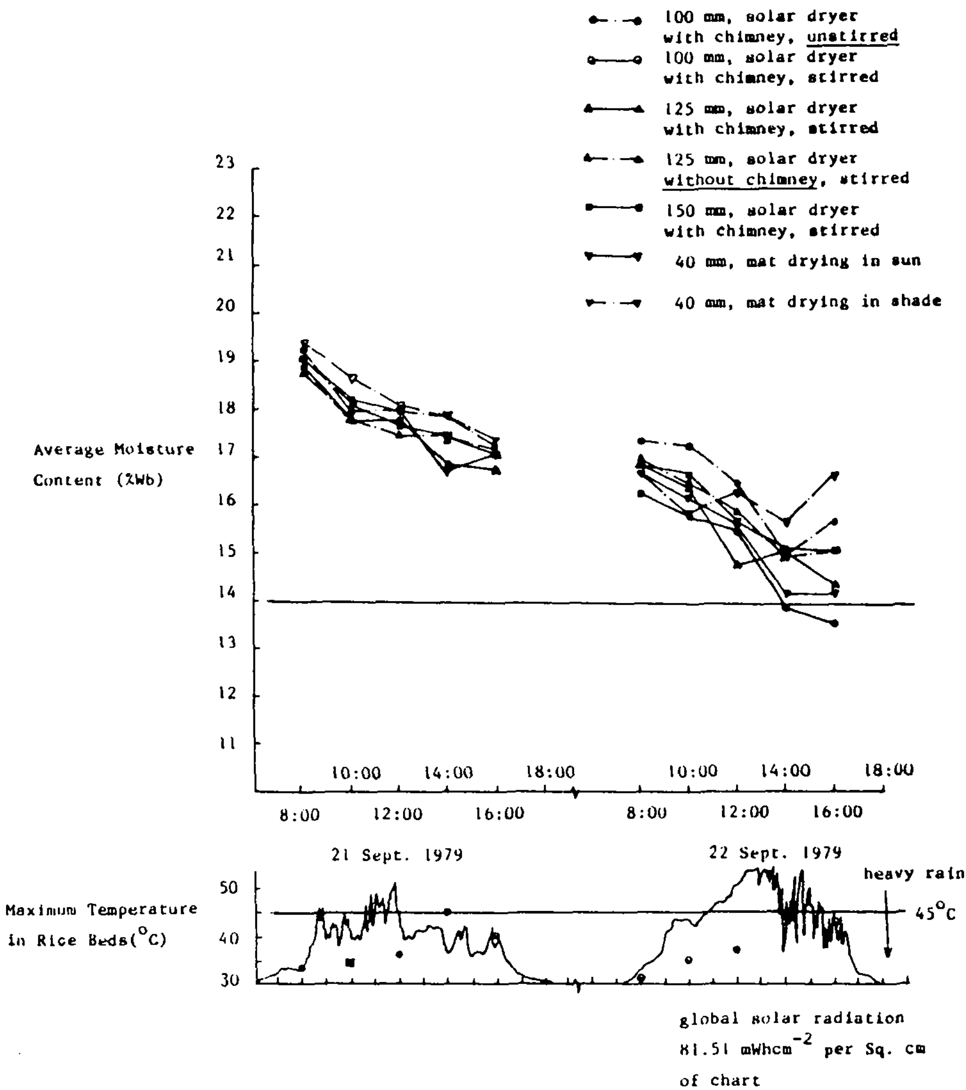


Fig. 10. Drying Curves in Beds of Fresh Paddy

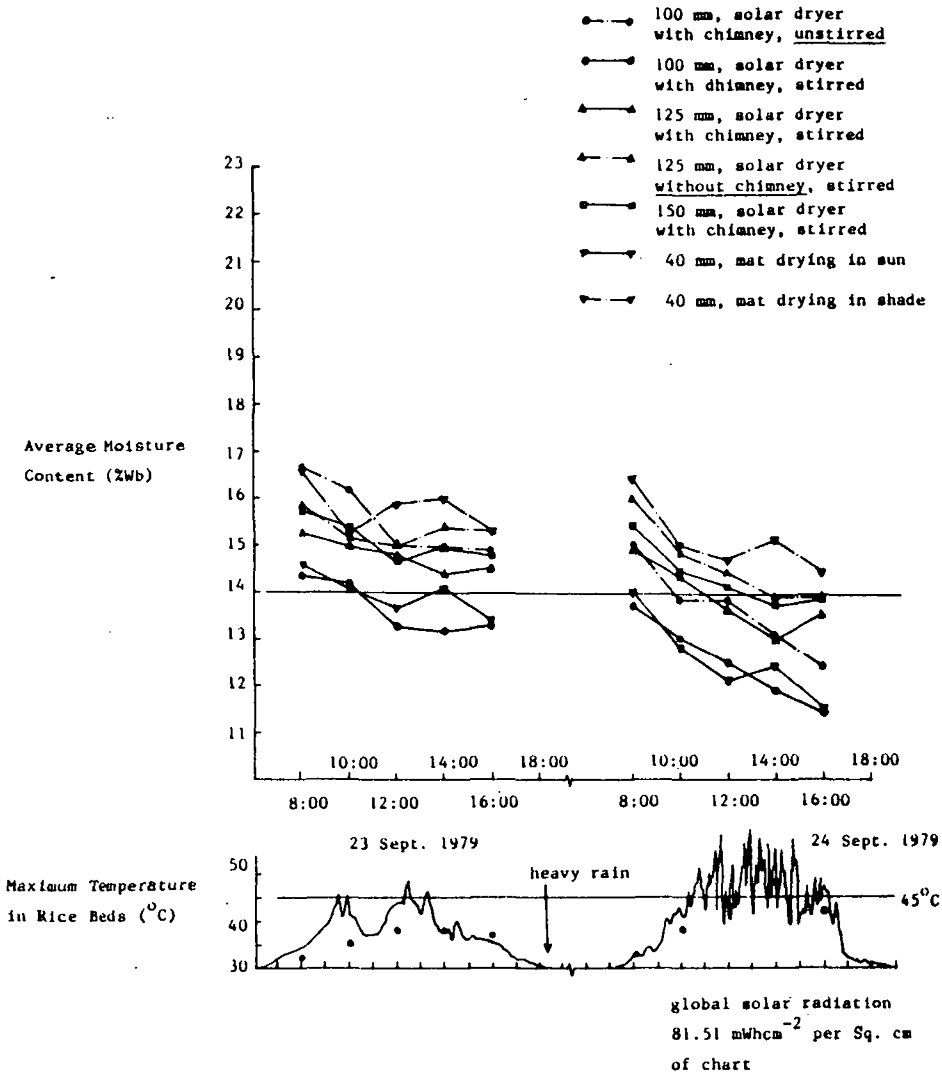


Fig. 10. *(continued)*

Table 1. Milling and Germination Test for the Stirred Beds of Humidified Paddy.
Paddy: RD 7, Humidified from initial moisture content of 14.1 to 23% wb.
Date of Drying: 21-24 August 1979
Tested by: Rice Division

Drying Conditions	*Moisture Content (%wb)*		*Drying Period to 14%wb (day)*	*Occurance of Temp. >45°C*	*Germination (%)*	*Milling Quality*		
	Oven (130°C-2hr)	*Dole Moisture Tester*				*Milled (%)*	*Head Yield (%)*	*Broken (%)*
Paddy before humidifying	11.37	13.75	–	–	89	68.8	50.8	18.0
100 mm, dryer with chimney	9.70	9.75	1½	3	96	70.2	53.8	16.4
125 mm, dryer with chimney	10.58	10.95	2½	4	96	69.2	46.0	23.2
125 mm, dryer without chimney	10.35	10.55	2½	2	97	69.0	43.6	25.4
150 mm, dryer with chimney	10.85	13.15	2½	0	97	69.0	44.4	24.6
40 mm, mat drying in sun	9.53	9.75	1½	1	97	70.0	40.8	29.2
40 mm, mat drying in shade	11.14	13.35	3½	0	86	69.6	50.0	19.6

Remark The head yield of the 100 mm, dryer with chimney is *the best* but of the mat drying in sun is *the worst.*

Table 2. Milling and Germination Test from Beds of Fresh Paddy.
Paddy: RD 7, Fresh harvested paddy
Initial moisture content: 19% wb.
Date of drying: 21-24 September 1979
Tested by: Rice Division

Drying Conditions	*Moisture Content (%wb)*		Drying Period to 14%wb day)	Occurance of Temp. >45°C	Germination (%)	*Milling Quality*		
	Oven (130°C-2hr)	*Dole Moisture Tester*				*Milled (%)*	*Head Yield (%)*	*Broken (%)*
100 mm, chimney, unstirred	11.63	7.83	3½	0	89	73.8	57.4	16.4
100 mm, chimney, stirred	10.78	11.13	2	1	91	72.0	57.2	14.8
125 mm, chimney, stirred	12.18	12.98	3½	0	89	71.0	57.2	13.8
125 mm, no chimney, stirred	13.45	7.98	4	0	85	73.6	57.0	16.6
150 mm, chimney, stirred	13.20	13.63	4	0	90	70.8	54.8	16.0
40 mm, mat drying in sun, stirred	13.01	13.33	2	0	87	70.2	48.8	21.4
40 mm, mat drying in shade, stirred	13.59	7.98	>4	0	90	73.2	60.0	13.2

Remark The head yield of the 40 mm mat drying in sun in *the worst.*

EXPERIMENTS ON A SOLAR-POWERED INTERMITTENT ABSORPTION REFRIGERATOR

by

R.H.B. EXELL AND SOMMAI KORNSAKOO

ABSTRACT

Two prototype ammonia-water intermittent absorption refrigerators have been designed and tested as a step towards the development of a village size refrigerator. They each have two flat-plate solar collectors of area 2.5 square metres and flat auxiliary mirrors attached to the eastern and western edges to enhance the solar heating by manual tracking. Slots in the collector casing are used to allow convective dissipation of the heat of absorption.

Model I contains 67 kilograms of ammonia-water solution with concentration 0.46 from which ammonia is vaporized by solar heat. The ammonia is condensed and collected in a receiver in thermal equilibrium with a 3.5 cubic metres tank of water kept at 3°C cooler than the mean ambient temperature by thermally insulating the tank during the day and exposing it at night. On a bright day over 14 kilograms of liquid ammonia can be distilled. At night the ammonia is evaporated to produce refrigeration and is reabsorbed into the solution through inlets to the collector feeder, while the heat of absorption escapes from the collector surface. In one test 25 kilograms of ice were produced from 32 kilograms of water at 28°C.

Model II is similar to Model I but the collectors have a smaller heat capacity and semicircular cylindrical mirrors under north-south oriented strips of black absorber plate giving a theoretical concentration ratio of 2. The performance of this system was not quite as good as that of Model I due to losses in the cylindrical mirrors.

1. *Introduction*

A solar powered refrigerator for making ice and storing perishable food and medical vaccines would be useful for remote areas in developing countries where conventional energy sources such as oil and electricity are unobtainable or expensive. In such areas the refrigeration system must be simple in design and must not depend upon the availability of skilled labour. It must be designed so that it can be manufactured locally at a cost that the people for whom it is intended can afford.

As long ago as 1972 Merriam(1) proposed that effort should be directed towards the development of a solar ice maker for rural areas. It should be capable of producing an output of 60 to 70 kg of -10°C ice per day from an input of 10 to 12 m^2 of solar radiation and the services of a full time unskilled operator.

Solar powered intermittent ammonia-water absorption refrigeration using flat-plate collectors was pioneered by Chinnappa(2). Numerous experimenters have since undertaken similar work for such systems offer promise of providing what is required for rural areas. In the Asian Institute of Technology a small prototype ammonia-water intermittent absorption refrigerator with a 1.44 m^2 flat-plate solar collector was tested in 1977 as a first step towards the development of a village size refrigerator (3). The unit contained 18.7 kg of ammonia-water solution of concentration 46% ammonia by weight. On a bright day 3.5 kg of liquid ammonia were obtained and 6.4 kg of ice were produced. The ice kept 3.5 kg of fruit below 15°C while the ambient temperature reached 37°C in the afternoon. No oil or electricity was used.

The specific goal of the project currently under way is to develop solar powered refrigerators for making ice and storing perishable agricultural products sufficiently simple in design to be manufactured locally and operated manually. They must have a high reliability and minimum maintenance requirements, and must be independent of any external energy supply such as kerosene or electricity.

2. *Design Concept*

Fig. 1 shows the flow diagram of the system, and Fig. 2 shows the ideal cycle. The operation of the system is divided into four processes as follows.

(1) a to b (morning): With valves A, B and C closed the ammonia-water solution in the solar collector is heated from ambient temperature 30°C and solution pressure 317 kPa to the generating temperature 77°C at which the pressure 1170 kPa is the saturation vapour pressure of pure ammonia at ambient temperature, the concentration remaining constant at 46% of ammonia by weight.

(2) b to c (midday): With valve A open, and valve B and C closed ammonia is vaporised from the solution at constant pressure, condensed, and collected in the receiver at ambient temperature (point e in Fig. 2). The solution concentration is reduced to 40% and the solution temperature rises to 87°C.

(3) c to d (evening): With valve A, B and C closed the solution is cooled to the temperature 39°C at which the pressure is 317 kPa, the concentration remaining constant.

(4) d to a (night): With valve A closed, and B and C open the liquid ammonia evaporates in the evaporator at constant pressure 317 kPa and temperature -8°C (point f in Fig. 2). The ammonia vapour is reabsorbed into the solution increasing its concentration to 46% while the solution temperature falls from 39°C to 30°C by releasing the heat of absorption to the surroundings.

3. *Construction Details*

The system is constructed throughout of seamless black steel pipe with welded connections. The physical arrangement of the components is shown in Fig. 3. Two slightly different units were constructed and their performance compared.

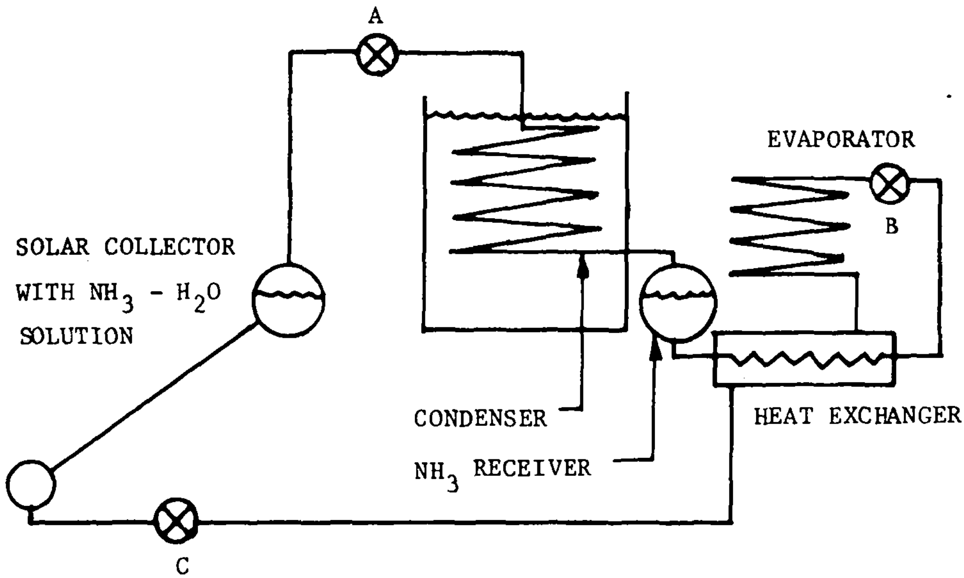


FIG. 1 EXPERIMENTAL INTERMITTENT UNIT IN AIT

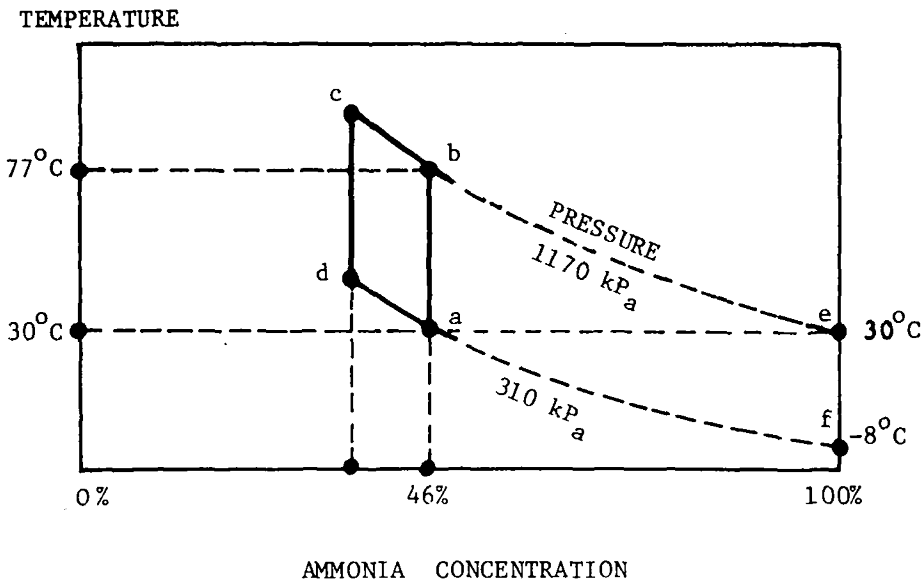


FIG. 2 AMMONIA-WATER ABSORPTION CYCLE

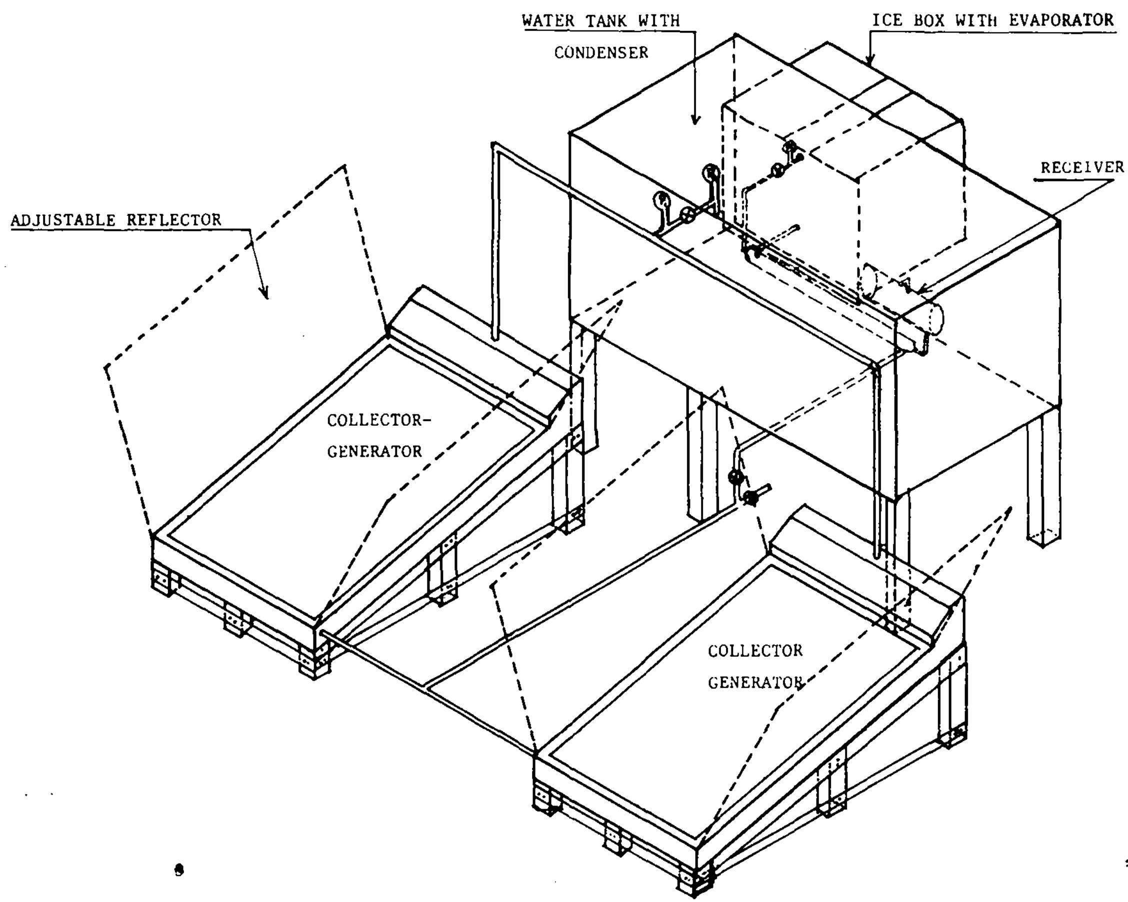


FIG. 3 : ISOMETRIC VIEW

Model I is simply a modified enlargement of our original small prototype. It has a solar collector divided into two 2.5 m^2 panels with adjustable mirror boosters attached to the eastern and western edges for manual solar tracking. To release the heat developed in the collectors during the absorption process at night slots in the collector casing are used to allow heat transfer to take place by natural convection. The slots must be closed for the generation process during the daytime.

The solar collectors contain ammonia-water solution from which ammonia is vaporised by solar heating during the day. The ammonia is condensed in the condenser immersed in a tank of cool water and collected in a receiver placed outside the water tank, but in direct thermal contact with it, so that the liquid ammonia level can be observed easily.

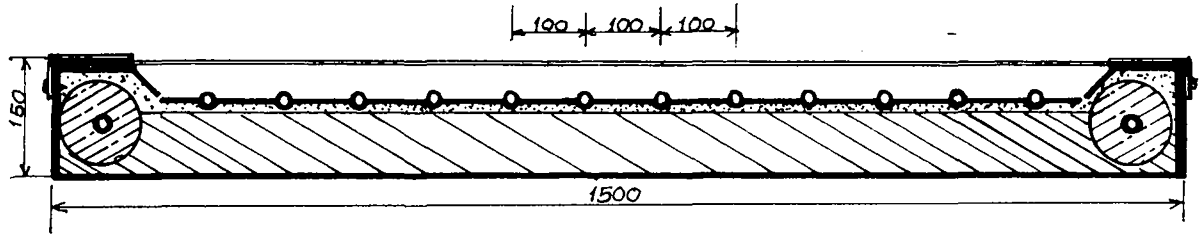
Model II is similar to Model I except that the heat capacity of the collector has been reduced by halving the number of risers and using cylindrical mirrors arranged below gaps between the riser fins to complete the collector area. The system gives a maximum theoretical concentration ratio of two for both direct and diffuse solar radiation. There is also a reservoir of extra solution that can be allowed to flow through the collector when weather conditons are good. The cross sections of the collectors in Model I and II are compared in Fig. 4.

The design of *the collectors* was based on the heat transfer analysis of Moore and Farber(4). In Model I the collector has fourteen 25 mm diameter seamless black steel pipe rises 2.20 m long and 100 mm apart connecting a 100 mm diameter bottom feeder to a 125 mm diameter top header, each 1.50 m long. The outermost risers are thermally insulated to provide return lines for internal circulation of the heated solution by thermosyphoning. Copper sheet, 1.5 mm thick soldered to the risers and painted dull black, forms a collecting area of 2.5 m^2. The collector has a single glass cover. Insulation 100 mm thick made of glass wool and polystyrene foam is placed underneath the collector plate. The collector is embedded in a glavanized iron casing and supported by a wooden stand tilted at an angle 14^o to the horizontal facing south. Each unit has two collectors and contains 67 kg of ammonia-water solution of 46% ammonia concentration by weight. The top header is half full to a level observed in a sight glass.

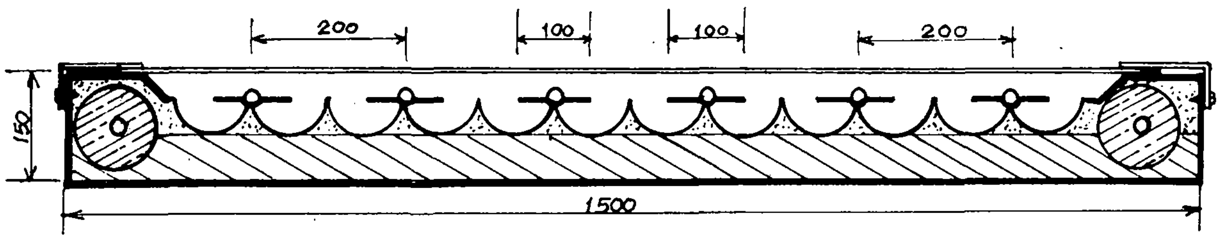
Plane mirror reflectors are mounted on the eastern and western edges of each collector and can be adjusted manually to obtain maximum energy input on the collector. Each mirror has the same size as the collector plate.

The rectifying column is a 25 mm diameter steel pipe 1.25 m high through which the ammonia vapour from the solution rises during regeneration. This pipe serves to remove unwanted water vapour by condensation on the walls. There is a horizontal steel pipe 25 mm in diameter connecting the top ends of the rectifying columns. Another steel pipe with a shut-off valve is connected between the middle of the horizontal pipe and the condenser.

The cooling water tank is made of 3 mm thick metal sheet and holds 3.5 m^3 of



MODEL I



MODEL II

FIG. 4 : CROSS - SECTION OF COLLECTORS

water. The amount of water is designed to keep the temperature change less than 2°C during the regeneration process. The water tank is supported by a wooden stand.

The condenser immersed in the cooling water is made of 13 mm diameter steel pipe and has a total length of 12 m. It is needed to provide a heat transfer surface for rejecting the latent heat of condensation of the ammonia to the water bath at a sufficient rate to keep the pressure in the system as low as possible during regeneration and thus obtain the most efficient operation.

The liquid ammonia receiver placed outside the cooling tank but in direct thermal contact with it, consists of a 260 mm diameter steel cylinder 0.50 m long with a sight glass attached for observing the ammonia level clearly. During refrigeration the flow of ammonia from the receiver to the evaporator is controlled by a hand expansion valve.

The evaporator made of 13 mm diameter steel pipe 15 m long, is coiled and set in the interior of a stainless steel box of dimension 5.60 dm x 8.86 dm x 5.00 dm to form two cool storage chambers of total volume 200 dm^3. Aluminium plates 1.5 mm thick are attached to the outer surfaces of the evaporator coil to form an ice box containing the 32 dm^3 of water to be frozen, while a 12 dm^3 aluminium cold compartment is placed inside. The cool storage boxes are insulated on the outside with polystyrene foam 100 mm thick in a galvanized iron sheet casing. They have similarly insulated lids on top.

The counter-flow double-pipe heat exchanger consists of a 13 mm diameter inner pipe and 32 mm diameter outer pipe 1.25 m long. Between the tubes, semi-circular baffles are fixed at 25 mm spacing. The heat exchanger is connected between the receiver and the evaporator, and is thermally insulated. Unfortunately, the ideal head exchanger will increase the refrigeration effect only 7 or 8% but it was nevertheless considered worthwhile including it.

The absorption line connected between the heat exchanger outlet and the feeder inlets, is made of 13 mm diameter steel pipe 7.5 m long. After evaporation the ammonia is reabsorbed into the solution through absorption inlets to the collector plate opposite the 3rd, 6th, 9th, and 12th risers of each collector. The heat of absorption is thus distributed evenly over the collector plates and is lost to the surrounding night air by natural convection and radiation. However, if the reabsorption is allowed to proceed too rapidly, the refrigeration temperature is not low enough to produce ice because overheating in the solution causes the pressure in the system to rise.

Photograps of the unit are shown in Figs. 5, 6 and 7.

4. *Results*

Test on Model I without mirrors

On a typical bright day in Thailand, (2 November 1978) the solar radiation falling directly on the collectors was 116.6 MJ.

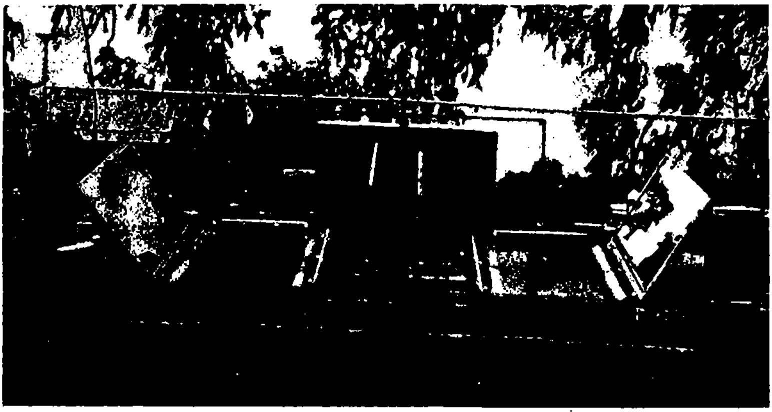


Fig. 5: FRONT VIEW

Fig. 6: BACK VIEW

Fig. 7: ICE BOX

With solar heating starting at 8 a.m., the generation of ammonia began at 11 a.m. and continued until 4 p.m. During generation the solution temperature rose from 35°C to 94°C and 9.4 kg of pure liquid ammonia were produced at the condensing temperature 27°C. After regeneration, at 5 p.m., slots at the top and bottom of the collector casings were opened to allow the surrounding air to cool the solution in the collectors. This took until midnight to reach the ambient conditions. The ambient temperature varied from 30°C to 21°C. Since the heat of generation calculated from standard data was 32.4 MJ, the efficiency of the solar collector was 28%.

Normally the refrigeration process takes place between midnight and 7 a.m. Starting with 25 kg of water at 25°C, about 20 kg of ice are obtained. This ice surrounds a central storage compartment of volume 12 dm^3 and keeps its temperature within the range 0°C to 4°C for the whole of the following day. The two other storage compartments are kept below 10°C all day by the same ice. On subsequent days it is easier to freeze water from melting ice because it is already cold; and unused liquid ammonia can be saved for cloudy days. In this way the storage compartments can be kept cold continuously.

Test on Model I with mirrors

The mirror reflectors were attached to each side of the solar collector in February 1979 and tests were conducted in March 1979. On a typical bright day (14 March 1979) the solar radiation falling on the collectors was 127.5 MJ. By adjusting the mirror reflectors every hour the total amount of incident radiation was increased by a factor 2.2.

During the regeneration period, the temperature and pressure of the ammonia-water solution rose from 27°C and 250 kPa at 7 a.m. to 105°C and 1307 kPa in the afternoon. At 10 a.m. the generation of ammonia began; 14.4 kg of liquid ammonia were distilled and collected in the receiver at the condensing temperature 30°C. Since the heat of generation calculated from standard data was 46.15 MJ, the efficiency of the solar collector was 16.5%.

During the refrigeration, which lasted from midnight to dawn, the temperature of the ammonia in the receiver was controlled by the absorption pressure, and hence by the solution temperature in the collector, which varied from 29°C to 40°C. The resulting evaporator coil surface temperature ranged from 27°C intially to -14°C, and returned to 1°C at the end of the process. This experiment could produce only 25 kg of ice from 32 kg of water at 28°C. Theoretically it should have produced 32 kg of ice. However, it was observed that the liquid ammonia produced could not all be used within the limited time of absorption due to the high solution pressure. This problem was solved in further experiments by removing the insulation of the top header to allow the heat of absorption to escape from the solution faster.

Three day run

Fig. 8 shows the results for an experimental run of three fine days from 17 March

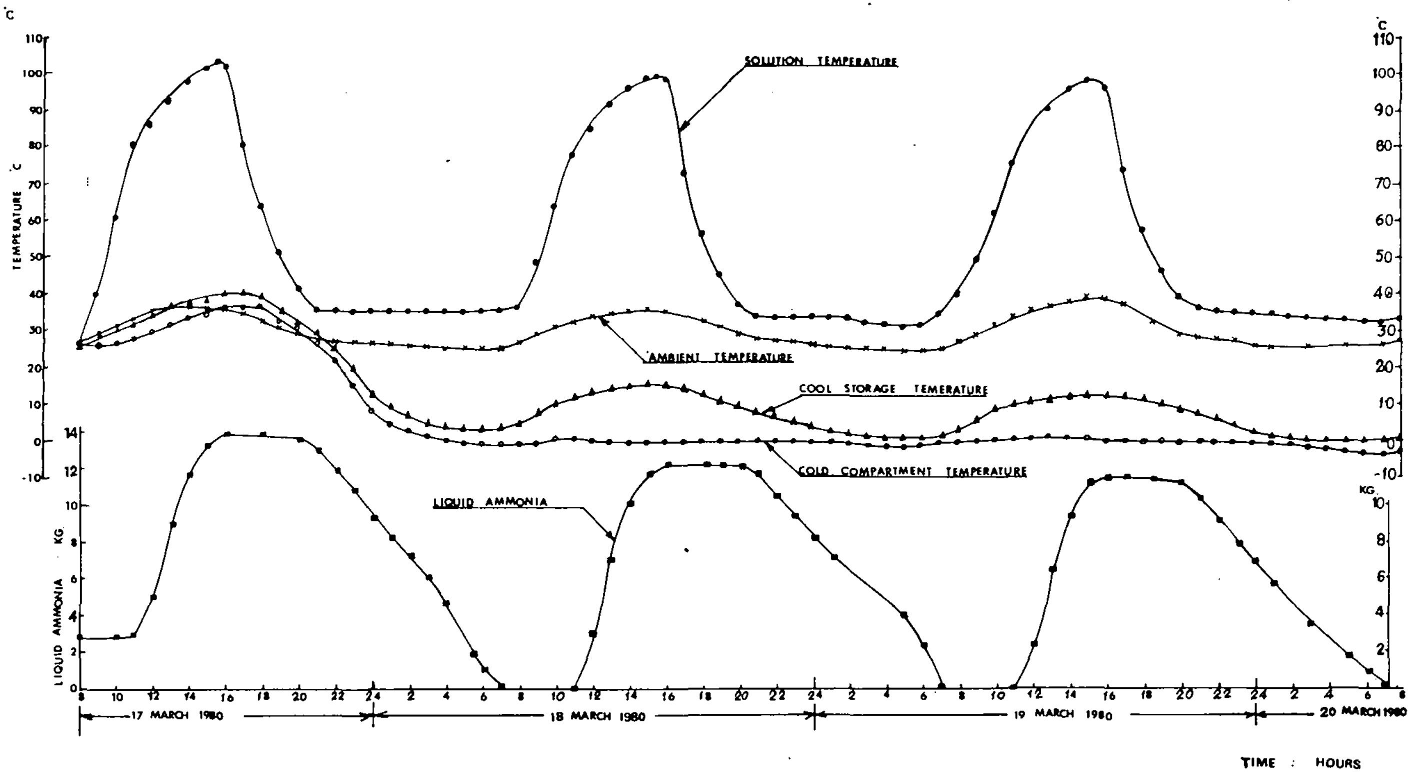


FIG. 8 : THREE- DAY RUN

- 19 March 1980. On the average 12 kg of liquid ammonia were produced each day. While the ambient temperature varied from about 25°C at night to about 35°C during the day, the ice compartment temperature remained constant at the ice point 0°C and the temperature in the cool storage compartments adjacent to the ice compartment remained in the range 2°C to 13°C.

Comparison between Models I and II

Fig. 9 compares the experimental results from Models I and II on the same day (4 January 1979). The booster mirrors were not used.

The criterion for judging the performance of the systems is the amount of liquid ammonia produced. It can be seen that, because of its smaller heat capacity, the generator of Model II produces liquid ammonia earlier in the day than the generator of Model I. But at the end of the day Model I had produced more liquid ammonia than Model II. This could be because the reflectivity of the cylindrical stainless steel reflectors under the first of the generator risers in Model II was not high. Thus the advantage expected due to the lower heat capacity of Model II was offset by the losses in the reflector system.

5. *Discussion*

Economics

A preliminary economic analysis of the refrigeration system shows that, assuming a life of 10 years, an interest rate of 10% per annum, and a maintenance cost 2% of the capital cost per year, the present value (1979) of the cost of the unit with a 5 m^2 collector is US$ 2,320, as constructed in AIT. Assuming an average daily ice production of 22.3 kg, the present value of the total income at the factory price of ice in Bangkok is $ 396, and at the retail price of ice in Bangkok is $ 1,200. Hence the cost of ice produced by our model is about six times the factory price in Bangkok, and about twice the retail price. This is not bad in view of the fact that the price of ice in remote areas is more than it is in Bangkok, and that improvements in the design can still make the system more efficient and less costly.

Problems

The system as it stands on the AIT Campus at present is not yet developed for manufacture and operation in the field. There are two major problems. The first is that hand valves are used to control the flow of liquids and vapours, the most important being at A and B in Fig. 5. These valves will not work properly after a period of time due to wear and leakage. It is probable that the system could be made automatic with valve A an ordinary non-return valve opening in the direction from the collector to the condenser. The expansion valve B could be an automatic pressure controlled expansion valve. These valves, which are an expensive part of the system, would have to be of high quality so as to remain working without maintenance for many years.

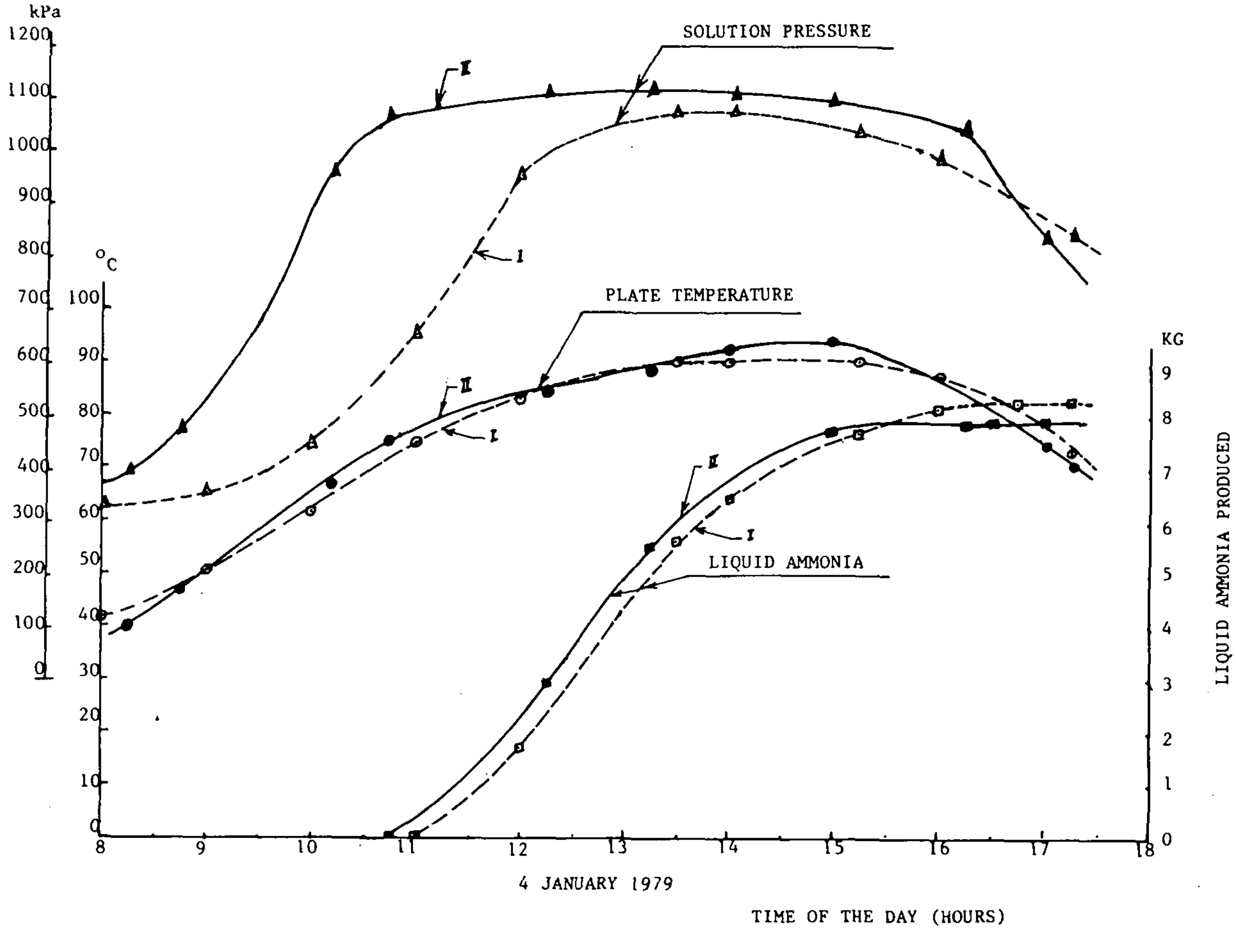


FIG. 9: COMPARISONS OF MODEL I AND II

The second major problem is that of the difficulty of removing the heat of absorption from the collector during the refrigeration period at night. In our earliest experiments with a small model(8) we removed the glass cover at night. This method would not be good in a large fixed installation, partly because the physical effort required to move the glass cover would be too great and there would be a risk of breaking the glass, and partly because the black collection surface would deteriorate rapidly due to such causes as the accumulation of dust. Alternative ways of getting rid of the heat would be removing the back insulation of the collector and the insulation over the header, or using extra tubes through the generator into which cool water can be allowed to circulate.

The Collectors

The development of the collector is interesting, and the suggestion made here would be applicable, not only to refrigerators, but to any other application where fluids are to be heated to temperatures in the range 80°C to 100°C in a tropical climate. The characteristic of this climate is that about half of the solar radiation is diffuse. Therefore ordinary concentrating collectors would not be good for most of the time, and the basic configuration should be of the flat-plate collector type. However, to achieve the higher temperatures required under less than the maximum possible solar radiation something better than the conventional flat-plate collector is needed. The new design proposed employs a selective surface on the black plate. Selective surfaces are now available on the market in sheet form that can be attached to the black plate.

The experiments used large mirrors equal in size to the whole collector plate. These mirrors are too large and can be damaged by high winds. They also give rise to geometrical losses for large solar declinations, since the orientation of the incoming rays causes a significant fraction of the reflected light to miss the collector. To avoid these problems the collector can be divided into strips running north-south with strip mirrors on each side. The width of all the strips, the width of the mirrors, and the separation of the strips should all be the same, say 10 cm.

The advantage of this design is that it could be manufactured easily by local industry since no optical precision is required and tracking need not be accurate. An adjustment of the mirrors each hour would be adequate.

6. *A Potential Application of the Intermittent Refrigeration*

There exists in Thailand a project sponsored by His Majesty the King, and undertaken by Chiang Mai University, for the introduction of high yield crops to hill tribes in the north to replace the growing of opium. the objectives is to grow high yield flowers such as gladiolus, statice, stock, carnation, tulip, etc., and to export them from Chiang Mai International Airport. After cutting and packing in the early morning the flowers must be kept cool at 0°C to 5°C before loading into refrigerated trucks for transportation from the hills to the airport in the afternoon, or overnight for transportation the next day.

A conventional refrigeration system cannot be used because a constant electricity supply is not available at the site. However, there is a high potential for a solar powered refrigeration system since solar energy is always available during the dry season when the flowers are harvested. The arrangement currently under study consists of a pre-cooling room cooled by radiation to the sky at night, and refrigerated compartments cooled by a solar powered ice bank system.

A preliminary design based on the intermittent ammonia-water absorption system developed in the Asian Institute of Technology, and on data available from Chiang Mai, shows promise. The system requires fifty flat-plate solar collector panels each of area 2 m^2 to produce 600 kg of ice per day for maintaining the cool temperature in the storage room under the estimated refrigeration load. Due to the cooler ambient temperature and the availability of cool running water at 20°C from the mountain, which can be used as cooling water, the amount of ammonia-water solution required and the heat capacity of the generator is 25% less than in the existing models at AIT. About 900 kg of aqua-ammonia solution will be used to produce about 240 kg of liquid ammonia during the regeneration period. The concentration will change from 0.50 to 0.32 and the distillation of ammonia will occur between solution temperature 59°C and 93°C. The evaporator temperatures will be in the range -33°C to -11°C at night.

Acknowledgements

The authors are indebted to the Overseas Development Administration, United Kingdom, for funds supporting the research, to two former students Bundit Jarimopas and Somchart Soponronnarit whose Master degree thesis work contributed much to the development of the refrigeration system, to Miss Nonglux Chitnomruth for carrying out some of the experimental investigations, and to the staff of the Asian Institute of Technology for cooperation in the construction of the units.

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A SIMPLIFIED NON-LINEAR MODEL LEADING TO A FULL RANGE VALID CALIBRATION TEST OF THERMAL SOLAR COLLECTORS THROUGH SIMPLE EXPERIMENTAL PROCEDURE

by

G.Y. SAUNIER

Preliminary Note

This paper differs from the paper entitled "Further Improvement of a Thermal Solar Collector Non-Linear Model"* of February 1980 in the sense that the basic equation (eq. 21) of the model is established through a simpler way.

It had been found that due to our semi-phenomenological approach there is no necessity to introduce explicitly the fin's effect although it is by no means neglected. This effect is naturally included in the thermal losses coefficients K_1, K_2, K_3 . . . as now defined in eq. (1) where T_f, the fluid temperature, is used instead of T, the plate temperature, which was used in the previous paper.

ABSTRACT

It is well known that the NBS procedure for characterizing thermal solar collectors suffers many imperfections, which, as a result, allows a comparison among different collectors valid only under the same climate and the same working conditions. Moreover it is often hopeless or, at the best, a tedious task to evaluate the performance of a given collector which one intends to use under conditions which are very different from conditions prevailing during the NBS calibration tests.

The present work intends to provide thermal solar collector manufacturers the opportunity to characterize their collectors by means of a set of few parameters easily assessed through a simple calibrating procedure. This set of parameters will be used in turn by solar energy system designers for simple and accurate evaluation of the performances of the collectors foreseen to be used under any given working conditions. This evaluation will be accurate regardless of the outlet temperature of the heat carrier fluid which could be as close as desired to the stagnation temperature (useful for solar refrigeration project for instance) as well as the solar flux, the wind speed and the ambient thermal conditions. Therefore validity of the calculation will be independent of the day time, of the season and of the geographical location.

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* The paper "Further Improvement of a Thermal Solar Collector Non-Linear Model", February 1980, was presented at the conference on Renewable Energy and Applications jointly organized by Technological Promotion Association (Thai-Japan) and King Mongkut Institute of Technology on February 25-28, 1980 and at the "Solar Energy Summer School", ICTP Trieste on September 2 to 20, 1980.

The actual paper assessed primarily the theoretical basis of the model which leads to very simple expressions of the stagnation temperature T_∞, the exact difference Δ_T between outlet temperature and inlet temperature, and, also, to a simple approximate expression of the useful energy gain Q_u when a large heat carrier fluid flow is used. In the expression of T_∞, Δ_T and $(Q_u)_{approx}$; the solar radiation, the wind speed, the ambient temperature and the infrared radiation are explicit, making calculation valid for any foreseen location.

Secondly, a simple procedure for determining the set of intrinsic parameters of a given thermal solar collector type is suggested to manufacturers.

Finally, comparison of the results of the actual model with those given by a much more sophisticated computer simulation program have shown that the actual model can accurately predict the performance of thermal solar collectors for the whole range of the outlet temperature, under wind of any speed and under solar flux values ranging from 400 W/m^2 to 1200 W/m^2.

I. *INTRODUCTION*

To evaluate the expected performances of a solar collector (flat plate type or medium concentration type) a solar engineer has three possibilities:

- either make use of a usual linear Hottel-Whillier model(1) where U, the overall thermal losses coefficient, has been measured by the manufacturer according to the NBS method. However, it is well known that the NBS procedure for characterizing thermal solar collectors allows valid comparison among different collectors only under the same ambient and working conditions than those prevailing during the manufacturer's tests.
- or make use of a set of curves drawn for a large range of ambient temperature, wind speed, and working fluid temperature. Note that it would be a tedious work to evaluate the performances of a solar system with this method even if manufacturers were willing to provide such sets of curves which is far from certainty.
- or (in the case of a solar collector designer), a computer programme should be worked out to solve a system of thermal transfer coupled equations(2). However, a computer is not always available for everybody, specially in developing countries.

The present model intends to provide solar energy system designers a more accurate tool than the NBS linear curves through which the performances of various kinds of solar collectors on the site of a planned solar system could be evaluated and compared. The collector performances could be evaluated very simply, provided 5 to 7 intrinsic parameters* are given by the manufacturer and, provided further that the following working conditions are assessed:

- the flow of the thermal fluid through the collector
- the ambient temperature and, when it is known, the ambient infrared flux.
- the wind speed.

Moreover, it should be noted that the quadratic approximation method used to establish eq. (9) to (21) could be usefully adapted for calculating the specific effect induced by design modifications (e.g. addition of more covers or use of a selective coating) on the thermal loss coefficients of the collector.

II. *THE MODEL*

The basic thermal network of a solar collector is summarized in Fig. 1.

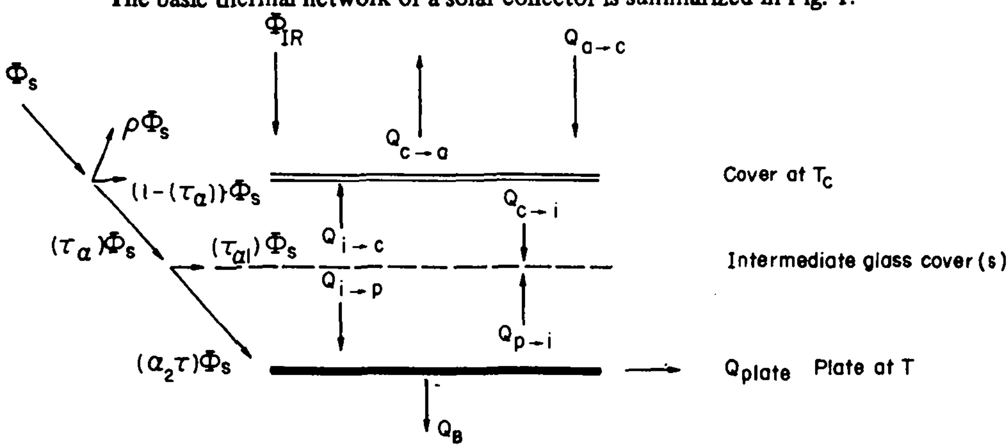

Fig. 1

$Q_{a \to c}$ and $Q_{c \to a}$	are the thermal exchange fluxes between the atmosphere and the front cover of the collector box.
$Q_{i \to c}$ and $Q_{c \to i}$	are the thermal fluxes between the intermediate covers and the front cover.
$Q_{i \to p}$ and $Q_{p \to i}$	are the thermal fluxes between the intermediate covers and the plate.
Q_B	is the thermal loss through the back insulation.
Q_{plate}	is the energy absorbed by the plate and ultimately transferred to the fluid.

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* See remark on page

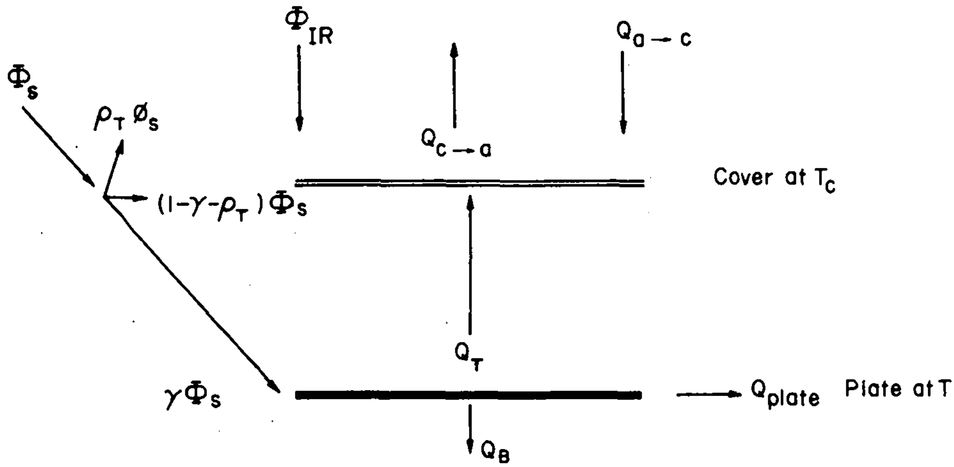

Fig. 2

The thermal network shown in Fig. 1 is rather complicated but it could be replaced by the simpler equivalent network shown in Fig. 2 where γ could be considered as an effective transmittance - absorptance product taking into account the effect of intermediate cover[5a] and the reflection losses on the front cover. γ could exhibit in a sophisticated version of the model a dependence on the angle of incidence of the direct radiation beam on the front glass cover and the ratio of the direct radiation to the diffuse radiation. In that case $\gamma\ \phi_s$ will be replaced by:

$$\gamma\ |f(i)\ \Phi_{direct} + \Phi_{diffuse}|$$

The necessity of introducing a dependence on the incident angle i through a function f(i) is currently under investigation. For the time being only the simpler expression $\gamma\ \Phi_s$ (where ϕ_s is the solar radiation reaching a unit area of solar collector) has been used in this work.

$Q_B = K_B\ (T_f - T_B)$ accounts for the thermal losses by pure conduction through the back insulation.

T_B is the ambient temperature at the back of the collector.

$$Q_T = \sum_{n=1}^{\infty} K_n\,(T_f - T_c)^n = \sum_{n=1}^{\infty} K_n\ \theta^n \text{ where } \theta = T_f - T_c \qquad (1)$$

Q_T is the net losses from the plate to the cover. It is obviously a complicated function of θ which describes the combined effects of conduction, convection, radiation phenomena and fin's effects.

THE FIRST BASIC ASSUMPTION SUBSTANDING THIS MODEL IS TO ASSUME THAT THE SERIES IN EQ. (1) IS A *RAPIDLY CONVERGENT SERIES OR, SIMILARLY, TO ASSUME* THAT:

$$K_1 >> K_2 >> K_3 >> K_4 \quad \ldots >> K_n \tag{2}$$

Moreover, Q_T is bound by:

$$(Q_T)_{Max} = \gamma\Phi_s - Q_B = \sum_{n=1}^{\infty} K_n (T_\infty - T_{c\infty})^n = \sum_{n=1}^{\infty} K_n \theta_\infty^n \tag{3}$$

where $\theta_\infty = T_\infty - T_{c\infty}$

T_∞ is the stagnation temperature of the collector.

$T_{c\infty}$ is the corresponding cover temperature in that case.

Eq. (3) means that if no heat is extracted by the fluid under steady-state performance, all the collected energy is lost through the cover.

Let us now define

$$Q_T = Q_1 + Q_2 \tag{4}$$

where

$$Q_1 = K_1 (T_f - T_c) + K_2 (T_f - T_c)^2 \tag{5a}$$

$$Q_2 = \sum_{n=3}^{\infty} K_n (T_f - T_c)^n \tag{5b}$$

A first improvement of the linear Hottel-Whillier model was to assume that the net thermal loss from the plate to the cover is given approximatively by the quadratic function Q_1 and moreover that Q_2 is negligible. That attempt has been described elsewhere.[3]

At that time, T_E the effective temperature of environment[2a] instead of T_c was used in eq. (5a). The second improvement of the model came from the use of T_c instead of T_E. This had allowed us to explicitly take into account the various environment effect especially the wind and ambient temperature effects.

The next logical step was to look for an approximate expresssion for Q_2 and our first try was to assume Q_2.

$$Q_2 = (\beta\theta + \delta\theta^2)\,\Phi_s$$

This version of the model was presented as a communication at the 1977 COMPLES Congress in Tunis.[4]

The above assumption was not very satisfactory from the basic principles point of view. As a matter of fact the above expression for Q_2 was more of a guess rather than a logical sounding approximation.

The purpose of the present work is to show that a more satisfactory form for Q_2 can be obtained as follows:

In accordance with the basic assumption of the model (see eq. (2)), assume that it is a good approximation to neglect the terms of degree higher than four in eq. (5b). Therefore,

$$Q_2 = (K_3\,\theta + K_4\,\theta^2)\,\theta^2 \tag{5c}$$

In eq. (5c) the truncation leads to an underestimated Q_2. In order to correct this understimation it may be assumed:

$$Q_2 = (K_3\,\theta + K_4\,\theta^2)\,\theta_\infty^2$$

or generally,

$$Q_2 = \nu K_3\,\theta_\infty^2\,\theta + \left\{(1-\nu)\,K_3\,\theta_\infty + K_4\,\theta_\infty^2\right\}\theta^2 \tag{5d}$$

Note that the calculated value of the upper limit of Q_2 (that is, when $T_f = T_\infty$) is the same by means of either eq. (5c) or eq. (5d).

Now from the linear theory of Hottel-Whiller or, from the previous form of this model presented in Cargese[3] and Tunis[4], we know that T_∞ according to the model used, is a more or less complicated function of Φ_s.

Q_2 is the sum of the third and fourth order correction terms. Therefore, it sounds reasonable to take a first order approximation for θ_∞, and to assume a linear dependence in ϕ_s. In other words, the SECOND BASIC ASSUMPTION SUBSTANDING THIS MODEL IS TO ASSESS THAT:

$$Q_2 = \beta\phi_s^2\,\theta + (\delta\,\phi_s^2 + \nu\,\phi_s)\,\theta^2 \tag{5e}$$

Remark: It is, by no means, stated that the three parameters: β, δ, ν, are absolutely necessary for characterizing a solar collector in the actual model frame work. One, two, or even all these may eventually be set equal to zero if experimental tests show that they do not provide a significant improvement in the model's accuracy.

Considering now the thermal transfer network shown in Fig. 2 and also according to eq. (4), (5a) and (5e), several heat balance equations are as follows:

For the system collector + environment:

$$(1-\rho_T)\,\phi_s + \phi_{IR} + Q_{a\to c} - Q_{c\to a} - Q_B - Q_{fluid} = 0$$

which, according to the definition of the effective temperature of the environment, T_E, given in Annex B, could be rewritten as:

$$Q_{fluid} = (1-\rho)\,\phi_s - Q_B - \epsilon\sigma(T_c^4 - T_E^4) - h_F\,(T_c - T_E) \quad (6)$$

The meaning of ρ_T, σ, ϵ, h_F are given in Annex A.

For the fluid,

$$Q_{fluid} = \gamma\phi_B - Q_1 - Q_2 - Q_B \quad (7)$$

or

$$Q_{fluid} = \gamma\Phi_s - (K_1 + \beta\Phi_s^2)\,\theta - (K_2 + \delta\,\Phi_s^2 + \nu\phi_s)\,\theta^2 - K_B(T_f - T_B) \quad (8)$$

We are ultimately looking for T_f, therefore T_c must be eliminated. To perform this elimination:

- First: we note that obviously $T_f \geqslant T_c \geqslant T_E$
- Second: we make THE THIRD MAJOR APPROXIMATION SUBSTANDING THE ACUTUAL MODEL, THAT IS TO SAY: WE NEGLECT THE SUM OF THE TERMS OF DEGREE HIGHER THAN TWO IN THE TAYLOR SERIES FOR T_c IN FUNCTION OF $\omega = T_f - T_E$,

otherwise said:

$$T_c = T_E + \omega\,\frac{(\partial T_c)}{(\partial T_f)_{T_E}} + \frac{\omega^2}{2}\,\frac{(\partial^2 T_c)}{(\partial T_f^2)_{T_E}}$$

or

$$T_c = T_E + a\omega + b\omega^2 \quad (9)$$

where

$$\omega = T_f - T_E \quad (10)$$

Accordingly with the above approximation:

$$T_c^4 = T_E^4 + 4a\,T_E\,\omega + 4\,T_E^3\,(b + \frac{3}{2}\frac{a^2}{T_E})\,\omega^2 \quad (11)$$

Substituting these expressions of T_c and T_c^4 in eq. (6), (7) and (8) and solving the result for a and b, we obtain:

$$a = \bar{K}_1 (G + \bar{K}_1)^{-1} \quad (12)$$

$$b = \frac{\bar{K}_2 (1 - a)^2 - 6\sigma\epsilon T_E^2 a^2}{G + K_1} \quad (13)$$

where

$$\bar{K}_1 = K_1 + \beta\phi_s^2 \quad (14)$$

$$\bar{K}_2 = K_2 + \nu\phi_s + \delta\phi_s^2 \quad (15)$$

$$G = 4\sigma\epsilon T_E^3 + h_F \quad (16)$$

The heat balance of a unit area of the collector plate now reads:

$$Q_{fluid} = \tilde{\phi} - \tilde{K}_1 \omega - \tilde{K}_2 \omega^2 \quad (17)$$

$$\tilde{\phi} = \gamma\Phi_s - K_B (T_E - T_B) \quad (18)$$

$$\tilde{K}_1 = K_B + (K_1^{-1} + G^{-1})^{-1} \quad (19)$$

$$\tilde{K}_2 = \bar{K}_2 (1 - a)^3 + 6\sigma\epsilon T_E^2 a^3 \quad (20)$$

Assuming the solar collector is in a steady - state, Q_{fluid} is the useful energy gained per unit of area of absorber. Therefore, the heat balance equation of the fluid is:

$$L\mu c_p \frac{d\omega}{dy} = \tilde{\phi} - \tilde{K}_1 \omega - \tilde{K}_2 \omega^2 \quad (21)$$

where $\omega = T_f - T_E$

L = length of the collector in the flow direction of the heat carrier fluid

μ = flow per unit of absorber area of the heat carrier fluid

c_p = specific heat of the fluid

III. *Calculation of the Stagnation Temperature, T_∞*

T_∞ is the temperature of the plate and the fluid when there is no useful energy withdrawn, that is to say, when $\frac{d\omega}{dy} = 0$ in eq. (21) (steady - state is assumed).

Then the equation for T_∞ follows:

$$\tilde{\Phi} - \tilde{K}_1 (T_\infty - T_E) - \tilde{K}_2 (T_\infty - T_E)^2 = 0 \tag{22}$$

which leads to

$$T_\infty = T_E + Z \tag{23}$$

where

$$Z = (U - \tilde{K}_1)/(2\tilde{K}_2) \tag{24}$$

$$U = (\tilde{K}_1^2 + 4\tilde{K}_2 \tilde{\Phi})^{1/2} \tag{25}$$

Remark: If $\tilde{K}_2$ is negligible, as it is assumed in the linear Hottel-Whillier model, eq. (22) leads to the well-known classical result which is:

$$T_\infty = T_E + \tilde{\Phi} / \tilde{K}_1 \tag{26}$$

IV. *Calculation of the Useful Energy Gain*

In order to calculate the steady state total useful energy gain of a solar collector of length "L", eq. (21) should be integrated. This equation is a non-linear differential equation (called Bernoulli differential equation) which is easily integrated after defining a new variable $v = (\omega - Z)^{-1}$. The solution reads:

$$T_{out} - T_{in} = (T_\infty - T_{in}) \left[1 - \frac{U}{U + [U - \tilde{K}_2 (T_\infty - T_{in})] \; [\exp(U/\mu c_p) - 1]} \right] \tag{27}$$

where T_∞ is the stagnation temperature

T_{out} is the outlet temperature of the fluid

T_{in} is the inlet temperature of the fluid

Then the total useful energy gain Q_u per unit of area of the collector and per second is obviously:

$$Q_u = \mu c_p (T_{out} - T_{in})$$

Special case: If $\mu c_p/U$ is very large, i.e. $T_{out} - T_{in}$ is small, the exponential term in eq. (27) could be written $1-U/(\mu c_p)$ and Q_u then takes the very simple form:

$$Q_u = \tilde{\Phi} - \tilde{K}_1 (T_{in} - T_E) - \tilde{K}_2 (T_{in} - T_E)^2 \tag{28}$$

Eq. (28) is a mathematical limit of eq. (27). From practical point of view, it is a better approximation to make use of:

$$Q_u = \tilde{\Phi} - \tilde{K}_1 \bar{\omega} - \tilde{K}_2 \bar{\omega}^2 \tag{29}$$

where

$$\bar{\omega} = (T_{out} + T_{in})/2 - T_E$$

Remark: If $\tilde{K}_2$ is negligible, eq. (27) leads to the Hottel-Whillier expression, which is:

$$T_{out} - T_{in} = (T_\infty - T_{in})(1 - e^{-U/\mu c_p})$$

V. *Determination of the Intrinsic Parameters of a Solar Collector*

The fundamental assessment which is substanding the present model is to assume that the very complex interaction between the three basic thermal transfer phenomena results in a net heat exchange between the fluid and the environment which can be calculated by eq. (27) or eventually eq. (29), provided the intrinsic parameters of the collector are known.

To determine the set of parameters, we ought to perform measurements of the collector's performances and, through a least - square fit, compute the "best" values for the parameters.

Suggested Procedure:

(a) Determination of K_B: Measure a set of negative values of Q_u by pouring in the collector hot water at various inlet temperatures. The front glass cover will be covered by a thick mattress of insulating material (as polystyrene foam) of thickness and a known thermal conductivity coefficient λ. Moreover let us measure the temperature T_i on the inside surface of the insulating mattress in contact with the front cover glass of the collector and the temperature T_o on the outside surface.

It is easily shown that the characteristic coefficient K_B of the overall thermal loss through the back and the sides of the collector is given by:

$$K_B = \text{average value of } [|Q_u \exp| - \frac{\lambda}{e}(T_i - T_o)| / (\bar{T} - T_B)] \quad (30)$$

$$\text{where } \bar{T} = (T_{in} + T_{out}) / 2$$

(b) Determination of the other parameters: Because it is a very simple experiment, measure the stagnation temperature T_∞ for as many values as possible of the solar energy flux, Φ_s. Obviously in these experiments, $Q_u{}^{exp} = 0$.

These measurements, even made for numerous value of ϕ_s, are not sufficient for determining the value of the main parameters K_1, K_2, and λ of the collector, keeping in mind that K_B has been previously evaluated.

This assessment can be easily demonstrated if we assume that the very small high order correction parameters - *β, δ and ν - are set equal to zero and that T_E and the* wind speed are constant. Then $\tilde{K}_2$ and $\tilde{K}_1$ keep constant value when measuring T_∞ for various values of ϕ_s. Note that eq. (23) can be rewritten if the term K_B $(T_E - T_B)$ which is very small is neglected:

$$T_\infty = T_E + |(r_1^2 + 4r_2\,\phi_s)^{1/2} - r_1|$$

$$\text{where } r_1 = \tilde{K}_1 / \tilde{K}_2 \quad \text{and} \quad r_2 = \tilde{\gamma} / K_2$$

Therefore, obviously, a fit to the experimental value of T_∞ will determine only the ratio r_1 and r_2 from which the absolute values of K_1, K_2 and γ cannot be calculated. Even if β, δ and ν are not equal to zero and T_E and the wind speed change from one experiment to another, we may calculate only the ratio of all parameters to K_2 through regression analysis and the calculated values will be highly inaccurate. Therefore, it is necessary to perform several measurements of the useful gain Q_u.

Large flow will be used in order that eq. (29) can be used. Since the solar radiation ϕ_s, the wind speed v, and the effective temperature of the environment are explicitly taken into account in the expression of Q_u, experimental measurements of $Q_u{}^{exp}$ can be made at any time, provided steady - state is achieved.

To calculate the intrinsic parameters K_1, K_2, γ, β, δ, ν the six non-linear simultaneous equations system given below is solved through an iterative procedure:

$$\frac{\partial D}{\partial K_1} = 0, \quad \frac{\partial D}{\partial K_2} = 0, \quad \frac{\partial D}{\partial \gamma} = 0, \quad \frac{\partial D}{\partial \beta} = 0, \quad \frac{\partial D}{\partial \delta} = 0, \quad \frac{\partial D}{\partial \nu} = 0$$

$$\text{where } D = \sum_n^N |(Q_u)_n^{exp} - \gamma\phi s_n + K_B(T_{E_n} - T_{B_n}) + \tilde{K}_1\,\bar{\omega}_n + \tilde{K}_2\,\omega_n^2|^2$$

The trial set of parameters for a flat plate solar collector can be found by assuming that:

– The collector is a linear thermal system, that is,

$$K_2^{(0)} = \delta^{(0)} = \nu^{(0)} = 0$$

– $\beta^{(0)}$ is negligible and set equal to zero

– $\gamma^{(0)}$ has a reasonable value around 0.8

$K_1^{(0)}$ can therefore be calculated by means of eq. (22) and (19) which leads to:

$$K_1^{(0)} = \frac{1}{N}\sum_{n=1}^{N} \left\{ \left| \frac{\gamma^o \phi_{s_n} - K_B (T_{\infty n} - T_{B_n})}{T_{\infty_n} - T_{E_n}} \right| - \frac{1}{G_n} \right\}^{-1}$$

V. *Test of the Model's Accuracy*

As a matter of fact, no test of the model based on purely experimental sets of measurements has yet been performed due to lack of experimental facilities. Such test will soon be performed at the AIT Energy Field Test Park.

Nevertheless, meanwhile, the model's ability to predict solar collector performances has been checked making use of performances of various types of solar collectors calculated by means of a simulation computer program by Devin et al[2b]. They claimed that their simulation program predicts very accurately the performances of real collectors which makes the actual preliminary check of the model strongly significant.

Calculations have been made for two types of solar collector: one, called SIN, is a single glass cover flat plate thermal collector with selective coating on the absorber. The second, called N2N, is a double glazzing flat plate collector with normal black paint on the absorber. For both of them $K_B = 1.4\ \mathrm{m/m^2/^oC}$.

The front loss parameters and the effective absorption coefficient γ have been evaluated by fitting values (given in Table 1) of the useful energy gain (given by Devin et al[2b]) and called here Q_{Dev}. The resulting value of front loss parameters are shown in Table 2.

Note that for purely practical reasons, mainly due to lack of time, a full self-consistent least-square evaluation of $\gamma, \beta, \delta, K_1, K_2$ has not yet been done. Instead two sets of values for γ, $\tilde{K}_1$ and $\tilde{K}_2$ have been calculated for the two sets of Q_{Dev} referring respectively to ϕ_s, equal to 1000 $\mathrm{W/m^2}$ and 800 $\mathrm{W/m^2}$ (Table 1) then a weighted average value* of γ was used to evaluate two new sets of K_1 and K_2 para-

* $\gamma = (1000\,\gamma_{1000} + 300\,\gamma_{800})/1800.$

meters. From these four values and eq. (19) and (20) β, δ, K_1 and K_2 have been calculated and are given in Table 2.

Then by means of eq. (12) to (20) and eq. (28), the useful energy gain values (Q_{cal}) predicted by the model have been calculated and are displayed in Tables 3 and 4.

In Tables 3 and 4 the standard deviation:

$$\sigma = \left\{ \frac{1}{N} \sum_{i=1}^{N} |(Q_{Cal})_i - (Q_{Dev})_i|^2 \right\}^{1/2}$$

is also given and provides some measure of the accuracy of the model predictions. These predictions concern two collectors performances when used under different ambient and working conditions rather than those which were prevailing during the fitting procedure.

In Figs. 3 and 4 curves show a striking agreement between the Devin's data and the actual model predicted performances, agreement which is ascertained by the low value of the standard deviation σ for whole range of the heat carrier fluid temperature, under wind speed ranging from 0 to 10 m/s and solar radiation ranging from 400 W/m^2 to 1200 W/m^2.

Results are given for only two solar radiation values in the case of SIN and for only one wind speed value in the case of N2N. That is because Devin et al[2b] were given results only for those cases and, obviously, for the sake of comparison there was no need for further calculations.

VI. *Conclusion*

Although the accuracy of the predicted performances of the model has not yet been fully ascertained by means of an extensive comparison with experimental data, a preliminary comparison with data published by Devin et al[2b] for two flat plate solar collectors seems to strongly indicate that the model is able *to predict accurately the performance of flat plate thermal solar collectors working under conditions very different from the condition prevailing during the fitting procedure of the set of intrinsic parameters.*

More investigations are needed and are underway. In particular, it should be carefully investigated whether the three third order correction parameters β, δ and ν are all needed to achieve a reasonable agreement with experimental results.

A further reduction of the phenomenological parameters number is currently investigated by considering a more sophisticated approximate expression of eq. (1) than the expression (5e) used here.

In spite of all these remaining unsolved subsidiary questions, the actual study shows that there is a good prospect for predicting, simply and accurately, the performances of solar collectors, even when the working outlet temperature is close to the stagnation temperature. However, this could be achieved only if manufacturers can be convinced to evaluate and indicate not only the usual, almost useless, linear thermal loss coefficient of their collector but some non-linear coefficients such as those defined in the actual model.

Table 1: Useful energy gain values selected to perform calculation of the model parameters through least-squares fitting procedure

ϕ_s W/m^2	T_E (^oC)	SIN T_{in} (^oC)	SIN Q_{Dev} W/m^2	N2N T_{in} (^oC)	N2N Q_{Dev} W/m^2
1000	26.6	25	840	25	750
		50	732	50	630
		75	596	75	507
		100	448	100	328
		125	296	125	141
		170	0	143	0
800	26.1	25	648	25	600
		50	540	50	477
		75	406	75	324
		100	266	100	177
		125	100	125	0
		140	0	–	–

Note that: $T_A = T_B = 27^oC$, $\phi_{IR} = 400\ W/m^2$, $V_{wind} = 2$ m/s and large heat carrier fluid flow is used.

Table 2. Instrinsic parameters of the model for two collectors quoted by Devin et al[(2b)] for which $K_B = 1.4\ W/m^2/^oC$ and ν have been set arbitrarily equal to zero.

Collector	γ	K_1	K_2 $(x\,10^3)$	β $(x\,10^6)$	δ $(x\,10^9)$
SIN	0.8233	4.7049	19.246	−1.1876	−2.9431
N2N	0.7393	6.4063	7.0588	−3.8566	25.870

Table 3. Comparison between S1N Solar Collector's performances given by the actual model (8th column) on the one hand and displayed by Devin(2b) (9th column) on the other hand. (Note that it is assumed $T_A = T_B$ 27°C, $\Phi_{IR} = 400\ (W/m^2)$

V (m/s)	Φ_s (W/m^2)	T_E (°C)	$\tilde{\Phi}$ (W/m^2)	$\tilde{K}_1$	$\tilde{K}_2$ $\times 10^3$	T_{in} (°C)	Q_{cal} (W/m^2)	Q_{Dev} (W/m^2)	σ
2	1000	26.6	824	4.2965	10.2820	25	831	840	
						50	718	732	
						75	592	596	8.3
						100	453	448	
						125	301	294	
						170	–4	0	
0	800	25.5	661	4.4118	6.5673	25	663	650	
						50	549	550	
						75	426	429	5.6
						100	296	295	
						125	157	153	
						152	–2	0	
2	800	26.1	600	4.6624	9.9405	25	665	648	
						50	543	540	
						75	408	406	7.3
						100	261	266	
						125	102	100	
						140	0	0	
5	800	26.5	659	5.0203	10.9940	25	667	647	
						50	535	538	
						75	390	388	8.1
						100	231	229	
						125	58	59	
						133	0	0	
10	800	26.7	659	5.2891	11.4190	25	668	646	
						50	530	533	
						75	377	376	9.3
						100	210	206	
						125	29	29	
						129	–2	0	

Table 4: Comparison between N2N Solar Collector's performances given by the actual model (8th column) on the one hand and displayed by Devin(2b) (9th column) on the other hand. (Note that it is assumed $T_A = T_B = 27^oC$, $\Phi_{IR} = 400\ W/m^2$, $V_{wind} = 2\ m/s$)

Φ_s (W/m^2)	T_E (^oC)	$\tilde{\Phi}$ (W/m^2)	$\tilde{K}_1$	$\tilde{K}_2$ $(x\ 10^3)$	T_{in} (^oC)	Q_{cal} (W/m^2)	Q_{Dev} (W/m^2)	σ
1200	27.0	887	4.3770	16.831	25	896	891	
					50	778	781	
					75	638	637	2.9
					100	478	479	
					125	297	293	
					150	94	96	
1000	26.6	740	4.0645	19.981	25	746	750	
					50	634	630	
					75	496	507	6.1
					100	334	328	
					125	146	141	
					143	–4	0	
800	26.1	593	4.7623	12.383	25	598	600	
					50	472	477	
					75	330	324	4.0
					100	173	177	
					125	1	0	
600	25.7	445	4.5157	16.303	25	449	443	
					50	326	323	
					75	183	186	3.6
					100	20	19	
400	25.3	298	4.7582	10.706	25	299	296	
					50	174	174	2.1
					75	35	35	

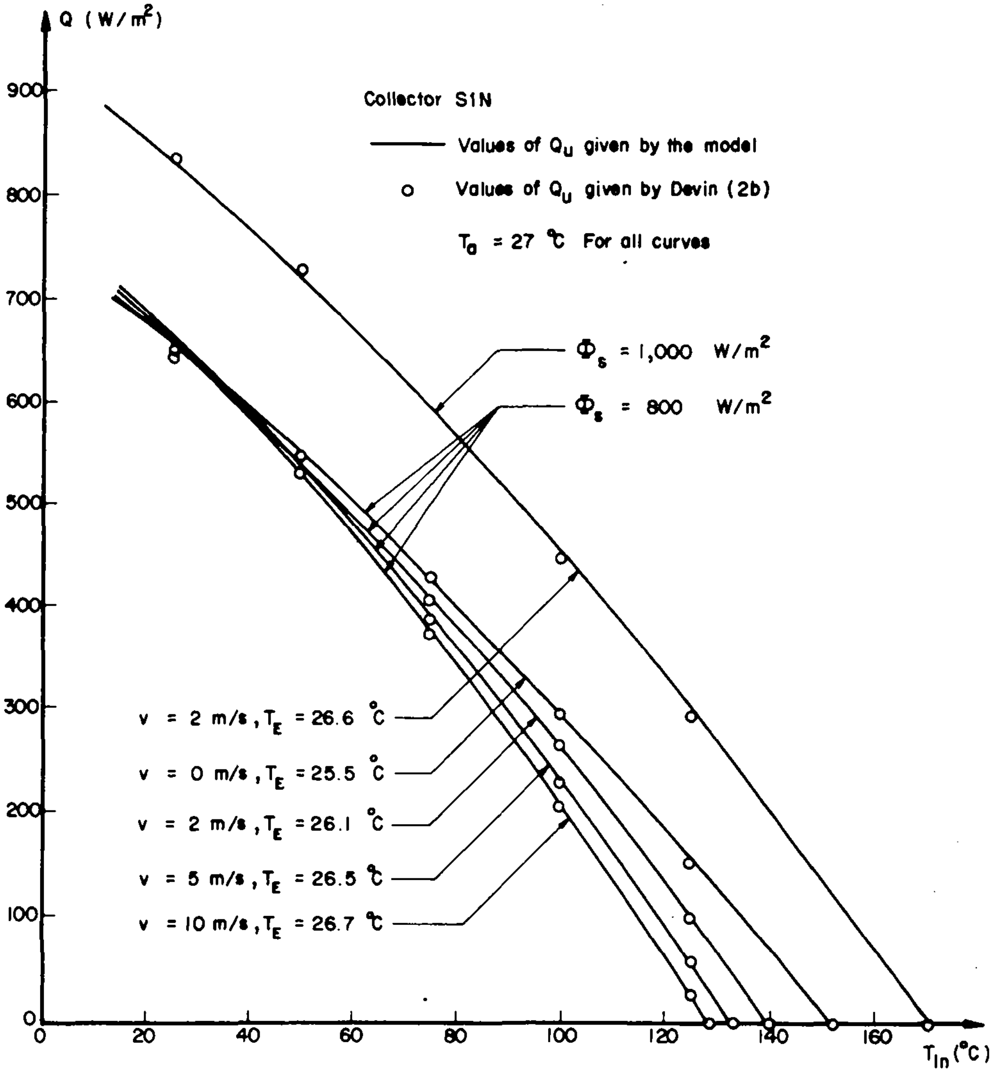

Fig. 3 Performance of the S1N Solar Collector Various Wind Speed and Two Solar Radiation Values

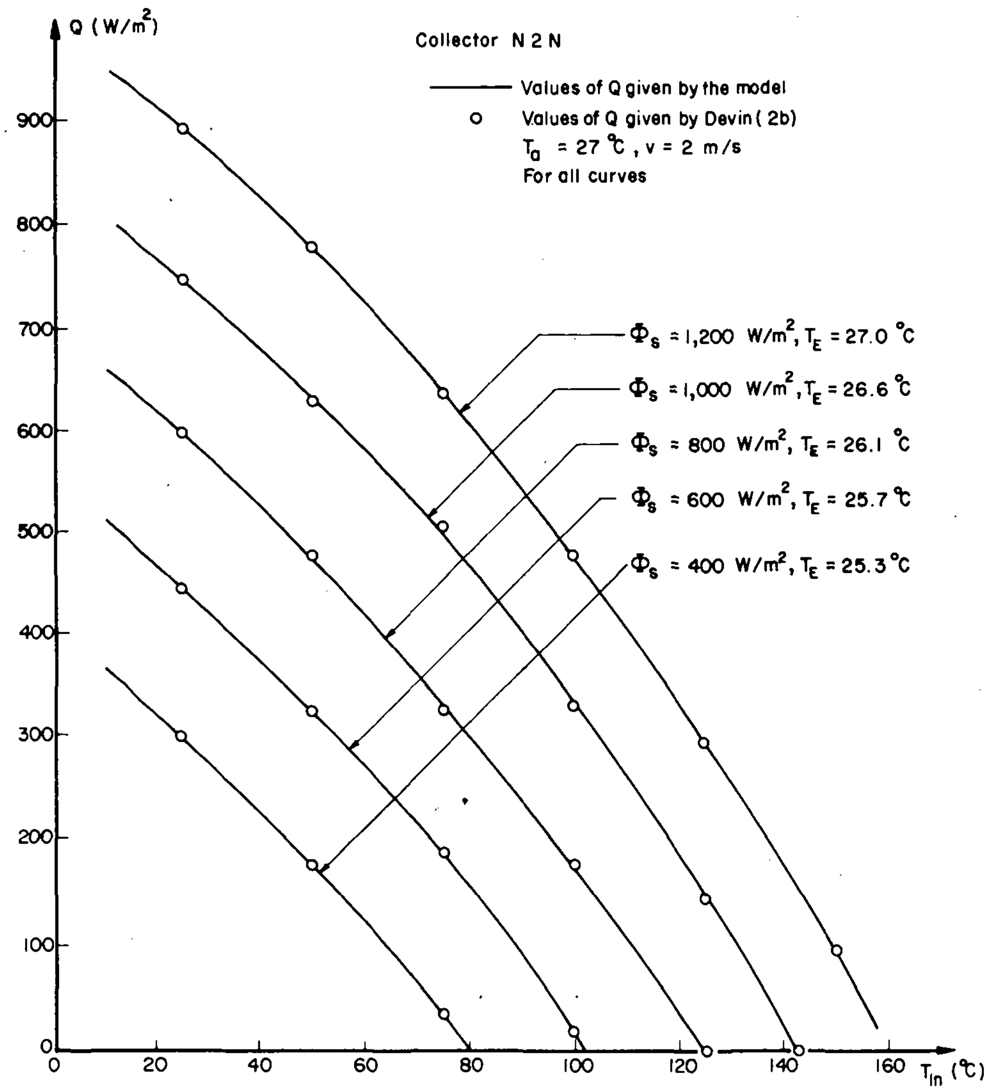

Fig.4 Performance of the N2N Solar Collector for Various Solar Energy Flux Values

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ANNEX A

SYMBOLS

Φ_s	=	Solar energy flux per second and per unit area of the collector cover (in W/m^2).
Φ_{IR}	=	Infra-red energy flux from the environment per unit area of the collector cover and per second (in W/m^2).
$Q_{a \to c}$	=	Heat transfer from the air to the collector by conduction and convection phenomena.
$Q_{c \to a}$	=	Heat transfer by conduction, convection, and radiation from the cover to the environment.
Q_F	=	Net heat loss from the front cover of the collector to the environment.
Q_B	=	Net heat loss through the back of the collector. It is a pure conduction phenomena.
Q_{plate}	=	Power absorbed by a unit area of the plate and ultimately transferred to the fluid.
T_a	=	Ambient environment temperature in the front of the collector.
T_E	=	Effective temperature of the environment (see Annex B).
T_B	=	Temperature of the ambient air in the back of collector which could eventually be different from T_a.
T_c	=	Temperature of the front cover.
T	=	Temperature of the plate.
T_∞	=	The stagnation temperature of the plate.
$T_{c\infty}$	=	The temperature of the front cover when the plate is at T_∞.
θ	=	$T - T_c$.
θ_∞	=	$T_\infty - T_{c\infty}$.
σ	=	Stephen - Boltzmann constant = $5.6/10^{-8}\ W/m^2/{}^\circ K^4$.
ϵ	=	Cover's hemispherical total emissivity, taken as 0.9 in this work.

h_F = Conduction - convection coefficient (in $W/m^2/°K$) which takes into account the wind effect. It is defined by McAdams[6] as $(a + bv)$ with v in m/s. For comparison of results, the values $a = 5.67$ and $B = 3.86$ are used by Devin et al.[2a] It should be noted that Watnuff et al.[7] have subsequently called for attention on the fact that the above expression may account partly for radiation heat transfer and that the correct expression to be used is:

$$2.8 + 3.0\ v \text{ for } 0 < v < 7\ m/s$$

T_F = Temperature of fluid.

ξ = $T - T_E$.

ω = $T_f - T_E$.

T_{in} = Inlet temperature of the fluid.

T_{out} = Outlet temperature of the fluid.

e = Thickness of the plate.

λ = Plate thermal conductivity.

τ = Transmittance of the cover.

ρ_T = Total reflexion losses coefficient.

α = Absorptance coefficient.

γ = Effective absorptance-transmittance factor.

K_B = Overall transfer coefficient through the back of the collector taking into account the side effect.

K_1 = First order heat transfer coefficient through the front.

K_2 = Second order heat transfer coefficient through the front.

β = Third order heat transfer coefficient through the front.

δ = Fourth order heat transfer coefficient through the front.

M_o = The flow per unit width of the collector plate.

c_p = The specific heat of the fluid.

L = The length of collector plate.

μ = M_o/L is the flow of fluid per unit area of collector plate.

ANNEX B

Most of the authors proposing thermal solar collectors model represent the thermal losses in terms of the difference between the plate temperature, T, and the ambient temperature, T_a, and/or the difference between the temperature of the front transparent cover of the collector, T_c, and T_a. This procedure is not very satisfactory since it implies that no net heat exchange will occur between a front glass cover at T_a and the environment which is not generally the case.

Also, due to the fact that neither the transparent cover of a solar collector nor the atmosphere are perfect black bodies, the steady state temperature of a piece of the transparent cover of the collector exchanging energy only with the environment (assume that the other surface not in contact with the environment is made perfectly reflecting and carefully insulated) will not be equal to T_a, the ambient temperature.

Devin et al from Saclay have defined T_E, the steady state temperature of such a piece of the front cover of a solar collector occuring when there is no net heat exchange with the environment, as the solution of the following heat balance equation:

$$\epsilon\Phi_{IR} + \alpha\Phi_s - \epsilon\sigma T_E{}^4 - h_F(T_E - T_a) = 0$$

where

Φ_{IR}	is the infrared flux generated by the environment.
Φ_s	is the incident solar energy flux.
T_a	is the ambient temperature.
ϵ	is the hemispherical absorptance coefficient of the cover for infrared radiations. It is assumed that $\epsilon = 0.9$ for ordinary glass and for radiations of wave length greater than 2.5 μm.
α	is the hemispherical absorptance of the cover for visible radiations. We use $\alpha = 0.04$ for glass.
σ	is the Stephan Boltazman constant equal to 5.6×10^{-8} W/m^2/$^\circ$K
h_F	is the conduction-convection coefficient (in W/m^2/$^\circ$K) which takes into account the wind effect. It is defined by McAdams (6) as (a+bv) with v in m/s. For the sake of comparison of our results with Devin et (2) we have used a = 5.67 and b = 3.86. Nevertheless it should be noted that Watmuff et al (7) have called for attention on the fact that the above expression may account partly for radiation heat transfer and hence the correct expression to be used is:

$$(2.8 + 3.0\,v) \text{ for } 0 < v < 7\,m/s$$

The main motivation of Devin et al when suggesting to make use of T_E instead of T_a in a thermal solar collector model is to improve the validity of extrapolation to real working conditions of solar collector performance tests undertaken under artificial sun (generally very rich in infrared radiation) instead of under real sun light.

In table 1B values of T_E (for an ordinary glass cover) are all calculated for - the same ambient temperature $T_a = 27°C$ - the same energy flux of radiation with wave length $\lambda < 2.5 \mu m$: $\Phi_s = 1000\ W/m^2$.

Infrared energy flux as high as 900 W/m^2 are recorded on their artificial sun test bed for solar collectors by Devin et al. Table 1B shows that the corresponding effective temperature of the environment in such a case is 63.3°C. This demonstrates how strongly T_E can differ from T_a in special environment.

Table 1B: Calculation of the effective temperature of the environment under artificial sun light and in two kinds of natural environment.

Environment	T_a (°C)	Φ_s (W/m^2)	Φ_{IR} (W/m^2)	v (m/s)	T_E (°C)
Artificial Sun light	27	1000	900	0	63.3
				10	35.8
				20	32.0
Natural Environment with "normal" level of Infrared radiation	27	1000	400	0	26.3
				10	26.8
				20	26.9
Natural Environment with "low" level of Infrared radiation	27	1000	300	0	18.2
				10	25.0
				20	25.9

A SOLAR POWER PLANT FOR REMOTE RURAL CONSUMERS: DESIGN AND EVALUATION OF EXPERIMENTAL PLANT

by

W. BRAZIER, N.R. SHERIDAN and M. DARVENIZA

1. *SUMMARY*

An experimental 4 kW_e solar generator for remote isolated consumers has been constructed at the University of Queensland's Central Solar Test Facility. The system is based on an organic Rankine cycle engine, developed by Ormat Turbines Ltd. of Israel, coupled to flat-plate collectors. Objectives of the experimental system are to enable engine and support plant testing to be carried out in an environment where qualitative experience, together with data on operation and limitations of the system, can be obtained and assessed to develop suitable design parameters and a specification of a prototype plant for installation in a remote location.

2. *INTRODUCTION*

In Australia, 99 per cent of the population is well serviced by grid reticulated electricity, in the main part being generated from coal or hydroelectric sources. The grid radiates from the capital cities in each state and services the more densely populated rural areas. Other areas have individual towns supplied by small diesel power stations. The remaining one per cent of the population tends to be settled in remote areas where no reticulation is available and is unlikely to be available at a reasonable cost. Capital cost of reticulation to these areas has been estimated to reach $A 35,000 in some cases and involve many kilometres of vulnerable overhead lines, which the electricity supply authorities maintain.

The Queensland electricity industry in association with the Electrical Research Board, approached the University of Queensland with a request to examine the feasibility of a remote stand alone power supply for an isolated consumer. Such a power supply should have an availability and reliability similar to grid reticulated supply as experienced by urban consumers and cost less than the average cost of grid extensions to remote consumers. The choice of a suitable plant tended towards a system employing some form of renewable energy, as the cost of fuel oil, even at that time (1976) was relatively high compared to the coal used by the grid, and in outback areas there was an added transportation cost. In retrospect, the decision to study a renewable energy source system was timely, given the current world situation with regard to oil cost.

With support from the electricity supply industry, extensive analysis of parameters for an effective solar generator for isolated consumers was commenced in 1976. The project, "A Solar Power Plant for Remote Rural Consumers," was necessarily divided into a number of sub-projects involving acquisition of insolation and weather data, determination of electrical load data, development of a simulation program for design optimisation, simulation of plant performance, plant design and performance evaluation, battery and inverter design and development of a microprocessor load controller.

3. *SYSTEM SELECTION*

For remote mainland areas, the choices for a renewable energy system are as follows:-

1. Solar photovoltaic (either flat-plate or concentrating).
2. Solar thermal (either high temperature concentrating or flat-plate).
3. Wind turbine.
4. Geothermal.

Brief comments on each of the alternatives follow:

1. Photovoltaic systems, while available in flat-plate arrays, were found to be too expensive. Besides, little data could be obtained to allow an assessment of long term performance. Concentrating photovoltaic technology was not well developed.
2. The technology existed for the manufacture of a Rankine cycle low grade heat energy converter, as had been demonstrated by Ormat Turbines of Israel Ltd. with their small but effective and reliable solar water pump, which was a Rankine cycle engine supplied with low grade heat from a flat-plate collector array.

   High temperature solar thermal technology was not sufficiently advanced to justify consideration of a system with a concentrating collector.
3. Many mainland areas, in which the proposed system would be used, generally experienced insufficient or unreliable wind. As a result, the selection of a wind turbine was not favoured.
4. A large portion of the remote area of Australia has access to artesian water which supplies most of the needs. Although this artesian (bore) water can be obtained at temperatures up to 70°C, continuous use tends to lower the supply temperature. While organic Rankine cycle engines could utilise these temperatures, it was found to be difficult, in the absence of satisfactory data, to assess the economic life of such systems.

Thus the most appropriate system appeared to be the solar thermal system with flat-plate solar collectors as the primary energy source. The Ormat energy converter appeared to be compatible with flat-plate collectors, and had a high proven reliability in severe environments ranging from arid desert regions to the icy wastes of Alaska. This system, the Ormat energy converter and flat-plate collectors, was consequently selected as a feasible system and design studies commenced.

To enable accurate performance monitoring of the system to be carried out, an *experimental* plant was constructed at the University of Queensland's Central Solar Test Facility (CSTF). As will be seen later, (Section 7) this location allowed the use of a smaller collector array than would be necessary for a *phototype* system, if installed in the selected location for field trials.

4. *FIELD SITE SELECTION*

To enable realistic system operating performance to be experienced, it will be desirable to test the prototype plant at a location typical of the remote areas for which the systems is intended. And, it would be useful to have data on such a site for use in simulation studies. Climatic data and electricity requirements of a typical consumer would be required.

As a result, it was decided to find an electricity consumer in a relatively remote location for which climatic data was available or could be inferred. The electricity requirements would be obtained by a power survey extending for more than a year.

The site selected was a property "Saltern Creek", near Barcaldine, in central west Queensland. It is some 600 km inland and more than 900 km from the Queensland capital, Brisbane.

The characteristics of the consumer on this property are:

1. Electricity is currently supplied via existing electricity mains from a diesel power station at Barcaldine.
2. The consumer load pattern is average for the type of residence, number of persons, and general standard of living in the area.
3. No electric water heating is involved as the residence has a solar hot water systems.

5. *ACQUISITION OF INSOLATION AND WEATHER DATA*

To facilitate prototype design, insolation and meteorological data is required for the field site. Insolation data for Longreach from the Commonwealth Scientific and Industrial Research Organisation (CSIRO) were obtained. Other data were available for Barcaldine. Both these locations are sufficiently close to the selected site to be considered representative of conditions experienced.

The data were used as input for the simulation studies [1], which were carried out, using the University of Wisconsin's TRNSYS program, to enable system design parameters to be selected.

6. *SURVEY AND SPECIFICATION OF CONSUMER REQUIREMENTS*

An important consideration in the design rationale of the proposed system was that the quality of the electricity supply from the plant should be similar to that available from single-wire-earth-return distribution networks in rural area. It was therefore necessary to determine electrical load data for the consumer in sufficient detail for plant design, particularly the size (or rating) of plant components.

A survey of the consumer load data available from the electricity supply authorities (and from the literature) soon revealed that detailed data were not available for single domestic consumers. The data that were available were either billing data for individual consumers (i.e. quarterly energy usage) or after-diversity maximum demand and daily and seasonal load characteristics of groups of consumers. While these are useful in establishing general trends, such data are not sufficiently detailed for the design of a solar plant which alone must supply the electricity needed by an isolated consumer throughout each day, and hopefully for every day, now and in the foreseeable future. Of course, the type of data required is dependent on the design procedure adopted. In this project, the broad approach has been to develop comprehensive models of the main components of the plant and to study the operation of the plant by computer simulation. Then, the overall design of the plant, considered as a system with insolation as input and consumer electricity as output, could be optimised by selecting and sizing the components on a system basis. Such simulation studies require not only detailed input insolation data, but also detailed electricity output load data, including variations with time of day, with day of week, from season to season and from year to year. A further consideration was accepted as part of the plant design, namely, that a micro-processor controller be developed to limit the maximum demand of the consumer without inconveniencing domestic appliance usage.

Analysis of electricity load characteristics was undertaken in three categories. Firstly, kW rating and energy consumption data for domestic appliances were examined to determine the likely maximum demand and the annual energy consumption of a typical domestic consumer. Secondly, general demand and energy consumption patterns of groups of domestic consumers were examined using electricity supply data from distribution authorities in Queensland. Finally, detailed measurements were made of the electricity consumption characteristics of a single consumer at the selected field site. The end-results of these studies include a specification (for a single domestic consumer) of the design maximum demand in kW_e, a design daily electricity consumption in MJ (or kWh), and likely diurnal and seasonal variations. It is assumed that electricity from the solar plant will not be used for the hot water system. From the analysis and estimation of load characteristics, the following data can be considered applicable to a household with all-electric appliances except for a non-electric hot water system (if solar, with no electric booster).

(i) *Maximum Demand* - a peak power of 6.5 kW averaged over a 15 minute interval or 8.5 kW averaged over a 5 minute interval. By using a load controller, it should be possible to limit the maximum demand to 3 kW.

(ii) *Energy Consumption* - for a well-established consumer, an average electrical energy consumption of 54 MJ (15 kWh) daily, with maximum and minimum values of 90 and 36 MJ (25 and 10 kWh) for a newly-connected consumer in a rural area, 36 MJ (10 kWh) would be a more appropriate average figure. The average daily consumption is dependent on the season, and may be as high as 72 MJ (20 kWh) in summer, if the consumer uses electric radiators. The annual growth rate is 1.8 MJ (0.5 kWh) (in average daily consumption).

(iii) *Daily Load Characteristics* - the load level presented by a domestic consumer is below 1.5 kW for most of the time, and is below 500 W for about half the total time in a year. Some 80% of the annual electrical energy used in a domestic residence is consumer at a load level of less than 1.5 kW (even though maximum load levels may be 4 to 5 times higher).

7. *SYSTEM DESCRIPTION*

Availability of the Ormat Solar Energy Converter (OSEC) with input conditions that could be made compatible with the operation of flat-plate collectors suggested the basic configuration of the plant should allow circulation of the primary working fluid (water selected for simplicity) from collectors to converter and return as a closed cycle. The experimental plant configuration, (Fig. 1), allows on- and off-design testing to be carried out with a view to gaining experience in operation of the Ormat engine, together with the construction and operation of a system in which the role of the thermal energy transfer circuits (in this case containing water) is significant due to the amount of piping involved. For optimum energy conversion, system operating temperature and water flow rates were selected to give good converter efficiency and the resulting collector efficiency has a reasonable value of 50 per cent (Fig. 2). In operation, water is heated in the collector panel (approximately 10 per cent of the required collector surface), and circulated to a heat exchanger in which portion of the energy contained in the hot water is used to vaporise the organic fluid subsequently driving an impulse turbine and induction generator (Fig. 1). Thermal storage has not been included to date, but could be added as either a series or parallel element between collectors and vapour boiler as indicated in simulation studies by Brice [1].

Since the 28.6 m^2 panel of collectors is insufficient to supply the energy requirements of the OSEC, a collector simulator consisting of an electric heater and control system was designed to make up the shortfall in energy allowing the OSEC to operate at suitable conditions, whilst maintaining system performance dependent on insolation, and other meteorological conditions. System operation with a simulated collector area of up to approximately 300 m^2 can be assessed. Budget limitation on the financing of the experimental plant dictated that the 28.6 m^2 collector panel be used rather than a full size panel. This approach allows collector area to be optimised by plant performance studies without the expense of modifying the panel, and provides reinforcement of plant parameters as suggested by simulation studies [1].

8. *SYSTEM EVALUATION*

Typical performance curves, for clear sky conditions on July 7, 1980 at latitude 27.5° S, display the operating pattern experienced (Fig. 3). The estimated system output of 68.4 MJ (19 kWh) daily, necessary to ensure satisfactory performance when battery energy storage and power conditioning apparatus are added to the system (has been realised with the system) fed from a simulated collector area of 266 m^2, except that no allowance for water pumping has been made in the electrical output curve (Fig. 3). To allow approximately 1920 watts for circulator operation and maintain sufficient system output for the consumer, the system output should be increased.

The relationship between vapour generator temperature, temperature difference across the vapour generator and electrical output can be clearly seen (Fig. 3). The condenser temperature was maintained at 38-40° C throughout the day. Water circulation to the vapour generator was commenced at 08.50 h and the temperature was allowed to reach 80° C before the turbine valve was opened. A stable temperature between 74 and 78° C was achieved for most of the operating period. Changes in temperature, temperature difference and electrical power after 14.00 h are due to a reduction in load as turbine operation deteriorated towards shut-down time, which occurred at 15.17 h due to the vapour generator temperature becoming too low. The general curvature of the insolation curve can be visualised in the curvature of the average of the temperature difference curve.

Analysis of the system under summer conditions has shown that the experimental plant even when operating with a simulated collector area of 320 m^2, will have an energy shortfall if it is to meet consumer demand and pumping load. It is clear that the performance will have to be improved or the consumer demand relaxed if the system is to prove satisfactory.

9. *CONCLUSION*

The successful establishment of an experimental solar power plant at the University of Queensland's Central Solar Test Facility has been described. The design performance of the proposed prototype plant will need to be better than that achieved by the experimental plant to date so that some improvements in component performance and component matching will be required.

Although not detailed in this paper, the anticipated cost of the proposed system is excessive unless collector cost can be substantially reduced by the use of a more cost-effective collector, or application of a solar pond as combined energy source, sink and storage medium. Further evaluation of the plant is expected to enable a specification for a prototype 4 kW_e solar plant for remote rural consumers to be produced. The prototype plant will enable an economically competitive alternative to small diesel plant, or the extension of reticulated supply over large distances, to provide electricity to isolated consumers from renewable solar energy.

10. *ACKNOWLEDGEMENTS*

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The Queensland Electricity Authorities Research Committee.

The University of Queensland, Departments of Mechanical and Electrical Engineering.

The South East Queensland Electricity Board.

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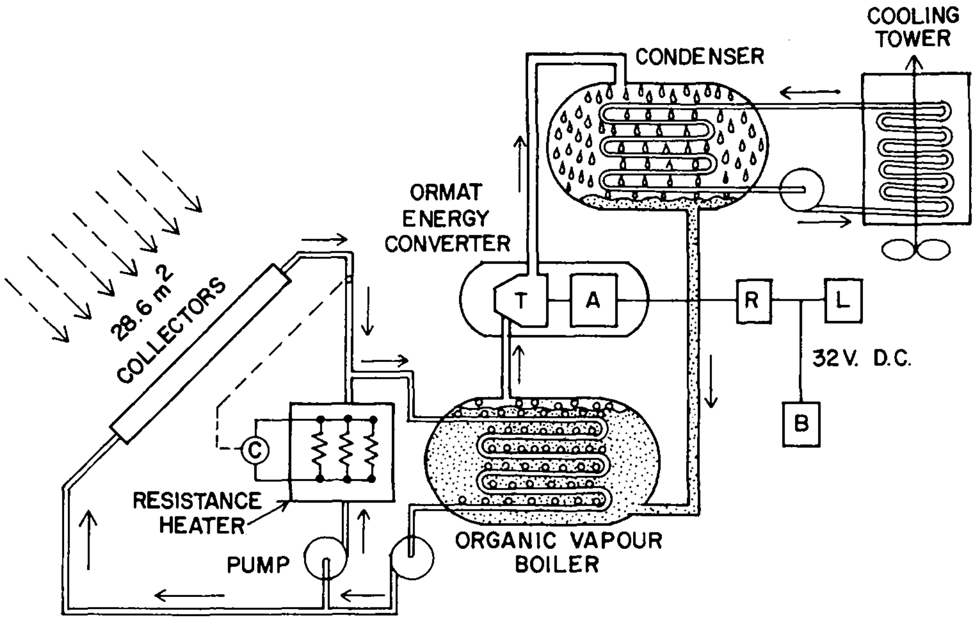

T – ORGANIC VAPOUR RANKINE CYCLE TURBINE
A – ALTERNATOR (600 - 800 Hz)
R – RECTIFIER
B – BATTERY
C – CONTROLLER
L – TEST LOAD

FIGURE I. EXPERIMENTAL PLANT CONFIGURATION

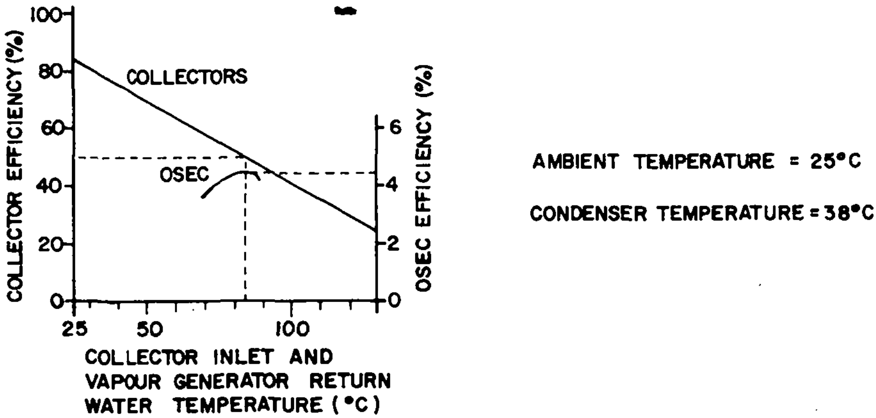

FIGURE 2. PERFORMANCE CURVES FOR COLLECTOR AND OSEC

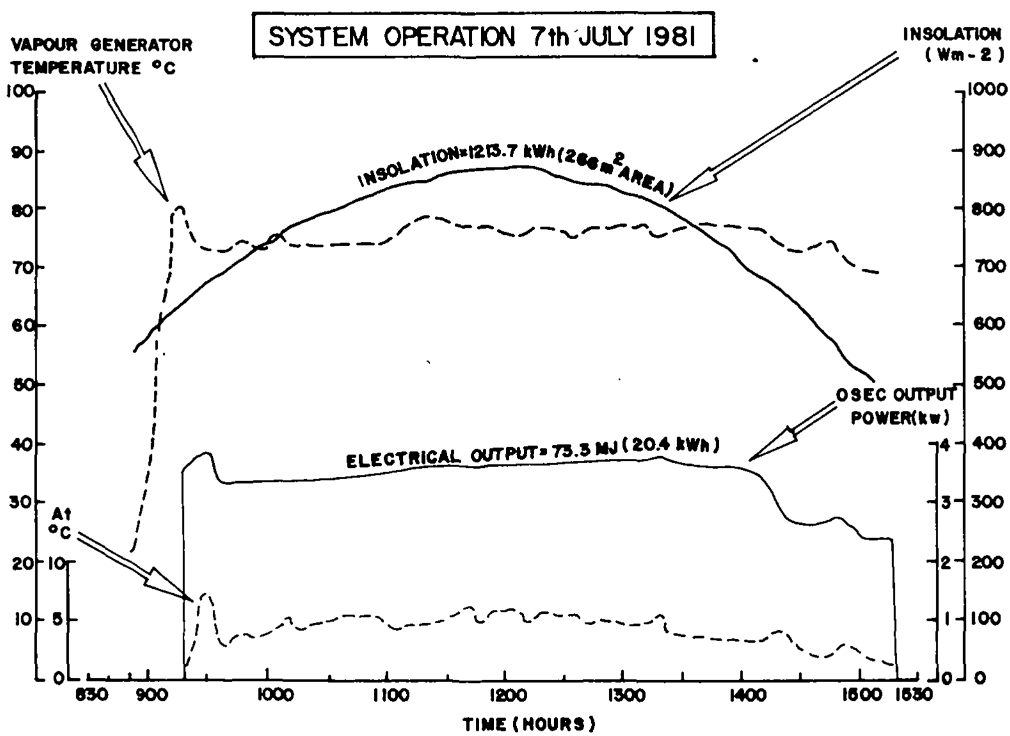

FIGURE 3. MEASURED PERFORMANCE OF OSEC EXPERIMENTAL PLANT

RENEWABLE ENERGY SOURCES AND THE DEVELOPMENT OF RURAL COMMUNITIES: SOME PRACTICAL EXAMPLES

by

M. G. CLEMOT

I. *INTRODUCTION*

Important international Symposium and Conferences in the last years were devoted to the theme of Science and Technology dedicated to development, or more precisely to the use of renewable energy sources for the benefit of small rural communities.

Wishes and recommandations that closed these meetings all put in evidence the huge untapped energy potential, and the need for international collaboration.

The extensive availability of these energy sources, which we classify as solar, wind, biomass and geothermal systems, makes them particulary promising for the solution of difficult development problems in rural areas of tropical and subtropical regions.

The purpose of this paper, by referring to recent realizations of French Industry, will be limited to the presentation *of field applications* implemented in collaboration with developing countries, in various parts of the world. This activity is an important part of the french program in solar energy. Main projects and implementations will be commented during slide projection.

Technologies and techniques are right now available for exploitation of these resources. By integrating them through collaboration and exchange between developed and developing countries they must help in solving problems for the development of many rural zones:

- problems connected to supply of water for population
- pumping for irrigation
- water desalination
- generation of heat for refrigeration
- implementation of decentralised low power generation units for electricity and so on . . . .

The extension of their applications and the growing number of local industries they will generate should contribute significantly in the coming years to the improvement of living conditions in such rural areas.

More than 100 solar units were installed or are under implementation on the field in 25 countries: in Latin America, South America, Eastern and Western Africa, North Africa, in the Middle East and Pacific islands.

From several hundred watts to 80 kW, using photovoltaic or thermodynamic conversion for power less than 10 kW and mainly thermodynamic conversion for larger power, these field implementations represent a unique source of information and of experience.

Evaluation and expertise of these field implementations are available for improving integration of solar technology into rural areas, technological economical and sociological factors including maintenance problems, management and policies obtained on the field must help in improving integration in local environment and in solving problems of transfer of technology and exchange between countries.

II. *FIELD APPLICATIONS USING THERMODYNAMIC CONVERSION*

2.1 *Solar thermodynamic*

During the last decade SOFRETES was implementing about 70 solar pumps in the "1 kW" power range. Most of these solar pumps were installed in small villages for people and cattle feeding. Solar energy being associated to development, concept of rural communities: schools, dispensaries or small hospitals were located under the solar flat plate collectors. In Table 1 are indicated main specifications of thermodynamic units, field applied.

Following technology improvements and collaboration experience, larger units were developed, increasing the field of application. In 1975, in MEXICO a 33 peak kW solar pump was implemented. After 1978, were developed larger powers necessary for irrigation and electricity supply purposes.

Flat plate collectors using selective coating (black chrome) increase overall efficiency by functioning at 90°C - 95°C. Thermal storage at 95°C allow 24 hours/day operation duration.

Some examples:

KARMA in NIGER

A 10 kW solar pump was installed in 1979 on Niger River for 200 acres crop irrigation.

This implementation is the result of an industrial collaboration with local industry, ONERSOL was supplying and installing the 600 m^2 solar collectors arrays.

Table 1. THERMODYNAMIC SOLAR UNITS FIELD APPLICATIONS in rural communities

Year	*Type and Location*	*Collectors*	*Conversion*	*Applications*	*Remarks and Specifications*
From 1969 to 1980	1 kW solar pumps in 20 countries	fixed flat plate collectors 70 to 80 m^2 T $\simeq$ 75 °C	Piston engine. Fluid: Butane Freon	water pumping for villages and livestock 25 m^3/day 30 m depth	Pilot unit operational units which can be considered as demonstration and evaluation units
1975	33 kW San-Luis de la Paz (Mexico)	1500 m^2 fixed flat plate collectors T $\simeq$ 75 °C	turbine, gaz gear	electricity for pumps driving	operational irrigation and demonstration
1979	75 kW DIRE (Mali)	4000 m^2 flat plate collectors	"Screw" engines	150 ha crop irrigation drinkable water	thermal storage, operation during 10 h/day
	KARMA (Niger) 10 kW	700 m^2 locally manufactured		20 to 30 ha crop irrigation	industrial and scientific collaboration with ONERSOL
1980	33 kW RYADH (Saoudia Arabia)	fixed flat plate collectors selective coating		240 kWh/day 2/3 electricity 1/3 mech. energy	thermal storage, 24 h/day at 95 °C
	EGYPT 10 kW	T = 95 °C		water pumping + reverse osmosis desalination	scientific + engineering + feasibility studies + industrial
				water pumping + cooling chamber	Collaboration with EGYPT
	DIAKHRAO (Senegal) 240 kW h/day			220 kW h/day 24 h/24 h	thermal storage 24 h/day electricity power unit 20 kW
1981	CORSICA 100 kW	coss segmented 120 m^2, 250 °C linear moving boiler	turbine (BERTIN) flugene FC 75	electricity demonstration and evaluation unit	thermal storage gilotherm 250 °C

DIRE in MALI

This solar plant supplying 80 peak kW, 400 kWh/day, was implemented in a very remote area of MALI.

4000 m^2 flat plate collectors were assembled and installed on site by local manpower. A 300 m^3 thermal storage (water at 75°C) supplies electricity for lighting.

RYADH in SAUDIA ARABIA

A 33 peak kW unit is under operation in RYADH. A 900 m^3 hot water (95°C) reservoir supplies energy 24 h/day.

As an average the solar unit is attended to supply 260 kWh/day.

BAKEL in SENEGAL

Next March a 350 kWh/day solar pump will be implemented in BAKEL SENEGAL to irrigate 200 acres. This is a joint project between French Aid, US Aid and government of SENEGAL involving industrial collaboration between the 3 countries.

EGYPT

As the result of a 3 years collaboration program between FRANCE and EGYPT, at the scientific and industrial levels including exchange of scientists and technicians - 2 solar units are under implementation:

A 10 kW unit coupled to reverse osmosis unit for water desalination on the Red Sea.

A 10 kW with a 4°C cooling chamber for fish conservation on ASWAN DAM LAKE.

The next step will be the extension of the solar units by adding solar collectors built by EGYPTIAN INDUSTRY in the frame of a joint venture with FRENCH INDUSTRY (solar collector manufacturing for solar water heaters and thermodynamic conversion process).

Before implementation in rural zones, tests are performed on units using concentration segmented mirrors working at a temperature of 250°C (see Table 1). These tests are made on a 100 kW solar unit under implementation in CORSICA French Island of Mediteranean Sea.

2.2 *Geothermal electric power generation*

The thermal energy conversion units and generators designed for solar energy conversion can be used efficiently to produce energy and electricity by tapping geothermal sources.

Low temperature thermodynamic technology using hot water from the hot springs can generate 10 to 200 or 300 kW for small communities at a low cost (about half the capital cost of equivalent solar electric systems). Cost of kWh produced by hot spring is less than 0.10-0.20 US dollar.

Development of higher temperature thermodynamic systems (200-300°C) will also allow tapping higher geothermal potential.

Numerous hot springs available in countries of ASIA and the PACIFIC (the PHILIPPINES, INDONESIA, NORTH of THAILAND etc . . .) could be efficiently used to generate power for rural communities by using the binary thermodynamic cycle associated to direct use of the hot spring for other applications (drying . . .).

III. *FIELD APPLICATIONS USING PHOTOVOLTAIC SYSTEMS*

Four to five french companies were installing about 40 to 50 photovoltaic systems, in LATIN AMERICA, AFRICA, MIDDLE EAST and FAR EAST, RTC, GUINARD, BRIAU, ELF, PHOTOWATT and others are active in the field from several hundreds watts to 10 peak kW systems for telecommunication, water pumping, lighting...

More than 500 TV educational programs using solar cells were installed during the last decade in remote villages of WESTERN AFRICA.

Slides show some realizations:

- generator for telecommunication in FRENCH PACIFIC ISLANDS.
- educational TV system in village of WESTERN AFRICA.
- some photovoltaic solar pumps in LATIN AMERICA; AFRICA and FRENCH PACIFIC ISLANDS.
- A 10 peak kW supplying 30 kWh/day installed in MALI for supplying electricity to a rural dispensary.

Industrial efforts in photovoltaics and the increasing number of field applications show that solar energy will contribute significantly to the development of rural communities by implementing decentralized energy systems well adapted to their environment.

A 25 kW peak solar pump installed by GUINARD in the South of FRANCE (MONTPELLIER) opens the way to the use of this energy source for irrigation.

This is one of the most promising way for developing rural areas of many developing countries.

IV. *COST CONSIDERATIONS AND CONCLUSIONS*

At present stage, costs of solar systems for energy generation are expensive.

However, we must consider that economics in remote and rural areas is different from economics in urban areas of developing countries and from economics in industrialized countries.

Depending on the distance from the main town, or from the energy center, at present economical conditions the cost of kWh produced by conventional alternative e.g. Diesel engine, (in the 25 to 100 HP range) can reach the high figure of 1 US dollar to 2 US dollars (case in some remote area of African countries).

This figure represents about the cost of kWh produced by solar systems in the considered power range.

Although, competitiveness of solar energy will improve in the future by:

- improving performance (R and D)
- mass production
- local use of materials, equipments and manpower,

compared to conventional alternatives (increase of their cost and shortage) it is yet necessary to decrease the solar energy cost for reaching acceptable figures.

One of the most promising way to reach this objective, appearing from the above experience is to promote industrial collaboration between the developed and developing countries engaged in this field.

Associated to scientific collaboration, industrial collaboration means exchange of people, mutual training, common projects design, use of local materials and equipment, use of local engineering, manpower and skills, through joint ventures or other industrial bodies.

Concerning photovoltaic systems, it is generally admitted that at present conditions, the solar cells, themselves represent about 30% of the capital cost. Efforts consisting to decrease drastically the cost of solar cells manufacturing will be not sufficient to decrease the total cost of the system. Evidently the effort must also be made on the remaining 70% (batteries, auxiliary equipment like pumps and engineering) generally available in many countries.

For solar thermodynamic systems, about 50% to 60% of the capital cost is readily available, in users countries (flat plate collectors manufacturing, particularly).

Improving economics of solar energy, through transfer of technology and exchange between the countries will be then, at the benefit of developed and developing countries.

SELF-SERVICE IN TECHNOLOGY TRANSFER

by

A.G BATHELT

Every year research and development results worth billions of dollars are being neglected often by countries which cannot affort big scale research activities on their own either due to the cost or the facilities and manpower involved. All over the world, governments of the so called "rich" countries sponsor numerous R. & D. projects in their governmental laboratories, the universities, and the private industry sector. The resulting findings in most cases are not confidential and, therefore, easily available to interested parties. Not only an institution like the Regional Center for Technology Transfer (RCTT), established by the United Nations Economic and Social Commission for Asia and the Pacific (UN-ESCAP), but also the appropriate organisations in developing countries may find it extremely valuable to study systematically progress and final reports about research activities conducted in developed countries in order to

- expose latest developments in the field of interest
- determine guidelines for research and development suitable for institutions of higher learning
- determine technologies already developed and available for immediate transfer
- provide directions for entrepreneurs to promote introduction and application of new products
- advise decision-making bodies of the government before national policies with far reaching consequences are being defined.

The Federal Republic of Germany, among others, even promotes this one-way flow of information because she has realized that the industrial countries' economic development, especially in recent decades, is largely due to making the most of their scientific and technological potentials. Therefore, it seems absolutely necessary to promote first of all an adequate scientific and technological infrastructure in the developing countries. Without this infrastructure and without linkage of R. & D. efforts to the productive sector, R. & D. resources available in the developing countries would be tied up and possibly increase the technological dependency.

The federal government stresses energy research and the development of new technologies to cope with the world wide energy crisis, taking not only the situation in Germany but also the growing energy demand in developing countries into account. For this, efforts to

- save energy and decrease energy losses during conservation and storage of energy
- increase exploration and efficient use of coal and other fossil energy sources
- use less valuable fuels
- intensify development of technologies to effectively use renewable energy sources and long term storage
- develop the necessary infrastructure for the particular new energy source
- increase support of the developing countries to aid in developing their own energy sources

have to be made. The decentralized energy supply in developing countries places hopes particularly on solar energy. However, to utilize solar energy efficiently the development of appropriate energy conversion techniques as well as storage facilities for thermal and electrical energy is a necessary prerequisite. Based on international cooperation with developing countries in the past the following areas of application of solar energy seem to be of greats interest:

- heating of water
- pumping of water
- refrigeration and drying of food stuffs
- desalination of water
- power plants
- heating and cooling of buildings

Besides solar energy, wind energy has widely received attention. Important requirements for decentralized usage of wind energy in developing countries are robust plants which require only little maintenance. The federal government, therefore, has asked to develop plants which allow to employ cheap and easy to exchange components possibly be manufactured in the developing countries.

The Federal Republic of Germany has publicly stated and is willing to bring its science and technology capacity and the know-how generated in its state-supported research and technology facilities into its development assistance policy and into the scientific and technological cooperation with developing countries.

In a programme jointly sponsored by the Federal Ministry for Economic Cooperation and the Federal Ministry for Research and Technology special technologies are developed or adapted which are particularly appropriate to the requirements of developing countries. So as to open the vast potential and know-how of Germany's research facilities for the developing countries the two ministries have set up the "German Appropriate Technology Exchange" (GATE) department of the German Agency for Technical Cooperation (GTZ).

GATE houses a question and answer service to identify German technologies, procedures and know-how able to help solve the problems arising in developing countries. This makes it possible to transfer to the developing countries modern technological, economic and organizational know-how which is in public ownership and to enhance the prerequisites for their use there, thus to develop and raise economic and social potential.

The government-owned GTZ is responsible for evaluating and implementing technical cooperation projects which mainly comprise assignments of experts and provision of materials and training possibilities. At the same time there is awareness of and consideration for the developing countries' needs and their specific context in which technology is employed presupposing comprehensive knowledge, including information about the culture, history, law, and politics of these countries.

But no matter how sincere an adviser from a developed country may be the possibility of adoption of economic and technological models unsuitable for local conditions calls for a more intense participation on part of the developing country in order to take local social, economic and political factors in addition to technological ones better into account.

It is suggested that small groups of experts in the field of renewable energy sources are being established by the developing countries in order to examen systematically findings resulting from studies and investigations made in the developed countries. The creation and support of these groups could be part of the development aid given by the developed countries which would perfectly fit the intention "to help the developing countries to help themselves". Although, developing countries are markedly different from one to another and each country needs to achieve a capacity to make the technological choices relevant to its needs, one goal should be common to all of them and that is to take full advantage of all offered and possible chances to get the most out of the available pool of information. However, this would be only one little step in the right direction, since the actual technology transfer on a big scale asks for close cooperation of the countries involved. This is not as trivial as it may sound and a number of developing countries have already begun to intervene actively to the inflow of technology by establishing national registries of technology, reviewing and renegotiating technology contracts, and outlawing various restrictive practices, in order to avoid disadvantages with regard to cost, independence, and learning during and after the transfer of technology.

Positive examples of technology transfer in all phases between the participants from industrial and developing countries are the solar village projects with Mexico, Indonesia and Egypt, where beginning with project selection, through conception and implementaion to evaluation of results and findings close cooperation was demonstrated.

The advantages for the developing countries in such cooperation derive particularly from their direct access to the know-how of the partners from the industrial countries, from tapping the research and development infrastructure of the industrial countries for a jointly defined programme, from strengthening their own research and development capacities and from putting the jointly made findings into practice.

APPENDIX

An invaluable aid to get an overview of R. & D. projects sponsered presently by the Federal Republic of Germany concerning new sources of energy is the annual report about energy research and technologies, presented by the Project Management for Energy Research (PLE) of the Julich Nuclear Research Establishment. Between the beginning of 1974 and the end of 1979 the PLE had processed approximately 1730 projects concerning fossil sources of primary energy, efficient use of energy, and new sources of energy.

Of these, approximately 1050 projects with a total volume of about US $ 2.5 billion were already approved, 80 projects had been submitted to the Federal Ministries with a recommendation and 590 projects were still in the preparatory and discussion phase.

The following is a listing of R. & D. projects about renewable energy sources presently under investigation in the Federal Republic of Germany.

THERMAL UTILIZATION OF SOLAR ENERGY

Development and Testing of Collectors

- Flat plate solar energy collectors
- Development of industrial scale manufacturing processes for solar heating system components
- Development of air-tight solar collector casings.
- Development of solar heating controls for water-heating and building-heating systems.
- Development of large scale production methods for components of solar energy collection.
- Development of solar selective absorber coatings for aluminium roll bond heat exchangers.
- Improvement of thermal efficiency of flat plate solar collectors.
- Roll-bonded heat type panels.
- Flat plate heat pipe collectors made by rollbonding.
- Development and optimization hermetically sealed flat plate collectors with gas filling/selective absorbing thin films.

- Basic investigations of solar energy conversion with fluorescent collectors.
- Development of direct evaporating collectors for small solar powered plants and small solar cooling facilities.
- Development of high temperature resistant solar abosrber surfaces.
- Development of practical methods for the determination of the stagnation temperature and the durability of solar collectors.
- Development of a production plant for selective coating of aluminum solar absorbers.
- Serial production of sun absorbing heat exchanger panels for utilizing solar radiation and environmental heat.
- Development of simple solar collectors.
- Development and establishment of methods to prove the performance of solar collectors and solar systems for heating.
- Cooperation in the field of solar energy with partner institutes in Brasil, India, Iran, Indonesia, Mexico, Philippines, Australia, Niger, Columbia and Pakistan.
- Joint German-Indian research and development program for selective coatings.
- Testing solar panels for air heating.
- Fluorescent dyes for solar energy collectors.
- Development of novel absorption layers for high temperature solar collectors.

Heating and Hot Water Systems

- Measuring program for a solar heating plant.
- Technical and scientific investigations carried out at solar energy experimental facility in Wiehl/FRG.
- Measuring program for hot water supply in prefabricated houses using solar energy.
- Solar equipment system-packages for old and new buildings to provide warm water and partial heating.
- Program for future investment ZIP/installation of solar technological plants in buildings belonging to the Federal Government itself.

- Heat-pipe solar absorber.
- Execution of the preliminary-phase BMFT-solar-house project.
- Flat plate collectors as facade elements for water preheating and heat insulation.
- Solar houses Colorado/Freiburg - Collector manufacturing.
- Solar house Freiburg.
- Open-air swimming pools with solar heating.
- Comparison of energy systems with solar collectors, solar absorbers and heat pumps for space heating and domestic hot water supply.
- Investigation into the use of glass faced buildings as solar energy collectors for heating energy conservation.
- Development of temperature sensors suitable for longterm continuous operation for technical control equipment in solar systems.
- Pilot test facility for solar systems.
- Small solar heated swimming pool with energy-saving equipment.

Cooling and Process Heat

- Utilization of solar energy for the production of fresh water making use of a multi-stage-flash desalination process (SMSF).
- Use of solar energy in industry.
- Comparison of concepts for solar-heated or solar-driven absorption and compression cooling machines for air-conditioning and food preservation purposes.
- Energy analysis and investigation of possibilities of using solar energy in a winery.
- Application analysis and technical design of a hightemperature kiln run by solar energy for the improvement of building materials (for instance bricks) in developing countries.
- Development and construction of a simple solar-powered water pump.
- Development and construction of a prototype piston engine with Freon 113 vapour having an output of 2-10 kW.

- Development of independent solar refrigeration plants using concentrating collectors, absorption refrigeration circuits and energy storage system.

Greenhouses and Drying Plants

- Operation measurements for a solar collector drying plant.
- Plant for drying grain with solar energy.
- Pre-drying of green fodder by means of solar energy.
- Comparing research and demonstration project on the use of solar energy to heat energy-saving glass houses.
- Plant for drying grain with solar energy.
- Reducing heat consumption of greenhouses by more intensive use of solar energy by means of energy recovery and storage.

ELECTRICAL UTILIZATION OF SOLAR ENERGY

Photovoltaic Power Converters

- Development of a continuous coating process for mass production of CdS thin-film solar cells.
- Development and production of prototypes of photovoltaic power stations.
- Concentrators in combination with photovoltaic devices.
- Solar cells based on amorphous silicon.
- Development of a process for an inexpensive production of thin film solar cells on an industrial scale.
- Investigation of new solar cells.
- Preparation of thin amorphous silicon films for solar cell application.
- Development and test of solar generator prototypes for concentrating systems.
- Direct transformation of solar energy to electrical energy using an optical system for light intensification.
- Analysis design and realization of a 5 kW photovoltaic generator.
- Research and development of an amorphous silicon MIS thin film solar cell.
- Development of a CdSe thin film solar cell.

- Development of single crystal CdTe solar cells for terrestrial application
- Physico-chemical studies on copper sulphide in view of its behaviour in the CdS-Cu_2S solar cell.
- Development and testing of a submersible pump driven by a solar cell generator.
- Development of a thin film preparation technique for ZrO_2/Y_2O_3 electrolytes on porous support structures.
- IEA - Small solar power systems project (SSPS).
- Construction and testing of an experimental plant using solar cells and concentrating collectors.

Thermal Power Stations

- 10 kW Solar power plant.
- Tests with concentrating collectors for solar farm plants.
- EURELIOS Solar thermal demonstration power plant of 1 MW, of the European Community.
- Organic working fluids for prime mover systems of solar power plants.
- Solar thermal power station 100 kW.
- Joint Indian-German program on solar energy.
- Test with concentrating collectors.
- Gas-cooled solar tower power station for the generation of electrical energy in the range of 20 MW.
- Prequalification of the MAN-Solarfarm-Module Type 3/32 as part of a demonstration program.
- Development and test of slide-valve controlled screw engines with the corresponding steam cycle installation as basis for the design of small solar power plants (50-500 kW).
- German-Australian 70 kW solar power station (STEP 70).

BIOLOGICAL AND CHEMICAL UTILIZATION OF SOLAR ENERGY

Photochemical Conversion

- Photoelectrochemical decomposition of water using solar energy.

- Water oxidation and nitrogen reduction with a photochemically generated electron donoracceptor couple.

CONBINED SOLAR ENERGY PLANTS

- Testing of solar plants in a village in Egypt, Pilot project "Mit Abu El Kom".
- Solar village, Indonesia.
- Technical and economical optimization study on the use of solar energy for a village in Greece, Part I, study for the project definition.
- SONNTLAN Phase II.
- Test station for solar collectors in Brazil.

SUPPLEMENTARY MEASURES

- The spatial and time distribution of diffuse sky radiation and direct solar radiation in the Federal Republic of Germany.
- Determination of climatological parameters of global radiation and direct solar radiation.
- Interrelationship of the irradiance produced by the sky component of solar radiation on differently oriented receiving surfaces.
- Technical use of solar energy.
- Processing of satellite data.
- Practical experiences with existing solar plants.
- The deployment of solar energy: Investment strategies for the Federal Republic of Germany in a Western European context.
- Solar technology - Research report from the point of view of roofers.
- Satellite image evaluation.

WIND ENERGY

Large Wind Energy Converters and Storage

- Development construction and test of prototype wind energy converter 52 m diameter, 265 kW terminal power.
- Engineering and economical possibilities of largescale wind energy systems converting wind power into electrical power with special attention to storage systems.

- Investigations for the construction of large rotorblades for GROWIAN and for the dynamic behaviour of the complete system GROWIAN.
- Critical assessment of GROWIAN I.
- Wind energy converter GROWIAN II.
- Study for the preparation of a final design and construction of a prototype atmospheric-thermal up-wind power plant, preliminary design of larger units.
- The coastal wind situation of the Federal Republic of Germany with regard to wind energy utilization (especially planning of wind power plant networks).
- The wind conditions in the interior of the Federal Republic of Germany with respect to wind power conversion (especially compound network planning).
- Production, development manufacture and test of the GROWIAN-rotor blade.
- Research into the utilization of wind power in middle mountainous regions under consideration of available facilities for energy storage.
- Construction and operation of the large wind energy converter GROWIAN I.
- Development and manufacture of rotor blades for the 265 kW Voith wind energy converter.
- Formulation of a measurement and test program GROWIAN.
- Construction of a gust generator for the development of wind-turbines with associated research program.
- OPTIWA-Optimization of large scale WEC's.
- Operational behaviour of wind power plants.

SMALL WIND ENERGY CONVERTERS, WIND MEASUREMENTS, APPLICATIONS

- Meteorological measurements in coastal areas for the selection of locations for wind energy plants.
- Measuring wind data at high altitudes (150 m tower).
- Construction and investigation of the operation of a wind energy converter.
- Evaluation of a 15 kW wind power plant determination of transferable power data and evidence of the profitability of the power generation.

- Performance comparison of small wind energy converters.
- Interpretation and standardization of meteorological measurements for the verification of wind energy conversion system performance specifications.
- Reference plant with integral storage for wind energy conversion.
- Wind energy converter system with vertical axis rotor.
- Wind energy concentration within vortex flow fields and their utilization for the generation of energy.
- Utilization of wind energy for heating.
- The environmental and meterological aspects of WECS.
- Development of a 5.5 m diameter vertical axis wind energy converter.
- Contribution of wind energy in a combined solar and wind energy converter.
- Experiments into the dynamic loads on a WEC with vertical axis as well as the start-up and over-load control.
- Investigation of the variability of the wind vector up to a height of 200 m in the German coastal area regarding wind energy utilization.
- Development and testing of a wind-powered space heating system.
- Development of a simple wind speedometer for application in countries of the developing world.
- Development of a simple anemometer for wind classification.
- Blade technology program for large wind turbine generators.
- Development of a wind energy converter of medium performance range up to 50 kW.
- German-Argentine research and development project for the utilization of wind energy.
- Behaviour of a long-term heat storage for wind energy.
- Comparative study of the possibilities of integrating wind power into the national electricity supply systems of selected countries.
- Simultaneous measurements of high time resolving power of wind velocity at different high altitudes for improved design of large wind energy converters.

GEOTHERMAL ENERGY

- Magma and heat content of the magma reservoir of the 11 000-year old Laacher See Volcano (Eifel).
- Geophysical investigations in the basement rocks of the Urach research borehole.
- Geomagnetic and magnetotelluric soundings in the area of the Central European rift system.
- Petrographic and mineralogical studies on the problem of the geothermal anomalies in Southern Germany and their tracing by geophysical methods.
- Investigation of thermal and mineral springs in the Eifel Mountains regarding geothermal indications.
- Seismic investigations of structural and lithological parameters in anomalous, geothermal areas, example Urach.
- German participation in the international project "Deep Research Hole Iceland".
- Fracturing studies in the deepened Urach well.
- Exploration of temperature field in the Urach region down to a great depth and test of geophysical and geochemical methods.
- Investigations of exploration methods for geothermal anomalies (Magneto-telluric and geoelectric soundings).
- Pilot project to utilize geothermal energy of low enthalpy.
- Refrigerants.
- Experiments in an artificially created frac at shallow depth, providing basic information for the development of technologies for an industrial exploitation of terrestrial heat from hot dry rock.
- Pilot-study: Geochemical prospecting for geothermal resources by $^{3}He/^{4}He$ techniques.
- Development and construction of a temperature probe for measurements in deep boreholes.
- Participation in geophysical measurements in connection with hot-dry-rock deposits (Los Alamos).
- Development of an active audiomagnetotelluric device.
- Geothermal demonstration project, Saulgau.

- Electrical conductivity measurements on rocks as a function of pressure, temperature and status of the rocks.
- Exploration and utilization of geothermal energy for the basic load supply of existing heating systems.
- Development and demonstration of the hot dry rock technology, Fenton Hill project, Los Alamos, USA.

OPTIMUM COLLECTOR SLOPE FOR A SUBTROPICAL COUNTRY

by

C.T. LEUNG

ABSTRACT

Solar collectors of the flat plate type can utilize both the direct and diffuse components of the solar radiation. It is always desirable to tilt the flat plate collector at some optimum angle so as to pick up the maximum amount of solar radiation from the sun. In this paper, the effects of the tilt angle on the variation of insolation on inclined surfaces in Hong Kong, latitude = 22.304°N, have been investigated using the recent 10 years average daily irradiance data between 1969-78.

It has been found that the optimum angles of tilt for the Hong Kong flat plate collectors in the annual, summer and winter modes of collection are 20°, 10° and 40° respectively and the corresponding amount of insolation received are 5636 MJm^{-2}, 3042 MJm^{-2} and 2819 MJm^{-2}. Another point of observation is that the variation of insolation received on inclined surfaces is not at all sensitive to the angle of tilt in the neighbourhood of the optimum angle of operation. Even if the actual slope of the flat plate collector is set at ±5° off the optimum tilt angle, the amount of insolation received would only be decreased by one or two per cent.

1. INTRODUCTION

Solar collectors of the flat plate type can utilize both the direct and diffuse components of the solar radiation. It is always desirable to tilt the flat-plate collector at some optimum angle so as to pick up the maximum amount of solar radiation from the sun. For all year around performance, it is the usual practice as a rule of thumb to set the flat plate collector tilt angle, β, equal to that of the latitude, ϕ, at which the solar system is placed i.e. $\beta = \phi$. However, if it is desirable to improve the winter performance as in the case of a heating system in the Northern Hemisphere, the angle of tilt is usually set at $\beta = \phi + 10°$. In case when the maximization of the summer performance is needed, such as in a solar cooling system, the tilt angle may be set at $\beta = \phi - 10°$. However, these are only very rough guide lines for designers.

In Hong Kong, the effects of tilt angle on the variation of insolation incident on inclined surfaces were first investigated by Bruges in his study on a solar heating system for the Stanley Public Bath house [1]. The ratios of the relative amount of insolation received on inclined surfaces to horizontal surfaces in Hong Kong had been calculated and tabulated based on the simple assumption that conditions at the earth surface were nearly the same as at the extra-terrestrial conditions. In this paper, the effects of the tilt angle on the variation of insolation on inclined surfaces in Hong Kong are to be further investigated using the recent 10 years average daily irradiance data between 1969-78. Optimum tilt angles for flat plate collectors for yearly, summer and winter modes of collection in Hong Kong are to be recommended. These results may be useful to other subtropical countries with similar meteorological conditions.

2. COMPUTATION OF AVERAGE DAILY SOLAR INSOLATION ON INCLINED SURFACES

Knowledge on the amount of solar irradiance incident on inclined surfaces is required for the determination of the optimum tilt angle for the operation of the flat plate collectors. Solar irradiances incident upon horizontal surfaces are available in most parts of the world. However, radiation data on tilted surfaces are extremely rare and one has to rely on various computational methods for their estimates.

A simple method of estimating the monthly average daily radiation on surfaces tilted towards the equator has been developed by Liu and Jordan [2]. To compute the daily insolation on an inclined surface, the diffuse component has to be first separated from the total horizontal solar radiation. If the sky diffuse radiation and the ground reflected diffuse radiation are both assumed to be isotropic, the monthly average daily insolation on an inclined plane, H_β can be computed from the following expression [2]:

$$\bar{H}_\beta = (\bar{H} - \bar{H}_d)\bar{R}_b + \bar{H}_d\left(\frac{1+\cos\beta}{2}\right) + \rho\bar{H}\left(\frac{1-\cos\beta}{2}\right) \tag{1}$$

where $\bar{H}$ = monthly average daily total radiation received on a horizontal surface.

$\bar{H}_d$ = monthly average daily diffuse radiation received on a horizontal surface.

β = angle of tilt of the inclined surface from the horizontal.

ρ = ground reflectance which usually ranges between 0.2 and 0.7.

$\bar{R}_b$ = the ratio of the monthly average beam radiation on the tilted surface to that on a horizontal surface.

The ratio $\bar{R}_b$ is a function of the transmittance of the atmosphere which is in general difficult to evaluate due to the everchanging meteorological and weather conditions. However, Liu and Jordan [2] suggested that $\bar{R}_b$ can be approximated by the ratio of the daily extraterrestrial radiation on a tilted surface to that on a horizontal surface,

$$\bar{R}_b \cong \frac{\bar{H}_{o\beta}}{\bar{H}_o} \tag{2}$$

For surfaces facing directly toward the equator, $\bar{R}_b$ in eqn. (2) can be expressed as

$$\bar{R}_b = \frac{\cos(\phi-\beta)\cos\delta\sin\omega_s' + (\pi/180)\omega_s'\sin(\phi-\beta)\sin\delta}{\cos\phi\cos\delta\sin\omega_s + (\pi/180)\omega_s\sin\phi\sin\delta} \tag{3}$$

where $\omega_s = \arccos(-\tan\phi \text{and} \delta)$,

$\omega_s' =$ minimum of $[\omega_s, \arccos(-\tan(\phi-\beta)\tan\delta)]$,

and ϕ, δ are the latitude and declination of the sun respectively.

When calculating the monthly averages of $\bar{R}_b$ in eqn. (3), average declination δ values for the month are used. In this study, the 15th day of the month is chosen to calculate the monthly average values.

Actual long term average data measurements for diffuse radiation $\bar{H}_d$ are to be used in eqn. (1) for computation as far as possible. However, in places where actual measurement data are not available, values of diffuse radiation, $\bar{H}_d$ have to be estimated.

3. SOLAR IRRADIANCE DATA FOR HONG KONG

3.1 Daily Total Global Solar Irradiance

Measurements of the daily total global solar irradiance have been carried out in Hong Kong by the Royal Observatory for many years since June 1958 up to the present [3]. Values of total global irradiance are obtained from recordings of a bimetallic actinograph, British Meteorological Office Pattern MkIII, with a wavelength range between 0.3 μm and 4 μm and accuracy to within 5%. The instrument has been calibrated against a standard recorder at the Kew Observatory. All the radiation data collected in Hong Kong are at a station (King's Park) located at 22° 19' N, 114° 10' E and the scale of reference used is based on the International Pyrheliometric scale of 1956. The statistical analysis of a continuous set of data available for the recent ten years period between 1969 and 1978 has been performed. Values of the Hong Kong average daily total global irradiance on a horizontal surface for each month of the year are shown in figure 1 in which the maximum and minimum monthly average values are also shown. The average daily total values range from 18.84 $MJm^{-2}d^{-1}$ in the summer month of July to 11.48 $MJm^{-2}d^{-1}$ in the winter month of January. Over the year, the average daily value is 14.84 $MJm^{-2}d^{-1}$. The seasonal variation is quite typical of the subtropical climate in Southern Asia. The monthly variability is considerably large, especially in the months of March and November. This may be mainly due to the unstable climatic condition during the transition from cold to warm weather and vice versa. The steadiest period is at the beginning of summer in the month of May with a range of only 26.8 per cent of the monthly mean.

3.2 Daily Diffuse Solar Irradiance

Up to the present, there have been no measurements of the diffuse solar irradiance in Hong Kong and one has to rely on theoretical methods for their estimates. A number of investigators have found that the average daily diffuse irradiance fraction of the daily total on a horizontal surface, $\bar{H}_d/\bar{H}$ can be correlated to the cloudiness index, $\bar{K}_T$. The parameter $\bar{K}_T$ represents the fraction of the mean daily extraterrestrial horizontal irradiance $\bar{H}_o$ arriving at the surface of the earth and is defined as

$$\bar{K}_T = \frac{\bar{H}}{\bar{H}_o} \tag{4}$$

The correlation developed by Page [4] was of the linear form:

$$\frac{\bar{H}_d}{\bar{H}} = 1.00 - 1.13\,\bar{K}_T \tag{5}$$

Liu and Jordan had also presented a different correlation [5] and Klein [6] later developed the following mathematical expression for their correlation:

$$\frac{\bar{H}_d}{\bar{H}} = 1.390 - 4.027\,\bar{K}_T + 5.531\,\bar{K}_T^2 - 3.108\,\bar{K}_T^3 \tag{6}$$

The monthly average values of the daily diffuse solar irradiance in Hong Kong have been calculated by the above two correlations with cloudiness index based on the Hong Kong meteorological data for the ten years period between 1969 and 1978 and the results are presented in table 1. Both methods of correlation indicate that the highest fraction of diffuse solar irradiance occurs in the month of March and the lowest in November. Over the year, the estimated fraction may vary between 0.601 and 0.354 strongly depending on what method of correlation is being used.

The magnitudes of the monthly average daily diffuse solar irradiance in Hong Kong are presented graphically in figure 2 in which the monthly average daily total values are also shown for reference. It is to be noted that both correlations predict a similar pattern of yearly variation though the Liu and Jordan's correlation gives consistently slightly lower estimates. Over the year, the monthly average daily diffuse solar irradiance in Hong Kong is high in the summer and low in the winter. The values range between 7.39 $MJm^{-2}d^{-1}$ and 4.44 $MJm^{-2}d^{-1}$ based on Liu and Jordan's correlation of estimates. However, since the estimated values differ from method to method and the deviation may be as high as 19%, future experimental data on the local measurements of the daily diffuse horizontal solar irradiance are needed in order to confirm which correlation is the best to use for the Hong Kong Climate. In this study, the Liu and Jordan's correlation is used because it has the wider and more universal applicability.

4. RESULTS AND DISCUSSION

Using $\rho = 0.2$, R_b from eqn. (3) and the values of the total and diffuse solar irradiances for Hong Kong, the insolation on inclined planes is computed by equation (1). Results of the monthly total insolation on inclined surfaces in Hong Kong for slopes from 10° to 90° at increments of 10° are shown in table 2. Figure 3 presents the same results but for four slopes; $\beta = 30^\circ, 50^\circ, 70^\circ$ and 90°. The insolation on the horizontal surface $\beta = 0^\circ$ is also shown in the same figure for comparison. It can be seen that for the summer months between April and September, the insolation on inclined surfaces decreases rapidly with the increasing angles of tilt. However, in the winter months, there seems to be no obvious trends of the insolation variation with the angles of tilt.

The ratios of the relative amount of insolation received on inclined surfaces to horizontal surfaces, H_β/H, using the same 10 yr. solar irradiance data of Hong Kong have been calculated and the results are shown in table 3. It has been found that for tilt angles greater than 30°, the ratios $\bar{H}_\beta/\bar{H}$ are greater than unity in the winter months between October and February. On the other hand, the ratios are less than unity in the summer months between April and September. Therefore, in order to maximize the winter collection in Hong Kong, the tilt angle has to be set at least greater than 30°.

Tables 4 shows the total amount of insolation received on inclined surfaces at various tilt angles for the three different modes of collection: (a) yearly (b) summer (April to September) and (c) Winter (October to March). The variation of the annual, summer and winter total insolation received on inclined surfaces as a function of tilt angle is shown graphically in figure 4. It can be seen that for each of the three different modes of collection, there is a unique optimum angle of tilt. The optimum angles of tilt for the maximum annual, summer and winter modes of collection in Hong Kong are 20°, 10° and 40° respectively and the corresponding amount of insolation received are 5636 MJm^{-2}, 3042 MJm^{-2} and 2819 MJm^{-2}.

Another very important point of observation is that the variation of the insolation received on inclined surfaces is not at all sensitive to the angle of tilt in the neighbourhood of the optimum angle of operation. In other words, even if the actual slope of the flat plate collector is set at ±5° off the optimum tilt angle, the amount of insolation received would only be decreased by one of two per cent. This percentage is far too small to be significant as compared to the annual or seasonal fluctuations in the total amount of insolation in Hong Kong, which are usually as high as 20 per cent of the mena.

So far, the analysis in this paper has been based on the computation of average daily insolation on inclined surfaces using daily irradiance data. However, there exist other methods of computing average daily insolation on inclined surfaces using hourly irradiance data [7, 8, 9]. A comparison of results using the Hong Kong daily and hourly irradiance data had been performed and the agreement of the results obtained by the two different approaches was in general quite good [10]. Therefore, it is expected that the results of the optimum collector slopes would not be too much different even if hourly irradiance data were used in the computation.

5. CONCLUSION

The effects of the tilt angle on the variation of insolation on inclined surfaces have been analysed using the 10 yr. daily irradiance data for Hong Kong and it is noted that the amount of total insolation received is not at all sensitive to the tilt angle near the optimum angle of collection. For the annual, summer and winter modes of radiation collection, the optimum angles of tilt for the Hong Kong flat plate collectors are found to be 20°, 10° and 40° respectively and the corresponding amount of insolation received are 5636 MJm^{-2}, 3042 MJm^{-2} and 2819 MJm^{-2}.

NOMENCLATURE

$\bar{H}$ = monthly average daily total radiation received on a horizontal surface, $MJm^{-2}d^{-1}$

$\bar{H}_d$ = monthly average daily diffuse radiation received on a horizontal surface, $MJm^{-2}d^{-1}$

$\bar{H}_\beta$ = monthly average daily total radiation received on a surface inclined at β degrees to the horizontal, $MJm^{-2}d^{-1}$

$\bar{H}_o$ = extraterrestrial monthly average daily insolation on a horizontal surface, $MJm^{-2}d^{-1}$

$\bar{H}_{o\beta}$ = extraterrestrial monthly average daily insolation on a surface inclined at β degrees to the horizontal, $MJm^{-2}d^{-1}$

$\bar{K}_T$ = ratio of the monthly average total to the monthly average extraterrestrial radiation on a horizontal surface, dimensionless

$\bar{R}_b$ = daily ratio of the extraterrestrial radiation on a tilted surface to that on a horizontal surface for the month, dimensionless

Greek Symbols

β = surface tilt from the ground, degrees

δ = declination, degrees

ϕ = latitude, degrees

ω = hour angle, degrees

ω_s = sunset hour angle for a horizontal surface, degrees

ω_s' = sunset hour angle for a tilted surface, degrees

ρ = albedo

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Table 1. Calculation of the Hong Kong monthly average diffuse irradiance on a horizontal surface by the cloudiness correlation methods.

MONTH	$\bar{H}_o$ $[MJm^{-2}d^{-1}]$	$\bar{H}$ $[MJm^{-2}d^{-1}]$	$\bar{K}_T = (\bar{H}/\bar{H}_o)$	Page's Correlation $(\bar{H}_d/\bar{H})$	Page's Correlation H_d $[MJm^{-2}d^{-1}]$	Liu and Jordan's Correlation $(\bar{H}_d/\bar{H})$	Liu and Jordan's Correlation H_d $[MJm^{-2}d^{-1}]$
JAN	25.21	11.48	0.455	0.486	5.58	0.410	4.71
FEB	29.41	11.76	0.400	0.548	6.44	0.465	5.47
MAR	33.81	11.95	0.353	0.601	7.18	0.521	6.23
APR	37.36	13.87	0.371	0.581	8.06	0.499	6.92
MAY	39.06	16.13	0.413	0.533	8.60	0.451	7.27
JUN	39.58	17.06	0.431	0.513	8.75	0.433	7.39
JUL	39.30	18.84	0.479	0.459	8.65	0.389	7.33
AUG	38.07	18.16	0.477	0.461	8.37	0.390	7.08
SEP	35.30	17.02	0.482	0.455	7.74	0.386	6.57
OCT	31.23	15.33	0.491	0.445	6.82	0.378	5.79
NOV	26.64	13.87	0.521	0.411	5.70	0.354	4.91
DEC	24.12	12.51	0.519	0.414	5.18	0.355	4.44

Table 2. Variation of the Hong Kong monthly average insolation on inclined surfaces at various tilt angles [$MJm^{-2}d^{-1}$]

MONTH	*Angles of Tilt (degrees)*								
	10	*20*	*30*	*40*	*50*	*60*	*70*	*80*	*90*
JAN	12.83	13.90	14.65	15.06	15.13	14.84	14.20	13.24	11.98
FEB	12.59	13.16	13.45	13.45	13.16	12.59	11.75	10.68	9.40
MAR	12.32	12.45	12.33	11.96	11.37	10.56	9.55	8.39	7.11
APR	13.88	13.63	13.11	12.35	11.37	10.19	8.87	7.45	5.98
MAY	15.77	15.11	14.19	13.02	11.64	10.12	8.50	6.88	5.46
JUN	16.46	15.57	14.42	13.04	11.48	9.81	8.10	6.49	5.40
JUL	18.22	17.26	16.00	14.47	12.72	10.82	8.87	7.00	5.56
AUG	17.95	17.37	16.45	15.22	13.71	11.97	10.08	8.12	6.23
SEP	17.39	17.39	17.01	16.27	15.18	13.79	12.13	10.26	8.24
OCT	16.31	16.93	17.16	17.01	16.48	15.59	14.35	12.81	11.02
NOV	15.44	16.65	17.48	17.89	17.88	17.44	16.59	15.34	13.75
DEC	14.27	15.70	16.76	17.42	17.65	17.46	16.83	15.81	14.40

Table 3. Variation of the ratio of the relative amount of insolation received on inclined surfaces to horizontal surface for Hong Kong (Lat. = 22.304°N)

MONTH	$\bar{H}$, $[MJm^{-2}d^{-1}]$	$\bar{H}_\beta/\bar{H}$				
	$\beta = 0^o$	$\beta = 10^o$	30^o	50^o	70^o	90^o
JAN	11.48	1.12	1.28	1.32	1.24	1.04
FEB	11.76	1.07	1.14	1.12	1.00	0.80
MAR	11.95	1.03	1.03	0.95	0.80	0.59
APR	13.87	1.00	0.95	0.82	0.64	0.43
MAY	16.13	0.98	0.88	0.72	0.53	0.34
JUN	17.06	0.96	0.85	0.67	0.47	0.32
JUL	18.84	0.97	0.85	0.68	0.47	0.30
AUG	18.16	0.99	0.91	0.75	0.56	0.34
SEP	17.02	1.02	1.00	0.89	0.71	0.48
OCT	15.33	1.06	1.12	1.08	0.94	0.72
NOV	13.87	1.11	1.26	1.29	1.20	0.99
DEC	12.51	1.14	1.34	1.41	1.35	1.15

Table 4. Variation of the total insolation on inclined surfaces in Hong Kong for the three modes of (a) yearly (b) winter and (c) summer collection [MJm^{-2}]

Mode of Collection	*Angles of Tilt (degrees)*								
	10	*20*	*30*	*40*	*50*	*60*	*70*	*80*	*90*
(a) Yearly	5585	5636	5571	5392	5105	4721	4254	3725	3101
(b) Winter (Oct - Mar)	2543	2696	2789	2819	2784	2687	2530	2317	2056
(c) Summer (Apr - Sep)	3042	2940	2782	2573	2321	2034	1724	1408	1046

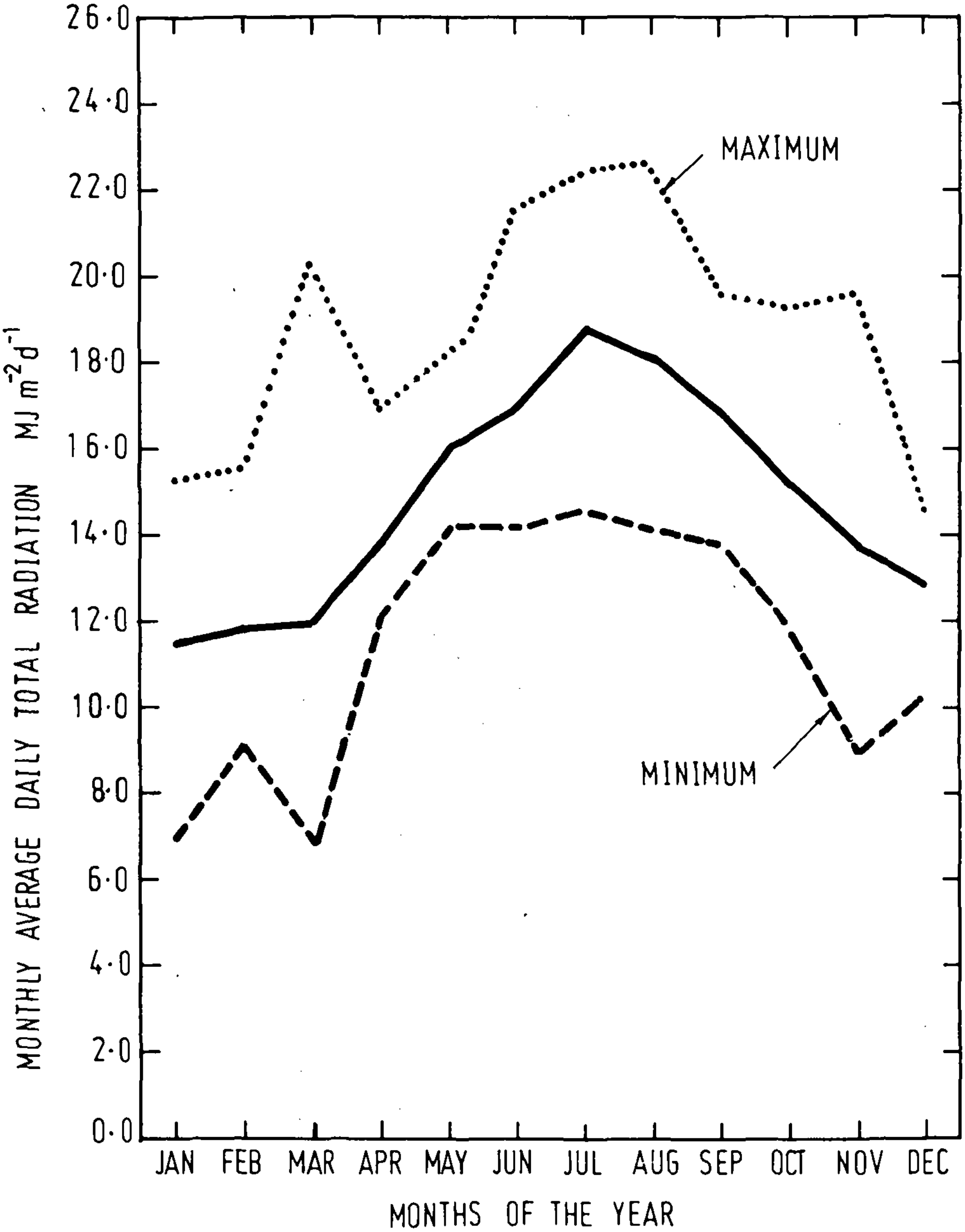

FIG. 1 MONTHLY VARIATION OF THE AVERAGE DAILY TOTAL SOLAR RADIATION IN HONG KONG

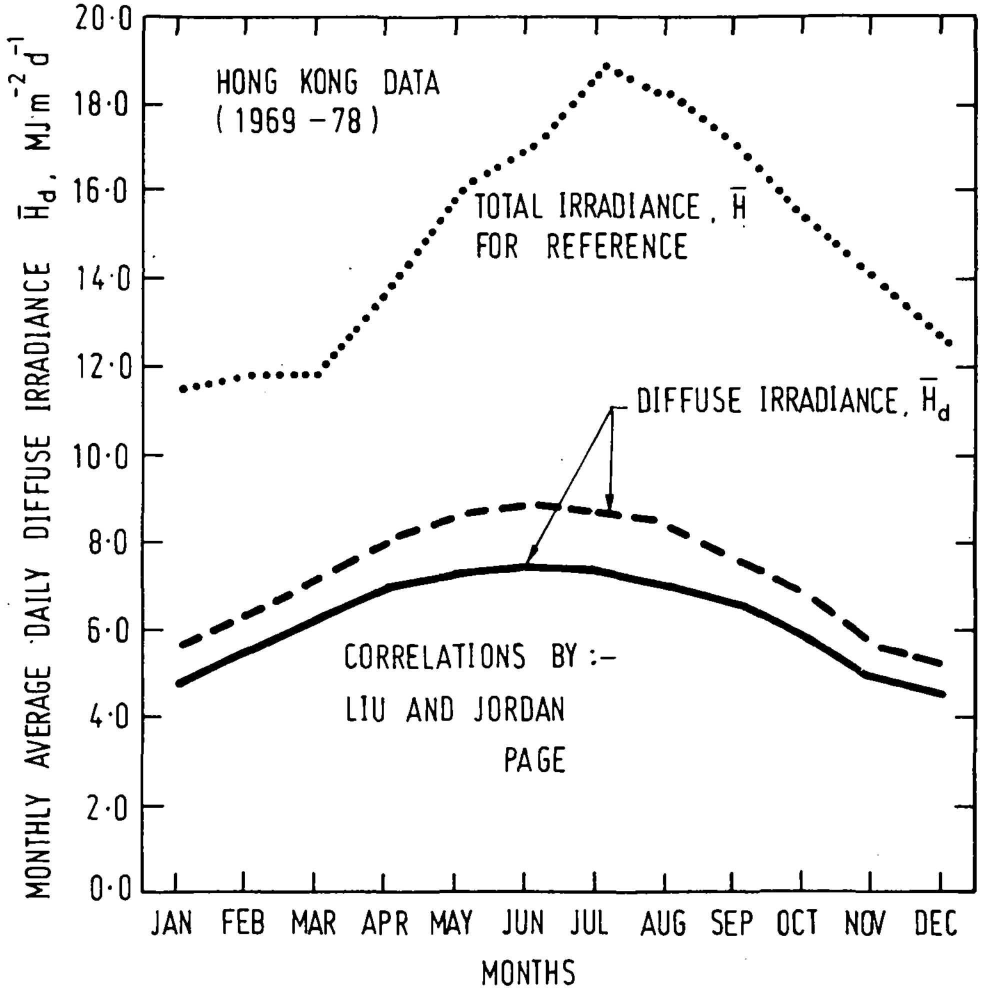

FIG. 2 COMPARISION OF THE MONTHLY VARIATION OF THE ESTIMATED DIFFUSE SOLAR IRRADIANCE IN HONG KONG

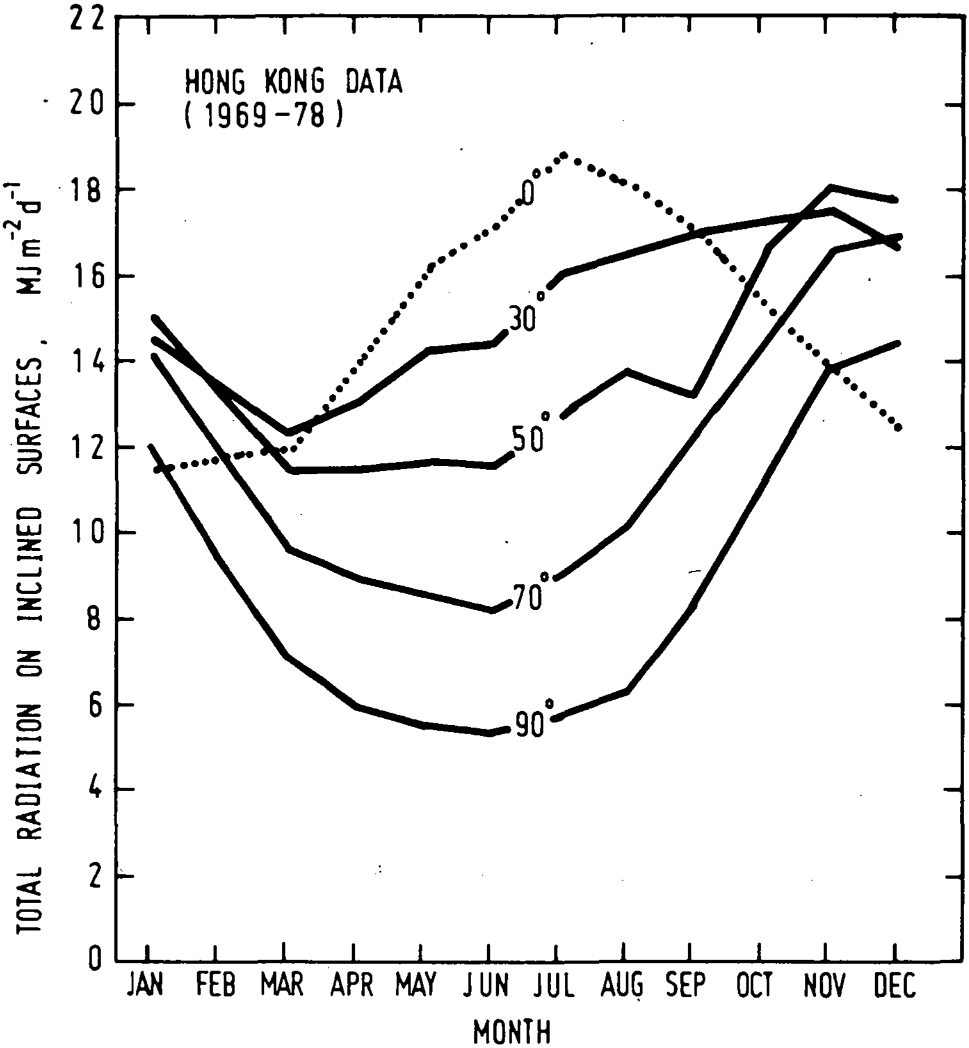

FIG. 3 MONTHLY VARIATION OF TOTAL RADIATION ON AN INCLINED PLANE FOR DIFFERENT TILT ANGLE

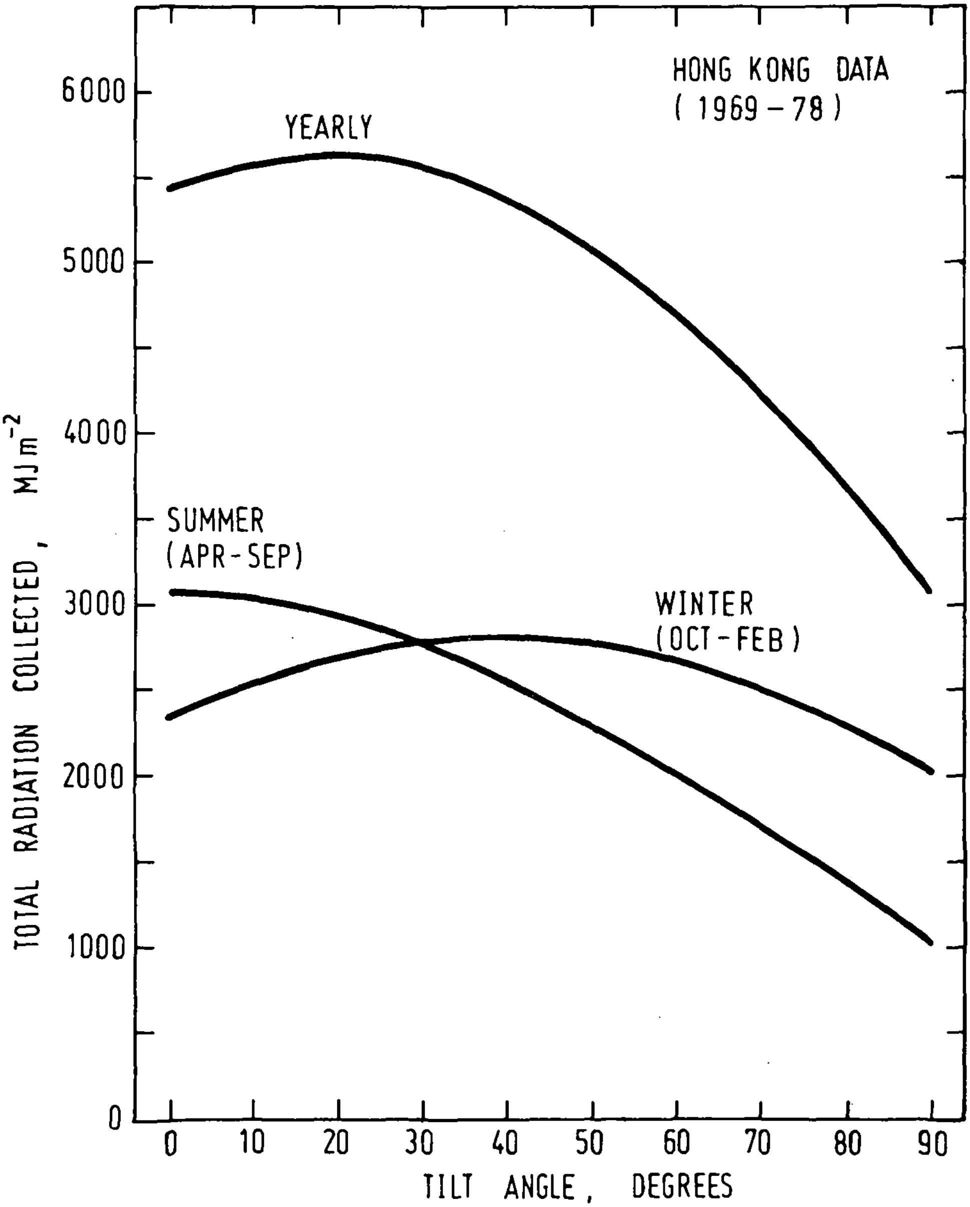

FIG. 4 VARIATION OF TOTAL RADIATION INCIDENT ON INCLINED SURFACES AT DIFFERENT TILT ANGLES FOR THE YEARLY, WINTER AND SUMMER MODE OF COLLECTION.

ELECTROCHEMICAL SOLAR CELL WITH THIN FILM n-CdSe PHOTOANODE

by

T.K. BANDYOPADHYAY, M.N. MAZUMDAR and S.R. CHAUDHURI

ABSTRACT

Result of solar energy conversion through photoelectrochemical cells based on polycrystalline thin film of n-CdSe electrodeposited on titanium substrate as photoanode in Se^{2-}/Se_n^{2-} electrolyte are presented.

Under polychromatic radiation maximum conversion efficiency and fill factor were found to be 0.5% and 0.36 respectively. The onset of photoresponse was around 600 nm and conversion efficiency at this wavelength was 1.45%. The quantum efficiency for electron flow at short circuit was maximum (0.47) around 550 nm. From the saturation value of open circuit photopotential, the value of flat-band potential was found to be - 1.37 V vs. SCE. An approximate estimate of the donor density was made and the value was found to be in the range of 2×10^{17} to 2×10^{19} cm^{-3}. The poor efficiency of the cell has been interpreted in terms of a shortening of the depletion layer width resulting in electron-hole recombination.

INTRODUCTION

The global energy crisis has stimulated enormous interest to search for renewable energy resources. Of all the possibilities, conversion of solar energy into useful forms appears to be most promising as the reserve is unlimited and the conversion process is free from pollution hazards. During the last few years solar energy conversion through photoelectrochemical cells (PECs) has assumed considerable interest [1] and conversion efficiency upto 12% has been claimed [2]. But most of these investigations were based on single crystal semiconductors as photoelectrodes. In order that an energy converter may be put to terrestrial applications, the ease and cost of fabrication should also be taken into account. Here are described the results of investigations on solar energy conversion through PEC of the type.

n-CdSe/Na_2Se - Na_2Se_n (aq.)/Pt, using polycrystalline thin film of n-CdSe (Band gap = 1.7 eV) electrodeposited on titanium substrate as photoanode.

EXPERIMENTAL

Preparation of n-CdSe photoanode:

The film of n-CdSe was prepared by simultaneous electrodeposition of Cd and Se onto a titanium substrate from a mixture of cadmium sulfate and selenious acid as catholyte and 2(N) H_2SO_4 as anolyte using Pt anode [3]. Electrodeposited cadmium selenide on titanium was annealed at 550° C for 1 hour in nitrogen atmosphere and then etched in acid mixture of HNO_3, H_2SO_4, CH_3COOH and HCl. Ohmic contact with the titanium sheet with a copper wire was made through indium and all the exposed metal was insulated with epoxy resin.

Cathode: The cathode was a pure platinum wire 9 cm. long and 1 mm. in diameter attached to a piece of platinum foil of area 4 cm^2.

Electrolyte: Na_2Se - Na_2Se_n (aq.) electrolyte was prepared by the heat treatment of a mixture of 1.0 gm. of Se powder and 4.0 gm. of $Na_2S_2O_4$ in 50 ml nitrogen-purged 10% NaOH at 70° C till brown or purple colour appeared indicating complete reduction. White crystals of Na_2Se were precipitated on cooling the solution. The crystals were washed with 10% NaOH. Solutions were prepared by dissolving Na_2Se in nitrogen purged 5M NaOH. The total concentration of selenide was determined gravimetrically by exposing a known volume of the solution to air and weighing the precipitated selenium. The electrolyte employed was 0.1M with respect to sodium selenide.

Construction of the photoelectrochemical cell (PEC):

With the n-CdSe as photoanode and platinum cathode the following cell was constructed:

n-CdSe/Na_2Se - Na_2Se_n (aq.)/Pt, in a glass vessel of 3.5 cm. in diameter and 10 cm. long.

Current - Voltage properties:

The V-I characteristics of PEC were studied using a 1000 W tungsten lamp with a standard silicon solar cell. Measurements were carried out with both polychromatic and monochromatic radiations under constant nitrogen purge. Monochromatic light was produced using Karl Zeiss filters. The potentials where referred were measured with respect to a saturated calomel electrode (SCE). Intensity of monochromatic radiation was measured using watt-meter.

Wavelength response:

Relative photocurrent was measured as a function of excitation wavelength. The intensity of the emergent light from the filter was kept constant for all the wavelengths.

RESULTS AND DISCUSSION

The dependence of photocurrent upon wavelength of incident radiation is shown in Fig. 1. The onset of photocurrent was around 600 nm. Maximum value of quantum efficiency for electron flow at short circuit (φ_e) was found to be 0.47 and this occurred around 550 nm.

Under polychromatic excitations maximum conversion efficiency (η) and fill factor (F.F.) were found to be 0.5% and 0.36 with the open circuit voltage (V_{oc}) and short circuit current (I_{sc}) as 0.31 V and 4.5 mA respectively at a light intensity of 100 mW/cm^2, i.e. under conditions simulating AM 1 sunlight (Fig. 2). Under monochromatic excitations at 600 nm η was found to be 1.45%. Table 1 shows the cell characteristics for monochromatic excitation at 600 nm.

Open circuit photopotential was measured as a function of light intensity (Fig. 3) and was found to saturate at high intensities, e.g., around 800 nm under polychromatic excitation. Treating the saturation value of open circuit photopotential as a measure of flat-band potential (V_{FB}), the value of V_{FB} in the present case was found to be - 1.37 V vs. SCE - a value less than that for single crystals [4].

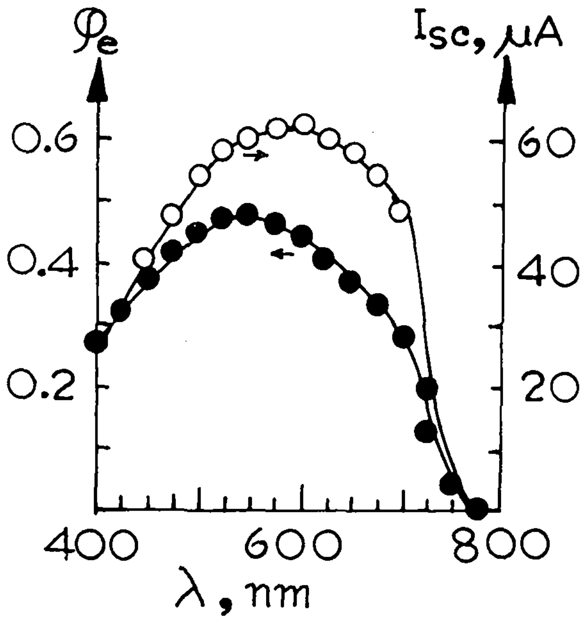

Fig. 1: Plot of relative photocurrent, I(0), and quantum efficiency for electron flow at short circuit, φ_e (0) with wavelength (λ).

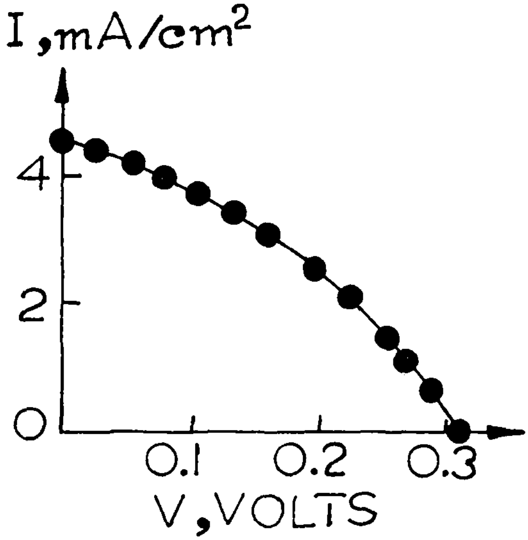

Fig. II: I-V characteristics of the PEC at 100 mW/cm^2 intensity.

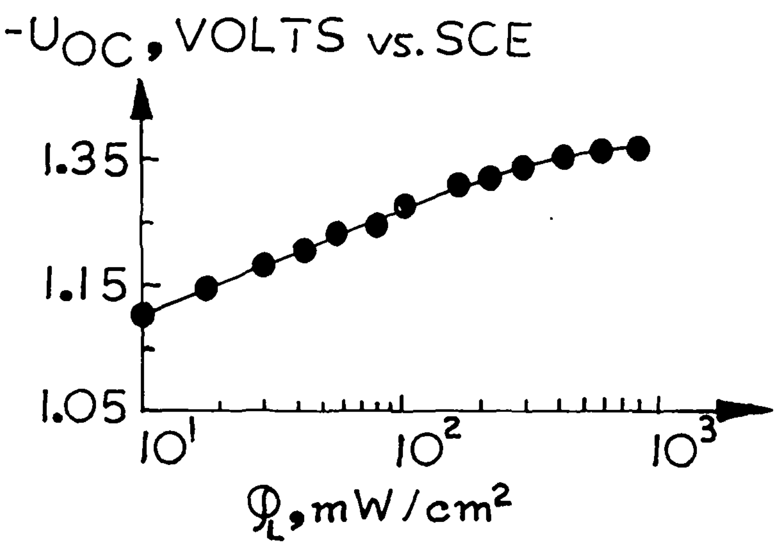

Fig. III: Variation of open circuit photopotential (U_{oc}) with light intensity (φ_L).

Table 1. Characteristics of the photoelectrochemical cell, n-CdSe/Na_2Se – Na_2Se_n (aq.) / Pt.

Intensity *mW*	V_{oc} *Volts*	I_{sc} $\mu A/cm^2$	P_{max} μW	φ_e *at short circuit* %	φ_e *at* P_{max} %	η %
0.31	0.210	59	4.27	39.3	23.3	1.38
0.60	0.219	116	8.89	39.9	24.1	1.48
1.10	0.228	210	16.00	39.4	23.5	1.45

Abbreviations: V_{oc}, open circuit voltage; I_{sc}, short circuit current; P_{max}, maximum power; φ_e, quantum efficiency for electron flow; η, power conversion efficiency.

Quantum efficiency for electron flow, $\varphi(\lambda)$, is related to donor density, N_D, by

$$\varphi(\lambda) = 1 - \exp\left[-\alpha_\lambda \left(\frac{2\Delta\psi_{sc}\epsilon_f\epsilon_o}{|e| N_D}\right)^{1/2}\right] \qquad \ldots\ldots\ldots\ldots (1)$$

where $\Delta\psi_{sc}$, voltage drop across the space charge layer, ϵ_f, dielectric constant of the semiconductor, ϵ_o, permittivity of vacuum, $|e|$, absolute value of electron charge and α_λ, absorption coefficient having value of 10^4 to 10^5 cm^{-1} for direct bandgap semiconductor, CdSe. Assigning different values to N_D, corresponding values of $\varphi(\lambda)$ were calculated and from the theoretical curves of φ vs N_D, a rough estimate of the donor density corresponding to the quantum efficiency of 0.47 was made and the value of N_D was found to be in the range of 2×10^{17} to 2×10^{19} cm^{-3} - a value comparable to that of single crystals [4].

The quantities characterizing efficiency of a photoelectrochemical cell are photocurrent and photovoltage. The rate of minority carriers generation by illumination determines the photocurrent provided the minority carriers can react efficiently with the species of the electrolyte at the electrode-solution interface. Otherwise there will be electron-hole recombination in the space charge layer. Corrosion of the photoelectrode by reaction with the minority carriers will also have a deleterious effect. Under polychromatic illumination, a large portion of the solar spectrum remains unutilised and, therefore, efficiency of the cell is likely to be poor as compared to illumination under monochromatic radiation.

The photovoltage is limited by band bending at equilibrium. The flat-band potential, again, determines the amount of band bending in the dark. The intrinsic band bending at the interface is a measure of the width of the depletion layer, W, which is related to the flat-band potential, V_{FB}, by

$$W = W_o \, (V - V_{FB})^{1/2} \qquad \ldots\ldots\ldots\ldots \; (2)$$

where V is the applied potential relative to the same reference electrode as that of V_{FB} and W_o is the width of the depletion layer for a potential of 1V across it and is given by

$$W_o = (2\epsilon/_{q\,N_D})^{1/2} \qquad \ldots\ldots\ldots\ldots \; (3)$$

Since the donor density, N_D, has an optimum value, therefore, the contribution of W_o to any alteration in the value of W should not be significant. Therefore, a decrease in flat-band potential will lead to a shortening of the depletion layer width resulting in electron-hole recombination. The overall result will be a lowering of the conversion efficiency.

Since the electrolyte concentration was high, the low value of flat-band potential may be attributed to a high surface charge density. Again, for a regenerative photoelectrochemical cell to operate efficiently, the reaction occurring at the photoelectrode has to be exactly reversed at the counterelectrode. But electrolysis causes local changes in the composition of the electrolyte next to the electrode-solution interface leading to concentration polarization. This can be minimised by shortening the distance between the two electrodes as much as possible so that equilibration of the electrolyte composition may be achieved by diffusion. Efficiency of the cell could be improved by more controlled sintering to increase the grain size and by minimising absorption loss through solution path. Also the possibility of formation of nodules [5] on the film which would scatter light can not be overruled. Nonetheless, the possibility of improvement exists and the reduction in efficiency could be well offset by the ease and low cost with which large area photoanodes can be prepared by electrodeposition.

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MATERIALS FOR SOLAR ENERGY UTILIZATION: IMPROVEMENT IN SOLAR STILL EFFICIENCY

by

GIRISH CH. PANDEY

ABSTRACT

The effect of blue dye on the performance of solar still has been reported, both, as a function of dye concentration as well as water depth. The thermal efficiency of the still has been found to increase with the increase in dye concentration as well as increase in water depth. On the basis of cost benefit analysis, 100 ppm has been found to be the optimum value. Possible explanations for relatively better performance of blue dye at lower concentrations compared to black dye has also been given. Use of such stills as heat storage basin in addition to water distillation, has been suggested.

INTRODUCTION

It is now well established that solar energy has good prospects but economic considerations mainly come in the way of its popularisation. In some of our recent communications (1-5) an attempt has been made to indicate that solar energy may turn out to be feasible even now in rural sectors. The low energy per capita requirement as well as plenty of space and man power time play an important role in this. Such an use will obviously lead to improvement in the quality of life of rural people at much low cost input. The effectiveness will depend on one important factor i.e. technology should be such as to be able to utilize the locally available resources both in terms of raw material and labour. However, adaptation/acceptance of the new technology by the rural people is one of the major problems which is not so in case of urban population. This is true for all the third world countries.

Provision of potable water in rural areas is one such example. Although there is plenty of ground water in desert and coastal areas but very high content of dissolved solids make it unfit for human consumption. Scattered and low population in these areas restrict setting up a centralized treatment plant due to economic considerations. The solar water distillation may turn but to be a more useful and economic alternative specially in view of the fact that size of the plant can be decided according to the requirement.

The mechanism and principle of solar water desalination is very simple and requires only a meagre recurring expenditure but the efficiency of this system (solar stills) is fairly low. The research input, therefore, is required to increase the efficiency of the stills. Several studies on different aspect of performance of basin type solar stills like, effect of climatic, operational and design parameters, including their theoretical analyses have been reported (6-21). A number of new (design) concepts like tilted tray (10, 22, 23), tilted (23, 24) or vertical wick (25) or double basin (26, 27) type solar stills have also emerged. Efforts have been made to exploit the multi-effect concept in solar distillation (15, 28, 31).

All this work is mainly directed towards improvement/change in the design parameters of stills. However, very little effort has been made to increase the thermal absorption capacity of the raw water itself, which obviously increases the efficiency of the still. With this view in mind a project on the "absorption of solar radiations by water in presence of dyes in solar stills" was taken up. It may be mentioned that prior to our work (32) on black dye, no systematic work on this aspect has been reported except two papers dealing with the preliminary studies only (17, 33). In the present communication the effect of blue dye on the still performance and possible utilization of this system as a heat storage basin, has been reported.

EXPERIMENTAL

Spectroscopic Study:

The absorption spectrum of the aquous solutions of the dye in the ultraviolet-visible region were taken. Two bands were observed in the spectrum but no co-relation could be obtained in respect of absorptivity versus dye concentration. This study, therefore, was discarded.

Solar Stills

Two types of stills have been used for this study. In view of the failure of spectral study, small stills were fabricated for the preliminary work on the performance of dye. On the basis of this, suitable dyes were selected and studied in big stills. The stills were encased in a wooden box insulated by glass wool. The details of these have been given in Table - 1.

Table - 1. Design Parameters of Solar Stills

Parameter (Basin Material)	*Small Still (Aluminum Sheet)*	*Big Still (G.I. Sheet)*
Basin Area	0.5 m x 0.5 m	0.8 m x 0.9 m
Effective Area	0.239 m^2	0.672 m^2
Glass Thickness	4 m m	4 m m
Glass Cover Angle	12^o	10^o
Insulation Thickness	3 c m	4 c m

The stills were left for 4 days after mixing the dye, so as to simulate the periodic conditions. The amount of distillate, ambient temperature as well as glass cover and water temperatures and solar intensity were recorded on daily and hourly basis as per requirements.

RESULTS AND DISCUSSIONS

Analysis

The thermal efficiency (η) of solar stills is given by the equation:

$$\eta = \frac{\text{Heat Transferred to glass by evaporation } (Q_{ew})}{\text{Total solar energy received } (A \times H_s)}$$

$$\text{Or} = \frac{M_e}{L \times Hs} \times 100 \qquad \ldots\ldots\ldots\ldots\ldots\ldots \quad (1)$$

Where Q_{ew} heat loss due to evaporation of water inside the still

A = Area of the still (m^2)

H_s = Solar energy received integrated over one day (k cal/m^2 day)

L = Latent heat of vaporization (cal/gm)

M_e = Distillate output of the still (liters/m^2 day)

The value of thus depends upon a number of parameters responsible for heat and mass transfer within the still. The working principle and heat distribution in the still has been shown in Figure - 1. In traditional basin type stills, solar energy absorbed by black bottom, under steady state, is used for (1) heating of the raw water (2) conduction losses through insulation and (3) convection and radiation losses from water to inner surface of the glass cover. Mathematically, this can be written as:

$$\tau_g \cdot \alpha_w\ H_s \cdot T_a = Q_b + Q_{rw} + Q_{cw} + Q_{ew} \qquad \ldots\ldots\ldots\ldots \quad (2)$$

$$= h_b\ (T_w - T_a)\ A + h_{rw}\ (T_w - T_g)\ A$$

$$+ h_{ew}\ (T_w - T_g) + M_e L \qquad \ldots\ldots\ldots\ldots \quad (3)$$

and $$A\,\alpha_g \cdot H_s + Q_{rw} + Q_{cw} + Q_{ew} = Q_{ra} + Q_{ca} \qquad \ldots\ldots\ldots\ldots \quad (4)$$

FIGURE I : HEAT DISTRIBUTION IN STILL

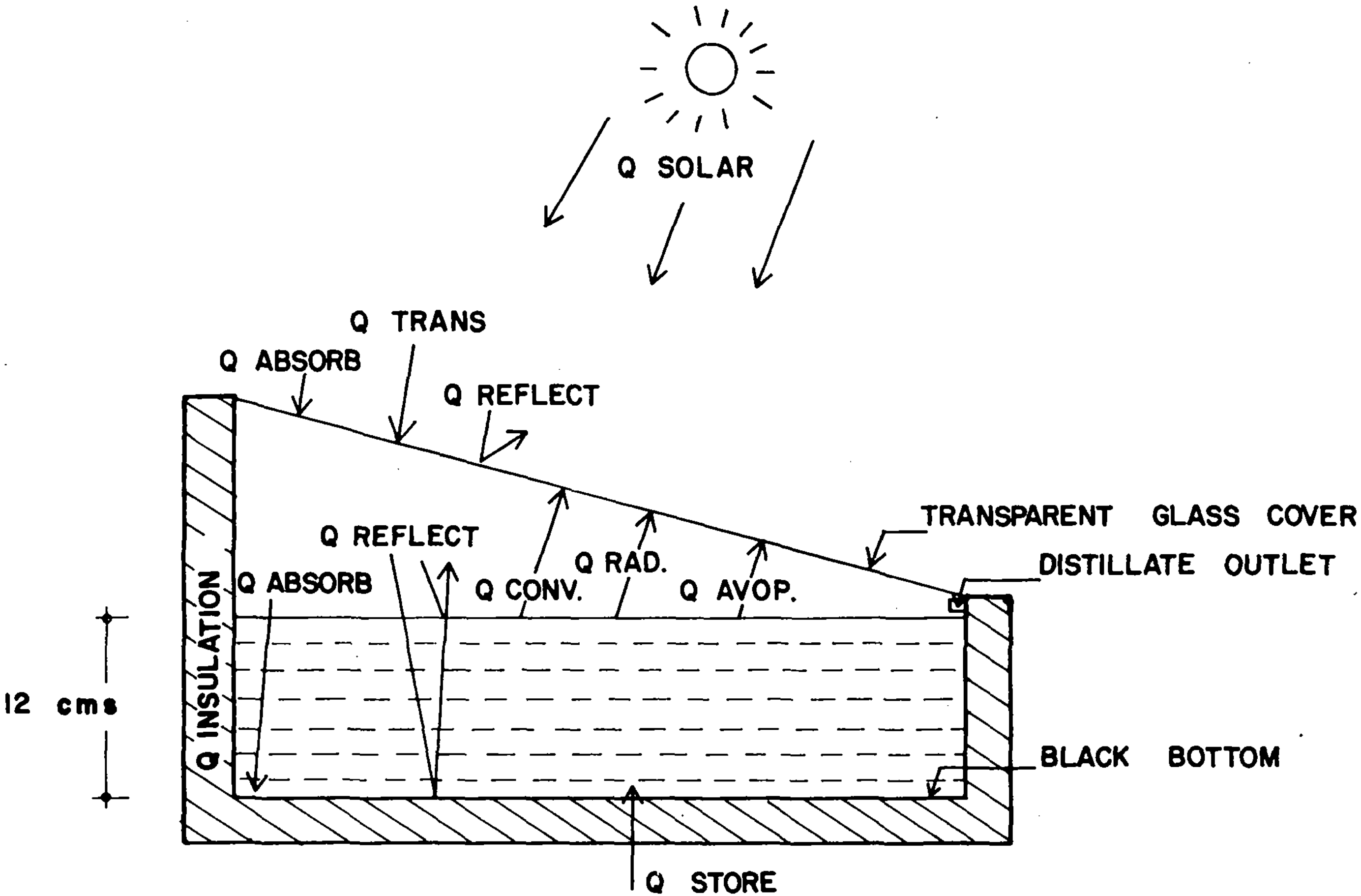
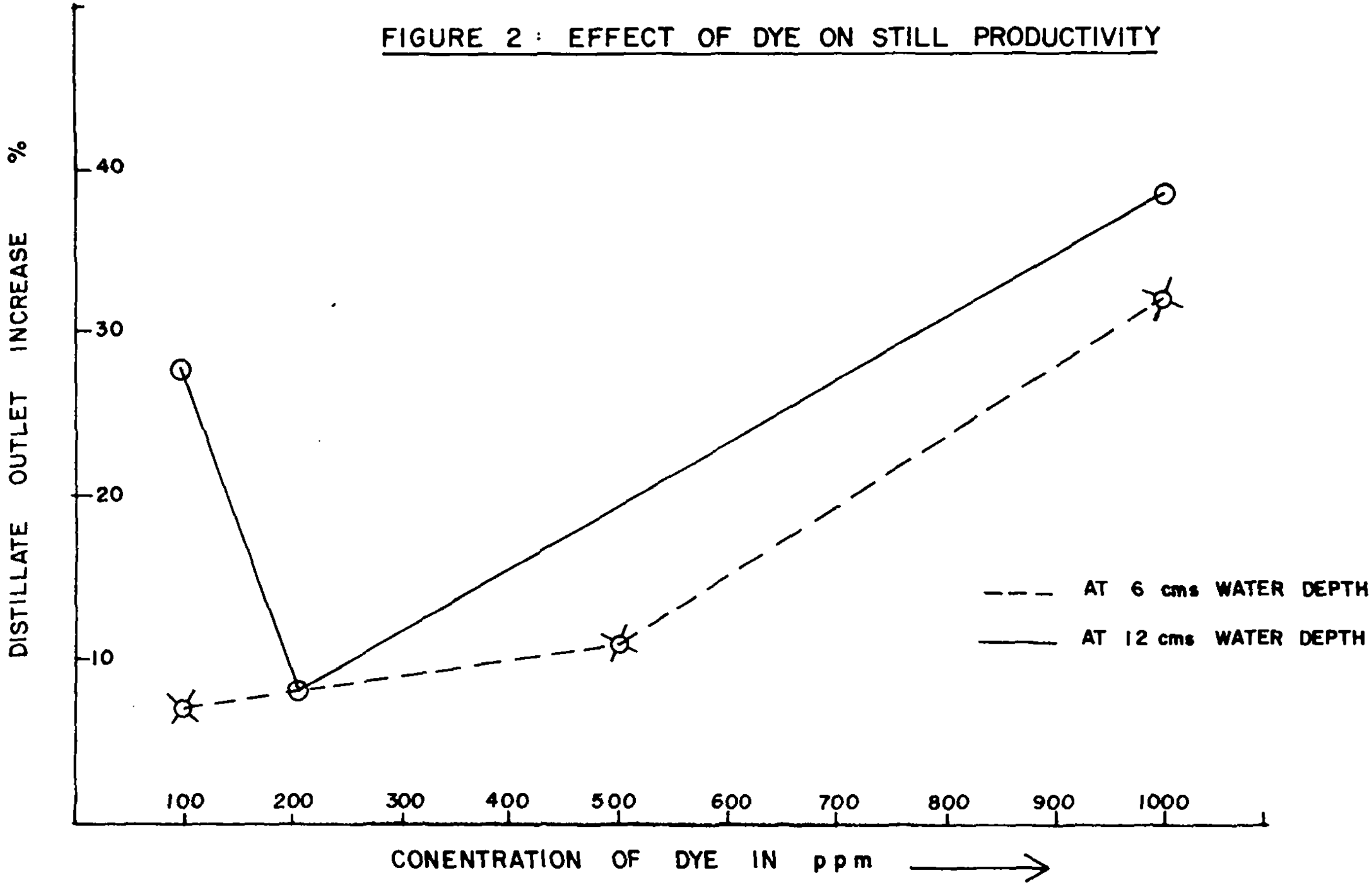


FIGURE 2 : EFFECT OF DYE ON STILL PRODUCTIVITY



where

A	Area of the Still
α_w	Absorvity of the blackened surface of the basin containing the water.
τ_g	Transmittance of glass cover.
α_g	Absorptivity of the glass cover.
H_s	Intensity of solar radiation.
Q_b	Rate of heat loss by conduction through bottom insulation and the side walls.
h_b	Equivalent conductive heat transfer coefficient.
h_{rw}	Equivalent radiative heat transfer coefficient for the heat loss by radiation from the water to glass cover.
Q_{rw}	Rate of heat loss by radiation exchange within the still between the water and glass cover.
Q_{cw}	Convective heat loss in the still.
Q_{ew}	Heat loss due to evaporation of water inside the still.
h_{ew}	Effective evaporative heat transfer.

An observation of these equations indicates that the utilization of incident solar radiation in solar stills is highly inefficient because:

(i) The heating of water is being done by black bottom surface which first absorbs the incident solar energy i.e. indirect heating of water.

(ii) The solar energy absorption by black bottom increases its temperature which in turn increases the conduction losses (i.e. $T_w \gg T_a$; eqn 3) and

(iii) The radiation and convection losses also become considerably high due to higher water surface temperature i.e. $T_w \gg T_g$ (eqn. 3).

This has also been experimentally confirmed as evident from the studies of Gomkale and Dutta (34), who on the basis of their cumulative heat balance studies on solar stills at Central Salt and Marine Chemicals Research Institute, Bhavnagar (India) have reported that, for 2 cm water depth and 20° cover angle, the bottom losses correspond to 16% of the total solar radiation received and a similar amount is lost through convection and radiations in the still. In other words as much as one third of the total incident energy account for these thermal losses which is further increased when indirect heating of water is also considered. Thus an attempt to find ways to overcome above mentioned problems will automatically increase the thermal efficiency of the still.

Experiments were done to obtain the optimum value of the water depth in presence of suitable water soluble dye which was found to be 12 cms. This system thus was able to overcome above mentioned problems, since the dye mixed with water was capable of absorption of solar energy directly. In fact the large mass/area compared to black bottom made it more effective in terms of absorption of incident solar energy. The higher water depth reduced the thermal losses considerably. The results on this dye indicated about 40% increase in the productivity when compared to without dye under similar conditions.

The analysis presented is qualitative but the observations on blue dye shown an increase in productivity compared to reference (Tables 2 and 3). The results exclusively correspond to the effect of blue dye both in terms of thermal efficiency as well as productivity. These results, if compared (not reported here) with those of traditional still performance (having low water depth) show much higher efficiency.

The above mechanism, however will not hold good, as found experimentally also, if the colour intensity of the dye mixed water or the water depth is low.

Discussions

The study was undertaken to obtain the optimum conditions with special reference to the concentration of dye and the water depth, for the still performance in presence of blue dye.

The optimum values for the insulation and water depth were determined and found to be 4 cm and 12 cm for big and 3 cm and 6 cm for the small still respectively. The effect of dye has been reported in terms of per cent increase in productivity (p) determined relationship:

$$p = \left[\frac{\text{Still Productivity with dye}}{\text{Still Productivity without dye}} - 1 \right] \times 100$$

The still productivity without dye has been calculated using pre-determined co-relation factor of the experimental still with respect to the reference still under similar conditions (water depth, solar intensity orientation etc) i.e. still productivity without dye = productivity of reference still x co-relation factor. It may be mentioned that co-relation factor did not vary more than 0.1 (i.e. between 0.9 - 1.0).

Then relevant data on the effect of dye as well as water depth have been shown in Figure II which indicates:

(1) that productivity increases as a function of water depth, 12 cm being the optimum value.

(2) The productivity increases directly with dye concentration, however, larger concentrations does not give corresponding increase in still

Table - 2. PERFORMANCE OF METHYLENE BLUE on DISTILLATE OUTPUT

	Water depth (C.M.)	Conc. of Dye	Productivity in Lm^{-2} day^{-1} With Dye	Without Dye	Per cent increase in productivity
SET. I	4	100 ppm	1.004	0.837	19.9
	4	100 ppm	0.962	0.837	14.9
	4	100 ppm	1.129	0.949	18.9
	4	100 ppm	1.066	0.920	15.8
		Average increase = 17.3%			
SET. II	6	100 ppm	1.066	0.983	8.4
	6	100 ppm	1.004	0.941	5.6
	6	100 ppm	1.066	0.983	6.4
	6	100 ppm	1.025	0.983	4.2
		Average increase = 6.6%			
SET. III	6	500 ppm	0.962	0.920	4.5
	6	500 ppm	0.983	0.878	10.8
	6	500 ppm	1.066	0.920	15.8
	6	500 ppm	1.025	0.899	14.0
		Average increase = 11.2%			
SET. IV	6	100 ppm	1.255	0.920	36.4
	6	100 ppm	1.171	0.878	33.3
	6	100 ppm	1.171	0.920	27.2
	6	100 ppm	1.171	0.899	30.2
		Average increase = 31.7%			

Table - 3. PERFORMANCE OF METHYLENE BLUE ON DISTILLATE OUTPUT AT 12 CM WATER DEPTH

	Water depth (C.M.)	Conc. of Dye	Productivity in Lm^{-2} day^{-1}		
			With Dye	Without Dye	Per cent increase in productivity
SET. I		100 ppm	1.063	0.764	39.1
		100 ppm	1.004	0.791	26.9
		100 ppm	1.063	0.866	22.7
		100 ppm	1.123	0.885	26.8
		100 ppm	1.123	0.918	22.3
		100 ppm	1.316	0.906	45.2
		100 ppm	1.264	0.997	26.7
		Average increase = 29.9%			
SET. II		200 ppm	0.935	0.850	10.0
		200 ppm	0.944	0.842	12.1
		200 ppm	0.848	0.814	04.1
		200 ppm	1.302	1.207	07.8
		200 ppm	1.412	1.300	08.6
		Average increase = 8.5%			
SET. III		1000 ppm	2.284	1.636	39.6
		1000 ppm	2.514	1.822	37.9
		1000 ppm	2.366	1.726	37.6
		1000 ppm	2.425	1.763	37.5
		Average increase = 38.1%			

productivity which may be due to the fact that a solid film is formed on the water surface which restricts both the free absorption of incident solar energy as well as evaporation.

(3) The concentrations lower than 100 ppm have been found to give inconsistent and low distillate output.

(4) The cost benefit analysis suggests 100 ppm dye concentration at 12 cm water depth as the optimum value.

(5) Dye is fairly stable in sunlight, although the extent of productivity decreases with time slowly.

CONCLUSIONS:

Two important conclusions are worth mentioning:

(1) This dye gives good increase in productivity at fairly low concentration compared with 100 ppm black dye which increases the productivity by 15% only which could be due to some contribution from the high energy ultraviolet portion of solar spectrum (though very little due to screening by the glass cover), and

(2) This still, if insulated from the top during nights, may also be used as heat storage system which, in addition to water distillation, may also be utilized for other purposes where low temperatures are required (e.g. grain drying).

ACKNOWLEDGEMENT

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EMITTANCE MEASUREMENTS ON COPPER FILMS USED AS BASE LAYERS IN SOLAR ABSORBERS

by

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and K.I. VASU

INTRODUCTION

In the photothermal conversion of solar energy, surfaces are coated with black paints to absorb the solar radiation. The efficiency of the conversion system is limited due to the high emissivities of these paints. To improve the efficiency selective coatings are preferred in medium and high temperature applications. These coatings exhibit good absorption in the spectral range corresponding to the solar spectrum and low emission in the thermal infrared range. Various types of selective surfaces are being tried among which the absorber-reflector tandem is one.[1] The design of such a stack is shown in Fig. 1.

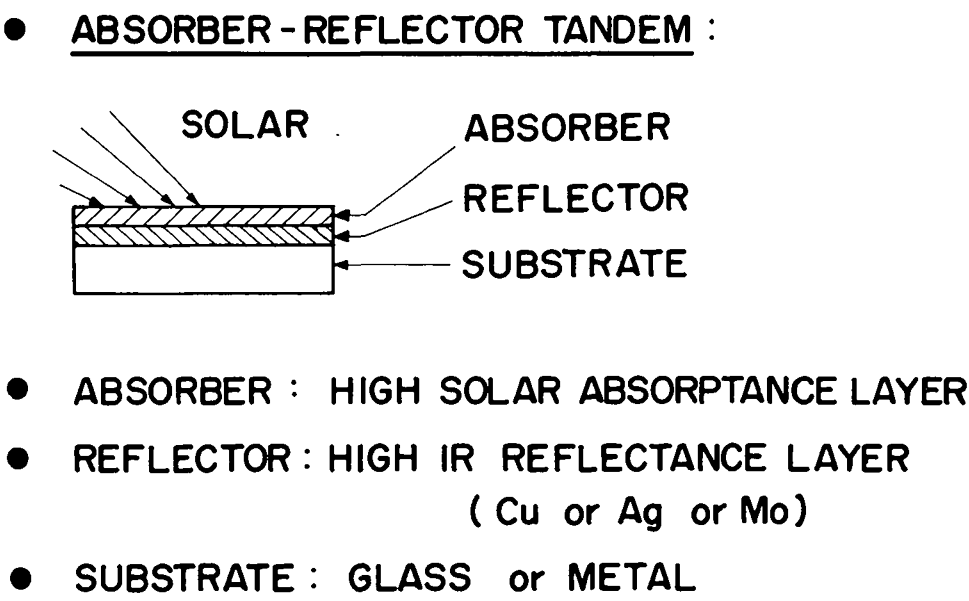

FIG. I.

The substrate is normally of metal or glass, in contact with the heat removal fluid that is circulated in the system. The reflector layer is a film, coated onto the substrate, and having high infrared reflectance (and hence low emittance for the thermal infrared). The absorber layer has high absorption for the solar radiation. The entire stack, therefore, acts as a selective coating. The efficiency of the stack depends on:

(i) the absorbing capacity of the absorber layer

(ii) the emittance of the base layer, and

(iii) the changes that take place in the above properties of these layers due to further heating or aging effects.

The effect of temperature and aging has been studied on the enitre stack by many investigators and changes in efficiency due to degradation have been reported.[2-5] For a better understanding of the stack and its efficiency it is better to do the following studies indcpendtly on the various layers:

(i) Optimisation of deposition conditions

(ii) Annealing and aging studies.

With this view, an attempt has been made in this paper to study the base layer first. The materials that are normally used for base layers are copper, silver, nickel etc. for low and medium temperature applications and molybdenum and tungsten for high temperature applications.

Copper, because of its good emissivity and high thermal conductivity is normally preferred. Various methods such as:

(i) electroless deposition

(ii) sputtering

(iii) vacuum evaporation

(iv) electrodeposition

are used for preparing the copper films. The choice of the method depends on (i) the substrate used (ii) the size of the system (iii) the cost factor (iv) the temperature at which it has to withstand, and (v) the efficiency required.

The films prepared by the above mentioned techniques normally do not have the same properties as the bulk materials. This is mainly because (i) during deposition, depending on the deposition conditions, many defects and impurities get into the film, and (ii) the surface topography is not the same as that of the bulk material.

It is possible to minimise these defects and control the surface topography by a proper choice of deposition parameters and suitable annealing techniques. This results in a film, which has properties similar to those of the bulk materials. Harding[3] has deposited sputtered films and observed that annealing improves the IR reflectance of the films.

In this paper, the authors present the results of their studies on the influence of the deposition parameters and annealing on the emittance of copper films prepared by various methods and make a comparative study.

EXPERIMENTAL:

The copper films for the present study were prepared by:

(1) Electroless deposition

(2) R.F. Sputtering, and

(3) Vacuum evaporation

The choice of these deposition methods was determined primarily by the use of optically flat glass as substrates.

Electroless Deposition

The baths used for the electroless deposition[6] and their composition are given in table-1.

COMPOSITION OF SOLUTIONS USED FOR ELECTROLESS COPPER DEPOSITION:

Sl.No.	SOLUTION	COMPOSITION
1	ETCHANT	CrO_3(250 g/L) + H_2SO_4 (125 g/L)
2	ACTIVATOR	$SnCl_2$ (100 g/L) + HCl (40 ml/L)
3	SENSITIZER	$PdCl_2$ (0·1 to 1·0 g/L) + HCl (5 to 10 ml/L)
4	COPPER BATH	$CuSO_4.5H_2O$ (10 g/L) + NaOH (10 g/L) + $NaKC_4H_4O_6$ (50 g/L) Reduction Agent : FORMALDEHYDE (~100 ml/L of Cu BATH)

TABLE-1

The glass slides cleaned by a detergent and washed in distilled water were first dipped in the etchant solution, leading to the formation of pits on the glass surface. The size and number of pits depend on the time for which they were immersed in the etching solution. The slides were then removed from the bath, washed thoroughly in running water and then dipped in the activator bath. The Stannous chloride gets into the pits and forms as a film. The excess of the Stannous chloride was removed by washing in water and the slide was then dipped in the sensitizer bath. The Palladium chloride in this bath reacts with the Stannous chloride layer that was already deposited and converts it into Stannic chloride. The Palladium particles stick to this layer and act as nucleation centres for the copper deposition. The slides were next dipped in the copper bath, in which Formaldehyde had been added. The copper film now gets deposited on to the slide. The effect of the dipping time in each solution, on the emittance (calculated from IR reflectance) of the films, is presented in the results.

R.F. Sputtered Films

The RF Sputtering was carried out in a Leybold Heraeus RF sputtering unit.

The glass substrates were cleaned with a cleaning solution (Balzers) and then loaded into the system. The system was evacuated to 2.6×10^{-3} Pa and then filled with Argon to a pressure of 1.64 Pa. The cathode was a 3" dia copper substrate. The deposition rate was fixed with a quartz crystal monitor. Three deposition rates (1.5, 2 and 3 Å/Sec) were used for sputtering the films. The thickness of the films was maintained at 1500 Å.

Vacuum Evaporated Films

The films were evaporated in a 12" vacuum coating unit. The slides were cleaned with a detergent and subjected to ionic bombardment. The evaporation was carried out at 1.33×10^{-3} Pa.

EMITTANCE MEASUREMENTS:

The IR reflectance of the as deposited films was measured in a Perkin Elmer 599 Spectrophotometer and from this data the IR emittance at 27°C was calculated.[7] The films were then annealed at various annealing temperatures in a vacuum of 2.66×10^{-3} Pa. The emittance of the annealed films was calculated from their IR data as done above. The results are presented below:

RESULTS AND DISCUSSIONS:

Electroless deposited copper films

The effect of dipping time in each bath on the emittance is presented in Tables 2 to 5.

The dipping time in the first bath was varied from ten to twenty minutes. The dipping times in the other baths were kept constant. The effect of the variation of the dipping times on the emittance of the film is shown in Table 2.

OPTIMIZATION OF THE DIPPING TIME IN THE FIRST SOLUTION:

Sl.No.	DIPPING TIME (MIN) IN VARIOUS SOLUTIONS				IR Emittance AT 27 °C
	First	Second	Third	Fourth	
1	10	2	2	2	0·19
2	15	2	2	2	0·11
3	20	2	2	2	0·22

OPTIMIZED DIPPING TIME IN THE FIRST SOLUTION = 15mts.

SOLUTION: CHROMIC ACID + SULPHURIC ACID

TABLE-2

Table 3 shows the variation in emittance with changes in dipping times in the second bath. The dipping times in the other baths were kept constant.

OPTIMIZATION OF THE DIPPING TIME IN THE SECOND SOLUTION:

Sl.No.	DIPPING TIME (MIN) IN VARIOUS SOLUTIONS				IR Emittance AT 27 °C
	First	Second	Third	Fourth	
1	15	1	2	2	0·38
2	15	$1\frac{1}{2}$	2	2	0·51
3	15	2	2	2	0·12
4	15	$2\frac{1}{2}$	2	2	0·22
5	15	3	2	2	0·24
6	15	$3\frac{1}{2}$	2	2	0·61

OPTIMIZED DIPPING TIME IN SECOND SOLUTION = 2 Minutes.

SOLUTION: STANNOUS CHLORIDE

TABLE-3

OPTIMIZATION OF THE DIPPING TIME IN THE THIRD SOLUTION:

Sl. No.	DIPPING TIME (MIN) IN VARIOUS SOLUTIONS				IR EMITTANCE AT 27 °C
	First	Second	Third	Fourth	
1	15	2	1	2	0·32
2	15	2	$1\frac{1}{2}$	2	0·31
3	15	2	2	2	0·11
4	15	2	$2\frac{1}{2}$	2	0·21
5	15	2	3	2	0·52

OPTIMIZED DIPPING TIME IN THE THIRD SOLUTION = 2 Minutes

SOLUTION: PALLADIUM CHLORIDE

TABLE - 4

Similarly, variations in emittance due to variation of dipping time in the third bath and forth bath are shon in Tables 4 and 5.

OPTIMIZATION OF THE DIPPING TIME IN THE FOURTH SOLUTION:

Sl.No.	DIPPING TIME (MIN) IN VARIOUS SOLUTIONS				IR Emittance AT 27 °C
	First	Second	Third	Fourth	
1	15	2	2	1	0·28
2	15	2	2	$1\frac{1}{2}$	0·19
3	15	2	2	2	0·10
4	15	2	2	$2\frac{1}{2}$	0·08
5	15	2	2	3	0·05
6	15	2	2	$3\frac{1}{2}$	0·06
7	15	2	2	4	0·07

OPTIMIZED DIPPING TIME IN FOURTH SOLUTION = 3 min.

SOLUTION : COPPER BATH - TABLE - 5 -

The optimum dipping time in our four baths has been found to be:

First bath : 15 minutes

Second bath : 2 "

Third bath : 2 "

Fourth bath : 3 "

For films formed from the same bath, it was observed that the emittance values were not the same for films formed at different timings. The films formed immediately after adding Formaldehyde had low emittance, with the emittance increasing for films formed at later timings. This may be due to the depletion of copper in the bath with time.

Sputtered Films

The emittance of the sputtered films is given in Table 6.

SPUTTERING CONDITIONS

- COPPER CATHODE (7·6 cm DIA.)
- CATHODE TO ANODE DISTANCE - 5·0 cm
- SPUTTERING PRESSURE - 1·64 Pa
- THICKNESS OF FILM - 1500 Å
- EMITTANCES OF THE FILMS BEFORE ANNEALING

Sl.No.	D.C. Voltage KV	Current mA	Deposition rate, Å/Sec	Deposition time, Sec	IR Emittance at 27 °C
1	1·60	200	1·5	1000	0·05
2	1·85	220	2·0	750	0·05
3	2·75	310	3·0	500	0·05

TABLE-6

Though there is not much difference in the emittance of the films formed at different rates, a closer look shows that films formed at higher rates have low emittance as compared to that of films formed at lower sputtering rates.

Evaporated Films

The emittance of the as formed evaporated film is around 0.03 as shown in Table 7, and is found to be the best among all the films.

ANNEALING STUDIES:

The values of emittance for the films, in the as deposited condition and after annealing at different temperatures are presented in Tables 7, 8 and 9 for the films formed by the evaporation, electroless and sputtering technqies respectively.

EVAPORATED COPPER FILMS

ION BOMBARDMENT CLEANING DONE AT 6·65 Pa FOR 15 MINUTES.

VACUUM EVAPORATION DONE AT 8·64 x 10^{-3} Pa

RESULTS OF ANNEALING:

Sl.No.	VACUUM	ANNEALING TEMP. °C	IR. Emittance at 27°C
1		AS FORMED	0·03
2	8·64 x 10^{-3} Pa	190	0·01
3	" " "	280	FILM BROKEN

TABLE - 7

The variation in emittance with the annealing temperature is similar for films prepared by all the three methods.

Annealing at 100° C has marginally reduced the emittance where as, annealing at 200 °C has significantly reduced it. Annealing at higher temperatures has resulted in an increase in emittance. These results are similar to the electrical resistance variation with temperature,[8] where it has been explained how the electrical resistance gradually changes with temperature, becoming a minimum at annealing temperature around 150°C and increasing abnormally at temperatures above 250° C. This was mainly attributed to defect annealing in the first case and agglomeration in the second case. As the results on emittance show a similar variation, the present change in emittance may also be attributed to annealing and agglomeration.

RESULTS OF ANNEALING OF ELECTROLESS COPPER FILMS

Sl.No.	VACUUM	ANNEALING TEMP. °C	Emittance at 27°C
1		AS DEPOSITED	0·05
2	$2{\cdot}67 \times 10^{-3}$ Pa	100 °C	0·04
3	” ” ”	190 °C	0·03
4	” ” ”	280 °C	0·07

TABLE-8

RESULTS OF ANNEALING OF SPUTTERED COPPER FILMS

Sl.No.	VACUUM	ANNEALING TEMP. °C	IR EMITTANCE AT 27°C
1		AS FORMED (Dep. rate= 3Å /Sec)	0·05
2	$8{\cdot}64 \times 10^{-3}$ Pa	190 °C	0·01
3	” ” ”	280 °C	0·02

TABLE-9

CONCLUSION:

The studies on the emittance of copper films as dependent on (i) the deposition parameters in the three different deposition methods used and (ii) the annealing of the films in vacuum lead to the following conclusions:

1. In the electroless deposition of copper films, minimum emittance was obtained with films deposited with 15 minutes, 2 minutes, 2 minutes and 3 minutes dipping times in our four successive baths.

2. The emittance was found to be 0.05 for sputtered films and electroless films and 0.03 for the evaporated films in the as deposited condition.

3. Annealing of the films at 200° C. reduced the emittance of all the films whereas annealing at 300° C leads to an increase in emittance. A more exact range of annealing temperature at which degradation sets in can be determined by in-situ measurements. Further work is being carried out in this direction.

4. The adhesion is good for films prepared by all the three methods.

ACKNOWLEDGEMENTS:

The authors are thankful to Mr. J. Balachandra, Department of Metallurgy, I.I.Sc., for valuable advice on electroless coatings. They also thank the authorities of Indian Space Application Centre, Bangalore, for providing facilities for RF sputtering. Thanks are also due to Mr. Sarat Ahuja and Mr. G. Mohan Rao of Regional Instrumentation Centre, I.I.Sc., for assistance.

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SYSTEM DESIGN FOR TOBACCO CURING BY UTILIZATION OF SOLAR ENERGY

by

K. BALAGOPAL, C.R.K. MURTHY, M. RAMAKRISHNA RAO
and A. THOMAS

ABSTRACT

Flue Cured Verginia (FCV) Tobacco is a delicate commercial crop. Colour and aroma which depend on curing are the primary factors that determine the quality of tobacco for use in cigarettes.

The general practice of curing is to load the harvested tobacco from the field, in a barn having a volume of about 171.6 m^3. About 2815 Kg of wet leaf can be loaded for each charge of curing. The barn can accommodate yields from 5 acres of land (about 17000 Kg of wet leaf) which can be processed in seven charges of curing - the limit for a barn during a season. The coal consumption of a barn for a season is about 9 tons. The expenditure on fuel, forms about 25 per cent of the cost of FCV tobacco. There are about 77,000 barns in India and the annual coal consumption for this purpose is about 0.7 million tons. Solar energy is available in abundance in tobacco growing areas and its utilization for this purpose will reduce the cost of production in addition to better quality of the produce since the entire process will be under systematic control.

Yellowing, fixing, leaf drying and midrib drying are the four distinct and continuous process of curing. When green leaves containing about 80 per cent of moisture are subjected to curing they undergo the above transformation is slow and continuous manner starting at a temperature of 30°C and ending at 71°C. The duration of the entire process is about 120 hours. Thus the complexity of the process of curing demands stringent specification on the system design.

The various systems of this process utilizing solar energy are the collection, storage, distribution and control of process parameters like temperature and humidity. Each one of these systems need careful considerations for optimum operation.

Solar air heating system has been chosen for collection of solar energy. The absorber configuration of the air heater are so chosen as to give maximum plate efficiency for the designed rate of flow of air. Each module of the collector having an area of 2 m^2 has been designed for cost effectiveness, convenient handling and maintenance. The energy collected from the collectors will be stored in bubble bed storage system the capacity of which has been designed for continuous 24 hours operation of the system.

The other auxilliaries like fans, dampers, instruments and controls have been designed for optimum performance of the system.

The ducts will be run inside the barn in such a way as to get uniform distribution of air throughout the barn. An interfacing is also provided in the design to use the existing system of heating in case of emergency.

This paper discusses in detail all the design parameters of the systems and possible results that can be achieved and also the comparative study of other systems.

INTRODUCTION:

Processing of commercial crops by utilizing Solar Energy is an important necessity to meet the energy needs of rural parts of India. Tobacco is one of the important commercial crops which has a wide international market. India is one of the largest Virginia Tobacco producing countries, particularly in the regions of Guntur and Rajamundry of Andhra Pradesh and Hunsur of Karnataka. A very large number of farmers in these regions are engaged in cultivating this tobacco crop.

Curing is an important process that decides colour and aroma which are the primary factors that determine the quality of tobacco for use in cigarettes. In the production of flue-cured tobacco the cost of flue curing alone constitutes 25% of cost of production. For obtaining one kilogram of cured leaf, a barn consumes 2.86 Kg of coal. Till today the process of curing is more of an art rather than technology. Introduction of solar energy for this purpose will not only reduce the running costs of curing of tobacco, but also it will enable to maintain uniform quality and a scientific methodology for the management of the process.

TOBACCO CURING PROCESS:

In tobacco technology 'Curing' usually refers to the changes undergone by harvested fresh leaves under regulated conditions of temperature and humidity. The purpose of curing is to produce dried leaf of suitable physical properties and chemical composition.

The general practice of curing of tobacco is to load the harvested and graded tobacco in a barn having a volume of about 171.6 m^3. About 2815 Kg of wet leaf can be loaded for each charge of curing. The barn can accommodate the yields from 5 acres of land (about 17,000 Kg of wet leaf) which can be processed in seven charges of curing during one season. The normal practice of grading, stringing and loading are shown in Figs. 1-4.

FIG. 1. GRADING OF TOBACCO

FIG. 2. STRINGING OF TOBACCO

FIG. 3. TRANSPORTATION OF TOBACCO TO BARN

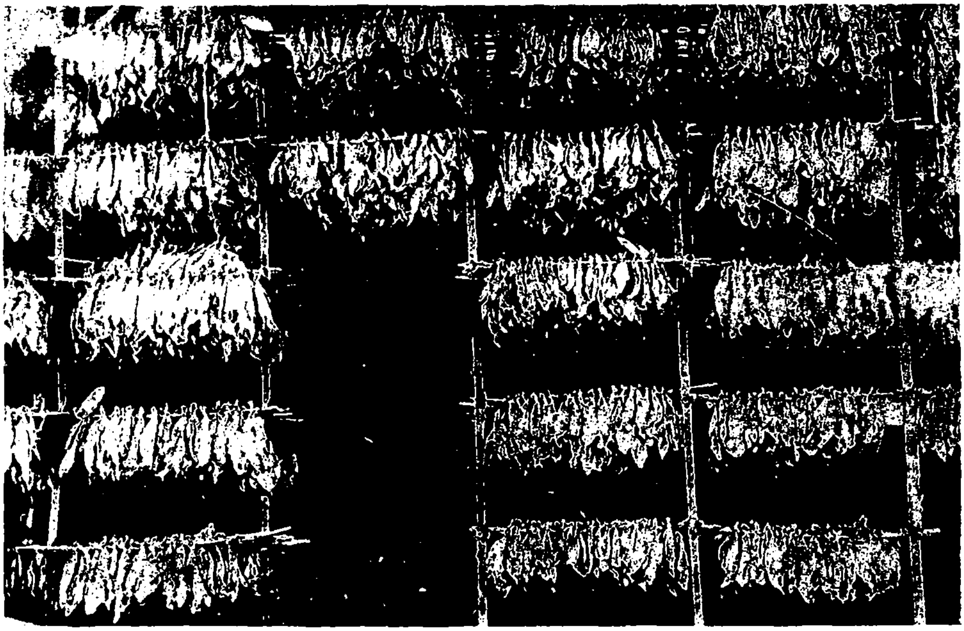


FIG. 4. LOADING OF TOBACCO IN BARN

The flue curing process can be divided into four stages.[1] At the first stage small inputs of fire is introduced in the furnace and a moderate temperature is maintained until the leaf is thoroughly yellowed. This stage requires 30-40 hours. The temperature should start at 30°C and gradually rise to 40°C at the end of this stage. The change of colour from green to yellow, along with other biochemical processes takes place while the cells are metabolically active. Care must be taken to keep the temperature below 40°C to avoid drying the leaf too rapidly. As the leaf begins to yellow, the humidity must be decreased by slowly raising the temperature and gradually increasing the ventilation.

The second stage is the colour fixing. During this stage, moisture must be removed as fast as it is given off by the leaf. Best results are obtained in this stage if the temperature is gradually increased from 40°C to 49°C. This process normally takes 5-10 hours.

The third stage is to dry the leaf lamina after completion of the yellowing process. This is accomplished by maintaining the temperature between 49°C-63°C for 35-40 hours after colour fixing.

The fourth stage is the drying of the midribs or 'stems'. The ventilators should be barely closed and the temperature must be increased from 63°C to 71°C at the rate of 2°C/hour. The temperature is maintained at 71°C unitl the stems are completely dried out. The duration for this part of the process is 20-30 hours. The total time required for the entire process is 94 to 117 hours. The barn will be unloaded after proper conditioning of leaves for handling. The summary of the process is given in Table 1.

PROCESS OF CURING	TEMPERATURE in °C		TIME in hrs.	PROGRESSIVE TOTAL TIME
	DRY BULB	WET BULB		
YELLOWING	30 - 40	28 - 32	30-40	-
FIXING COLOUR	40 - 49	34 - 37	5-10	39-47
LEAF DRYING	49 - 63	36 - 43	35-40	74 - 87
STEM DRYING	63 - 71	43 - 46	20-30	94 - 117

TABLE 1. SUMMARY OF THE PROCESS

Usually coal or fire wood is used as fuel. Table 2 gives the details of coal consumption for one cycle. The coal consumption of a barn for a season is about 9 tons. There are about 77,000 barns in India and the annual consumption for this purpose is about 0.7 million tons.

COAL CONSUMPTION	
PROCESS	QUANTITY IN kg.
YELLOWING	130
FIXING	160
LEAF DRYING	480
STEM DRYING	380

THE VOLUME OF THE LOW PROFILE BARN IS 171·6 Cu.m. AND THE FUEL CONSUMPTION IS 1860 kg. OF WOOD OR 1150 kg. OF COAL. THE BARN WILL ACCOMODATE 2,815 kg. OF GREEN LEAF AND THE WEIGHT OF THE LEAF AFTER CURING WILL BE 415 kg. REDRYING PLANTS CONSUMES 6 TONS OF COAL IN ABOUT 24 hrs. OF OPERATION YIELDING ABOUT 30 TONNES OF REQUIRED TOBACCO LEAF. THE REDRYING PROCESS DEMAND STEAM AT A TEMPERATURE OF 100°C AND AT A PRESSURE OF 1·0 kg./cm^2. (ABSOLUTE)

TABLE 2. COAL CONSUMPTION

SOLAR RADIATION AVAILABILITY AND FEASIBILITY OF USING ITS ENERGY:

The normal season for tobacco harvesting is between December and March when the solar energy is available in these regions at an average rate of 5 $kWh/m^2/day$. Hence it is proposed to design and develop a solar energy application system for curing tobacco under the sponsorship of the Department of Science and Technology of Government of India. While designing the system, it is also taken into consideration the existing barn facilities in these rural areas and also the more efficient low profile barn developed by Central Tobacco Research Institute at Rajamundry. Figures 5 and 6 show the pictorial view and the ducting layout in the barn respectively.

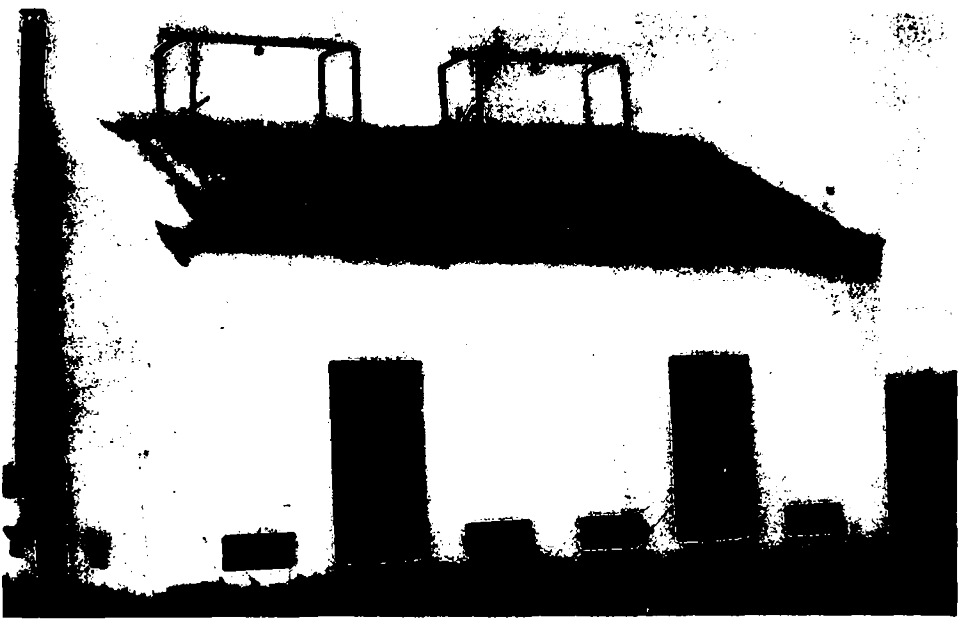


FIG. 5. BARN

Evaluation of system and the design of equipment for curing of tobacco using solar energy requires the data on three aspects of the basic process.

1. The amount of energy required.
2. The rate at which the process may be made to proceed.
3. The extent to which the process may be carried out.

This data has been obtained from the conventional process carried out in the existing barns. In this system, the flue gas from a coal fired furnace is passed through a pipe line system as shown in Figure 6 and it exhausts outside through a chimney. The barn is heated by the radiant heat from the flue pipe and the curing is done by convection current that are set up between bottom and the top openings of the barn. In this process the rate of drying depends upon the inlet air temperature and humidity, and flow of air through the barn due to the convection currents. The temperature rise of the air flowing into the barn is again directly proportional to the amount of radiant heat from the flue tubes. The figure 7 shows the barn conditions regarding dry bulb temperature, relative humidity and heat requirements.

Unlike the conventional process of curing, the heat input to a solar barn is directly proportional to the amount of hot air that is circulated through the barn. In order to follow the curing schedule, air has to be supplied at continuously increasing temperatures. Since the usable solar radiation is available for approximately eight hours in a day, this energy has to be stored at a highest possible temperature in a suitable storage system and it has to be used in the barn according to the requirement of the curing schedule. Basing on the data available, the design specifications are given in Table 3.

CONCEPTUAL DESIGN AND DESCRIPTION OF ALL SOLAR TOBACCO CURING SYSTEM:

Due to the intermittent nature of the energy availability from solar radiation and due to the continuous nature of the energy requirement for tobacco curing, it is imperative that storage facilities are necessary. The necessity is all the more accentuated due to the fact that even during the available time the intensity of solar radiation varies continuously. Thus the system design demands careful considerations for use with solar energy.

For making any design calculation, the heat input to the barn has to be calculated. The energy requirement for the barn fall into two categories. The latent heat required to evaporate the moisture from the tobacco and heat required to make up the structural losses of the barn due to difference between inside and outside temperatures. Assuming that the drying process takes place according to an exponential law, the latent heat requirement during the first 24 hours will be predominant whereas the structural loss, will be predominant on the final day when the difference between the inside and outside of the barn is 41°C. The Table 4 gives the data regarding the sequential moisture content in the leaf during the process.

The total energy requirement given in Table 5 consists of the latent heat requirement for moisture evaporation according to an exponential law as well as the heat losses from the structure of the barn.

In order to have an economic size of the system, the distribution of the heat requirement is assessed and a value of 470,000 K.Cal. per day is estimated.

At 5 kWh/m^2/day solar insolation under a 50% collector efficiency, the total collector area required would be 216 m^2. Various designs of air collectors have been

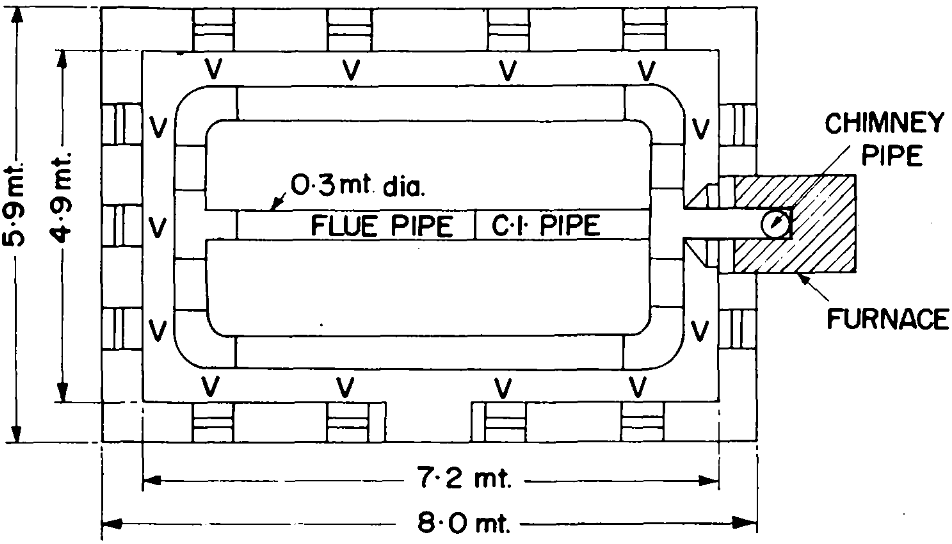


FIG. 6. DUCTING LAY OUT

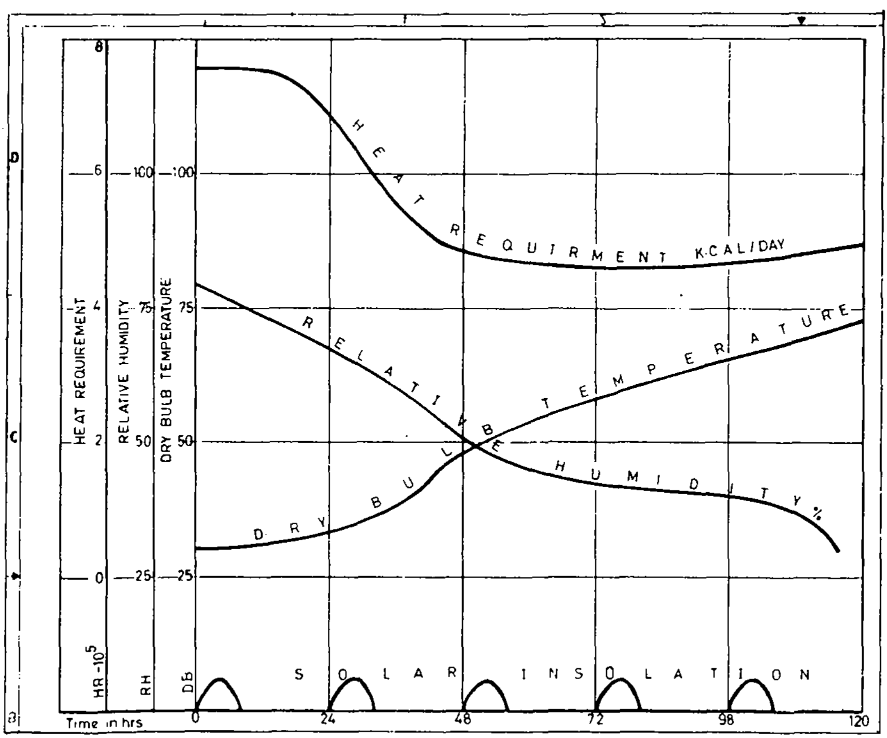


FIG. 7. BARN CONDITION

DESIGN SPECIFICATIONS

VOLUME OF THE BARN (7·32m x 4·88m x 3·96m)	171.6 m
GREEN LEAF PER CHARGE	2815 Kg
CURED LEAF PER CHARGE	415 Kg
INITIAL MOISTURE CONTENT	85 %
FINAL MOISTURE CONTENT	12%
INITIAL TEMPERATURE OF THE BARN	30 °C
FINAL TEMPERATURE OF THE BARN	71 °C
INITIAL RELATIVE HUMIDITY OF THE BARN	80 %
FINAL RELATIVE HUMIDITY OF THE BARN	30 %
TOTAL DURATION OF THE PROCESS	120 hrs.

TABLE 3. DESIGN SPECIFICATIONS

LEAF WEIGHT : GREEN - 2815 Kg
DRY 415 Kg

AMOUNT OF MOISTURE IN THE - WET LEAF - 2400 Kg
DRY LEAF - 50 Kg

THE DRYING PROCESS FOLLOWS THE EXPONENTIAL LAW (ASSUMPTION)

$$\frac{2400}{50} = e^{5X} \quad \therefore X = 0{\cdot}7742$$

	Amount of moisture in the leaf in Kgs.	Amount of moisture to be removed· Kgs.
Initial	2400	—
1 st Day	1106	1294
2 nd Day	510	596
3 rd Day	235	275
4 th Day	108	127
5 th Day	50	58

TABLE 4. SEQUENTIAL MOISTURE CONTENT IN THE LEAF DURING THE PROCESS

ENERGY REQUIREMENT

DAYS	ENERGY REQUIREMENT in K.cal.
I st Day	7,60,743
2nd Day	4,91,565
3 rd Day	4,60,899
4 th Day	4,74,978
5 th Day	4,94,424

TABLE 5. ENERGY REQUIREMENT

reported in the literature.[2] The air collectors designed for the solar barn are given in Figs. 8 and 9. They are being subjected for testing and evaluation. The efficiency of these collectors is about 50%.

The total collector area and the storage is divided into three banks, as shown in Fig. 10. The bank 1 feeds between 16.00 hrs to 24.00 hrs, bank 2 and 3 feed between 24.00 hrs to 08.00 hrs and 08.00 to 16.00 hrs respectively. The collector array-3 will feed to storage S3 and S4 on alternate days so that the cycle continues.

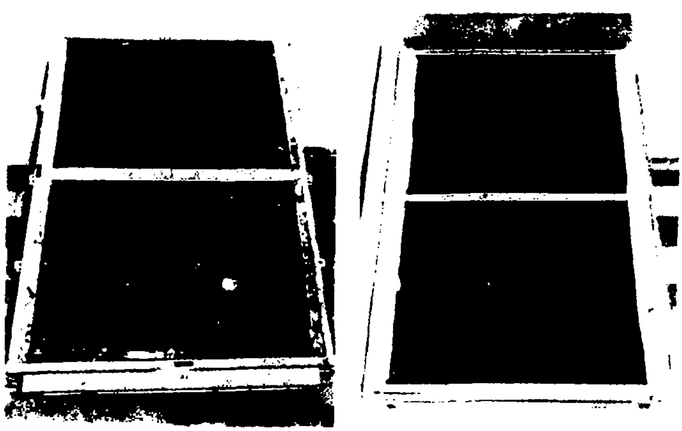


FIG. 8. AIR COLLECTOR

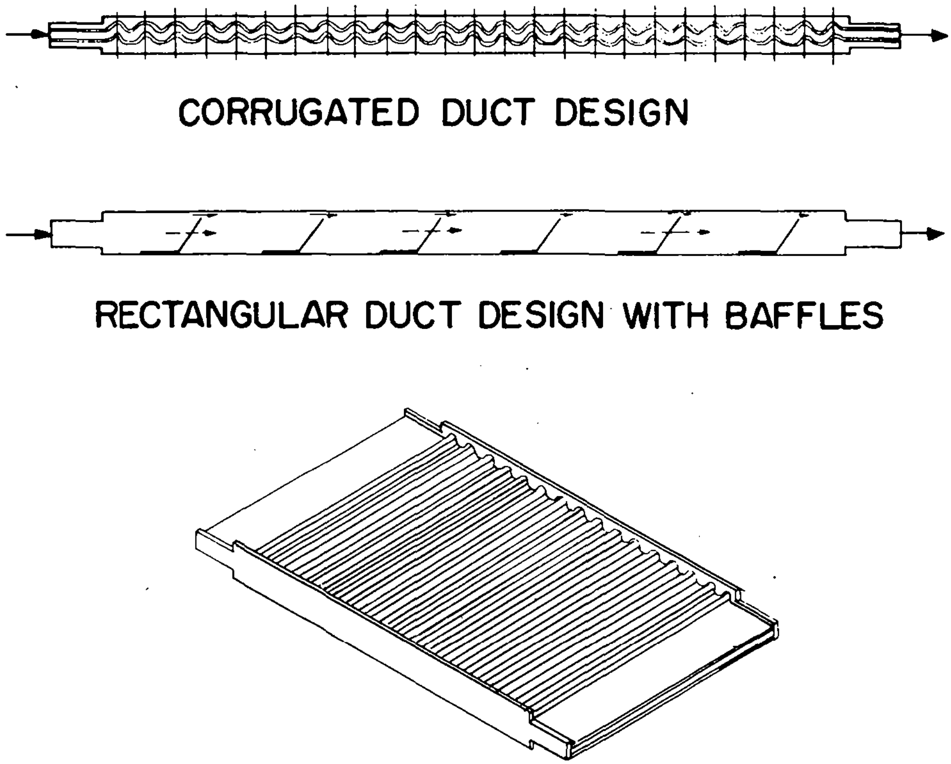


FIG. 9. CROSS SECTION OF THE AIR COLLECTOR

Each storage tank will thus be needed to store and supply for an eight hour requirement. Taking the specific heat of pebble at 0.185, and a suitable void fraction, a 14 m^3 volume will be required for pebble storage. Table 6 gives estimated collector area, volume of storage tank and blower capacity. Figure 10 shows the cross sectional elevation of thermal storage tank.

It is proposed to collect and store the radiant energy at the maximum temperature of 80°C and dilute the same to the requirement of the process so that continually increasing temperatures are available in the barn. The blowers used are to have variable throughputs, to take care of the varying intensity of solar radiation and give a constant maximum temperature of 80°C. In order to avoid the necessity of sending too small volume of flows during the period when the intensity of solar radiation is low (in mornings and evenings) three collectors of 2 m^2 each are arranged in series. Figure 11 shows the schematic layout of the proposed solar drying system. By the above arrangement enough care has been taken to maintain the collection efficiency at 50% at lower

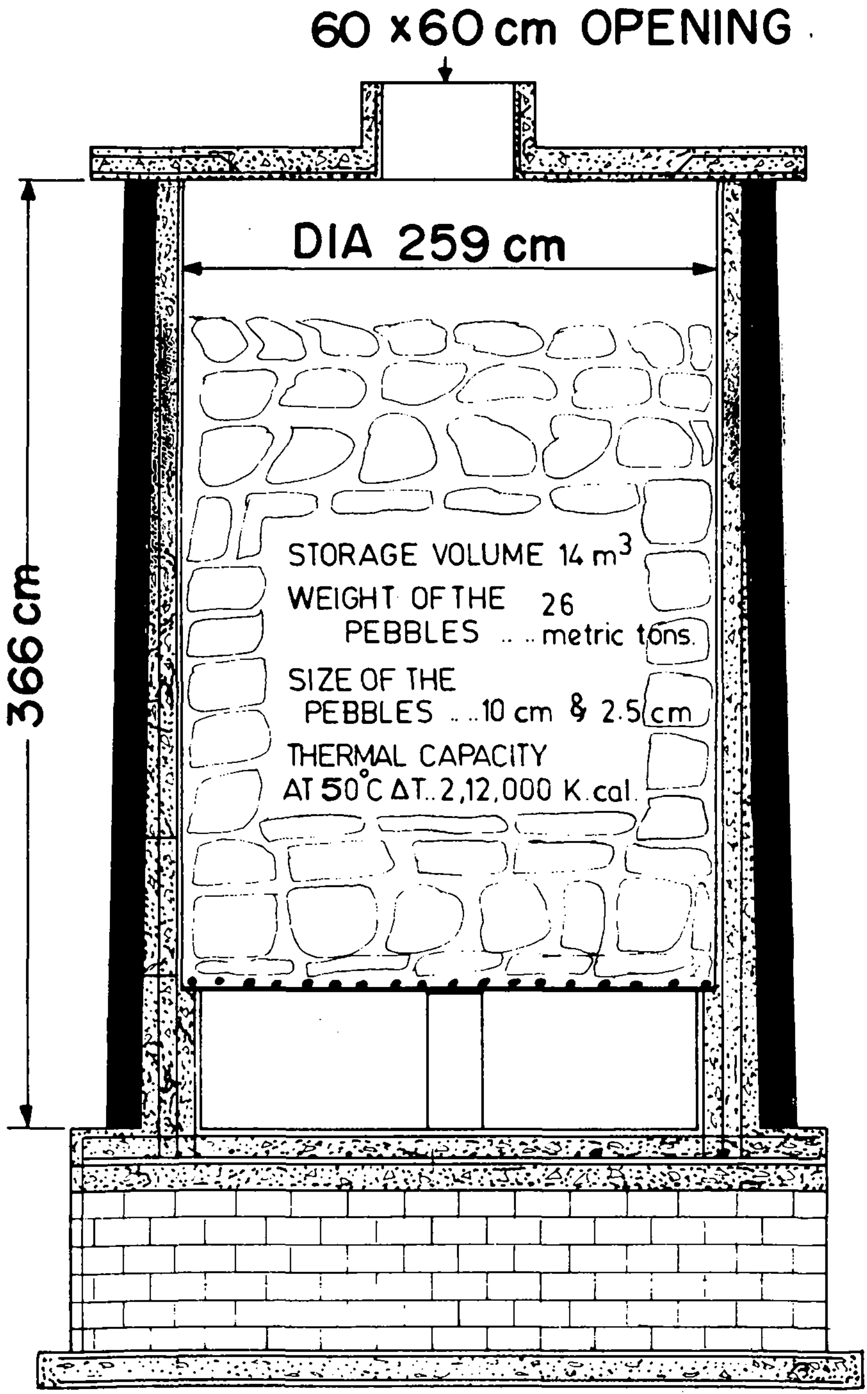
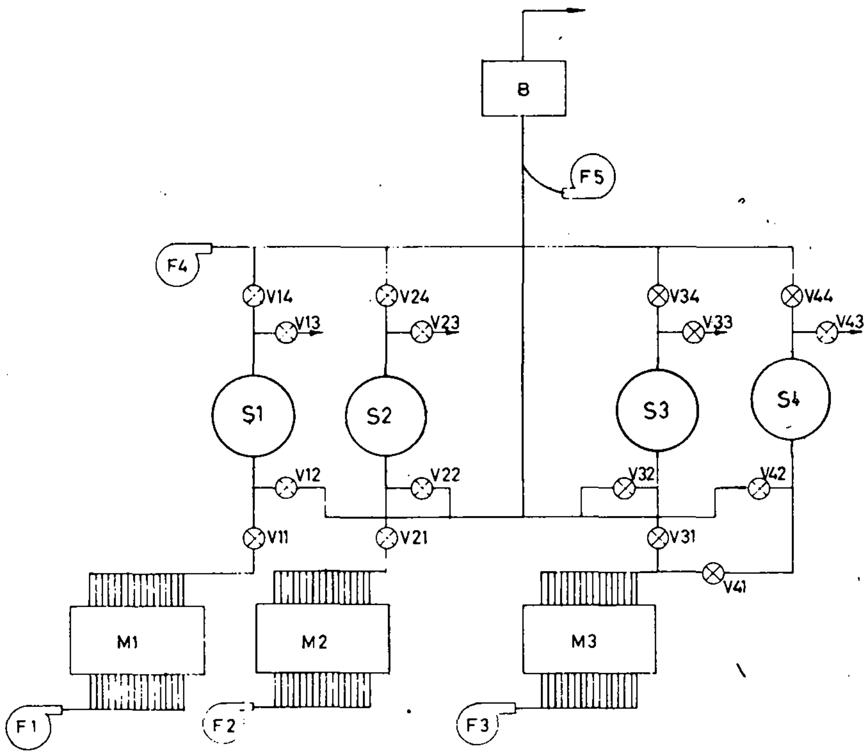


FIG. 10. CROSS SECTIONAL ELEVATION OF THERMAL STORAGE TANK



CHARGING CYCLE

Fan F1, collector Module M1, Storage S1 to Atmosphere. V11 & V13 open, V12 & V14 closed

DISCHARGE CYCLE

Fan F4, Storage S1 to Barn, Fan F5 for dilution to required Tempereture.

V13, V11 are closed. V14, V12 are open.

SCHEME

S1 works between 16-00 to 24-00 hrs.

S2 works between 24-00 to 08-00 hrs.

S3 or S4 works between 08-00 to 16-00 hrs. (on alternate days)

LEGEND

B – Barn

S – Storage tank

F – Fan

M – Collector Module

V – Baffle valve

ALL SOLAR DRYING SYSTEM

FIG.11

throughputs. When higher radiation is available, higher throughputs of air can be resorted to as the collection efficiency will necessarily be higher than at lower throughput of air. Collector fans F1, F2, F3 work only 8 hours in a day, F4, F5 work continuously it is expected that the energy consumption of all three fans will be approximately 5 to 8% of the total energy collected. The complete plan of solar drying system is given in Fig. 12.

When the leaf is completely dry, sufficient care has been taken to maintain low vertical velocity in the barn in order to avoid leaf fall out. Vertical velocity of not more than 2 m/min have to be ensured at all points in the barn where the tobacco is hung. The overall system specifications are given in Table 7.

CONCLUSION:

Through the solar energy process it may be possible to achieve more controllable condition in the barn. The possibility of tobacco catching fire due to dried leaf falling on hot raidant flue pipe is eliminated. When the new set up is ready for operation, valuable studies can be undertaken to reduce the curing time and to obtain better quality tobacco. By suitable modifications, the solar barn can be used for drying other crops like paddy, chillies, groundnut etc., which are grown in this region. The economic viability could also be achieved if the barn is made to operate for about 300 days in an year for drying the cereals and pulses.

ACKNOWLEDGEMENTS:

The authors are thankful to Mr. A. Mangapathi Rao of Bharat Electronics Limited for his valuable advice and keen interest in designing the system. Thanks are due to Department of Science and Technology for financial assistance. The authors gratefully acknowledge the authorities of Nagarjuna University, Gunter, Indian Institute of Science, Bangalore and Tobacco Research Institute, Rajamundry for providing the necessary facilities for this collaborative programme.

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SOLAR INSOLATION AT GUNTUR –	5 KWH/m^2/DAY
216 m^2 COLLECTOR AT 50% (η) DELIVER	4,65,362 K.cal/day
STORAGE VOLUME	14 m^3
PEBBLES WEIGHT	26 tons
BLOWER CAPACITY........ AT MID DAY	3000 m^3/hr
STORAGE MAX. TEMP.	80 °C

TABLE 6. ESTIMATED COLLECTOR AREA, STORAGE TANK AND BLOWER CAPACITY.

SYSTEM SPECIFICATIONS	
AREA OF COLLECTORS	216 m^3
NUMBER OF STORAGE TANKS	4
THERMAL CAPACITY OF EACH STORAGE TANK .. (AT ΔT = 40 °C)	2,12,000 Kcal
VOLUME OF EACH STORAGE TANK	14 m^3
MAXIMUM FLOW RATE OF AIR THROUGH COLLECTOR MODULES AND STORAGE TANKS ..	3000 m^3/hr at midday
MAXIMUM FLOW RATE OF DILUTING AIR	6000 m^3/hr
MINIMUM FLOW RATE OF AIR THROUGH COLLECTOR MODULES AND STORAGE TANKS..	600 m^3/hr
PRESSURE LOSS ACROSS 3 COLLECTORS IN SERIES	18 mm - H_2O
PRESSURE LOSS ACROSS EACH STORAGE TANK..	8 mm - H_2O

TABLE 7. SYSTEM SPECIFICATIONS

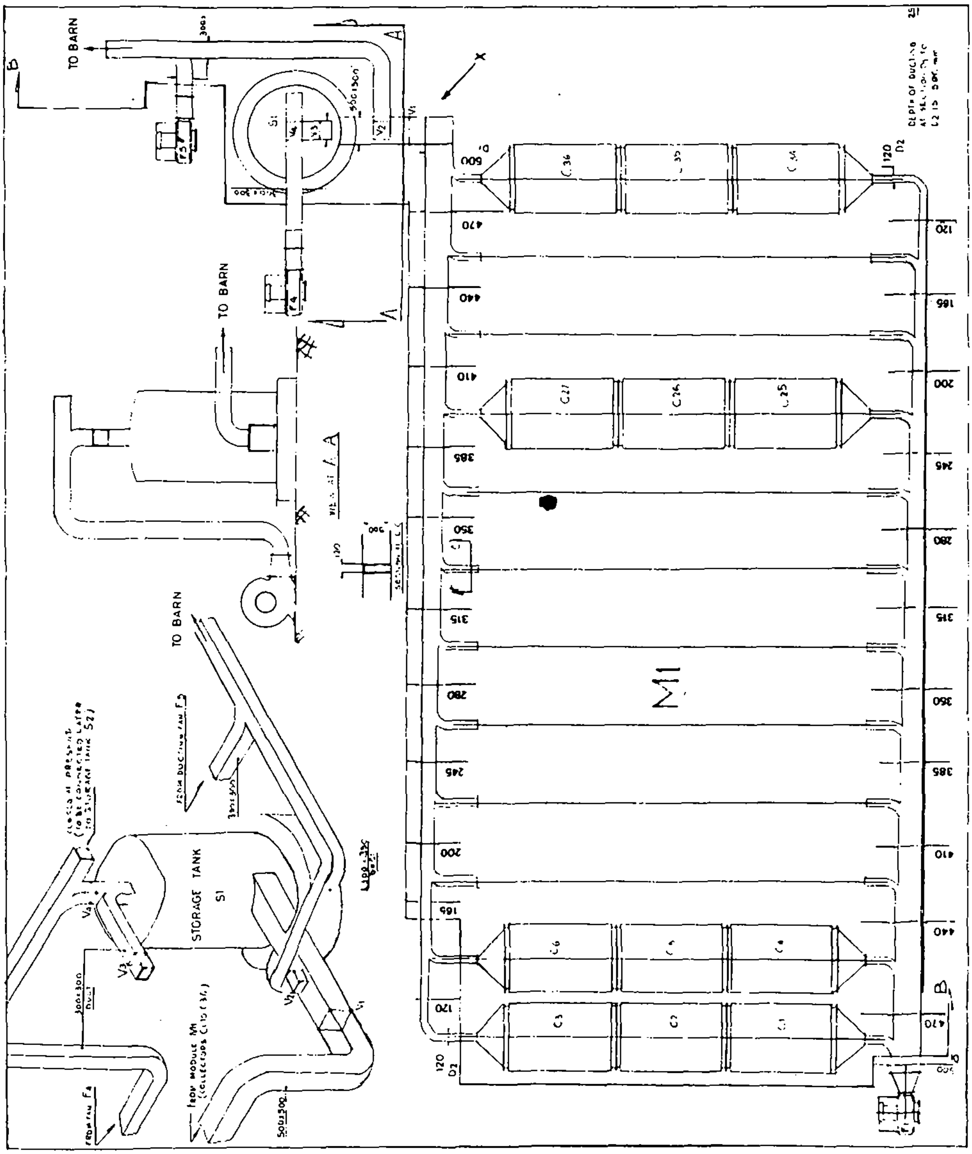

FIG. 12. PLAN OF SOLAR DRYING SYSTEM

SOLAR ENERGY SYSTEM FOR CONTINUOUS PROCESSES

by

S.C. BOSE

ABSTRACT

The National Industrial Development Corporation (NIDC), pioneers in design, development and installation of solar energy dryers in India, have established a number of commercial solar energy dryers for drying of food grains, cash crops and spices. Their experience show that though there is considerable interest in the sub-continent on utilisation of solar energy, individual enterepreneurs have not yet evinced sufficient enthusiasm in the establishment of solar dryers, inspite the advantages such as lower direct cost of drying and better quality of the products. Similarly solar water heaters and other solar devices have not found much consumer acceptance.

Investigative problems for prospective utilizers of technology developed indicated, that there is likely to be a substantial scope for use of solar energy hot air/water system in continuous process industry viz. bulk processing of agricultural products, drying of parboiled paddy, mill-wet bagasse, cardboard laminates, plywood, pharmaceutical products, curing of tobacco, coffee, pepper, processing of tea, etc.

To evolve a techno-economically viable system and prove the efficacy of the solar energy system for continuous processing industry, a detailed analysis of various industries, were carried out. The study revealed that the Solar Energy System with a built-in heat source is techno-economically viable for continuous processes.

The present paper discusses economic aspect of

- Technically viable alternative systems
- Selection of insulation materials
- Choice of absorber and their collection temperature

Main emphasis in the paper has been towards evolution of an economically attractive solar energy system.

INTRODUCTION

The National Industrial Development Corporation (NIDC), pioneers in design, development and installation of solar energy dryers in India, have established a number of commercial solar energy dryers[1] for drying of food grains, cash crops and spices. Their experience show that though there is considerable interest in the sub-continent on utilisation of solar energy, individual entrepreneurs have not yet evinced sufficient enthusiasm in the establishment of solar dryers, inspite the advantages such as lower direct cost of drying and better quality of the products. Similarly solar water heaters and other solar devices have not found much consumer acceptance.

Poor acceptability of solar devices till date is mainly due to two factors, viz. the capital cost being generally higher and the popular belief that solar devices can only work intermittantly. Higher stress so far been on development of solar devices for domestic and agricultural sectors. Both these sectors in India do not have surplus capital to invest on solar devices. As such, even though the technology of solar dryers, water heaters, etc. have been adequately developed and a few demonstration models established, they have remained more of an innovative curiosity than as the expected pace setter. Discouraged by initial response the NIDC directed their energy to look for more receptive entrepreneurs.

Investigative probes for prospective utilizers of technology developed indicated, that there is likely to be a substantial scope for use of solar energy hot air/water system in continuous process industry viz. bulk processing of agricultural products, drying of parboiled paddy, mill-wet bagasse, cardboard laminates, plywood, pharmaceutical products, curing of tobacco, coffee, pepper, processing of tea, etc. A more responsive attitude from most of these industries was due to their ability to incur extra capital investment, provided they were convinced of the efficacy of the solar energy system in meeting at least part of their needs. The basic requirement of solar energy system for the continuous industry, besides being economically attractive, is high reliability, as any absence of heat even for a short duration in most of the processing operations would lead to spoilage of the end product thus affecting their economical operation.

To evolve a techno-economically viable system and prove the efficacy of the solar energy system for continuous processing industry, a detailed analysis of various industries, were carried out. The study revealed that most of the continuous processes require hot air and/or water at more or less uniform temperature below 90°C, except for curing of flue cured virginia (FCV) tobacco. Curing of FCV tobacco calls for precise control of both temperature and humidity as shown in Fig. 1.[2] It was felt, study of solar energy system for curing of FCV tobacco will be most appropriate towards evolution of a viable solar energy system for continuous processing and testing its efficacy. To achieve this objective NIDC established a 'Solar Barn' at Rajahmundry, India, in March 1980, with the active cooperation of Central Tobacco Research Institute, to cure FCV tobacco. Technical aspect of the design of Solar Barn has already been reported.[3,4]

The present paper discusses economic aspects of

- Technically viable alternative systems
- Selection of insulation materials
- Choice of absorber and their collection temperature

Main emphasis in the paper has been towards evolution of an economically attractive system, as the author is convinced, unless the solar energy system is economically attractive, industry will not be attracted and this will also remain an innovative curiosity only.

2. *Alternative Systems and their Viability*

To obtain heat continuously by the use of solar energy either of the following alternatives[3] can be used:

(i) System in which all the heat requirements at specified temperatures are met from the solar energy only. This system must have sufficient heat collection and storage capacity, to meet round the clock heat requirement of the continuous process. Block Schematic diagram of this system is given at Fig. 2(a)

(ii) The solar energy system with a built-in supplementary heat source. In this system, bulk of the heat requirement will be met from solar energy when the same is available and balance will be met by the built-in supplementary heat source. The system can be with and without heat storage.

Block Schematic diagram of these are presented at Fig. 2(b) and (c).

Capital, operating costs and maximum fuel consumption in the subsidiary heat source for both the systems are outlined in Table 1.

Variation of operating cost estimates for both the system with percentage of time it is utilised at various levels of inflation in the price of fuel, used in subsidiary heat source, is presented in Fig. 3. Scrutiny of data presented in Table 1 and Fig. 3 shows that the solar energy system with built-in subsidiary heat source will only be economically viable.

Solar energy system with built-in subsidiary heat source without heat storage, as outlined at Fig. 2(b) was installed at Rajahmundry, India, in March, 1980. Actual capital cost incurred on this installation was Rs. 24,800/- against an estimate of Rs. 32,400/- (see Table 1). To cure 600 Kg of FCV tobacco in March 1980, in solar barn, 300 Kg of coal was consumed in the subsidiary heat source, to supplement the heat generated in solar absorber, compared to 700 Kg of coal in a conventional barn (used as control barn), during the study. Thus by use of solar energy, 400 Kg coal can be saved in

SOLAR ENERGY TOBACCO CURING BARN.

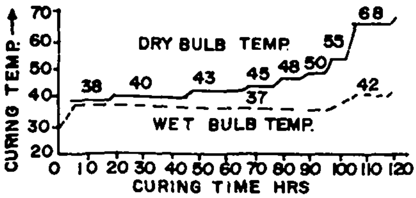

FIG. 1 STANDARD TOBACCO LEAF CURING TEMP. C°

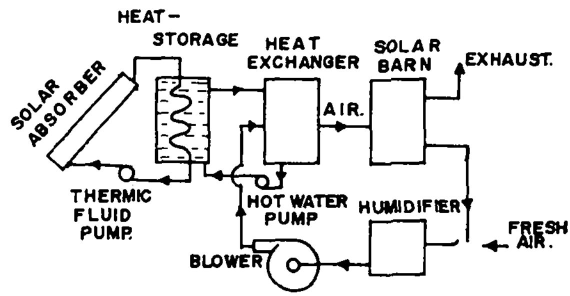

FIG. 2A. SOLAR ENERGY SYSTEM WITH STORAGE

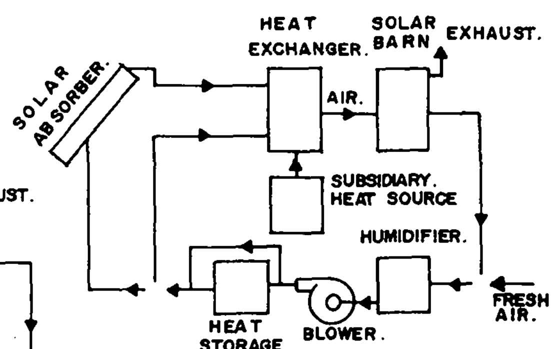

FIG. 2C. SOLAR ENERGY WITH BUILT IN SUBSIDIARY HEAT SOURCE & STORAGE

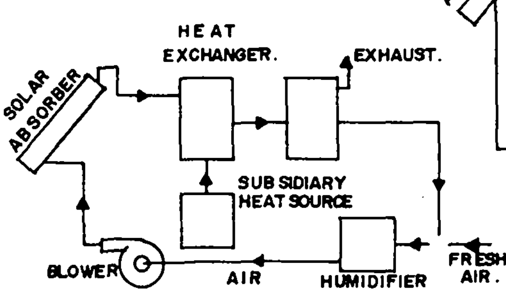

FIG. 2B SOLAR ENERGY SYSTEM WITH BUILT IN SUBSIDIARY HEAT SOURCE

Table 1. **Capital and operating Costs of Alternative System.**

	Case No. 1	Case No. 2	Case No. 3
1. Capital Cost	*Rs. 2,54,200	Rs. 32,400	Rs. 34,400
2. Curing Capacity per charge of green tobacco	1200 Kg	1200 Kg	1200 Kg
3. Weight of Coal consumed per 1200 Kg of charge	Nil	500 Kg	400 Kg
4. Operating Cost estimates at 30% utilization factor	Rs. 1.35	Rs. 0.33	Rs. 0.331

Note: Capital cost estimates based on insulation using 2" Mud-husk plaster.

* 0.12 US Dollars approximately = Re. 1.

curing 600 Kg of FCV tobacco. Cost of curing of FCV tobacco in solar barn was found to be Rs. 0.21 per Kg of green leaves compared to Rs. 0.49 in conventional barn.[4]

3. *Choice of Insulation*

In any continuous process, heat losses in process plant, equipment and fixtures, form a sizable portion of the total heat requirement. To maximise economic returns per unit capital investment, reduction of heat losses is generally considered desirable. Reduction of heat losses generally call for better insulation which incidently require higher investment. Results of the analysis on the requirement of capital investment, and saving in the requirement of heat for curing 1200 Kg of FCV tobacco in solar barns with the following types of insulation were carried out and presented in Table 2.

a. Type No. 1 – Conventional method of construction.

b. Type No. 2 – 2" mud husk plaster on the inside of walls instead of cement plaster.

c. Table No. 3 – 0.5" thermocole with Aluminium clading on the inside of walls instead cement plaster.

d. Type No. 4 – 0.5" synthetic foam as insulation on the inside of walls instead of cement plaster.

The cost of operation of the solar barns with different insulation indicated above, have been evaluated and presented have been given in Table 3. Effect of escalation in price of fuel used in subsidiary heat source on cost of operation is presented in Table 2, 3 and Fig. 4 reveals:

(a) Mud-husk insulation effects a saving in heat requirement by around 11% and synthetic foam around 22%.

Table 2. COST OF CONSTRUCTION AND TOTAL HEAT REQUIREMENT FOR CURING 1200 KG FCV TOBACCO IN SOLAR BARNS OF DIFFERENT INSULATION AT RAJAHMUNDRY, INDIA

	t_o °F	*Type No. 1*	*Type No. 2*	*Type No. 3*	*Type No. 4*
1. Type of wall					
(a) Construction detail		Normal brick construction with cement mortar and 0.5 inch plaster on both side of the wall.	Brick in mud mortar. Inside plaster 2 mud- and husk. Outside 0.5" cement plaster	Brick in mud-motor. Inside 0.5" thermocole with Al cladding. Outside 0.5" cement plaster	Brick in mud mortar Inside 0.5", synthetic foam. Outside 0.5" cement plaster.
(b) K value B.T.U./°F/hr/sq.ft.		0.24	0.15	0.02	0.013
2. Type of doors and windows					
(a) Construction details.		G.I. doors and windows	Double walled wooden door and windows	Same as 2	Same as 2
(b) K Value B.T.U./°F/hr/sq.ft.		1.24	0.14	0.14	0.14
3. (a) Type of solar Absorber		Double glass	type solar absorber		
(b) K Value B.T.U./°F/hr/sq.ft.		0.07			
4. Capital Cost		Rs. 25,600	Rs. 24,800	Rs. 28,700	Rs. 30,800
5. Heat requirement in B.T.U. for curing 1200 Kg FCV tobacco, duration 90 hrs.					
(i) Jan.	77	3,539,077	3,077,342	2,645,339	2,622,077
(ii) Mar.	83	3,343,907	2,970,258	2,618,283	2,599,331
(iii) May	91	3,109,611	2,838,589	2,585,018	2,571,365
(iv) July	86	3,250,150	2,916,718	2,604,756	2,587,959
(v) Sept.	86	"	"	"	"
(vi) Nov.	81	3,410,666	3,005,954	2,627,302	2,606,934
(vii) Average		3,317,260	2,954,263	2,614,242	2,595,934
6. Saving in Heat		0	10.94%	21.19%	21.74%

Note: = t_o = .7 t mean + .3 t max.

Table 3. Projected Annual Cost of Operation of Solar with Alternative Insulations

S No.		Type 1	Type 2	Type 3	Type 4
1	2	3	4	5	6
A.	*Estimates of Direct Costs*				
(a)	*Cost of fuel consumed*				
(i)	Weight of coal consumption per 1200 charge	460 Kg	360 Kg	305 Kg	301 Kg
(ii)	No. of charges per annum	30	30	30	30
(iii)	Annual coal consumption	13,800 Kg	10,800 Kg	9,150 Kg	9,030 Kg
(iv)	Cost of coal delivered at site @ Rs. 140/Tonne per annum	Rs. 1932/-	Rs. 1512/-	Rs. 1281/-	Rs. 1264/-
(b)	*Cost of Electricity consumed*				
(i)	Kwh consumed per charge	75 Kwh	75 Kwh	75 Kwh	75 Kwh
(ii)	Annual Consumption	2250 Kwh	2250 Kwh	2250 Kwh	
(iii)	Cost of power @ 0.25/Kwh	Rs. 562.50	Rs. 562.50	Rs. 562.50	
(c)	*Cost of Direct Mandays*				
(i)	Mandays required per charge		12		
(ii)	Mandays required per annum		360		
(iii)	Cost of Mandays @ Rs. 10/manday		3600/-		
	Sub-Total (A+)	Rs. 6094.50	Rs. 5674.50	Rs. 5443.50	Rs. 5426.50
B.	*Estimates of Indirect Costs*				
1.	*Depreciation*				
(i)	Civil Works @ 3%	294	270	387	450
(ii)	Solar Absorber @ 5%	500	500	500	500
(iii)	Blower @ 5%	200	200	200	200
(iv)	Subsidiary Heat Source @ 10%	180	180	180	180
2.	*Maintenance*				
(i)	Civil Works @ 1%	98.00	90.00	129	150
(ii)	Solar Absorber @ 2½%	250.00	250.00	250	250
(iii)	Blower @ 2½%	100.00	100.00	100	100
(iv)	Subsidiary Heat Source @ 5%	900.00	90.00	90	90
3.	Interest on Capital Investment @ 10%	2,560.00	2,480.00	2870	3080
	Sub-Total (B)	4,272.00	4,160.00	4706	5000
C.	Weight of Green Tobacco leaves that can be cured in 1 year.	36,000.00	36,000.00	36000	36000
D.	Cost of curing of FCV tobacco per Kg of green leaves	$\frac{10366.50}{36,000} = .29$	$\frac{9834.50}{36000} = .27$	$\frac{10149.50}{36000} = .28$	$\frac{10426.50}{36000} = .29$

(b) Annual cost of operation is lowest with mud-husk insulation even if:

(i) There is 150% escalation in cost of fuel used in subsidiary heat source;

(ii) The interest on capital investment is reduced from 10 to 5%.

(c) Effect of reduction of interest on capital investment on cost of operation, was found to be very marginal.

(d) Optimal reduction of capital investment and heat losses is necessary to minimise the operating costs.

Note: In some of the continuous processes e.g. tobacco curing, drying of bagasse, plyboards, parboiled paddy etc. waste material generated in the process can normally be burnt in the subsidiary heat source to generated the heat. These waste materials have no economic value, even under these cases optimal reduction of heat losses and capital investment was found to be necessary to minimise the operating cost.

Reduction of heat losses can also be considered as equivalent to generation of heat. The expenditure on insulation can be put as –

i. Use of mud-husk plaster provides a saving of Rs. 800/- in capital cost and makes available around 91,000 BTU/day additional heat in the solar barn.

ii. Use of thermocole insulation requires Rs. 3100/- additional investment and makes available around 1,74,000 BTU/day additional heat.

iii. Use of synthetic foam requires Rs. 5,200/- additional investment and makes available 1,80,000 BTU/day additional heat.

This approach immediately leads to the question "Which provides better return? - Additional investment on insulation or solar absorber?"

This aspect will be dealt in the next section.

4. *Choice of Soalr Absorber*

Economic evaluation carried out shows that net heat output per unit capital investment is higher with double glass type solar absorber under normally prevalent ambient conditions. Capital costs of single and double glass absorbers at Jan-Feb 1980 price level in India were evaluated and the same is given in Table 4.

For plants operating round the year, inclination of the absorber equal to the latitude of the place towards the equator was found to be give best results. Net heat available at different times of the year from a

(a) A vertical south facing absorber, and

Table Table 4. **Capital Cost Estimates of Solar Absorber (Air Heaters) Type in Rs. per sq.ft.**

	Inclined Absorber		*Verticable Absorber*		
	Less than 1000 sq. ft.	*More than 1000 sq. ft.*	*Less than 100 sq. ft.*	*More than 100 sq. ft.*	*Effective Absorbing Area*
1. Single Glass Absorber	Rs. 79.2	Rs. 53.0	Rs. 33.0	Rs. 28.0	86%
2. Double Glass Absorber	Rs. 87.0	Rs. 61.0	Rs. 41.0	Rs. 36.0	82%

Note: Inclinded absorber considered are for angles less than 35° from the horizontal. The cost indicated is inclusive of self-supporting structure, these absorber can be used as the roof of the building. Vertical absorbers indicated are self-supporting and can be used as walls.

(b) Tilted at 15° south facing absorber at Rajahmundry (Lat. 17°N) India, at different collection temperature were calculated, these are presented in Table 5.

In curing/drying operation, covered space is required the volume of this space is primarly determined by the rated capacity of the plant. The height of the space in the case of tobacco curing, is determined by optimum utilisation of covered space and maximum heat transfer between the surrounding hot air and tobacco leaf. The use of main absorber as roof of the covered space was found to be most economical. In a barn of 1200 Kg capacity maximum size of the absorber as the roof was found to be 300 sq.ft. To meet additional heat requirement, installation of subsidiary absorber on south facing vertical wall was considered. The effect of use of south vertical absorber on the operating cost of a solar barn with mud and husk insulation is presented in Fig 3 in the form of curves marked as IIA (II are the curves for solar barn with mud husk insulation).

Scrutiny of curves presented in Fig. 3 shows:

(i) Solar barn with mud-husk insulation without subsidiary vertical absorber provides best economic returns even if there is 50% escalation in the cost of fuel used in subsidiary heat source.

(ii) Installation of south facing vertical absorber will become attractive when the escalation in cost of fuel is more than 100%.

(iii) Additional investment on south facing vertical absorber are more remunerative than the investment on insulation.

5. *Choice of absorber collection temperature*

Scrutiny of Table 5 shows that net heat available from an absorber falls as the collection temperature is increased. Average net heat availability falls by around 5% for every 20° F increase in collection temperature for inclined surface and around 10% for south facing vertical absorber. Higher collection temperature generally calls for larger absorber area, and better insulation material, both of which in turn calls for higher investment. This generally leads to higher operating costs. Heat collection temperature in also depended of the process requirement.

Detailed study on the choice optimum collection temperature will be published at a later date. The result of the study indicates that optimum collection temperature should be less than 120° F and should meet the base requirement of the process. A reference to Fig. 1 indicates that the base requirement for curing of tobacco is 40° C (approx. 100° F). To meet the process temperature requirements beyond 120° F drawing of heat from subsidiary heat source was found to be more economical. For curing FCV tobacco, optimum absorber collection temperature was to be around 100° F.

SOLAR ENERGY TOBACCO CURING BARN

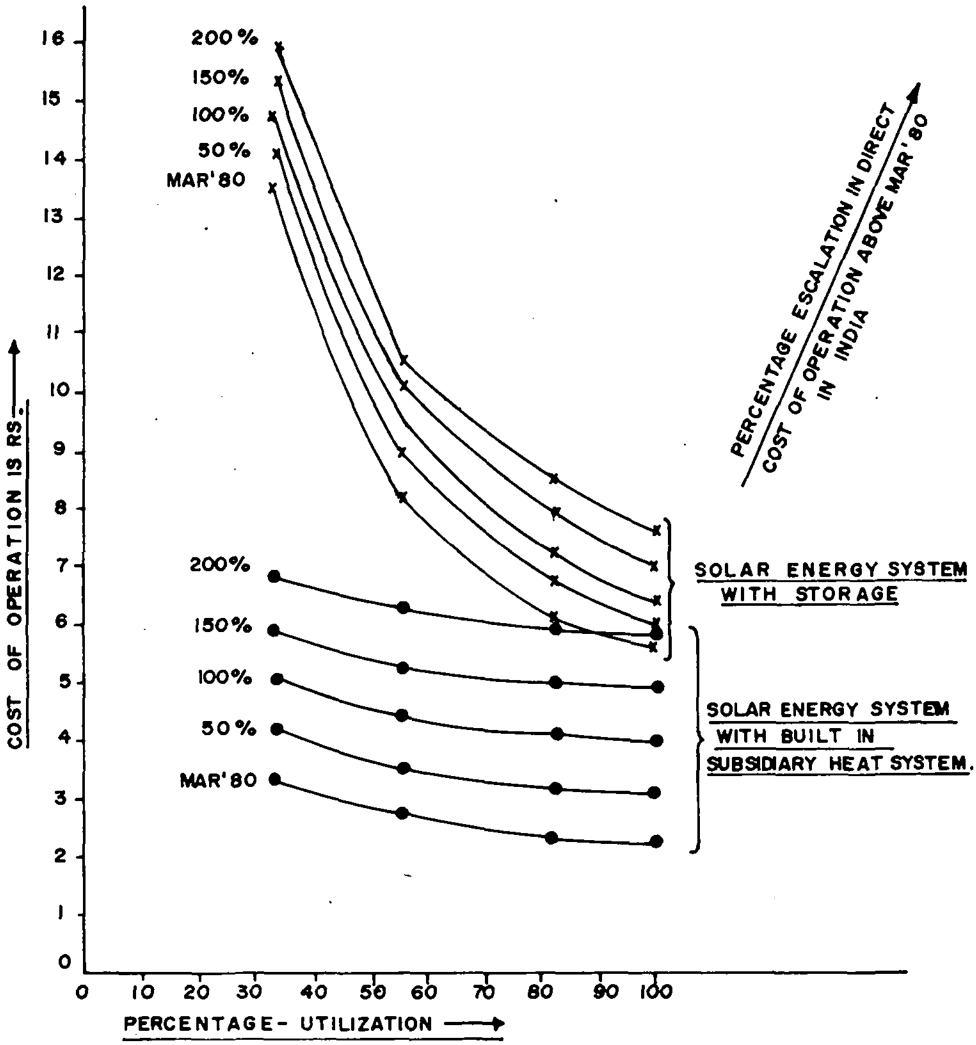

FIG. 3 VARIATION OF COST OF OPERATION IN COMPLETE SOLAR ENERGY SYSTEM AND SOLAR ENERGY SYSTEM WITH BUILT-IN HEAT SOURCE

Table 5. **Heat Availability on a South Facing Collector at Rajahmundry**

LAT – 17°N

	Heat available in an inclined absorber tiled at 15° in B.T.U./day/sq. ft.				*Heat Available in a south facing vertical absorber B.T.U./day/sq. ft.*			
	Collection Temp. 100°F	*Collection Temp. 120°F*	*Collection Temp. 140°F*	*Collection Temp. 160°F*	*Collection Temp. 100°F*	*Collection Temp. 120°F*	*Collection Temp. 140°F*	*Collection Temp. 160°F*
JAN.	1305	1245	1179	1108	1135	1075	1009	938
MAR.	1402	1342	1277	1206	633	573	508	437
MAY	1361	1302	1236	1165	500	441	375	304
JULY	1026	966	901	830	438	378	313	242
SEPT.	1105	1045	980	909	432	372	307	236
NOV.	1195	1135	1070	998	941	881	816	744

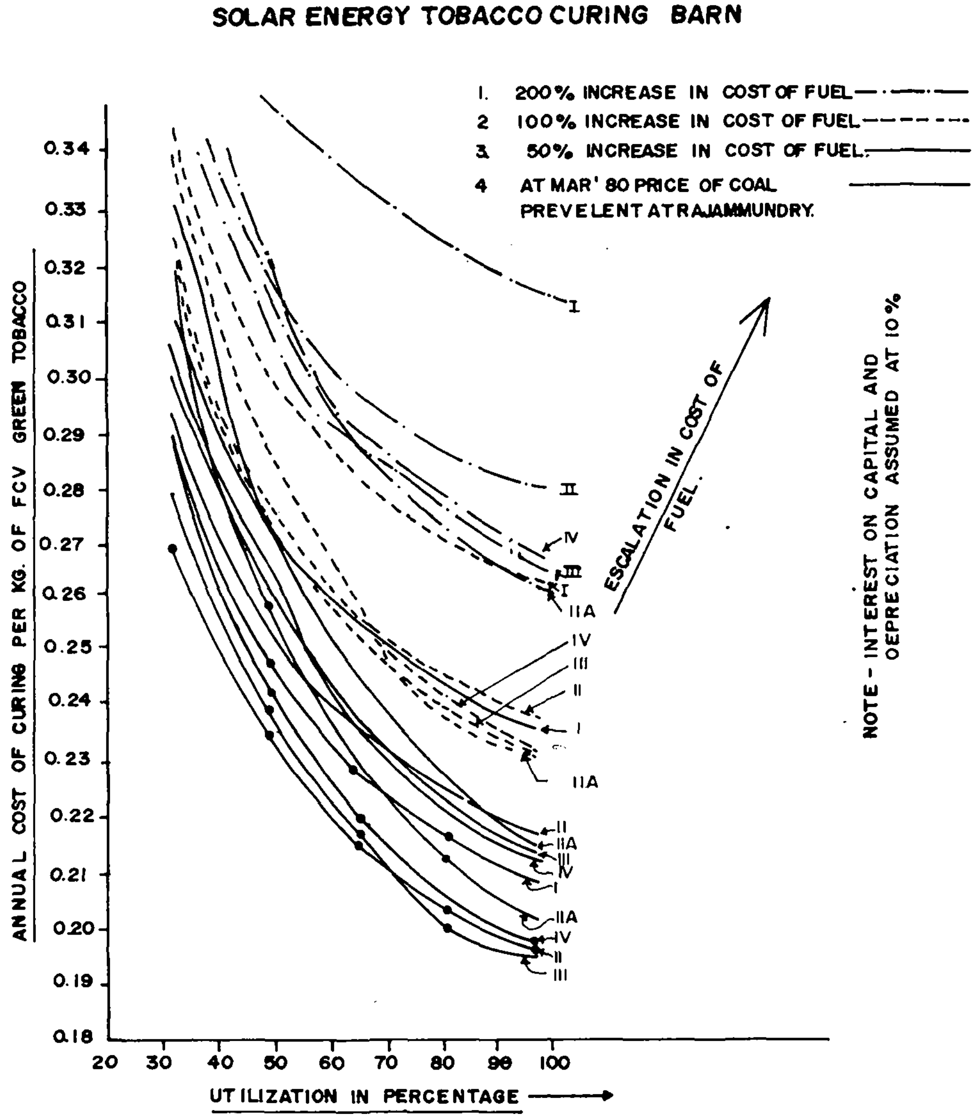

FIG. 4 VARIATION OF COST OF OPERATION OF SOLAR ENERGY SYSTEM. HAVING BUILT-IN SOURCE WITH DIFFERENT TYPES OF INSULATION

6. *Conclusion*

The study presented in the paper reveals that use of solar energy for continuous process is economically attractive. Solar energy system with the built-in heat source was found to be economical. Additional investment on south facing vertical absorber are more remunerative than additional investment on insulation. For making solar energy system economically attractive cost benefit study towards investment on each major element of the system is essential.

7. *Acknowledgement*

Author is thankful to Dr. N.C. Gopalachari, Director, Central Tobacco Research Institute, Rajahmundry for meeting the expenses towards establishment of the Solar Barn and help provided in carrying out the tests.

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LOW-COST SOLAR CELL MANUFACTURING TECHNOLOGY

by

R. VAN OVERSTRAETEN and R.K. JAIN

ABSTRACT

For developing countries where abundant sunlight is available, the use of photovoltaic generated power looks very promising. Among the various applications where the solar energy produced electricity could be used, the supply of water for drinking and for irrigation, and the electrification of villages in remote areas seem to be attractive for the rural development. For the indian conditions the solar generated power would be cost effective if it is available between Rs. 10 to Rs. 30 per peak watt. The United States Department of Energy (DOE) has set a goal of US$ 0.70 per peak watt by the year 1986. The purpose of the present paper is to make comparison between the different techniques which can be used for manufacturing solar cells. It states which technologies can be used to reach the cost goal set by the DOE. At this price a large number of rural applications in developing countries would be economically feasible.

I. *Introduction*

For a developing country like India where abundant sunlight is available, the use of photovoltaic generated power looks very promising. Among the various applications where the solar energy produced electricity could be used, the supply of water for drinking and for irrigation, and the electrification of villages in remote areas seems to be attractive for the rural development of India. For the indian conditions the solar generated power would be cost effective if it is available between Rs. 10 to Rs. 30 per peak watt. The Department of Energy (DOE) USA has set a goal of US$ 0.70/pW or of roughly US$ 1.0/pW (Rs. 7.5-8/pW) by the year 1986. To achieve this goal DOE predicts the cost of the primary silicon material of the order of US$ 0.01/pW, and of the fabrication of the substrate for solar cells at US$ 0.20/pW. This could be realized either by growing CZ ingot and slicing or using heat exchange method ingot or EFG method or dendritic web growth or using silicon on ceramics. The encapsulation materials would cost US$ 0.10/pW. The module assembly for large scale production is estimated around US$ 0.10/pW. Therefore, cell manufacturing cost has to be between US$ 0.20 - US$ 0.50/pW. The purpose of this paper is to compare the cost of different technologies to manufacture solar cells.

II. *Efficiency Limitations*

To compare different manufacturing techniques one has to take into account the following factors: the efficiency obtained by the particular process, the availability and the cost of the used materials, the investment cost of the equipment, the possibility of high throughput and the yield of the process.

In the present paper we will limit ourselves to silicon, because silicon solar cells are until now the only cells on the market.

A solar cell consists of a p-n sandwich (Fig. 1). Light is absorbed in the silicon and creates electron-hole pairs, which are separated by the p-n junction. On the front and back side of the cell metal electrodes conduct the current to an external load. Antireflection coating reduces the light reflectance at the surface of the cell. It is important to list the different limitations on the efficiency of the cell.

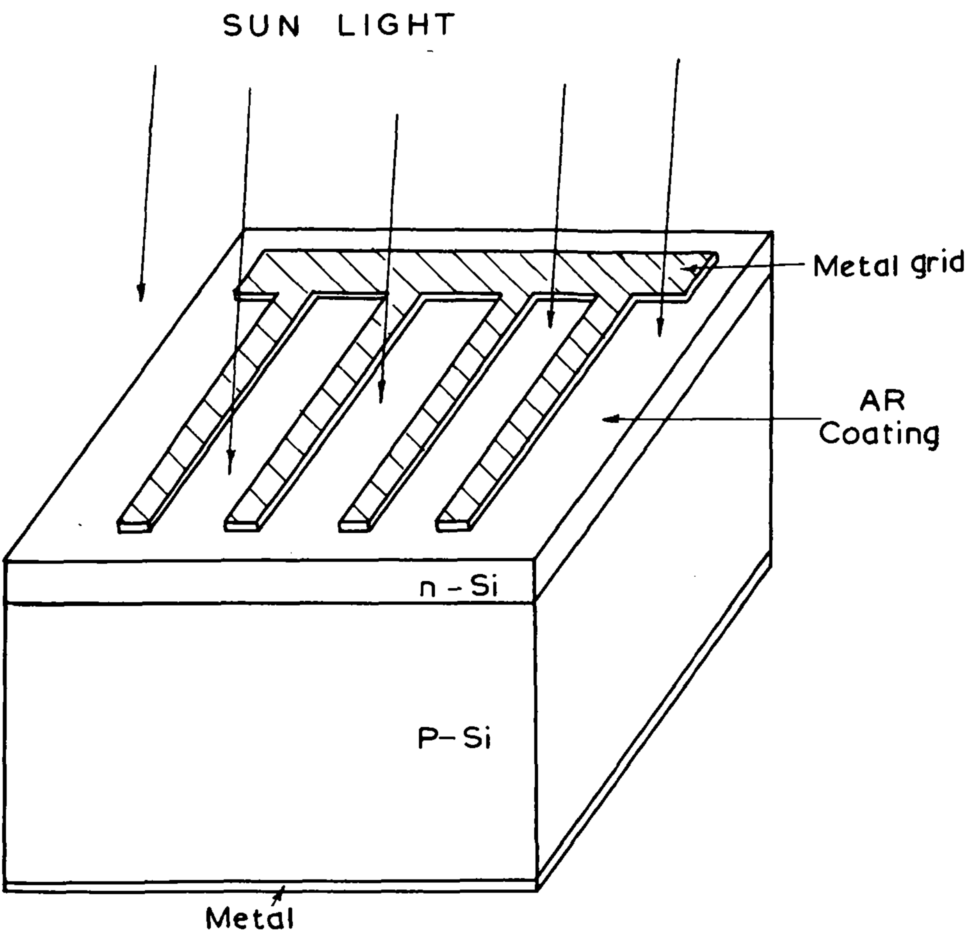

Fig. 1. Physical aspect of a n-p solar cell.

(a) Reflection loss

Reflection loss at the surface of the cell. This loss is caused by the mismatch of the refractive index of air and silicon. It can be reduced to 6-10% by using an antireflective coating (TiO_2, Ta_2O_5, multilayer, etc.). It can be further reduced by applying a selective etch which creates a pyramidal surface that already reduces the reflection to one third prior to applying the antireflective coating. The reflection has to be reduced to enhance the short circuit current.

(b) Incomplete absorption (Fig. 2)

The photon energy has to be large than the band gap to create an electron-hole pair. Part of the solar spectrum thus will be lost and also a large number of photons absorbed have more energy than necessary for the generation of an electron-hole pair. This excess energy is lost in dissipation of heat. This limitation is fundamental and is limited by the choice of the semiconductor material.

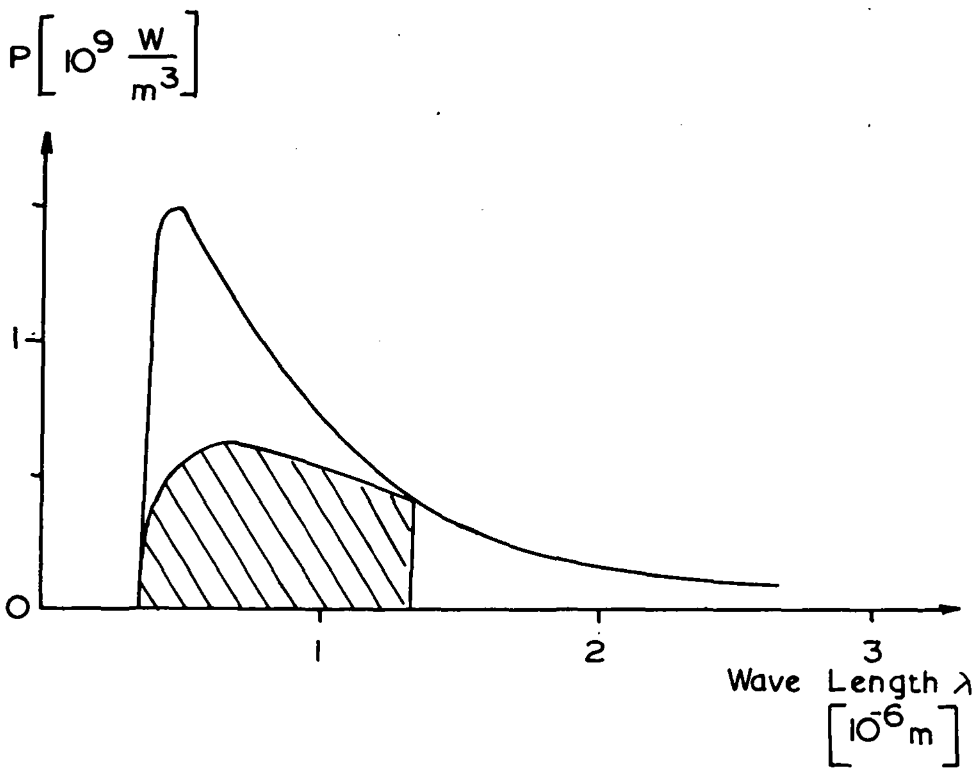

Fig. 2. Energy spectrum of the sunlight. The shaded area shows the maximum energy utilized in the generation of electron-hole pairs in silicon.

(c) Incomplete collection (Fig. 3)

The absorption of photons is a function of the wavelength of the light. The photons with longer wavelengths are absorbed deep in the material. The generated minority carriers must travel to the junction to be collected and to contribute to the photocurrent. Thus only those minority carriers will be collected which are generated within a diffusion length from the junction. The minority carriers generated further from the junction will recombine. The collection efficiency will thus be smaller than 100%. The collection efficiency is determined by the minority carrier mobility and lifetime. These parameters are influenced by the technology. A high collection efficiency requires a high lifetime, a low surface recombination velocity, a small junction depth and a back surface field. A high collection efficiency results in an enhancement of the short circuit current and of the open circuit voltage.

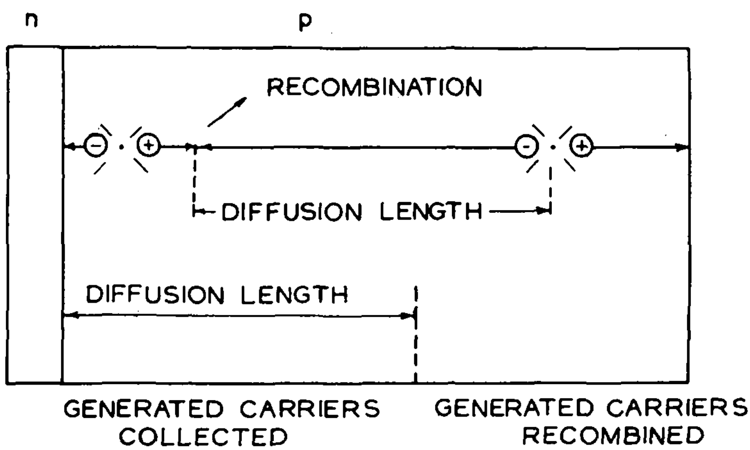

Fig. 3. This figure shows that minority carriers generated at a distance from the junction larger than the diffusion length are lost due to recombination.

(d) Voltage factor

The voltage factor is determined by the ratio of open circuit voltage V_{oc} to the energy gap. The voltage factor could be increased by a strong back surface field which increases V_{oc}.

(e) Fill factor

The fill factor is determined by a theoretical law: because of the exponential current-voltage dependence the fill factor can not be larger than 0.83 for a silicon solar cell at AM1 conditions. In practice, however other parameters affect this factor. The exponential law is not ideal, which can be modelled by a second (non ideal) diode and there is a leakage current in the diode, modelled by a shunt resistance R_{sh} (Fig. 4). These parameters are again technology and material dependent.

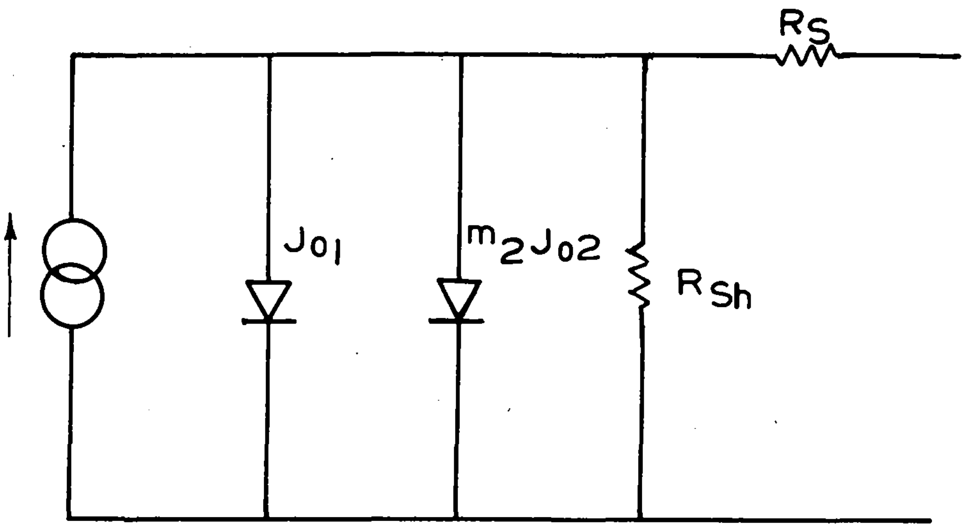

Fig. 4. Electrical model of a solar cell: current generator, ideal diode, non-ideal diode, shunt- and series resistance.

The series resistance has to be optimized for low metal coverage and for low loss.

All these limitations have to be taken into account when comparing the different cell manufacturing techniques.

III. *Manufacturing Techniques*

We will consider four steps in the manufacturing sequence for cell fabrication, namely wafer preparation, junction formation, antireflective coating and metallization.

(a) Wafer preparation

After sawing of the silicon wafer or sheet, it is necessary to treat the surface in order to get appropriate properties for the junction formation. It is necessary to remove the sawing induced damage of the crystal.[1, 2] It is important that this damaged region is as small as possible, to minimize the silicon loss as well as the etching liquids. Very well known is the HF/HNO_3 etching already widely used in the semiconductor industry. This acid etch can however cause big ecological and safety problems when applied in very large quantities, as will be the case in the next few years.

Another etching technique now being introduced is the orientation dependent etch. This can combine both damage removing and reflection reduction. Among others, hydrazin potassium hydroxide and ethylene diamine sodium hydroxide seem to be the most economical and safest product.[3] When properly controlled for uniformity of surface etching, this etching step can successfully be applied with high throughout and low material cost. The consumed material can easily be treated and recycled.

In order to finish wafer preparation, wafers are often cleaned chemically prior to junction formation. It should be noticed that acid cleaning is quite expensive. It is believed that deionized water rinse after etching can suffice for further processing. It should be noted that the wafer preparation techniques are valid for sheets of all shapes and surfaces.

(b) Junction formation

We will discuss three different techniques for the junction formation in silicon.

The junction formation is classically done by diffusion in an open tube furnace out of a gaseous or liquid source. The most wide spread method is that of phosphorus diffusion into a p-type doped silicon wafer at temperatures in the 900° C range. Although this technique is very well known and has proven its high throughput capabilities and its good reliability, it ihas some severe drawbacks:

– when using large diameter wafers, there can rise uniformity problems at high throughputs: low temperature and short diffusion times are necessary to obtain fairly low junction depths: this can cause the p-n junction formation to become critical, and some degradation of the diode characteristic and of the yield can be the consequence.

– the surface concentration (specially for phosphorus) can not be reduced because it is determined by the diffusion temperature. Also the junction depth can not be reduced below 0.3 μm due to uniformity problems mentioned above.

– to obtain a one sided diffusion one has to mask the other side prior to diffusion by an oxide. The resulting diode will be of good quality (high FF), but the process sequence is long and costly (Fig. 5): an oxidation step (at high temperature) followed by a photoresistcoat-develop-etch-resist-remove process. Another possibility is to use a mesa-structure (Fig. 6): after diffusion the front side is coated with resist and the back region is etched chemically: the procedure is a little simpler, but there still remains a lot of manipulation.

– at least, when combining this diffusion with a BSF-step (a diffusion of a dopant of the other type), there can be problems at the edges of the wafer due to p^+n^+ regions: these can cause shorts due to metallization, or can result in bad diode characteristics (p^+n^+ diodes). To avoid this, costly mask steps have to be introduced.

A second category of diffusion rejects some of the previous drawbacks, and is promising in obtaining high efficiencies: it concerns the diffusion out of a solid phase: in this category we can classify the chemical vapor deposition (CVD), the process of which a flow-chart is drawn on the next figure (Fig. 7). Phosphorus doped and boron doped oxides are deposited on the wafer on each side: the junction and the BSF are then obtained by a simultaneous drive-in. The big advantages here are:

– the very well controllable surface concentration: it is controlled by the amount of doping gas in the gas mixture when depositing the oxide. This can result in an enhancement of the short circuit current.

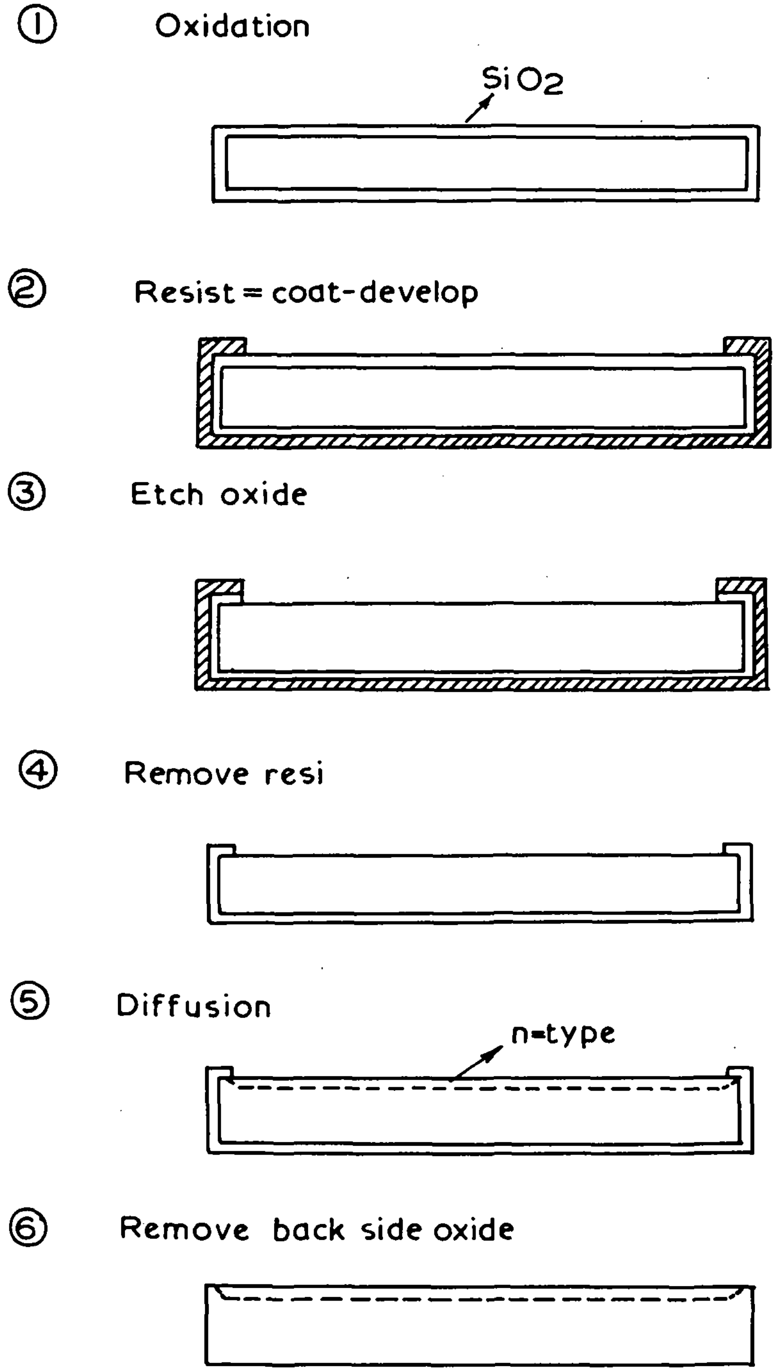

Fig. 5. Processing sequence to obtain a one sided junction.

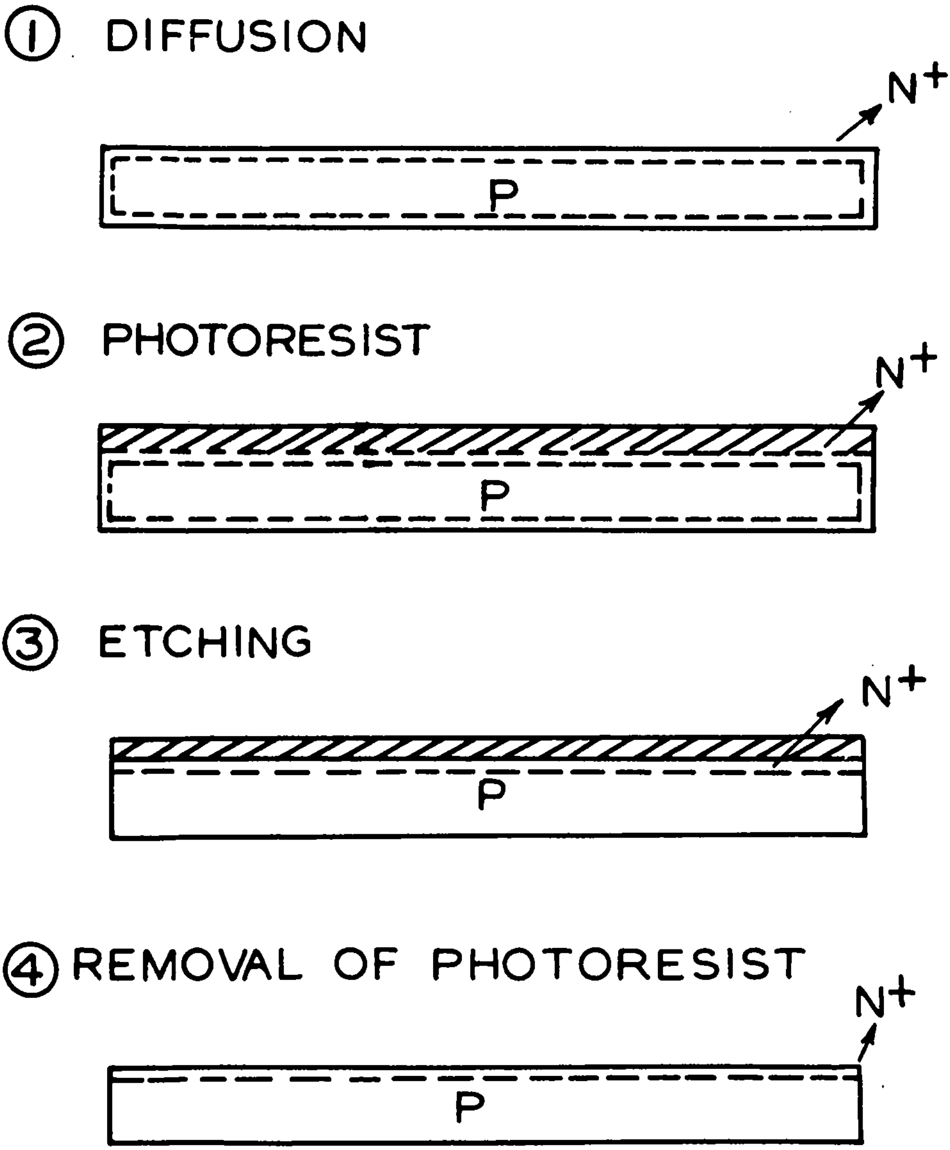

Fig. 6. Processing sequence to obtain a mesastructure.

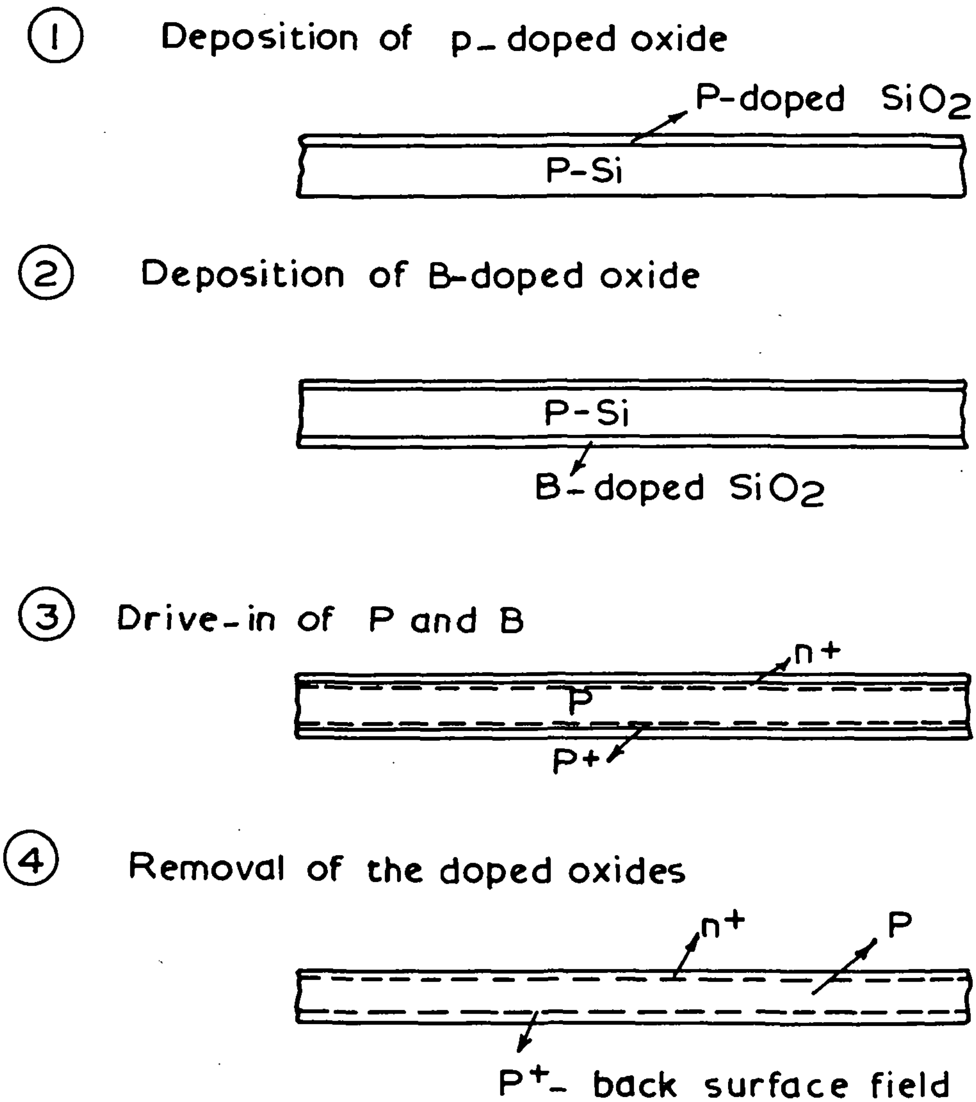

Fig. 7. Flow chart for making a solar cell with the use of doped oxides.

– the simultaneous realization of junction and BSF in one high temperature step.

– the absence of mask-and etch steps to remove the unwanted dopings on front or rear side of the wafer.

– the possibility of having a process very amenable to automation ((CVD) and drive-in can be continuous, 'diffusion' is batched).

Measured efficiencies of 16.5% have been reported with this technique.[4] A drawback of this CVD process is that it requires highly pure and thus very costly dopant gases. This is obviated by two related techniques: spin-on and spray-on. Here much cheaper liquid dopants are used, and the appratus to apply them is much simpler. Although efficiencies of around 12% have been reported,[5, 6] there seem to be a severe uniformity problem, that hold the fill factor FF low (thus far FF_{max} = 0.68).

All these techniques have however not yet resolved the edge problem of the wafers, without introducing additional steps to mask or to etch the cross-contaminated edges. This can however be resolved by the screen printing technique. This technique is almost the same as the CVD, spin-on and spray-on techniques, except in putting on the dopants. Here liquid dopants can be introduced in printable pastes, which can then be applied on the wafers. Because the geometry of the paste position can be very well controlled at no additional cost, one can take care that no cross contamination occurs, and even more, selective diffusion at the front side can easily be applied. High I_{sc} and V_{oc} values can be expected with these devices. Preliminary experiments yield more than 11% efficiency.[4]

The last technique we will discuss is the ion implantation. This technique is highly technological and highly cost-intensive and was believed to be too expensive for solar cells. However recent cost analysis of large volume production plants[7] indicated that ion implantation is an obvious way to make solar cells. The cost analysis turns out to allocate an even lower add-on cost for ion implanted cells compared to diffused cells (partly also due to process simplification) in a 20MW capacity plant.[7] The ion implantation however is not cost competitive on a small scale.

Ion implantation can meet all the above mentioned properties necessary for a high efficiency and high throughput solar cell sequence. The existing ion implanters have however to be adapted to the special solar cell needs: it is for example necessary to reduce the energies in the 5 to 25 KeV range to achieve the low surface concentrations and shallow junctions.[8] Also the holders have to be designed in order to be able to handle all the possible shapes and sizes of Si sheet. Work is under way to simplify the ion implanters to reduce the investment.

One problem that seems to be almost resolved is the annealing after implantation. Indeed when ions are implanted in the crystal, some annealing is necessary to get diodes of high quality and to make the implanted dopants electrically active. This can either be done thermally or by radiation. Multiple step thermal annealing[8] has been reported to yield very high eficiencies: up to 16% per free surface on a 3 inch wafer (with a J_{sc} = 35.6 mA/cm^2 free surface). This was however achieved using a very expensive metallization method: Cr-Au evaporation photolithography and 12 μm Ag electroplating. Another annealing technique uses a fast laser pulse. The advantage of this technique is that there can be a complete damage removal without lifetime degradation due to a high temperature step, and that this process lends itself to higher throughputs.[9] The laser annealing parameters are now being optimized. Some observed properties as low FF are not yet well understood.

(c) Anti-reflective Coatings

Anti-reflective coatings have to reduce the reflection on the surface of the cells. At the same time they are a protective layer and can play a role to passivate the surface. A wide range of anti reflection coatings is used: SiO, TiO_2, Ta_2O_5 and Si_3N_4 are all materials that have their refractive index approximately matched for transition from air or glass to silicon.

The technique most widely used to apply these coatings is the sputtering or evaporation technique. This vacuum process can produce films of very high quality and of very well controlled uniformity. This process allows also to deposit multilayer films, that can reduce the reflection to 3-6%. The main drawback are that the vacuum process is a batchprocess of limited throughput and fairly expensive.

TiO_2 can however also be applied by spin-on or spray-on. TiO_2 is then mixed in an alcohol, and after spinning or spraying, a short bake transforms the film in a glassy hard layer. The optical properties of these films are almost as good as the evaporated ones. The big advantage here obviously is the very cheap process. Very high throughputs at almost no investment costs can be achieved. Reflection can be reduced in the 7-10% range on bare silicon.

On anisotropic etched surface however, the uniformity of spinned layers will probably be very bad. In that case, spray-on seems a better candidate. For uniform layer however, one will surely need an evaporation technique. Care must be taken however, that one remains cost effective: an evaporated AR coating indeed only reduces the reflection from 11% to about 3%. One has certainly to consider whether a non-uniform layer, which reduces the reflection to about 6-7%, is not more cost effective. The choice is then between a 3-4% gain of reflection against the cost of a vacuum evaporation process step.

(d) Metallization

The metallization is the last step in the cell processing (Fig. 8). The front pattern is designed as the best compromise between metalcoverage and series resistance, with the technological limitations as the design input. The metallization process has to fultil the following conditions:

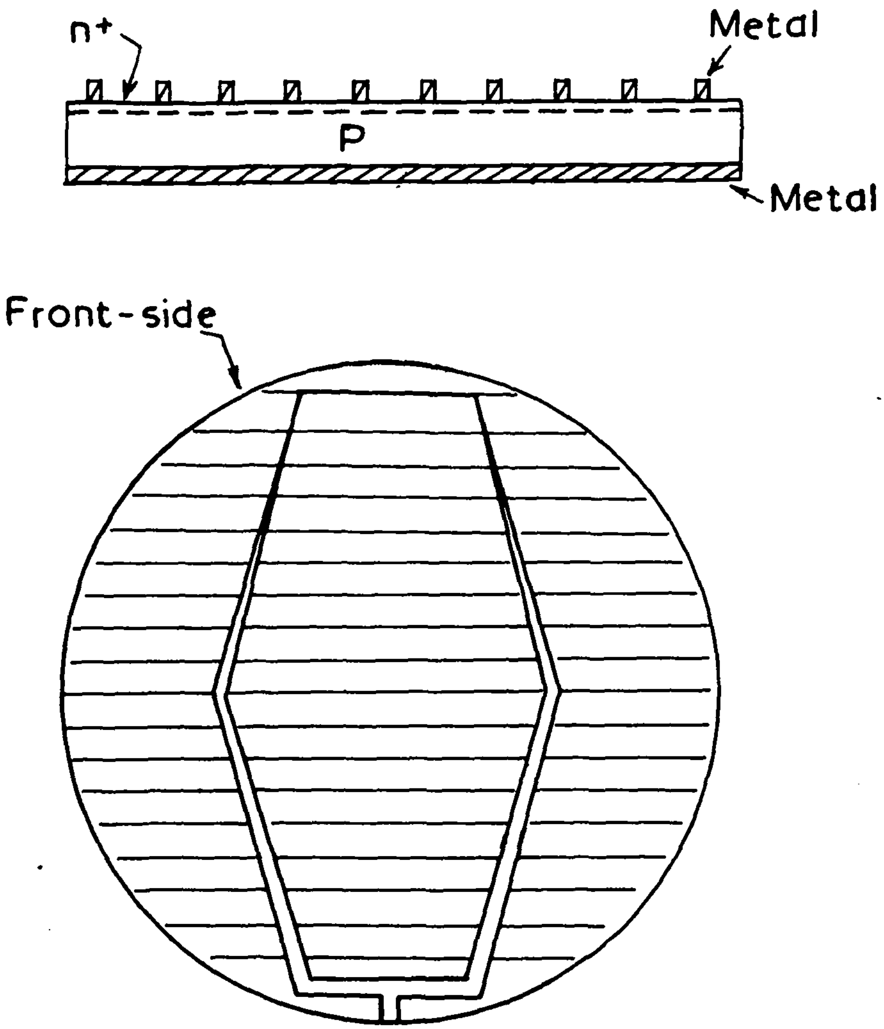

Fig. 8. Cross section of a solar cell showing the metal contacts. Example of front **metal** finger structure.

- the contacts on the silicon must be ohmic, with as low as possible contact resistance on both front and back side,

- the front metal has to have a low sheet resistivity,

- the contacts must be reliable: good adhesion and stability in time,

- the metallization process must be compatible with the other process steps.

Three distinct methods are reported:

The first one is the best known and widely used evaporation technique. Evaporation or sputtering of the metals is performed in a high vacuum chamber. The mostly used metal systems are Ti-Pd-Ag and Al-Ag. These systems have proven to yield good reliable contacts when the proper sintering steps are performed. Eventually the vacuum step can be followed by a Ag-plating on the front side to reduce even more the metal sheet resistance and consequently the series resistance.

The main drawback of this technique is the high cost. High investment costs together with relatively low throughputs and high material costs (high purity metals and low material yield) are its cause. Another difficulty is that such a process evaporates the whole surface. To define the pattern one has to use a photolithographical technique, either by etching or by lift-off. With these methods, it is possible to make patterns of very fine geometry with high accuracy. For cells designed for high concentration where series resistance becomes a predominant parameter, this technique has certainly no competitors. Although there exists a lot of appropriate equipment for this process on the market (for the semiconductor industry), this technique will not be the winner in the long run. Other techniques, requiring lower investments, simpler in operation, and having higher throughputs are coming on. A possible way to overcome this pattern definition problem, is to evaporate through metal masks. This technique reduces the operating time by a great amount, but at the expense of accuracy. The minimum linewidth is also limited here to 100 μm.

A second metallization system, also widely used for solar cells, is the electroless or electroplating. Here again, photolithography has to be used to define the front pattern usually in the AR coating. The most often reported technique is the Ni electroless plating. It is however not yet clear if this plating meets all the requirements; more specific is the question whether a good adhesive Ni contact is compatible with a shallow junction.[10, 11] The plating is often followed by a solderdip to make low resistive metal layers. Another plating system, very successfully as reported[11] consists of Palladium silicide – Palladium-Nickel and solderdipped for low resistivity. The good contact on shallow junctions is obtained by the controllable Pd_2 Si reaction on the silicon surface and appropriate heat treatments. Little is reported however on the costs of this system.

The third metallization method here described is the screen printing technique. A possible process sequence is represented in figure 9. A silver (Ag) paste is used for the

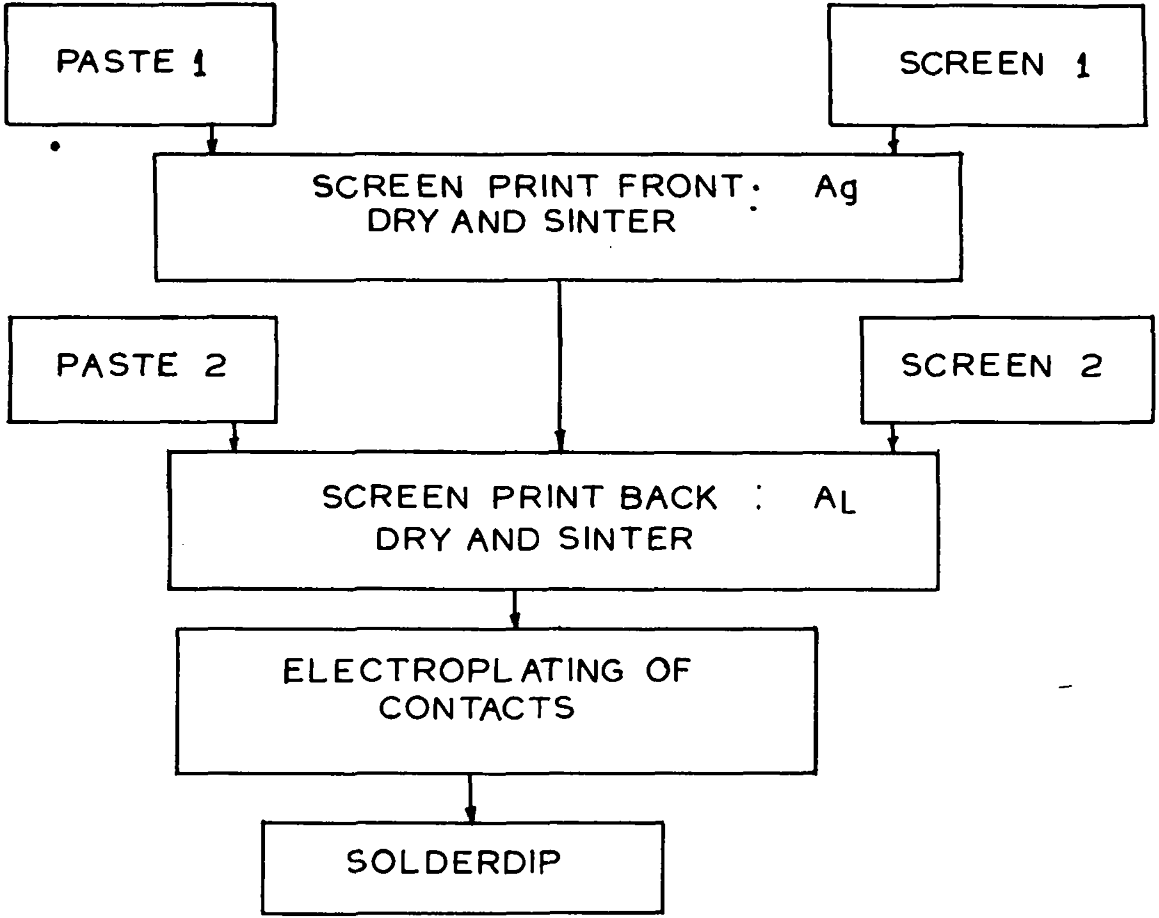

Fig. 9. Process sequence for screen printed contacts.

frontside, Al-paste and Ag-paste for the backside. After firing, both front and back are good reliable ohmic contacts. Contacts made in this way were reported to be very reliable.[12] Solar cells with average measured efficiencies of 13% have been made. Some major advantages that favour this technique are: very high throughput sequence, the investments are low, the material consumption is low and the material yield is almost 100%, the whole sequence can be made fully automated.

Progress in the field is however still possible until now only high temperature firing (greater than 800°C) resulted in reliable contacts on n^+ diffusions. This imposes a limit on the shallowness of the junction. In order to use the process on very shallow junctions (0.3 μm), a low temperature paste ought to be developed with reliable contacts on n^+ diffusion. This screen-printing technique is one of the serious candidate for the metallization step in the future, because of its inherent advantages.

The two most interesting technologies thus seem the following:

Diffusion – Ion implantation

– Screen printing

Metallization – Screen printing on back and front side

AR Coating – Spin-on

– Screen printing.

Since the ion implantation method is still in the developmental stage it is difficult to evaluate the cost of the process. For large scale production it is however expected that this process will be low cost. The most promising technology right now seems to be the total screen printing process. Total screen printing means: screen printing diffusion source, screen printing front and back contacts, screen printed AR coating. Detailed analysis[4] shows that the cost of the cell processing is only US$ 0.40/pW for cells with an efficiency of 11% and US$ 0.30/pW for cells with an efficiency of 15%.

IV. *Conclusion*

Different cell manufacturing techniques are used in the industry and several new technologies are studied in the research laboratories. Although it is too early to decide which process will be used in the long run, it looks like the use of ion implantation is promising and that the total screen printing approach is most attractive even for small scale production. Whether these technologies will still be used ten years from now will depend also on the kind of silicon material (polycrystalline, sheet, – – – –) will be used at that time. The total screen printing process certainly is capable of bringing the solar cell module cost below US$ 1.0/pW.

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PERFORMANCE PREDICTION OF A THERMAL TRAP SOLAR ENERGY

by

H.P. GARG, N.K. BANSAL and SANT RAM

ABSTRACT

The performance of a thermal trap solar energy collector from the point of view of the stagnation temperature has been investigated experimentally as well as theoretically. The theoretical model based on the Fourier series method to solve the heat conduction equation, predicts the experimentally observed measurements very well. It is found that the trap material should have an optimum thickness for attaining maximum plate temperature. The thickness of air gap has very marginal effect on the performance.

1. INTRODUCTION

The essential difference between an ordinary flat plate solar energy collector and a thermal trap solar energy collector consists in introducing a slab of transparent material (plastic) in the later between the cover and the absorbing plate. This material which is usually known as trap material has a high transmittance in the region of the majority of arriving solar radiations and a low transmittance in the region of long wavelength thermal radiation. In addition, the trap material should posses a low thermal conductivity. This would restrict the conduction heat transfer from the plate towards the front of the collector, thus minimising the upward convection losses due to the reduced temperature gradient across the air gap in the collector.

A thermal trap solar energy collector has been found to perform better than an ordinary glazed one by Phillips [1] who studied the effects of the thickness of the trap material on its performance, both with and without the presence of a cover glazing, making use of analytical and experimental results. For the analytical part a numerical model developed by Smith [2] and Lukens [3] based on finite difference technique was used. However, no data about the optimum performance of the collector were available.

The purpose of the present paper is to study the optimum performance of a thermal trap solar energy collector experimentally and verify it by a model, which has been developed using a simple technique named the 'Fourier series method'. The hourly variation of the plate temperature under no fluid conditions for various parameters such as different thicknesses of the trap material, the insulation and the air gaps have been studied.

2. THEORY

The configuration of the system under study is given in Figure (i). To develop a theoretical model we have made the following assumptions:

1. Radiation of variable intensity So(t) fall on the surface of the trapping system.
2. The lateral dimensions of the trap material are large compared to its thickness, that heat conduction in the transverse direction and the end effects are negligible.
3. The properties of the trap material like its density and thermal conductivity do not vary with its position.
4. The effect of long wavelength radiation emitted in the body of the translucent slab is neglected.
5. The absorption of solar radiation in the pate of semi transparent material exposed to radiation So(t) follows

   the law

$$I(x) = So(t)\,(1\text{-}r) \sum_{i=1}^{n} W_i \exp(-M_i x) \qquad \dots\dots\dots\dots\dots\dots (1)$$

   Where W is the weighting factor. In the present case W is assumed to be having value one.

6. The absorber plate of the heat exchanger is assumed to be in direct contact with the traping material producing no discontinuity in temperature across the interface.

2.1 *CONTROLLING EQUATIONS*

The controlling equations for each of the elements of Figure 1 are given as

ENCLOSED AIR

$$M_2\, C_{p_2} \frac{\partial T_2(t)}{\partial t} = h_{3,2}\, A[T_3(x,t)|_{x=0} - T_2(t)]$$
$$- U_1\, A\,[T_2(t) - Tam(t)] \qquad \dots\dots\dots\dots\dots\dots (2)$$

TRAP MATERIAL

$$\frac{\partial^2 T_3(x,t)}{\partial x^2} - \frac{\partial}{\partial x}\frac{I(x)}{K_3} = \frac{1}{\alpha_3}\frac{\partial T_3(x,t)}{\partial t} \qquad \dots\dots\dots\dots\dots\dots (3)$$

With boundary conditions

1. $$K_3 \frac{\partial T_3(x,t)}{\partial x}\Big|_{x=0} = h_{3,2}\,[T_3(x,t)|_{x=0} - T_2(t)] \quad \ldots\ldots\ldots (4)$$

2. $$T_3(x,t)|_{x=L_3} = T_4(t) \quad \ldots\ldots\ldots\ldots\ldots\ldots (5)$$

COLLECTOR PLATE

$$M_4 C_{p4} \frac{\partial T_4(t)}{\partial t} = -K_3 A \frac{\partial T_3(x,t)}{\partial x}\Big|_{x=L_3} + A a_4 \tau So(t)\exp(-\mu L_3)$$
$$- U_2 A[T_4(t) - Tam(t)] \quad \ldots\ldots\ldots\ldots\ldots\ldots (6)$$

Here U_2 is given as

$$\frac{1}{U_2} = \frac{1}{h_{3,2}} + \frac{L_5}{K_5} \quad \ldots\ldots\ldots\ldots\ldots\ldots (7)$$

SOLUTIONS OF EQUATIONS

The ambient temperature and the solar intensity So(t) are assumed to be given by the following Fourier series

$$Tam = Tamo + Re \sum_n Tamn \exp(in\omega t) \quad \ldots\ldots\ldots\ldots\ldots\ldots (8)$$

$$So(t) = bo + Re \sum_n bn \exp(in\omega t) \quad \ldots\ldots\ldots\ldots\ldots\ldots (9)$$

For the solution of the equation (3), T_3 (x, t) is assumed to be given by

$$T_3(x,t) = T_{30(x)} + Re \sum_n T_{3n}(x)\exp(in\omega t) \quad \ldots\ldots\ldots\ldots\ldots\ldots (10)$$

The solution of the equation (3) thus obtained is given by

$$T_3(x,t) = N + Kx - \frac{bo(1-r)\exp(-\mu x)}{\mu K_3}$$
$$+ \sum_n [(C_1 \exp(px) + C_2 \exp(-px))$$
$$\frac{-bn(1-r)}{2PK_3}\left(\frac{\exp(px)}{(\mu+p)} - \frac{\exp(-px)}{(\mu-p)}\right.$$
$$\left.+\frac{2P\exp(-\mu x)}{(\mu^2 - P^2)}\right)]\ \exp(in\omega t) \quad \ldots\ldots\ldots\ldots\ldots\ldots (11)$$

Where C_1, C_2, N and K are constants and $P = \left(\frac{in\omega}{\alpha_3}\right)^{1/2}$

The plate temperature $T_4(t)$ is also periodic; hence one can write $T_4(t) = T_{40}$

$$+ \operatorname{Re} \sum_n T_{4n} \exp(in\omega t) \qquad \text{.................} \quad (12)$$

Similarly enclosed air temperature $T_2(t)$ may be written as

$$T_2(t) = T_{20} + \operatorname{Re} \sum_n T_{2n} \exp(in\omega t) \qquad \text{.................} \quad (13)$$

From equations (2), (4), (5) and (6), one gets for the time independent part;

$$\begin{bmatrix} K_3 & -h_{3,2} & h_{3,2} & 0 \\ L_3 & 1 & 0 & -1 \\ 0 & h_{3,2} & -\left(\begin{matrix} h_{3,2} \\ +U_1 \end{matrix}\right) & 0 \\ K_3 & 0 & 0 & U_2 \end{bmatrix} \begin{bmatrix} K \\ N \\ T_2 0 \\ T_4 0 \end{bmatrix} = \begin{bmatrix} b_1 \\ b_2 \\ b_3 \\ b_4 \end{bmatrix} \qquad (14)$$

where

$$b_1 = \frac{-bo(1-r)(h_{3,2} + \mu K_3)}{\mu K_3} \qquad \text{.................} \quad (15)$$

$$b_2 = bo(1-r)\exp(-\mu L_3) \qquad \text{.................} \quad (16)$$

$$b_3 = -U_1 \, Tamo + \frac{bo\, h_{3,2}(1-r)}{\mu K_3} \qquad \text{.................} \quad (17)$$

$$b_4 = U_2 \, Tamo - (1-r)(1-\alpha_4 \tau)\, bo \exp(-\mu L_3) \qquad \text{...............} \quad (18)$$

Similarly the constants of the time dependent part are given by the following matrix equation;

$$\begin{bmatrix} K_3P-h_{3,2} & -(K_3P+h_{3,2}) & h_{3,2} & 0 \\ \exp(PL_3) & \exp(-PL_3) & 0 & -1 \\ h_{3,2} & [h_{3,2}] & -\left[\dfrac{h_{3,2}+U_1 \atop +m_2 C_{p2\, in\omega}}{A}\right] & 0 \\ K_3P\exp(PL_3) & -K_3P\exp(-PL_3) & 0 & \left[\dfrac{\frac{m\mu cp_4}{in\omega}}{A} + U2\right] \end{bmatrix} \begin{bmatrix} C_1 \\ C_2 \\ T_{2n} \\ T_{4n} \end{bmatrix} = \begin{bmatrix} b_{11} \\ b_{12} \\ b_{13} \\ b_{14} \end{bmatrix} \qquad (19)$$

Where

$$b_{11} = 0 \tag{20}$$

$$b_{12} = \frac{bn(1-r)}{2PK_3}\left[\frac{(\mu-p)\exp(PL_3)-(P+\mu)\exp(-PL_3) + 2P\exp(-\mu L_3)}{(\mu^2-P^2)}\right] \tag{21}$$

$$b_{13} = -U_1\,\mathrm{Tamn} \tag{22}$$

$$b_{14} = U_2\,\mathrm{Tamn} + \left[\frac{bn\,(1-r)\exp(-\mu L_3)(a_4\tau + ((\mu-P)\exp(PL_3) + (\mu+P)\exp(-PL_3) - 2\mu P\exp(-\mu L_3))}{2(\mu^2-P^2))}\right] \tag{23}$$

Matrix equations (14) and (19) are solved by matrix inversion method. The numerical calculations have been performed on ECIL Micro 78 Computer in Indian Institute of Technology, Delhi.

3. EXPERIMENT

To test the validity of the developed theoretical model for the thermal trap collector experiments were carried out for different trap thicknesses simultaneously varying the width of the air gap. Three test collectors were built being as closed to each other as possible, so that simultaneous testing of different configurations of the thermal trap solar energy collector could be done on the same day. The collectors were designed so that the internal components can be changed with a minimum of trouble and also that operation of one collector would not effect the performance of others. Three collectors on which the experiments were performed are schematically given in Fig. 2. The insulation used was fibreglass, and its thickness was kept 5.08 cm. The cover used was 0.3 cm thick. The plate temperature was measured using a copper constant thermo-couple which was, calibrated with the help of an electronic digital milli-voltmeter.

4. RESULTS AND DISCUSSIONS

Experiment was performed on 17 March, 1980 under no fluid flow conditions. The corresponding data for the solar radiation was measured on the collector surface, which was kept inclined at an angle of 45° from the horizontal, using Eppley Black & White Pyranometer made by Eppley Laboratory, Inc. Scientific Instruments. New Port R.I. 02840 U.S.A. The calibration factor of this pyranometer is 7.45 mv/cal/cm^2/min. The ambient temperature data was obtained from Meteorological Laboratory at New Delhi. The Fourier coefficients of the solar radiation and the ambient temperature are given in the table I and II. The following data was used for the calculations

Table 1. Fourier coefficients of the solar radiation corresponding to 17 March, 1980 at New Delhi

	n										
	0	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*
a_m	275.8027	429.69	232.04	49.416	43.96	39.017	9.157	21.16	16.037	3.926	9.332
∂_m	275.8027	3.245	0.1769	3.13	3.884	0.573	2.512	4.327	0.988	2.899	4.684

Table 2. Fourier coefficients of the ambient temperature corresponding to 17 March, 1980 at New Delhi

	n										
	0	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*
a_m	32.629	6.334	0.984	0.359	0.589	0.495	0.182	0.207	0.055	0.0607	0.039
∂_m	32.629	4.126	0.312	01.557	5.268	5.392	4.449	4.229	5.145	2.671	5.484

r	=	0.04
α_4	=	0.85
τ	=	0.9
$h_{3,2}$	=	9.25 $W/m^2\,^oK$
U_1	=	6.708 $W/m^2\,^oC$
U_2	=	1.5 $W/m^2\,^oC$

TRAP MATERIAL

ρ	=	1190.0 Kg/M^3
C_p	=	1500.0 $J/Kg.^oK$
K	=	0.2 $WM^{-1}\,^oK^{-1}$

PLATE MATERIAL

M	=	0.26012 Kg
A	=	0.0929 m^2
C_p	=	913.0 J/Kg.K
ρ	=	2800 Kg/m^3

AIR

M	=	0.00559 Kg
A	=	0.0929 m^2
C_p	=	1006.0 $J/Kg.^oK$
ρ	=	1.1774 Kg/m^3

In fugure 3, hourly variation of plate temperature obtained theoretically and measured experimentally for various trap thicknesses has been plotted. It is clearly seen that there is a good agreement between theoretical and experimental results.

It is interesting to note that as the trap thickness is increased from 0.002 m to 0.005 m, the maximum of the plate temperature is obtained at the trap thickness of 0.003 m. This result is an expected one since an increase in the thickness of the trap material reduces the incident energy at the plate but simultaneously it also reduces the upward conduction losses from the plate.

Fig. 5 shows the effect of increasing the width of air gap on the maximum of the plate temperature. As the gap increases the temperature decreases which is attributed to the increased convection.

5. CONCLUSION

The performance of a thermal trap solar energy collector has been studied experimentally and compared with the corresponding theoretical calculations performed using a model based on the Fourier series solution of the heat conduction equation. The theoretical model predicts the experimental results very well. It has been found that the trap material should have an optimum thickness for the maximum plate temperature. The air gap thickness, though effects the plate temperature marginally, should be kept to its minimum possible value for minimum upward convection losses.

The performance of the system under active fluid flow conditions is being investigated presently.

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NOMENCLATURE

A = Area, m^2

α = Absorptance, dimensionless

C_p = Specific heat, J/Kg-$^\circ$C

h = Convection heat transfer coefficient, W/m^2-$^\circ$C

I = Beam Strength, W/m^2

K = Thermal conductivity, W/m^2

L = Length, m

M = Mass, Kg

r = Reflectance, Dimensionless

t	=	Time, hr.
T	=	Temperature, ^{o}C
U	=	Overall heat loss coefficient, $W/m^2 \cdot {}^{o}C$
x	=	Coordinate, m
α	=	Thermal diffusivity, m^2/hr
τ	=	Transmittance, Dimensionless
μ	=	Absorption coefficient, 1/cm.

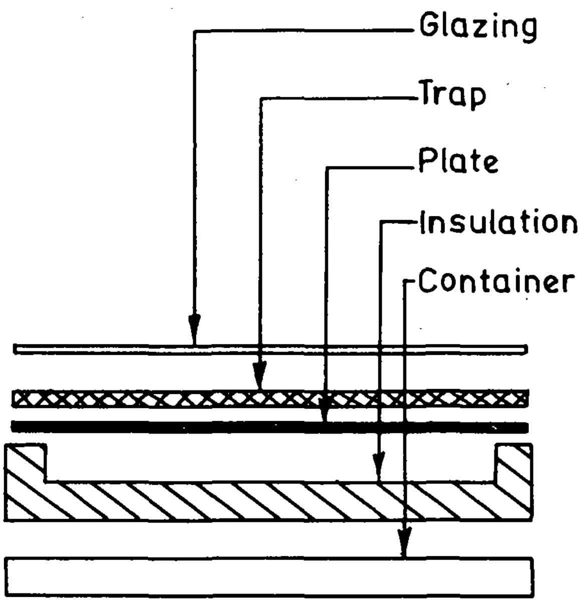
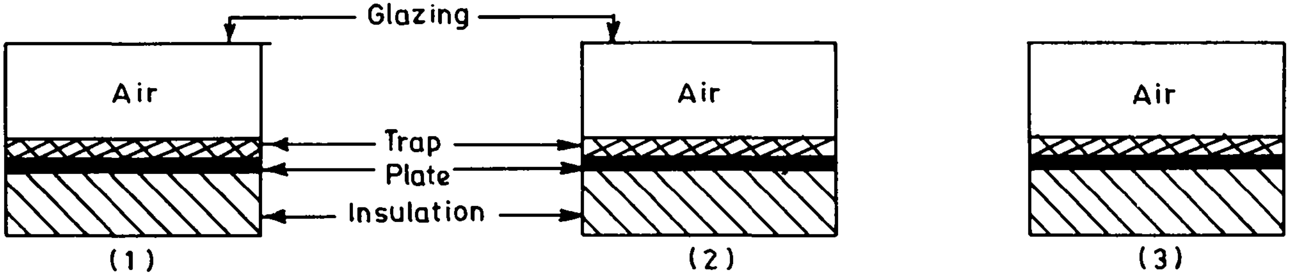


Fig.1. Exploded view of a thermal trap collector.



Trap Thickness = .002 m. Trap Thickness = .003 m. Trap Thickness = .005 m.

Fig. 2. THREE IDENTICAL SOLAR COLLECTOR.

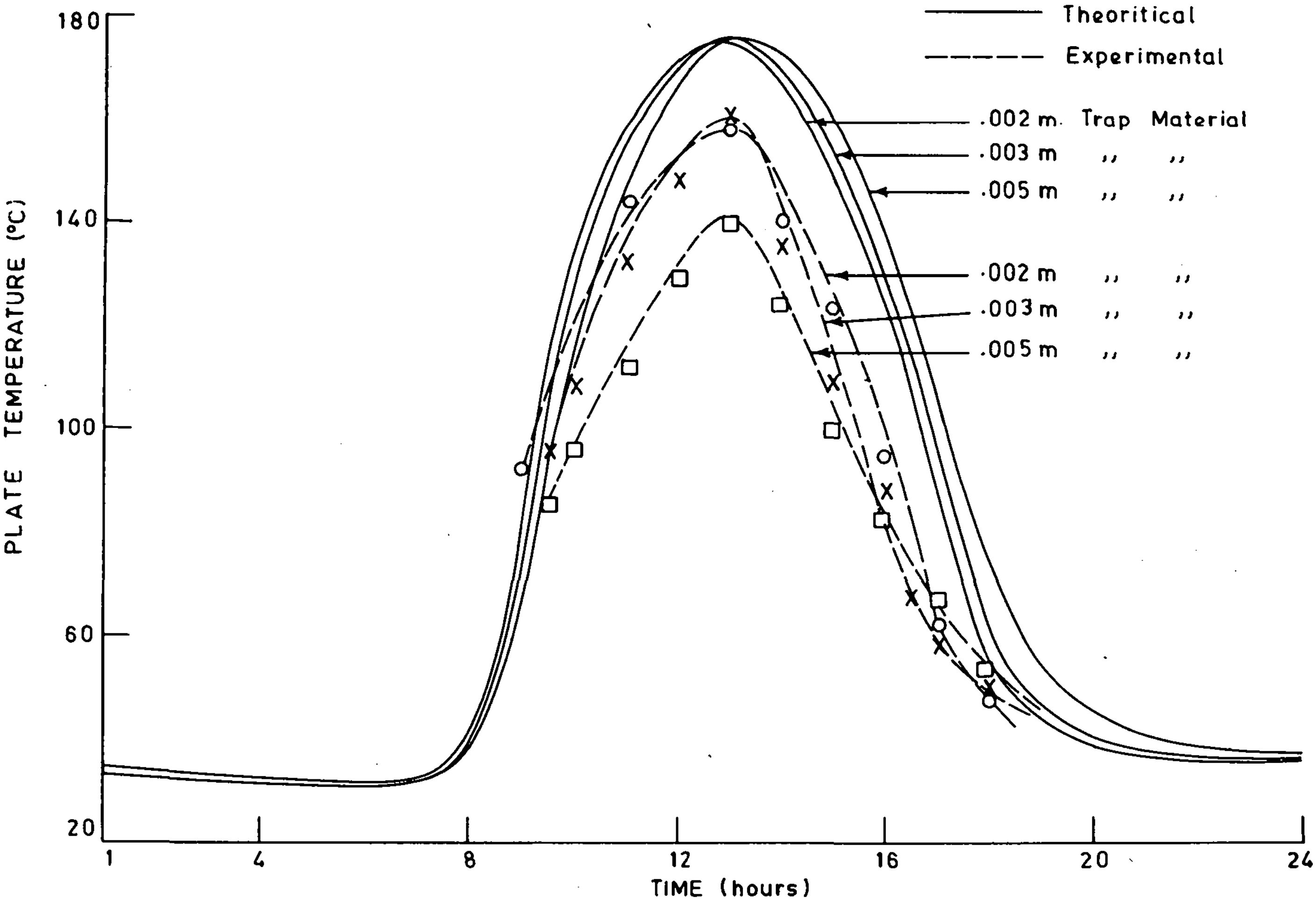

Theoritical
Experimental
.002 m. Trap Material
.003 m ,, ,,
.005 m ,, ,,
.002 m ,, ,,
.003 m ,, ,,
.005 m ,, ,,
180
140
100
60
20
PLATE TEMPERATURE (°C)
1
4
8
12
16
20
24
TIME (hours)

Fig. 3

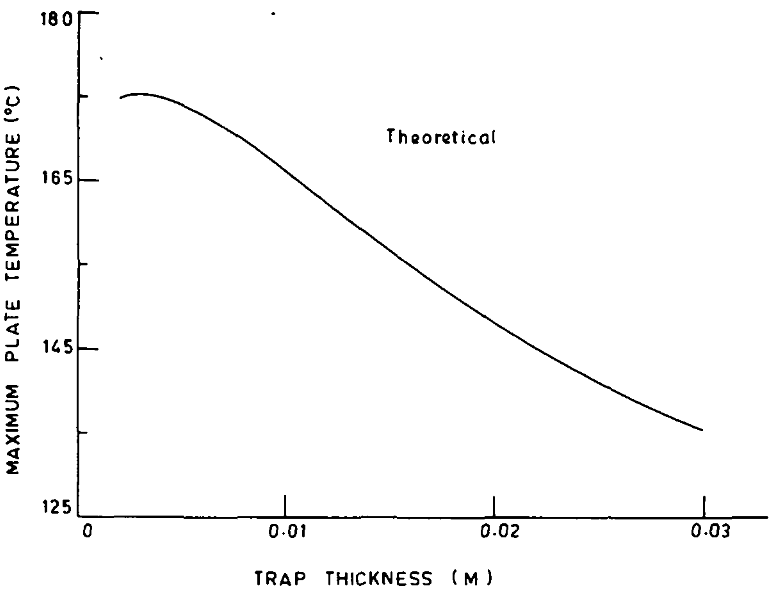

180
165
145
125
MAXIMUM PLATE TEMPERATURE (°C)
Theoretical
0
0·01
0·02
0·03
TRAP THICKNESS (M)

Fig. 4

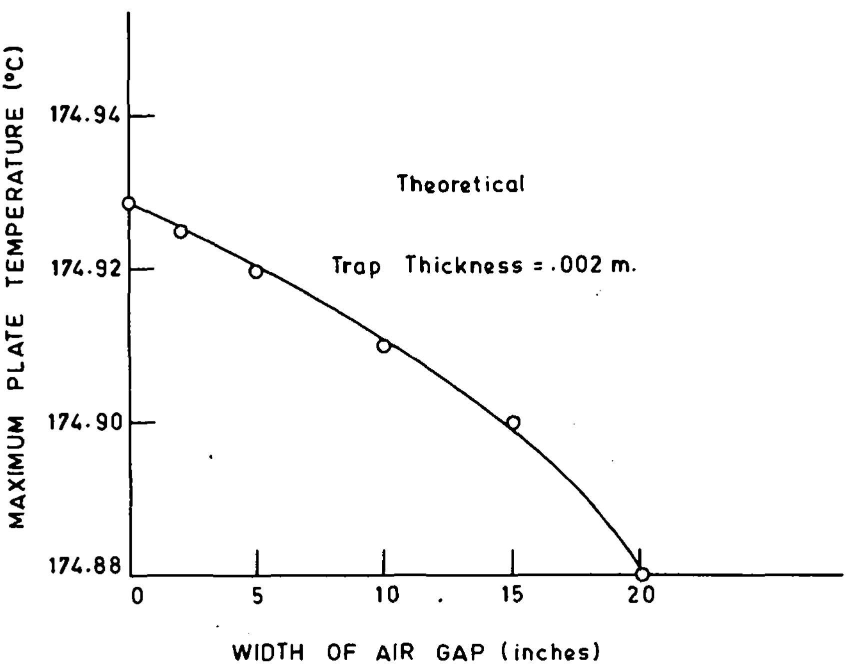

174.94
174.92
174.90
174.88
MAXIMUM PLATE TEMPERATURE (°C)
Theoretical
Trap Thickness = .002 m.
0
5
10
15
20
WIDTH OF AIR GAP (inches)

Fig. 5

STUDIES ON LOW-TEMPERATURE SALT-HYDRATE FOR THERMAL STORAGE

by

H.P. GARG and M. NASIM

ABSTRACT

A novel thermal - energy storage concept involving the use of salt-hydrate such as sodium Thiosulphate Pentahydrate, $Na_2S_2O_3 . 5H_2O$ is under investigation. With fusion temperatures of many salts lying between 0 and 100°C, such substances may be considered as likely materials to be used in conjunction with solar energy flat-plate collector system for domestic use. Phase change storage or latent heat storage is concluded to be the promising technique of storing the solar energy. The solid-liquid transformation of salt-hydrates is actually a dehydration or hydration of salt, although this process resembles melting or freezing thermodynamically. Three types of behaviour can be identified: Congruent, incongruent, and semicongruent melting. None of the congruent melting salt-hydrates have been judged for use in thermal storage because of cost and safety considerations.

INTRODUCTION

One of the major problem areas impending the utilization of solar energy for heating and cooling of buildings, for the generation of electrical energy, and for many other applications is the absence of a low cost, reliable, thermal storage system that does not require a large amount of space. Since solar energy is available only during a limited number of hours each day, and may not provide significant amounts of energy on cloudy or partially cloudy days, some means for storing the Sun's energy, when it is available, will ultimately be necessary if solar energy is to provide a large fraction of our energy needs. A large number of potentially viable storage systems for thermal energy have been devised, studied, and tested in the past including the use of water, rocks, salt-hydrate materials, etc. However, most of these systems require a large volume in order to store a significant amount of heat energy.

Maria Telkes (1) first studied the properties of glauber's salt, $Na_2SO_4 . 10\ H_2O$, the first material to be considered extensively for thermal storage in houses. Somewhat earlier than this, a longer lasting 'hot water bottle' to serve as bed warmer had utilized sodium acetate (2). The other material, disodium phosphate dodecahydrate, $Na_2HP_4 .$ $12\ H_2O$, appeared to be of interest as a candidate storage material. Sodium Thiosulphate Pentahydrate, $Na_2S_2O_3 . 5\ H_2O$, is selected for present study. Initital experiments are carried out with this material. This material is chosen in as far as it has been used extensively in storage systems and has a phase transition temperature which, being in the range useful for domestic storage.

The objective of the work is to investigate various properties of $Na_2S_2O_3 \cdot 5\,H_2O$ such as the phase separation, supercooling, nucleation, rate of crystallization and specific gravities with different concentrations and temperatures are studied and reported in this paper.

EXPERIMENTAL QUALITATIVE STUDIES OF TWO COMPONENT SYSTEM-SODIUM THIOSULPHATE PENTAHYDRATE ($Na_2S_2O_3 \cdot 5\,H_2O$).

This salt is the photographer's "hypo", although a less pure technical grade can be used for thermal storage purposes. It contains 64% $Na_2S_2O_3$ and 36% water by weight. The phase transformation reactions are

$$Na_2S_2O_3 \cdot 5\,H_2O \rightleftharpoons Na_2S_2O_3 \cdot 2\,H_2O + 3\,H_2O \text{ at } 47.7\,^\circ C$$

$$Na_2S_2O_3 \cdot 2\,H_2O \rightleftharpoons Na_2S_2O_3 + 2\,H_2O \text{ at } 48.8\,^\circ C$$

Sodium Thiosulphate Pentahydrate crystals melt partially incongruently to give solution and 2 H_2O crystals. At 47.7°C, $Na_2S_2O_3$ dissolves completely in its water of crystallization. The density of the salt is 1.72 gm/c.c. The heat of fusion is 50 K cal/kg. When comparing the heat content of this material with H_2O in the 43.3°C to 54.4°C temperature range, the heat content of this salt-hydrate is 5.5 times greater than that of water based on equal weights.

The results of several tests with sodium thiosulphate (Pentahydrate) are shown in Fig. 1. The salt was heated to 65.0°C, melted completely, supercooled below 37.5°C and crystallized at 47.6°C, solidifying completely. A nucleating agent has been found to eliminate supercooling.

TRANSITION TEMPERATURE

A transition temperature may be determined by a cooling or heating curve. Thus, for example, if water is cooled sufficiently, its temperature will fall continuously until 0° C is reached. After staying at 0° C until all the water has frozen, the temperature will again continue to fall. The heat evolved on freezing counterbalances the heat-losses and maintains the system at the freezing temperature as long as any liquid water is left.

The transition temperature of sodium thiosulphate pentahydrate is being studied (3). This is the temperature at which the hydrated sodium thiosulphate is in equilibrium with the anhydrous form

$$Na_2S_2O_3 \cdot 5\,H_2O \rightleftharpoons Na_2S_2O_3 + 5\,H_2O.$$

Under these conditions there are two components, sodium thiosulphate and water, and four phases, anhydrous sodium thiosulphate, hydrated sodium thiosulphate, solution and vapour. According to the phase rule, $F = C - P + 2$, the variance is zero, and there is only one temperature and pressure at which all these phases can be in

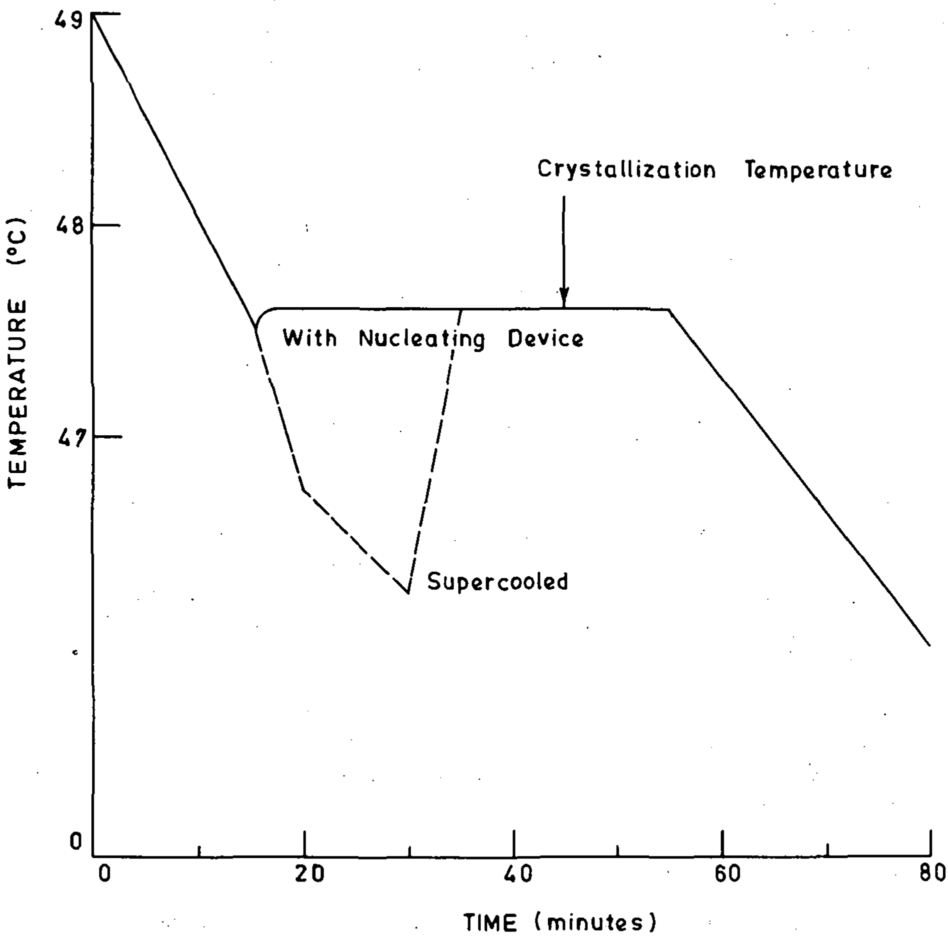


Fig.1. NUCLEATING DEVICE AVOIDS SUPERCOOLING OF $Na_2S_2O_3 \cdot 5H_2O$.

equilibrium. This temperature is 48.3 °C (Fig. 2) and it is just as definite as the freezing temperature of water where there are one component and three phases.

PHASE SEPARATION

In a multicomponent system often several phases are in equilibrium with one another. Such equilibria are extremely sensitive to variations in composition and temperature. This can be described by the phase diagram. Separation of phases occurs as a result of density differences between the various phases.

Sodium thiosulphate pentahydrate fulfils the requirements of low cost and high heat-of-fusion. It is not one component system, however, and there is always the risk of formation of four phases, thus making phase separation possible. The latter results in a disturbed chemical equilibrium and the phase diagram may no longer describe the performance of the system.

A phase diagram of $Na_2S_2O_3 . 5\ H_2O$ is studied and shown in Figs. 3 and 4 which indicate the solid and liquid phases that are present at each temperature and composition. A comparative study between molarity and molality has been shown in Fig. 5.

NUCLEATION

In any storage system based on salt-hydrates, energy input causes the bonds of hydration to break and the crystalline structure to break down. It is this melting of the crystals that stores the energy. When the time comes to retrieve this energy, the saltions need to recombine with themselves and with the requisite number of water molecules in a well-defined lattice structure, that is, the hydrate solid must nucleate and grow, thereby liberating the latent heat-of-fusion. Because of geometric restrictions and energy barriers to be overcome, spontaneous nucleation is not a very probable event. Either large supercooling to increase the probability of natural nucleus formation, a seeding agent to act as a trigger or some external forcing operation are required to cause nucleation. A piece of crystalline substance itself is of course an ideal nucleator.

Some substances, by virtue of similarities in crystalline structure, are known to nucleate other substances at only moderate supercooling. Borax ($Na_2B_4O_7 . 10\ H_2O$), being decahydrate itself, is one such substance that will nucleate sodium sulphate decahydrate ($Na_2SO_4 . 10\ H_2O$).[4] A short search was made for likely substances to nucleate sodium thiosulphate but no substance was found which leads to nucleation of sodium thiosulphate. However, sodium thiosulphate itself acts as a nucleating agent.

To measure the effectiveness and repeatability with which a crystal of sodium thiosulphate nucleates the saturated solution of $Na_2S_2O_3 . 5\ H_2O$, a standard constant temperature bath was modified to give sequential cooling and heating cycles. The temperature of a sample tube of solution could thereby be made to cool and warm cyclically about its melting point over longer periods of time (days and weeks).

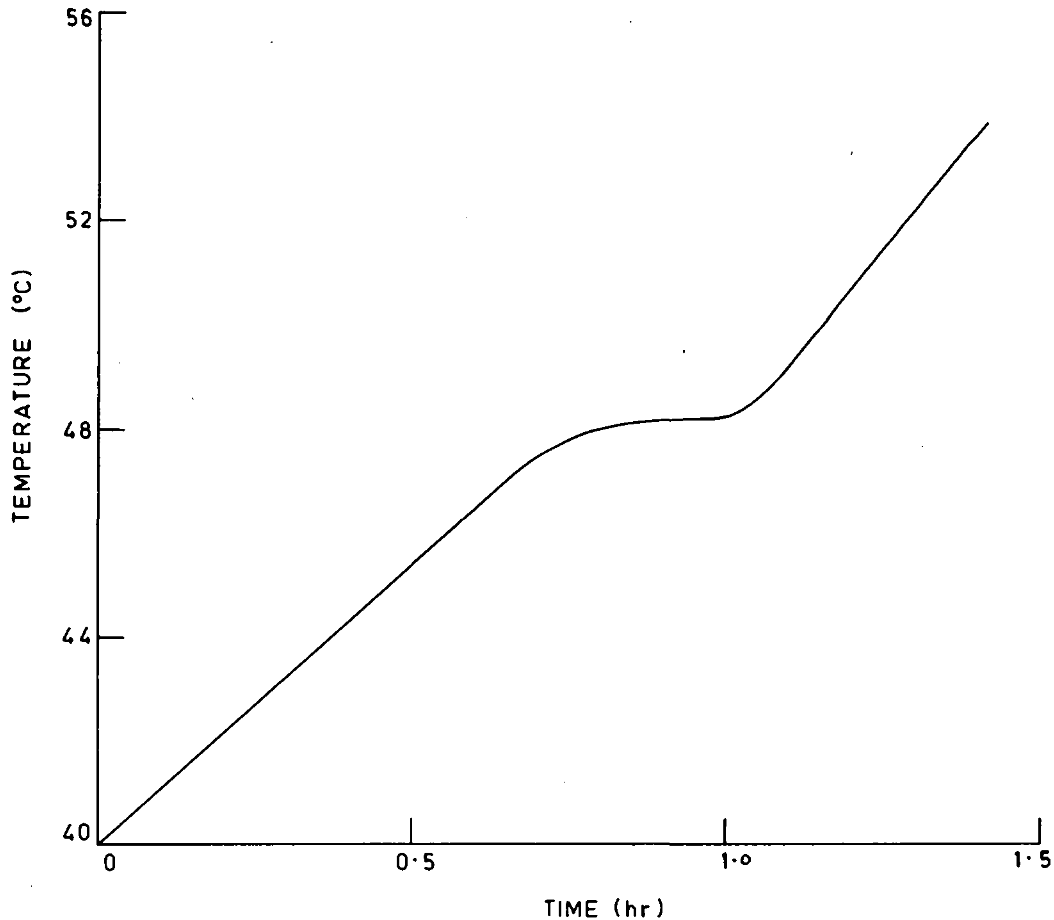


Fig. 2. TRANSITION TEMPERATURE OF $Na_2S_2O_3 \cdot 5H_2O$.

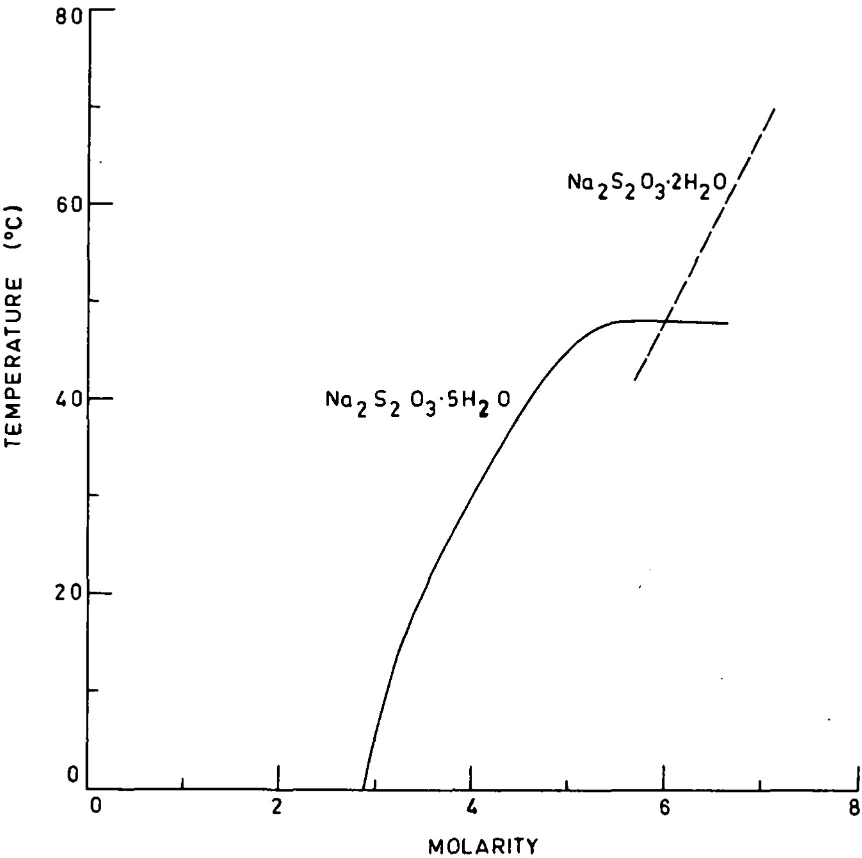


Fig. 3. PHASE DIAGRAM FOR AQUEOUS SOLUTIONS OF SODIUM THIOSULPHATE.

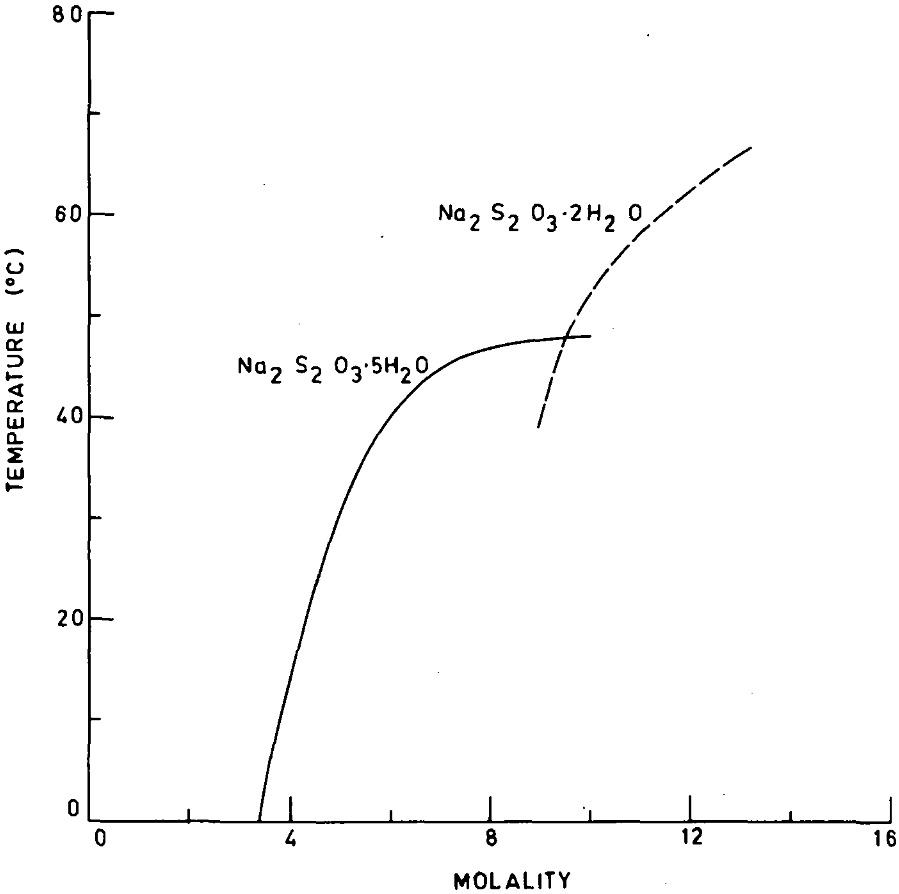


Fig. 4. PHASE DIAGRAM FOR AQUEOUS SOLUTIONS OF SODIUM THIOSULPHATE.

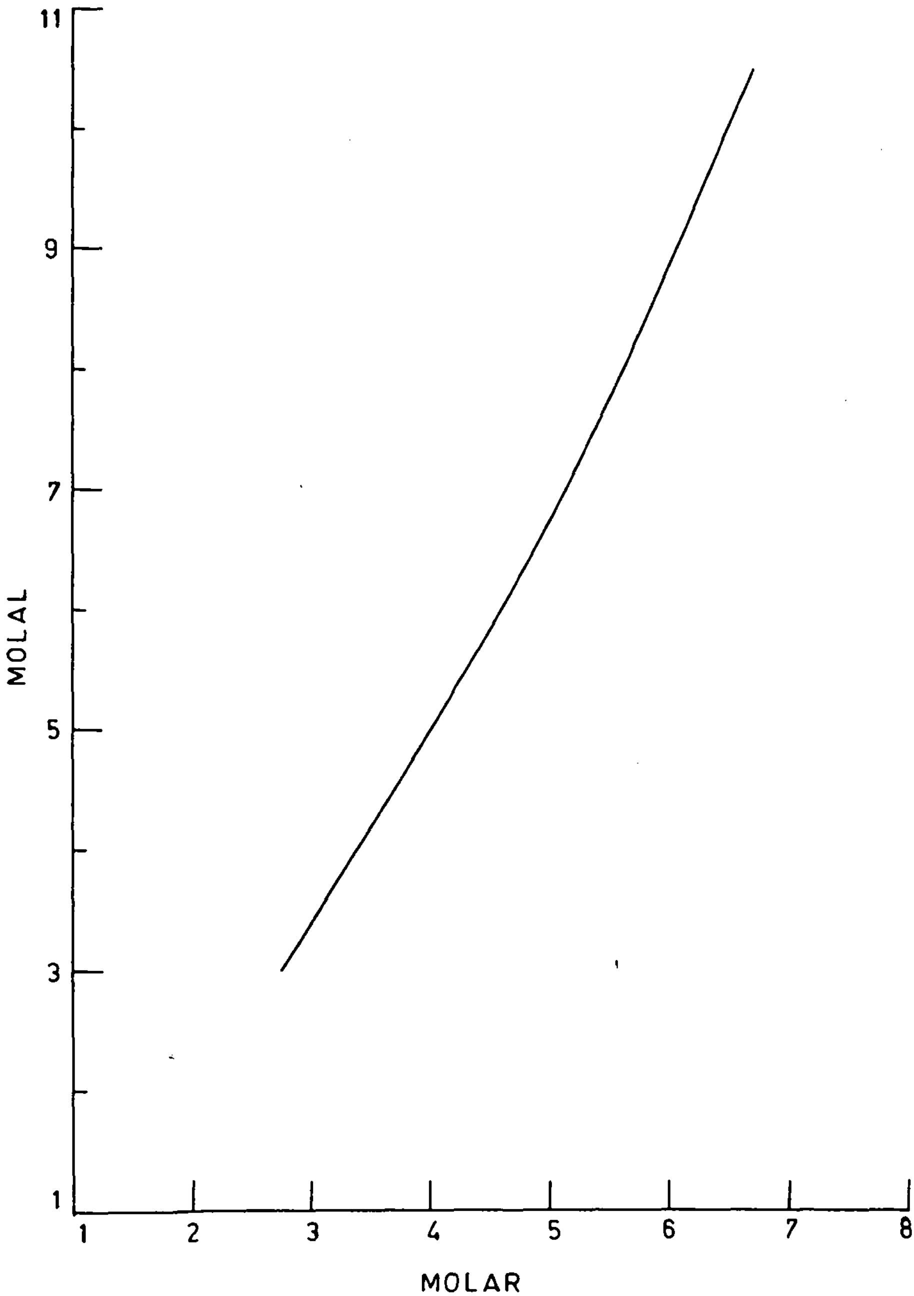


Fig.5. COMPARISION OF MOLARITY AND MOLALITY FOR AQUEOUS SOLUTIONS OF SODIUM THIOSULPHATE.

A thermocouple in the bath coolant sensed the end points of the temperature ramps, while one junction of a thermocouple mounted in sealed glass tube embeded inside the sample measured the temperature of the solution as a function of time relative to that of an ice both, the output being fed into a strip chart recorder. Each nucleation event is seen along cooling curves as a sharp increase in temperature resulting from sudden release of latent heat as the crystal nucleates and grows. Due to small sample size and effective heat-transfer to the bath fluid, the indicated temperature never reaches the equilibrium transition point of the crystals. After ramp reversal, the crystalline sample warms and eventually melts, as indicated by the smoother hump along the warming curves (Fig. 6). The presence of the melting hump near the expected temperature (48.3°C) lends confidence that the pentahydrate was the one that indeed nucleated.

RATE OF CRYSTALLIZATION

In the present investigation, the crystallization rate has been studied by taking into consideration the crystals growth with time as shown in Fig. 7. Crystals grow into a solution at a rate determined by the supersaturation or supercooling produced by cooling a solution beyond the temperature specified by its equilibrium solubility curve. The growth of crystals in sodium thiosulphate solution was more equiaxed.

SPECIFIC GRAVITIES OF AQUEOUS SODIUM THIOSULPHATE SOLUTIONS WITH DIFFERENT TEMPERATURES AND CONCENTRATIONS

Density measurements find numerous applications in Physical chemistry. The method used depends upon the accuracy required. Solutions of sodium thiosulphate in water containing 1, 2, 3, 4, 5, 6, 7, ... and 8 per cent sodium thiosulphate by weight were prepared. The salt and water were weighed out accurately into a relative density bottle i.e. pycnometer.

The density of each solution was determined accurately at 20°C and 50°C as shown in Fig. 8.

CONCLUSIONS

The study of sodium thiosulphate pentahydrate described above was undertaken from the view point of ascertaining the complexities which might arise in putting the concept of a continuous crystallization and sedimentation system into a practical unit. The most important conclusion from this study was that it would be difficult to utilize in practice heat exchangers in one component system which would be kept free of crystals throughout the crystallization cycle.

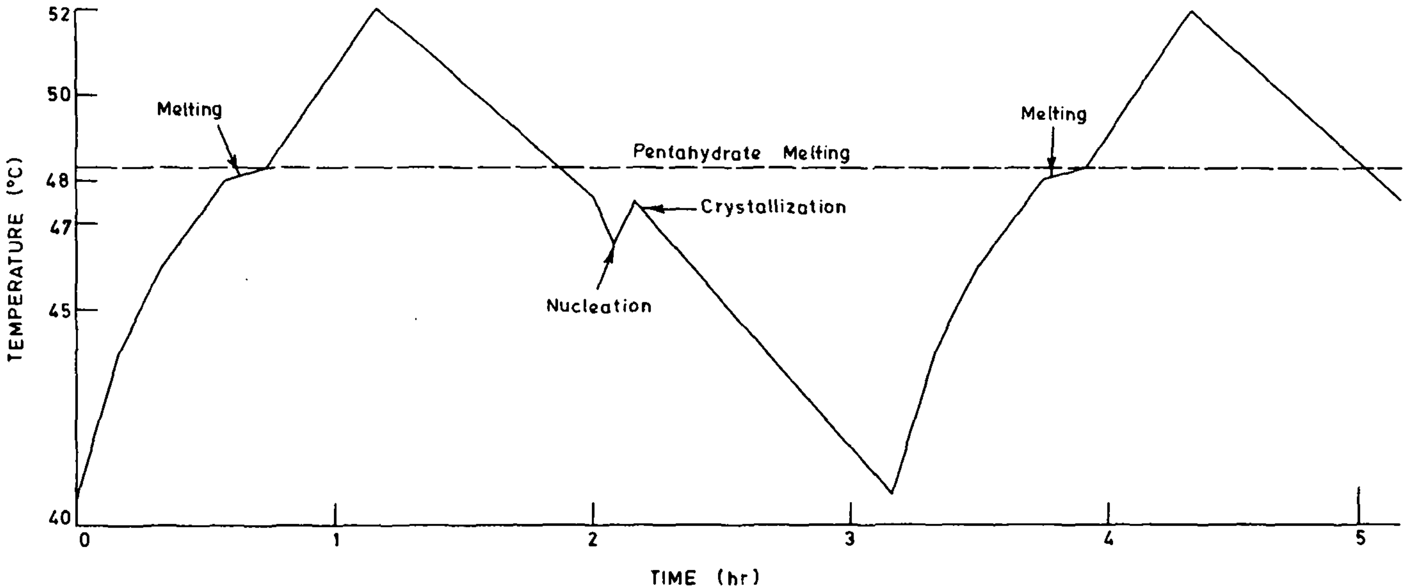


Fig. 6. AN EXAMPLE OF THE COOLING AND WARMING CURVES OF SODIUM THIOSULPHATE SOLUTION.

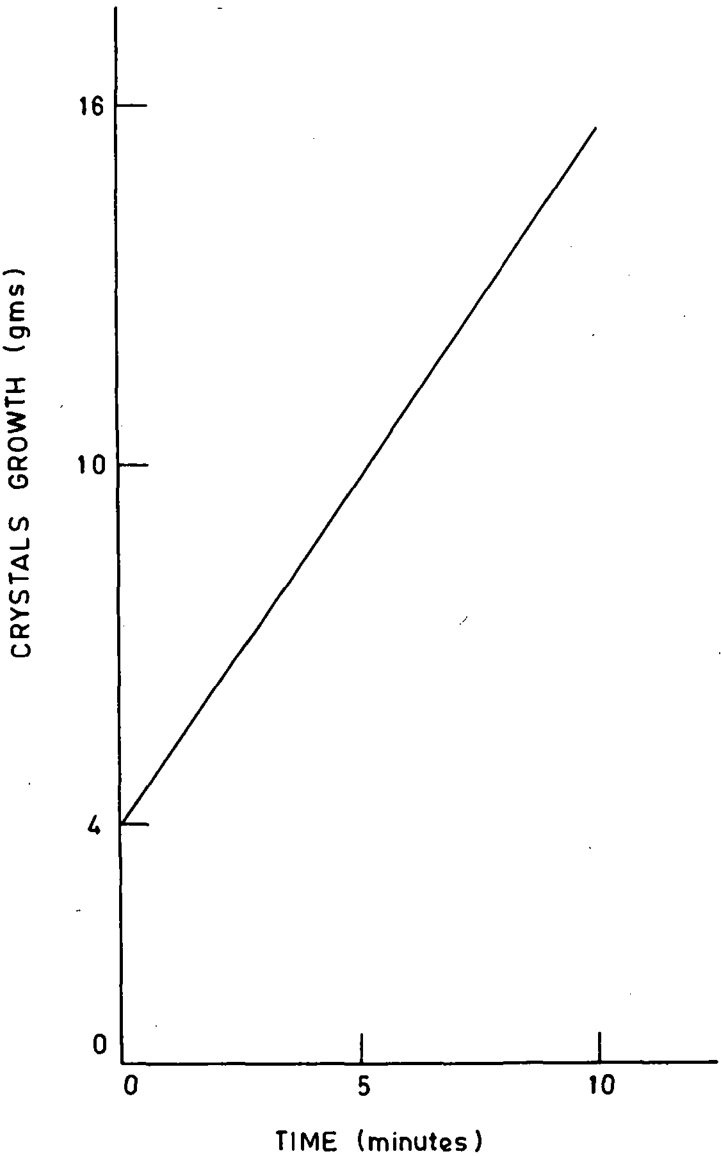


Fig. 7. RATE OF CRYSTALLIZATION OF SODIUM THIOSULPHATE PENTANYDRATE

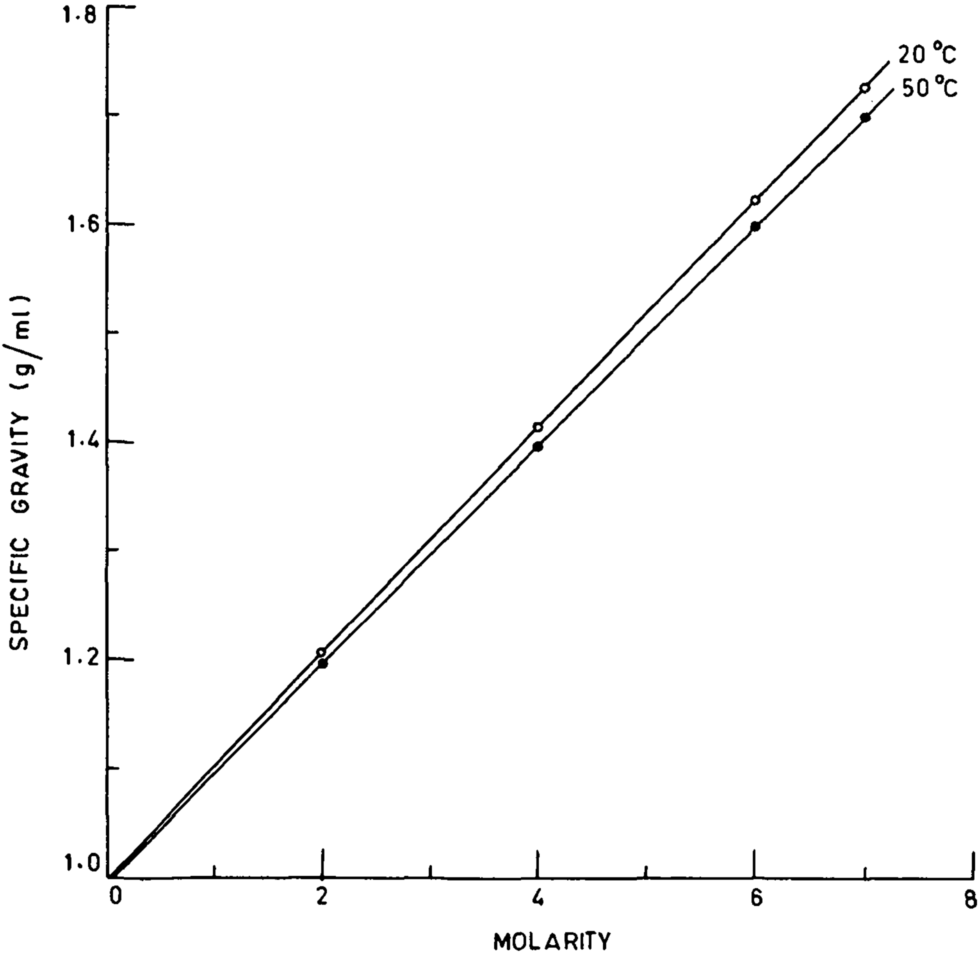


Fig. 8. SPECIFIC GRAVITIES OF AQUEOUS SODIUM THIOSULPHATE WITH DIFFERENT TEMPERATURES & CONCENTRATIONS.

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THERMAL PERFORMANCE STUDIES ON SOLAR AIR HEATERS FOR SPACE HEATING AND CROP DRYING

by

H.P. GARG, B. BANDYOPADHYAY, R.B. MAHAJAN
and V.K. SHARMA

ABSTRACT

This paper describes the design and performance test of three solar air heaters with an intention of utilizing solar energy for crop drying and space heating purposes. The first air heater is a conventional one whereas the second and third heaters are matrix type of different configurations. The performance of three air heaters have been compared when the pumping rate of inlet air is the same for all the heaters.

INTRODUCTION

Recently a great deal of attention has been paid on the problem of developing and optimizing the performance of solar air heaters. This is because the solar air heater is one of the important means of utilizing solar energy and can find applications in many processes requiring low and moderate temperatures. One of these processes is space heating, which has been found to be a quite reasonable process for maintaining a comfortable environment in buildings, specially in winter season. Solar drying is again a major application of solar air heaters with particular relevance to areas in the humid tropics. Information available on solar drying experiments conducted here and abroad definitely indicate that this drying method is superior to open air drying and can be developed further to benefit those with limited capital.

Solar air heaters can be classified into two broad categories; the first kind of it has a nonporous absorber of solar radiation while the second one has a porous absorber. A number of designs of solar air heaters and their performance studies have been reported by several workers,[1, 2, 3] which have helped a lot to gain insight into the design, performance and operation of these heaters for useful purposes.

Low fabrication cost and minimum maintainance cost are other attractive points of solar air heaters mainly because of absence of leakage and corrosion problem compared to liquid heaters. Keeping in mind the low cost of capital investment and utilization possibilities, mainly the agricultural drying, we have fabricated three different types of solar air heaters using indegineous materials. In this paper, we have reported the performance test procedure and data for these air heaters.

The performance equation:

The thermal performance of a solar collector is determined by passing the heat transfer fluid through it at a steady rate placing the collector outdoors under clear sunny conditions.

From the defination of overall instantaneous collector efficiency

$$\eta = \frac{Q_u}{AH} = \frac{m\,C_p\,(T_2 - T_1)}{H} \quad \ldots\ldots\ldots\ldots\ldots \quad (1)$$

One can find the efficiency η by experimentally measuring the air mass flow rate (m), inlet (T_1) and outlet (T_2) air temperatures and the solar insolation (H). 'A' is the collector area and C_p is the specific heat of air.

According to famous Hottel-Whiller-Bliss[4] equation, the collector efficiency η can be represented as

$$\eta = F_P\,[(\tau\alpha)_e - U_L\,(\frac{T_P - T_a}{H})] \quad \ldots\ldots\ldots\ldots\ldots \quad (2)$$

Where the plate efficiency factor (F_p) and the heat loss coefficient (U_L) can be considered essentially to be constant for any collector configuration and fluid flow rate. However, strictly speaking, this is an approximation which only gives a straight line curve when η is plotted against $\frac{T_P - T_a}{H}$. The scattered points in actual graph arround the straight lines are indications of the variation of heatloss coefficient (U_L) and the effective transmittance-absorptance product $(\tau\alpha)_e$ obviously alongwith the error in experimental measurements.

Here $T_P = \frac{T_1 + T_2}{2}$ and T_a is the ambient air temperature. Plot of equation (2) alongwith the plot of another important formula given by Whillier[5]

$$\eta = F_R\,[(\tau\alpha)_e - U_L\,(\frac{T_1 - T_a}{H})] \quad \ldots\ldots\ldots\ldots\ldots \quad (3)$$

Where F_R is the heat removal efficiency factor, gives the different rating parameters such as plate efficiency factor (F_P), heat removal efficiency factor (F_R), overall heat loss coefficient (U_L) and number of transfer units ($N = \frac{F_P\,U_L}{m\,C_p}$) etc.

Types of air heaters tested:

The different solar air heaters used for this investigation are shown in Fig. 1. All these have 5 cm. insulation on the rear side and all four sides and with a glazing of 3 mm. Thick glass sheet on the exposed side. The total absorber area of each of the collector was 112 x 80 = 8960 cm^2. These collectors were kept facing south at an inclination of 45° to the horizontal (latitude of Delhi being 28° 32'N). All were attached with an additional air duct with heating arrangement so that any required temperature of the inlet air can be obtained. An electrically driven air blower of capacity 190 watts, with flow rate adjustment disc was attached to the inlet duct. The three air heaters are shown in Fig. 2.

Type I: *Flat plate type conventional air heater:* This is a flat plate Jackated type air heater with 8 cm. space inside for air circulation. The flat absorbing plate was of galvanized iron of 20 gauge and coated with black board paint. The jacket was enclosed in a galvanized iron box which held it tightly. The air flow is paralled to the plate.

Type II: *Matrix type solar air heater* (air flow is parallel to the matrix): The air is circulated through the iron foils (waste from lathe machine) filled in the galvanized iron box having outside dimensions 123 x 91 x 20 cm^2 and 112 x 80 cm^2 absorbing area. This absorber area is considered of iron foils of different sizes spread on the box.

Type III: *Matrix type solar air heater with wire mesh:* (air flow perpendicular to the matrix): It is similar to that of type II just described; the only difference is that the iron foils are covered by galvanized wire mesh and this system is kept at an inclined position allowing air flow in perpendicular direction with the matrix. The air space between the glass and iron foils decreases along the length of the collector.

Experimental

For the evaluation of the day long performance of the heaters in typical autumn days (in the month of September and October) in Delhi, outdoor calorimetric tests have been performed. The test procedures are same as that performed by earlier workers like Gupta and Garg[6] and also as has been outlined by recent standard procedures of BSE and ASHRAE[7] within the limit of availability of the laboratory facilities.

To the heater, air at uniform flow rate was supplied by an electrically running blower of capacity 190 watts. The flow was controlled by means of a manually adjustable system attached to the blower. The heating unit inside the duct equiped with a thermostat takes care of maintaining a constant required temperature. Inlet and outlet temperatures were measured by laboratory type mercury bulb thermometers (accuracy ± 0.5°C) at a regular interval of half an hour. The ambient temperature was recorded by means of an automatic potentiometric recorder along with a copper-constantin thermocouple wire.

The solar intensity was measured by means of a pyranometer placed at an inclination of 45° facing due South, and was recorded automatically by a Kipp & Zonen automatic recorder. To measure the mean flow velocity at the outlet a photoelectric type air flowmeter (LYNX) was used and reassumed by a peter tube type air flow meter. Wind velocity was also recorded continuously by a Rimco strip chart recorder. The cover glass was kept clean so that dust factor remained unity. The pressure drop was measured by means of a manometer using water. Generally, the tests were performed on clear sunny days from 9 AM to 5 PM. Care was taken in setting up the collectors in a space where any significant energy could not be reflected from neighbouring buildings on to the collector.

Performance test results and discussions:

The performance test data for all these three air heaters are presented in table I. In fig. 3, the diurnal variations of temperature of outlet air along with the solar intensity in the plane of the collector for three different experiments on three different air heaters are presented. The diurnal variation of the overall efficiency for the three air heaters was presented in fig. 4. Here instead of comparing the efficiencies of the air heater at the same flow rate, the same amount of pumping power was employed so that the unequal frictional losses were also taken into account in the comparison of the efficiencies of the air heaters. Fig. 5 is the plot of η Vs $\frac{T_p - T_a}{H}$ for the three different air heaters at natural air inlet temperature. From three plots, the different rating parameters presented in table I have been found out. In finding out these parameters, we have assumed that the effective absorption transmittance $(\tau\alpha)_e$ factor for all the air heaters is 0.85.

The air heater performance for natural air inlet temperature shows that there is a rise of about 23.5°C at noon time for air heater II, whereas in air heater III the temperature rise is 13.5°C, and for air heater I, the temperature rise is only 8.6°C. For air heater I which is simply a black painted jacketed type the low rise of temperature is obvious because of lower film heat transfer coefficient. Air heater II & III are both of matrix type but in air heater III the air going inside the heater comes in direct contact with the glazing and thus there is a fair chance of dissipation of heat for this air heater which brings down the outlet air temperature.

From the diurnal efficiency curve we see that the maximum efficiency is shown by air heater I through out the day, the efficiency of the second air heater is somewhat less but has a tendency to maintain higher efficiency for a longer time probably because the iron foils provide storing capacity. The efficiency of the air heater III is poor because of the reason stated above. But it has also a tendency to keep a constant efficiency for a long time. From table I we see that air heaters I and II are better in performance though for higher temperature outlet air heater II is a good choice.

Conclusions:

Following important conclusions can be drawn from the present study:

1. For getting higher efficiency, the conventional air heater can be used but in this case the rise in temperature would be low compared to the matrix type.

2. For getting higher efficiency and higher outlet temperature, type II type of matrix solar air heater can be used. But in this case the pressure drop will be high compared to the conventional air heater.

3. The efficiency of air heaters type II and type III which are of matrix type has a tendency to remain constant for a longer period.

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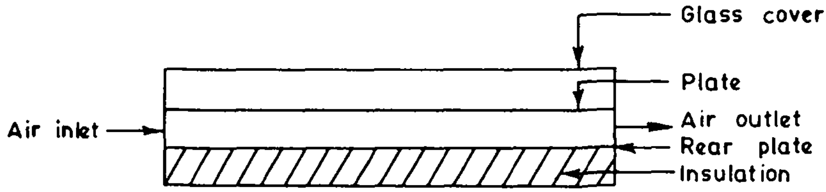
Table - I. Operating and rating parameters of the collectors

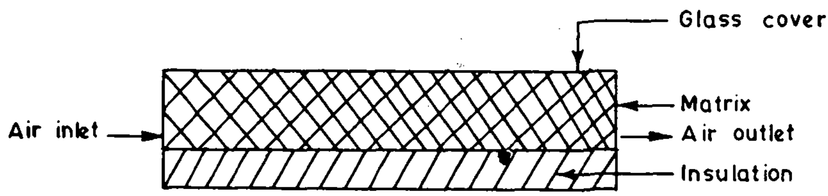
Collector	*Ambient Temp. (^{o}C)*	*Wind velocity (Km/hr)*	*Assumed Transmittance absorptance factor $(\tau\alpha)_e$*	*Mass flow rate of air (m) gm/cm^2-min*	*Total rate of discharge (Q) litre/ min*	*Rate of discharge per unit area (cm/min)*	*Plate efficiency factor Factor (F_p)*	**Heat loss coefficient (U_L) Cal/cm^2 ^{o}C sec.*
I.	28.3-40.5	3-5	0.85	0.279	2215.58	247.27	0.917	0.7×10^{-3}
II.	29.3-40.5	6-6	0.85	0.128	1015.48	113.34	0.894	0.3×10^{-3}
III.	27.5-40.5	4-8	0.85	0.104	826.60	92.25	0.440	0.6×10^{-3}

* Obtained from η (efficiency) Vs $\dfrac{T_p - T_a}{H}$ plot.



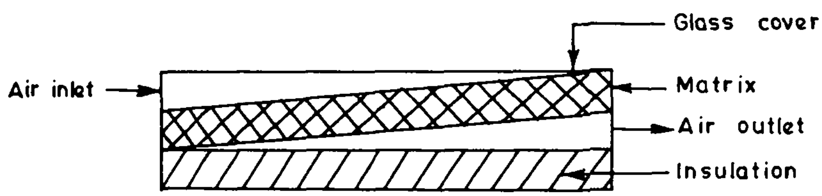
Flat plate type conventional air heater (air flow parallel to the plate)

Type I



Matrix type air heater (air flow parallel to the matrix)

Type II



Matrix type air heater (air flow perpendicular to the matrix)

Type III

Fig.1. TYPES OF SOLAR AIR HEATERS TESTED.

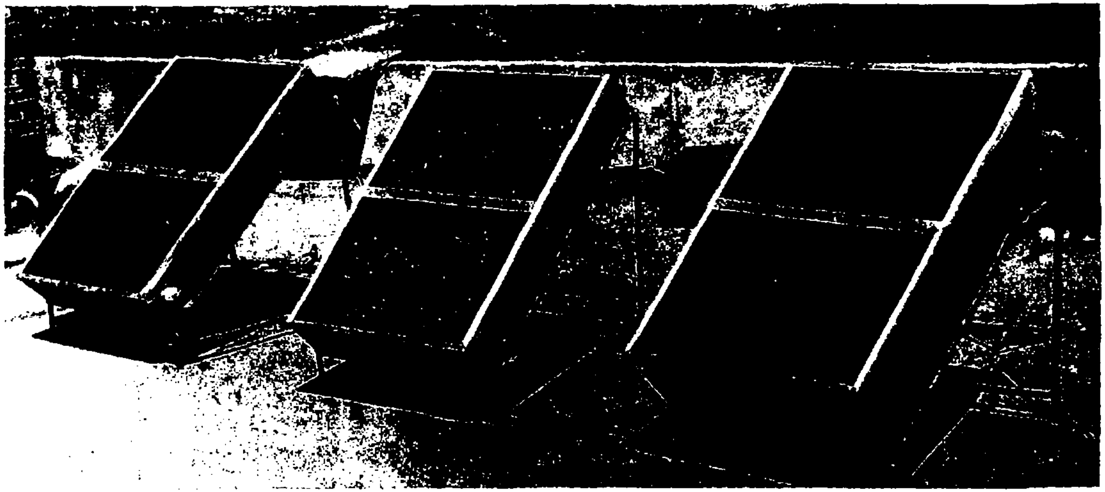


Fig. 2. SOLAR AIR HEATERS TESTED

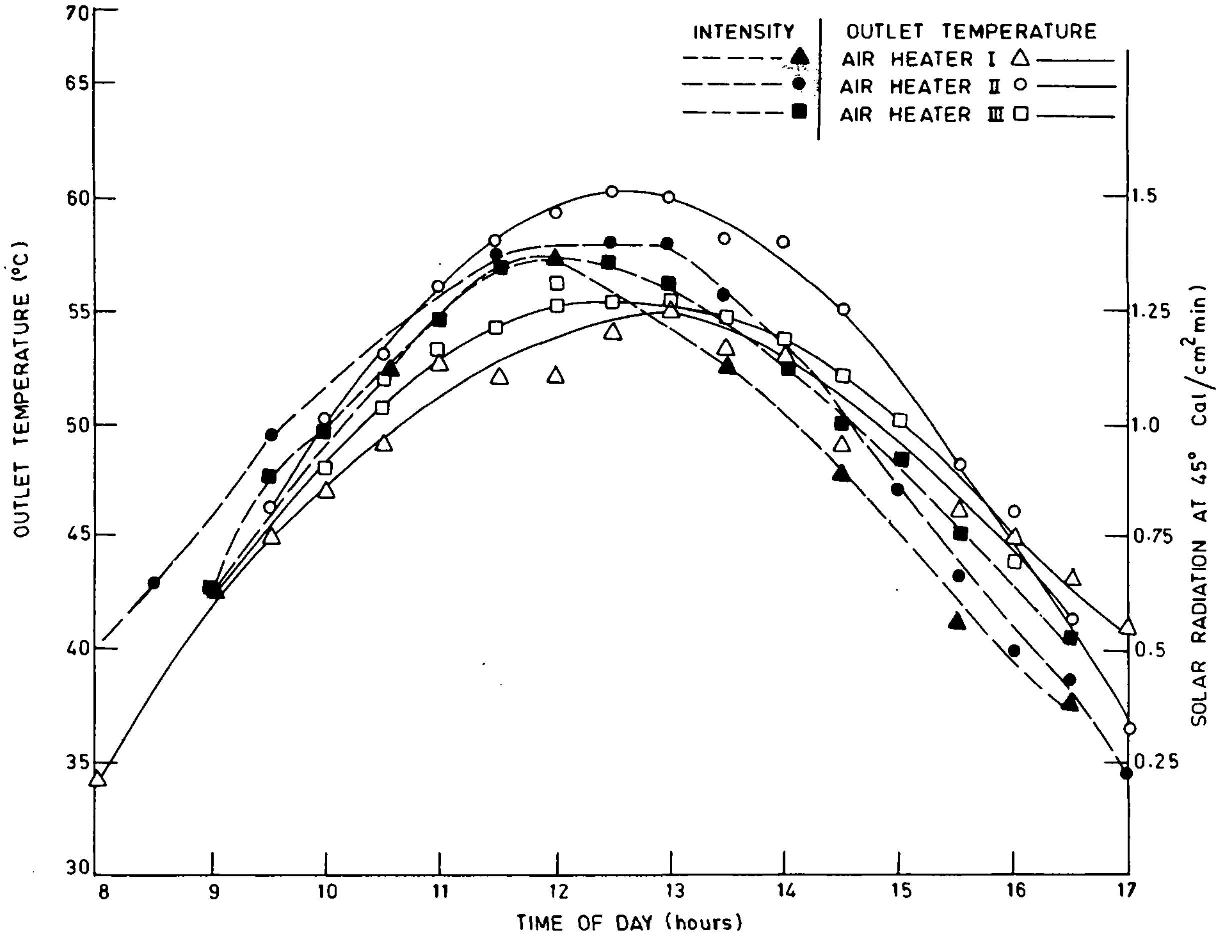


Fig. 3. DIURNAL VARIATION OF OUTLET AIR TEMPERATURE AND SOLAR INSULATION.

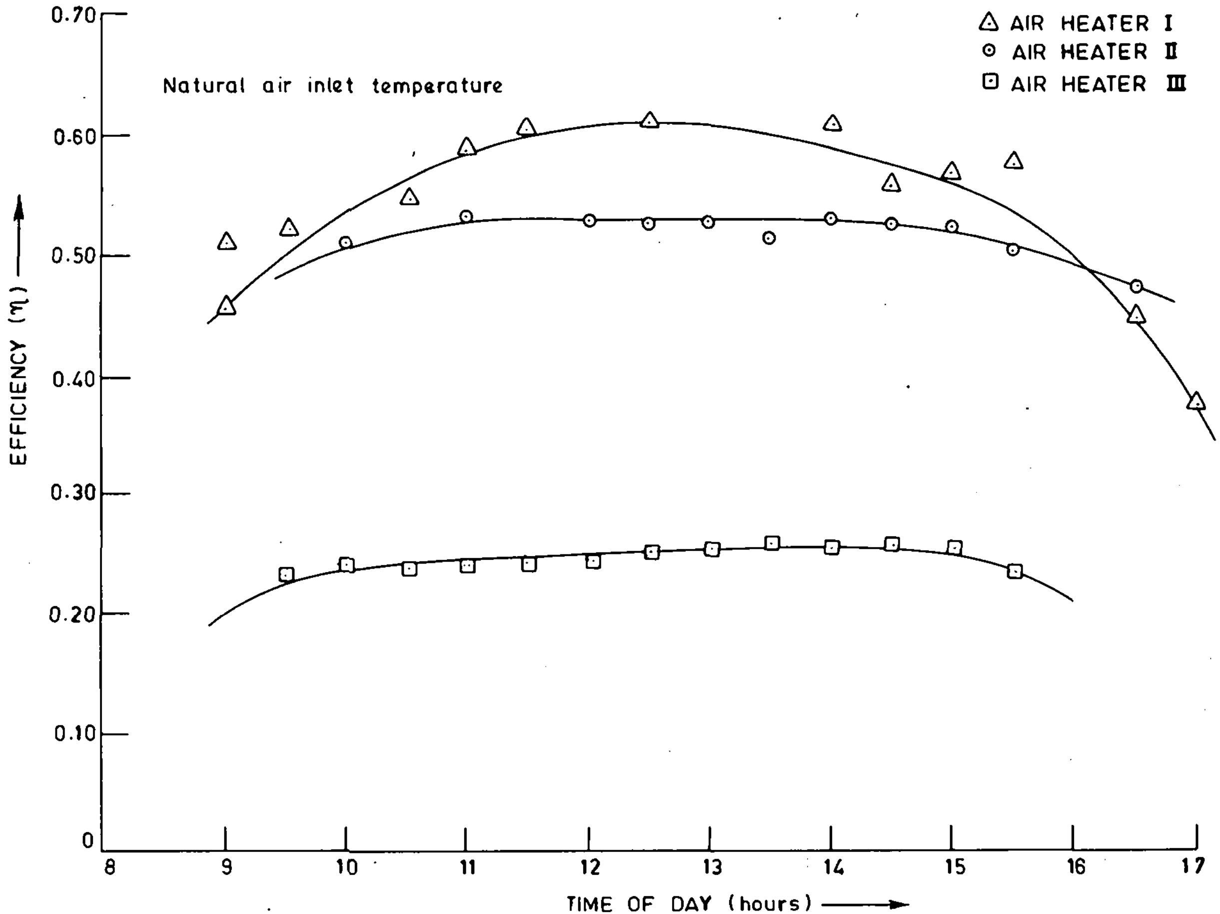


Fig.4. DIURNAL VARIATION OF EFFICIENCY OF THE SOLAR AIR HEATERS.

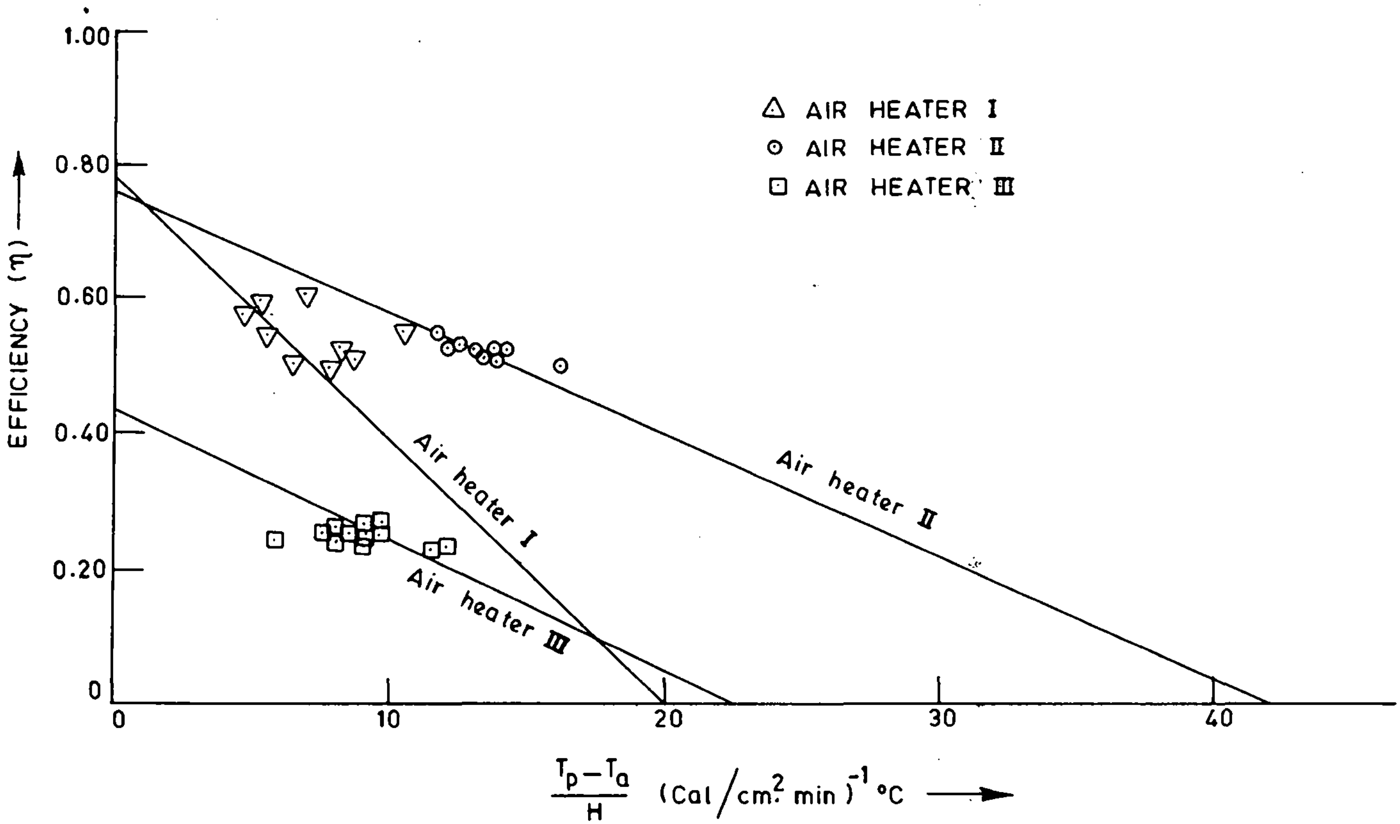


Fig. 5. PERFORMANCE OF AIR HEATERS.

SOLAR PHOTOVOLTAIC GENERATION AND STORAGE FOR SOME RURAL APPLICATIONS

by

P. BASU, K. MUKHOPADHYAY and H. SAHA

1. INTRODUCTION

Solar Photovoltaic systems (SPS) offer an interesting possibility for meeting the electrical energy needs of small remote villages having no access to utility grids. There is very little doubt about the desirability of this clean, noise-free and low-maintenance independent source of SPS electricity. The technical feasibility of SPS have already been demonstrated in a number of varied applications. What inhibits at present the largescale use of SPS on earth is however its too high initial cost. The reduction in the price of solar cell panels over the last few years is rather remarkable progressing steadily towards to DOE target of US$ 500 per peak Kilowatt by 1986. However, the overall cost of SPS is determined not only by the cost of solar cell panels, but also by the balance of systems (BOS) costs which includes the costs of (a) array structure and foundations (b) electrical and power conditioning components, (c) battery storage, (d) installation and (e) maintenance and operation. The importance of these BOS costs for SPS has been pointed out by NASA- LeRc demonstrations which indicate that with the reuction of solar cell module cost, the BOS cost will dominate the systems cost (Table 1) [1]. A detailed consideration on the basis of BOS costs as reported by NASA- LeRc reveal that the village energy centre SPS is three-to-four times more economic than the decentralised roof-top SPS units for meeting the same electrical energy needs of the village (Table 2) [2]. A further importance of BOS costs in SPS is that it ultimately determines the minimum conversion efficiency and allowable cost per unit area of the solar cell panels that are economically viable as shown in (Table 3) [3].

The nature of BOS costs is such that it will vary from country to country depending upon a number of socio economic factors. It is therefore necessary to analyse the BOS costs in some details for arriving at a realistic estimate of the SPS cost for a particular application in a particular place. This has been attempted in this paper assuming Indian market conditions. A number of typical applications of SPS for rural usage are envisaged. The size of solar cell panels and storage batteries required for these applications are determined. The BOS costs for each of these SPS are estimated and then compared with that reported by NASA- LeRc. The minimum acceptable conversion efficiency of solar cell modules on the basis of the estimated BOS cost is also computed and compared with that indicated in ref. 3.

The cost of storage battery plays a very important role in the BOS cost of a SPS. The requirements of the storage batteries and the relative performances of different storage couples for use in SPS are therefore considered in some depth. Recent trends of developments in this field are also indicated.

Table - 1. INSTALLED SPS COST PROJECTIONS

YEAR	*MODULE COST/PEAK WATT (U.S. $)*	*BOS COSTS/PEAK WATT (U.S. $)*
1978	13.00	15.00
1979	9.00	12.00
1980	5.00	10.00
1981	2.45	8.00
1986	0.61	5.00

Table - 2. SPS Costs For Village Energy Centre and Roof Top Installations

DAILY ENERGY NEEDS	*ENERGY CENTRE APPROACH*			*ROOF-TOP APPROACH*		
kWh/day	*Solar Panel Cost (U.S. $)*	*BOS Cost (U.S. $)*	*Total (U.S. $)*	*Aggregated panel cost (U.S. $)*	*Aggregated BOS costs (U.S. $)*	*Aggregated Total (U.S. $)*
Day time load E_D = 281 kWh/day	51,250	251,576	302,826	49,576	1,213,518	1,263,094
Night time load E_N = 7.64 kWh/day						

Table - 3. Allowable Cell Cost/Unit Area
(Power plant cost - $ 1300/kWe)

n_{cell}	*Array Cost*	*(Structural Cost + Wiring Cost)/Unit area*			
	Unit area	*$ .50/ft²*	*$ 1.00/ft²*	*$ 1.50/ft²*	*$ 2.00/ft²*
0.80	1.62	1.12	0.62	0.12	....
0.10	2.04	1.54	1.04	0.54	0.04
0.12	2.45	1.95	1.45	0.95	0.45
0.14	2.86	2.36	1.86	1.36	0.86
0.16	3.27	2.77	2.27	1.77	1.27

2. RURAL APPLICATIONS

Electrical energy is necessary for a few rural applications like (a) agro-irrigation, (b) small-scale industry (c) potable water supply, (d) Community centre, (e) Street lighting and (f) domestic lighting etc. Table 4 shows the daily energy requirements and the load pattern for these typical individual applications [4]. One would observe that the agro-irrigation, small-scale industry and the potable water supply appear as day time load to the SPS where the loads are driven either directly by the solar cell modules when the solar power generated (P_{SA}) exceeds the rated power of the load (P_L)or via the battery when $P_{SA} < P_L$. The Community TV centre, domestic and street lights are however nighttime loads which are fed via the storage batteries during night. Since the watt-hour efficiency (n_B) of the storage batteries are about 80%, the size of the solar cell panels and the storage batteries will be dependent upon the load pattern and the insolation pattern in the village.

3. PANEL AND BATTERY SELECTION

For the daytime load, let T_{so} and TsB be the period of time per day on an average during which the load is driven directly by the panels ($P_{SA} > P_L$) and through the batteries ($P_{SA} < P_L$) respectively. For the sake of simplicity, it will be assumed that the insolation pattern is trapezoidal in nature as shown in Fig. 1 with daily average of 8 hours of sunshine between 8 AM and 16 PM such that for every 1 kW/m^2 of insolation level a daily insolation of 5 kWh/m^2 is obtained which is a typical values for tropical countries. An insolation pattern factor (f) can thus be defined such that f x 8 = 5 leading to a value of f = 0.625 [4]. If now n_d be the efficiency of the SPS when the solar modules are driving the loads directly during T_{so}, then, the required power of the solar cell panels in peak watts is given by

$$\text{PSAMD} = \frac{E_D}{f n_d \,(T_{so} + n_B T_{SB})} \qquad (1)$$

where E_D is the daily energy requirement of the day time load.

For the nighttime load, which is always driven through the batteries,

$$\text{PSAMN} = \frac{1}{5} \frac{E_N}{f n_d n_B} \qquad (2)$$

where E_N is the daily energy requirements of the nighttime load.

The capacity (C_B) in ampere hour of the storage battery at the rated load (P_L) is determined by the daily load requirement for which sufficient storage is to be provided for the period T_B.

$$\text{Thus } C_B = \frac{P_L \times T_B}{V_D \times C_D/100} \qquad (3)$$

Table - 4. Electrical energy needs and load pattern of different systems

System	*Specifications*	*Working hours*	*Power (kW)*	*Energy (kWh/day)*
Micro-irrigation	Area = 1 ha, r = 3 mm/day d = 10 m n_p = 0.5 n_d = 0.7	8.00-16.00	0.3	2.4
Flour Mill	2 kW motor	8.00-16.00	2	16
Potable Water Supply	5000 litres/day 0.05 kW motor n_p = 0.35, d = 10 m	8.00-16.00	0.05	0.4
Community T.V. Centre	(a) 25 w F.L. + 50 W T.V.	(a) 18.30-21.30	0.075	0.225
	(b) Adult literacy centre 25 W F.L. (two nos)	(b) 19.00-21.00	0.05	0.1
	(c) Anchol panchayat 25 W F.L. (One no)	(c) 18.30-22.30	0.025	0.1
Domestic	One 25 W F.L.	19.00-22.00	0.025	0.075
Street Light	One 25 W F.L.	19.00-23.00	0.025	0.1

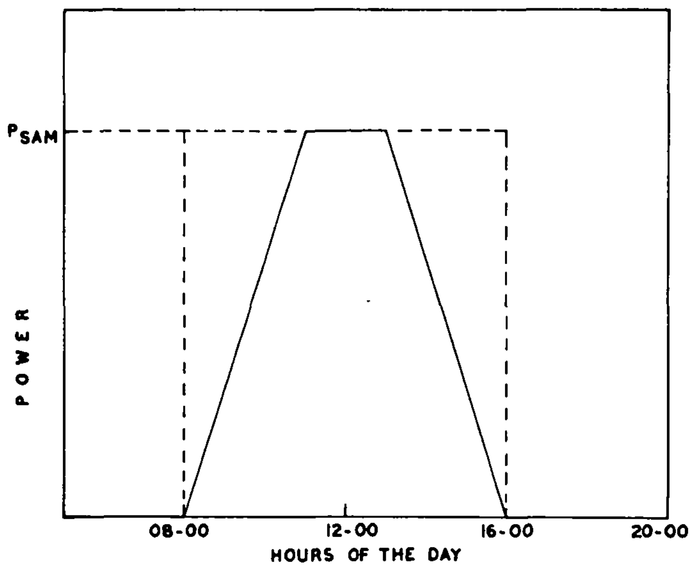


FIG-1. TRAPEZOIDAL INSOLATION PATTERN FOR THE PHOTOVOLTAIC ELECTRICAL POWER SYSTEMS.

Table - 5. Solar Panel and Storage Battery Size

Applications	*Energy NEEDS (Wh/day)*	*Solar Cell Panel (Peak Watts)*	*Storage Battery (Volts, ampere hours)*	*Aggregated BOS costs*
				(U.S. $)
Agro-irrigation	2,400	830	24 V, 66 AH	963
Village Industry	16,000	5,500	110 V, 100 AH	2,805
Potable Water Supply	400	137	12 V, 22 AH	252
Community T.V. Centre	425	164	24 V, 55 AH	331
Domestic Lighting	75	29	12 V, 30 AH	130
Street lighting	100	38	12 V, 35 AH	143

Table - 6. Percentage cost break up of BOS for different systems.

	Micro-irrigation	*Flour Mill*	*Potable Water Supply*	*Community T.V. Centre*	*Domestic lighting*	*Street light*	*NASA LeRc*
1. Array structure and site preparation	32.26	45.43	12.8	13.19	12.14	11.2	18
2. Storage	46.08	44.21	56.9	46.97	65.39	67.6	20
3. Electrical (including domestic service cons. & energy centre electl. wirings)	17.29	5.52	18.97	28.18	19.12	17.65	33
4. Installation	0.96	2.22	1.18	4.90	1.91	2.22	9
5. Maintenance	3.41	2.62	10.15	6.76	1.44	1.33	100
Total	100	100	100	100	100	100	100

Table - 7. List of Ratings of Different candidate Batteries for SPS (10 points best)

Type	*Criterion A*	*Criterion B*	*Criterion C*
Pb-acid (advanced)	9	10	9
Sodium Sulphur	10	5.75	6
Lithium Metal Sulphide	4	5.25	3
Zinc-Chlorine	5	6	5
Lead-Acid (SOA)	9	9.25	10

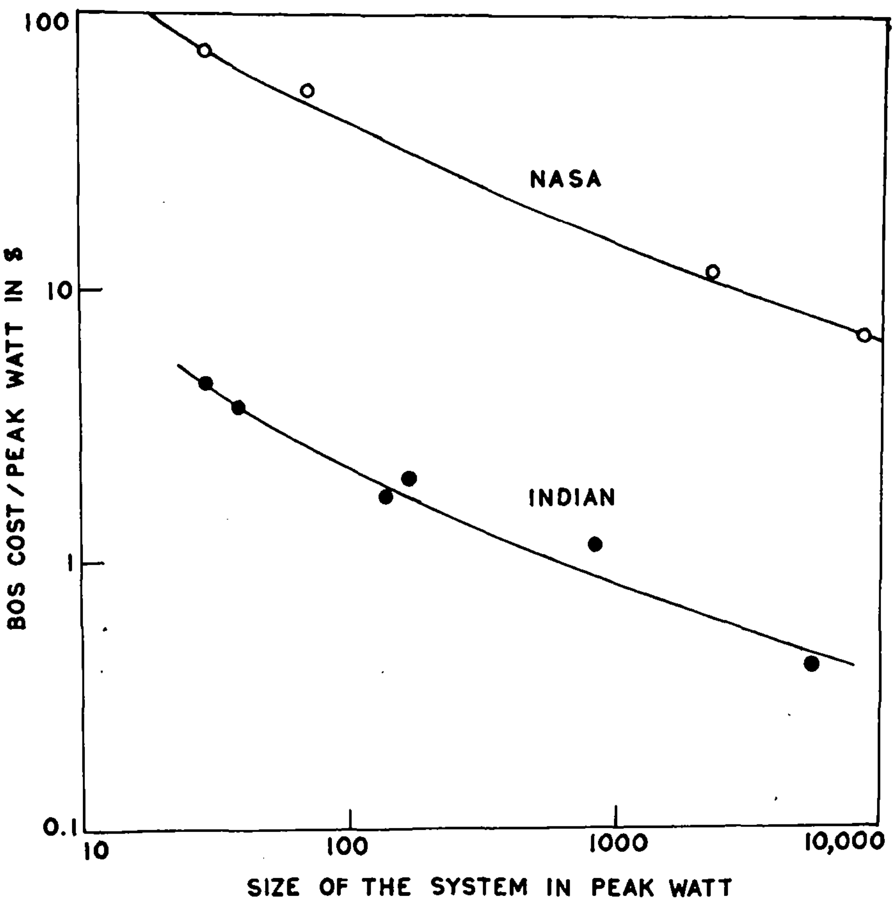


FIG-2. VARIATION OF BOS COST / PEAK WATT WITH SIZE OF THE INSTALLATIONS FOR DIFFERENT SYSTEMS.

where V_D is the average voltage during discharge of the battery and C_D is the manimum permissible depth of discharge. C_D is taken to be 80% for lead acid battery. T_B is taken to be equal to T_{SB} for day time load and nE_N/P_L for night time load, n being the number of hours for which storage is required.

On the basis of equation (1) through (3), and the energy requirements as shown in Table 1, the size of the suitable solar cell panels in peak watts and storage batteries in volts and ampere-hours for the typical village SPS applications are computed and shown in Table 5.

4. BOS COSTS

The BOS costs for each of these applications have been estimated from a survey of the local Indian markets. The aggregated BOS costs estimated for each of these applications are shown in Table 5. The percentage break up of the different components of the BOS costs are shown in Table 6. These are compared with that reported by NASA-LeRc [1]. The BOS cost per peak watt is computed on the basis of Table 5 and is plotted in Fig. 2. It is interesting to compare this figure with that reported by NASA. While the nature of variation of BOS cost per peak watt with the size of installation is similar in both cases, the absolute BOS cost/ peak watt is considerably less under Indian conditions. This is mainly due to the cheap labour cost in maintenance and installation in developing countries like India.

5. MINIMUM MODULE CONVERSION EFFICIENCY

Low cost thin film solar cells are usually less efficient than high cost single crystal solar cells. Since lower efficiency implies larger area and associated higher BOS costs, there is a thinking that solar cells having conversion efficiency less than 10 - 12% will not be economically viable. Table 3 of reference 3 supports to this conclusion. Since the structural and wiring costs in developed countries are more likely to be at least \$ 2.00/ ft^2, the minimum cell conversion efficiency appears to be at least 14% with allowable cell cost/unit area as \$ 0.86/ft^2. One notes that this leads to a cell cost of \$ 60/ peak kW- for a power plant cost \$ 1300/kW, which is rather difficult to achieve with a 14% efficient solar cell.

In developing countries like India, the BOS costs including the structural and wiring costs are considerably cheaper. Table 5 shows that the BOS cost is about \$ 0.5/peak watt for a system of capacity greater than 1 kW peak. From Table 6 one notes that the structural and electrical cost lies between 30-50% of the BOS costs so that it is about \$ 0.25/peak watt. Assuming a SPS cost of \$ 1300/kW, allowable cell cost turns out to be \$ 0.75/ft^2 or \$ 150/peak kW even with a cell conversion efficiency of 5% only. This indicates that cheaper BOS costs in developing countries permit the development of less efficient but low cost solar cells which are much more realistic than high efficiency and at the same time low cost solar cells. The case of thin film CdS/Cu_2S solar cells which are potentially very low cost but suffer from a low reproducible conversion efficiency in the range of 5-6% thus appears significantly brighter in developing nations.

6. STORAGE BATTERY

Table 6 shows that the cost of storage lies in the range of 45-65% of BOS costs of SPS in India and similar places. It is therefore necessary to reduce this cost as far possible without sacrificing the desirable characteristics of the batteries. Nickel-Cadmium batteries are good for many SPS applications because of their high charge retention, long cycle life and satisfactory low temperature capacity, but their price is about 3-5 times higher than that of equivalent lead-acid battery of comparable capacity. Ni-Cd batteries are therefore not used at present unless the power range is very small.

For higher ranges of power, a number of advanced storage couples which are potentially low cost may be considered such as (a) Advanced lead-acid (b) Sodium-sulphur (c) Lithium-metal sulphide (d) Zinc-Chlorine and (e) Iron-Redox. Recently Westinghouse R & D centre [5] has made a detailed analysis of different storage batteries systems for a medium power (25 kW approx.) SPS. They identified three criterions on the basis of very high volume production and decentralised installation viz.

Criterion A – Which involves material scarcity

Criterion B – Which considers the attributes of safety and reliability

Criterion C – Which relates to the developmental risk.

Table 7 shows a list of ratings (10 points best) of these batteries on the basis of the Westinghouse analysis. One can conclude that on the basis of the primary requirements and the high volume critierious Pb-acid batteries will continue to be used for SPS applications at present and in near future.

7. CONCLUSIONS:

BOS costs of SPS play very important role in determining its economic viability as alternative power sources for rural applications. The economy of scale of BOS costs indicates that SPS installation of less than kW range will suffer from high BOS costs. Thus for domestic lighting, street lighting, community centres and other low power applications, a centralised SPS for the entire village may be desirable. For agro-irrigation and small-scale industries with electrical energy requirements in the range of a few kilowatts, individual SPS may be economically operative.

The BOS costs in India and similar places are considerably lower than that in US and similar places. This in turn leads to a much higher allowable cost per unit area and lower efficiency of solar cells in India so that the technical feasibility of SPS in India and similar places is much greater. The case of low cost low efficiency CdS/Cu_2S also appears to be promising.

Finally, the storage cost accounts for about 50% or more of the aggregated BOS costs so that efforts should be made to reduce the storage cost as far as possible. Recent studies indicate that the advanced lead-acid batteries will continue to be used in SPS at present and in near future.

ACKNOWLEDGEMENT:

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SOLAR PHOTOVOLTAIC ENERGY SOURCES: A VIABLE ALTERNATIVE FOR RURAL DEVELOPMENT IN INDIA

by

B.M.S. BIST

1. *INTRODUCTION*

The world has entered on era of energy crisis of ever increasing magnitude. Harnessing of energy from alternate and renewable sources like solar energy has, therefore, become crucial for the very sustenance of human civilisation. The present global pattern of enrgy consumption is full of disparities. Not only is there a yawning gap between the energy consumed per capita in the developed and developing nations, but also there is usually a wide difference in the availability, and hence the per capita energy consumption, in the rural and urban areas of the same developing nation. These are exemplified by the fact that India, with 15 percent of world population, consumes only 1.5 percent of world energy as compared to 25 percent of energy consumption by U.S.A., with only 5 percent of world population. In India itself the urban sector, with 20 percent of the country's population, consumes 75 percent of its energy, where as the 80 percent population in the rural sector has to be content with only 25 percent of available energy. It is apparent, therefore, that for the development of humanity as a whole, it is not only essential to tap alternate energy sources for the future but also to ensure more equitable energy consumption by assuring its uniform availability, in conveniently useable form, all over the globe. Solar energy, with its virtually infinite potential, uniform and free availability and complementary nature of its various manifestations, may prove to be the mankind's future energy source, provided it can be harnessed on a large scale in a techno-economic and socially acceptable manner. This is by no means an easy task and its accomplishment demands strong will and aggressive strategy on the part of politicians, planners technologists and general public as a whole at the global level.

2. *RURAL ENERGY SCENE IN INDIA*

India is primarily a country of villages. There are approximately 576,000 villages in India. For the overall national development, the disproportionately low use of energy in the rural sector in India has to be made more equitable. The achievement of such a goal is critically dependent on the availability of energy in conveniently useable forms in the rural sector as well.

Energy is required in various forms for the Indian villages, primarily for cooking, water supply for drinking and irrigation, domestic and street lighting, farm operations including transportation, and for small-scale industries. At present, much less than 15 percent of energy used in rural India is supplied in the form of electricity and the rest is derived by burning firewood, charcoal, cow-dung, other organic wastes and oil. The estimated annual total energy needs of rural India would be around 550 billion units by 1990 and 1200 billion units by 2000 AD. This is a staggering requirement and a major portion of this would preferably be supplied as electrical energy, which is most convenient to use.

Before looking into the possibility of supplying energy to the rural sector by conventional means, it is essential to consider some of the very specific issues relevant to the context of Indian villages. The villages in India are generally widely scattered, sparesely populated and remotely located. Energy supply for the development of these villages must be based on local and renewable resources. The energy source must be pollution free, easy to maintain and operate, and must, above all be cost effective.

Out of the various forms of energy needs for rural India, electricity forms a convenient and important component. The Government of India has ambitious plans to take electricity to larger and larger number of villages in future. Nevertheless, if the electrical energy needs of Indian villages are met by conventional means, such as coal, oil, hydel or nuclear, the villages will have to depend solely on outside agencies for any requirement of maintenance or fuel supply. Moreover, electrifying villages in India by centralised power stations, based on conventional resources, is bound to involve huge expenditure on laying down to extensive distribution systems and to incur large transmission-line losses. According to a conservative estimate, electrifying all rural homes in India by conventional means would involve an expenditure of more than Rs. 300 billion and the whole task would probably take decades to plan and execute. Centralised power generation, and its subsequent distribution, is thus, not an ideal approach for electrifying majority of the Indian villages, particularly those situated in remote and inaccessible locations.

3. *PRESENT ENERGY SOURCES*

The use of coal, the present principal source of energy in India, is not only handicapped by its capacity to generate only centralised power, its associated pollution problems and its massive transportation requirements, but also by its equal need in other urban and industrial sectors of national importance. The meagre reserves of oil and gas can hardly be spared for the purpose of rural development, as these are irreplaceable in other sectors of vital national importance. India' present hydroelectric potential of 40 billion units per year can at best be extended to 120 billion units by 2000 AD. Moreover, hydropower besides providing a centralised generation, is cost intensive, time consuming for implementation, and fluctuating in potential, since it depends upon the vagaries of nature. The use of nuclear energy for rural electrification appears unlikely, because it provides only centralised generation of power and there are various environmental, sociological and political problems associated with its deployment and use. In addition to all these factors, it must be realised that centralised large power houses are essential for maintaining and expending India's urban industrial infrastructure thus, leaving very little power for use in villages.

It should, therefore, be clear that none of the conventional centralised energy sources alone can meet the future electrical energy requirement of the Indian villages. One must, therefore, turn towards alternate sources such as solar photovoltaic, solar thermal, bio-gas or wind generated electric energy to meet this requirement.

The direct generation of electricity, by means of solar photovoltaics, presently satisfies most of the rural requirements, except cost effectiveness. The photovoltaic electrical sources are completely decentralised, they depend only on the availability of solar energy as fuel, they are modular in nature, they are absolutely pollution free, they require minimal maintenance, and the cost per unit power does not depend on the size of the power plant. These photovoltaic energy sources, therefore, are ideal for Indian rural communities for their daily electrical energy requirement, provided their economic viability is proven.

4. *RELEVANCE OF PHOTOVOLTAICS*

In order to assess the techno-economic potential of solar photovoltaic power sources for rural development, one needs to recapitulate the existing situation. About 60 percent villages in India are small: they have on the average 500 people, 200 cattle heads and 200 hectares of cultivable land each. Most villagers are farmers and the average land holding per family is between 1 to 2 hectares. The mean annual rainfall of 100 cm fluctuates widely, year to year and region to region. These villages require hygienic water for drinking and domestic use, facilities for small-scale irrigation, domestic and street lighting, community educational and entertainment facilities, and power for some machines for agricultural operations and small-scale rural industry. The Government of India has ambitious plans to provide these villages with community bio-gas plants, educational T.V. sets (SITE and INSAT) and tube-wells for water supply for drinking and irrigation. Since most of the villages in India get plenty of sunshine, solar photovoltaic power should also be seriously considered for meeting these pressing needs of the villages, vis-a-vis other possible renewable sources of energy.

Hygienic water for drinking and domestic use can be supplied to an unelectrified village, by lifting and purifying the under-ground water, either by a solar photovoltaic water pumping system or a diesel pump set. A small village, having 500 people and 200 cattle, needs about 25,000 litres of water per day for drinking and other domestic purposes. (40 litres per person for drinking and domestic use and 25 litres per cattle head for drinking). As the photovoltaic power is expected to be available in India at the rate of about Rs. 30/- per peak watt by 1985, and cheaper thereafter, it is anticipated that photovoltaic pumping systems for drinking and domestic use would be the cheapest alternative beyond 1985-86, for remote unelectrified Indian villages.

For growing three crops annually, the mean annual rainfall of 100 cm. requires to be supplemented to the extent of 120 cm. by irrigation. For irrigating one hectare of land to the desired level, a maximum of 50,000 litres of water per day is required during intensive agriculture season. Again, cost projection for the alternatives i.e. photovoltaic, diesel and persian-wheel pumping system (the traditional mode of irrigation in India based on manual and animal labour), indicate that the photovoltaic pumping system, at a module cost of Rs. 30/- per peak watt, is the cheapest and will perhaps be the best alternative beyond 1985. The decnetralised photovoltaic power based systems may become economical, at a cost of Rs. 20 per peak watt, even in comparison to conventional centralised power sources based on fossil fuels or hydel. energy.

For providing electricity to rural homes for the purpose of lighting, a solar photovoltaic array, with proper storage system, would be ultimately more economical and sociologically acceptable. A 100 peak watt solar photovoltaic panel would generate on an average a minimum of 500 watt-hours of electrical energy per day throughout the year. This electrical energy is sufficient to meet lighting (2 bulbs of 25 watts for 4 hours), comfort (1 fan of 40 W for 4 hours) and entertainment needs (radio) of a rural home. It would be possible to provide at least 500 watt-hours per day per family at a total cost of approximately Rs. 1,500/- by 1987-88 as compared to the present average of Rs. 1,200/- per 100 W connection, plus the running and maintenance costs, if one goes by the present conventional central generating station and transmission-distribution net-work.

It would be possible.in future to provide power to the various community services in villages by solar photovoltaic panels/systems at a cost cheaper than that offered by other approaches. These include educational/entertainment T.V. sets, street lighting, powered machines for agricultural operations and small scale village industries.

5. *INDIAN SOLAR PHOTOVOLTAIC PROGRAMME*

The Government of India realised the potential of harnessing effectively the solar energy, particularly for Indian villages, as early as 1975. An integrated programme for the development of renewable energy sources was initiated at this stage through its Department of Science and Technology (DST). As a part of this integrated programme, a national solar photovoltaic programme was also initiated almost simultaneously. The Government of India's policy in sponsoring this photovoltaic programme, has been to achieve self reliance in this vital area of photovoltaic technology development and productionisation through indigenous efforts and resources. Central Electronics Limited (CEL), a Government of India (DST) Enterprise, was chosen for this purpose as the key agency in the country. It was assigned the tasks of co-ordinating and monitoring the various research and development activities in photovoltaics in the country, carrying out indigenous technology development, advanced engineering development and pilot plant production of commercially viable solar photovoltaic power sources and systems for terrestrial, particularly rural, applications. In addition various R & D projects were sponsored in other national research organisations in the photovoltaic area, under this programme. As a result of the concerted and co-ordinated efforts put up mainly at Central Electronics Limited, significant progress has already been achieved in this area.

PRESENT STATUS-DEVELOPMENT AT CEL

Complete infrastructure and technology for the regular fabrication of silicon photovoltaic cells, modules and systems has been established by indigenous efforts.

Concerted efforts for cost reduction and indigenous development of imported raw materials are being devoted presently. Extensive facilities for the test and evaluation of photovoltaic cells, modules and systems and solar radiation data collection and analysis have been established. The design, development, demonstration and installation of different types of photovoltaic systems, particularly for rural and remote area applications are accorded high priority in the project. A number of different photovoltaic systems have been developed and demonstrated, some of which are installed in the field for evaluation, feedback and actual use. These include photovoltaic systems for water pumping for rural drinking water supply at Awania (Gujarat) and Tijara (Rajasthan), ship-navigation equipment at Dwarka and Okha ports, educational cum-entertainment community radio sets for school children at Leh and Srinagar, communication sets etc.

6. *PLANNING FOR THE FUTURE*

The solar photovoltaic activities at Central Electronics Limited are envisaged to be enhanced many folds over the coming few years. As a consequence of the developed technology and installed infrastructure at CEL, it is planned to undertake a pre-commerical pilot plant manufacture and a large-scale demonstration programme for solar photovoltaic cells, modules and systems. The detailed project plan is presently under the active consideration of the Government of India.

In the plan, a phased pre-commercial pilot plant manufacture of solar photovoltaic cells, modules and systems has been visualised. It is projected to enlarge the present installed fabrication capacity to the level of 1000 kW/Year within a period of five years at the same time reducing the cost of production of PV modules to less than Rs. 30/- per peak watt.

The solar photovoltaic cells and modules, manufactured in the pilot plant, will be largely utilised in a number of installations in remote Indian villages for field evaluation and data feedback. These installations include water pumping systems for hygienic drinking water supply for villages, water pumping systems for rural agricultural stations, photovoltaic power systems for village community centres for energising TV, radio, light and possibly fans. In addition, the manufactured cells and modules will be utilised in various other photovoltaic systems for remote area applications like communication sets, radios and light beacons for ship navigation, microwave repeater stations, traffic signals, portable power sources etc.

Research and advanced engineering development leading to the ultimate indigenous and low-cost production of various solar photovoltaic materials are projected to be carried out in the proposed plan. Development efforts leading to the low-cost production of various photovoltaic system components will also be accorded high priority. The development of new materials/process technologies in solar photovoltaics will also be undertaken.

The above programme is expected to provide the full data and experience necessary for the subsequent venture on a larger commercial scale.

LOW-COST SOLAR WATER HEATER

by

N.M. NAHAR and K.S. MALHOTRA

ABSTRACT

A low cost collector-cum-storage type solar water heater has been developed. The cost of the heater is reduced by replacing window glass cover with 0.2 mm thick PVC film to avoid glass breakage in transportation and maintenance. In this paper performances of solar water heaters having double glazing as PVC and glass, have been compared. It was found that their performances are similar. Moreover by providing an insulating cover in the night water remains warm till next morning for taking bath etc. in early hours when sunshine is not there.

INTRODUCTION

Solar energy is so dilutely distributed over the entire globe that the investment per square metre on the solar collector is very high. In case of water heaters glass cover glazing contributes much towards the high cost of collectors. Obviously the efforts are being made to substitute glass with a cheap and long lasting material. Plastic is one such material as its performance is almost similar to that of glass. It is yet to be tested practically for its long life characteristic but it has one definite advantage over the glass that the breakage probability has been reduced to zero. As glass cover glazing alone contributes 25% to the total cost of the collector. The use of plastic can reduce its cost by 15-20%. Solar water heaters with glass as cover glazing are popular in Israel (1), Australia (2), USA (3), Japan (4), South Africa (5) and developed by Gupta & Garg (6), Garg (7) and Nahar (8) in India. But little efforts were made to replace glass by plastic material. Blaga (9) has reviewed state of art for use of plastics in solar energy applications. Glass can transmit upto 90 percent of the impinging short wave radiation (from 0.3 μm to 3.0 μm) at normal incidence, and stops longwave radiation (3.0 μm to 30 μm) emitted by the absorber to escape outward by transmission. It also has good weatherability. The main disadvantage of the glass being used as cover glazing is its low impact strength, which makes it very susceptible to easy breakage by hailstone of vandals. Other disadvantages are its relatively high density and poor resistance to thermal stresses. Another noteworthy drawback of the glass is that it absorbs thermal radiation emitted by the absorber plate. This causes the temperature of the glazing to rise, resulting in heat loss to the environment.

The plastics most commonly used for glazing in solar collectors are poly carbonate (PC), glass fibre-reinforced polyester (GRP) sheeting and polyvinyl flouoride (PVF) and fluorinated ethlene-propylene (PEP) copolymer which can withstand temperatures in the range of 100 to 190°C. But these are costly in comparison to polyvinyl chloride

(PVC) material and also we require temperature upto 60-70° C, therefore, PVC films can be used so that cost is reduced considerably.

With its light weight, better shatter resistance than glass, ease of fabrication and good transmission (94 per cent) of solar radiation PVC has been tried to replace glass as cover glazing in low cost collector-cum-storage type solar water heater. PVC is having more transparent than glass but unlike glass however it is partially transparent to longwave radiation. In this paper PVC has been tried for double glazed solar water heater. Performances of solar water heaters with PVC and glass as cover glazings have been compared.

DESIGN OF SOLAR WATER HEATER

The solar water heater consists of a rectangular galvanised iron tank (20 gauge thick) of dimension 1.12 x 0.88 x 0.10 m^3 having a capacity 90 litres. It is encased in a mild steel tray with 0.10 metre layer of fibre glass insulation below it and on its side. Two cover glazings have been provided on the top. The front face of the tank is blackened by black board paint. The hot water is taken from the heater outlet pipe by pouring cold water in the funnel. The heater is inclined at 41° from the horizontal and is oriented towards south to collect maximum solar radiation during the winter season at Jodhpur. Fig. 1 depicts photograph of two solar water heaters, one having glass and other PVC as glazing material. An aluminium reflector cum insulating cover (5 cm fibreglass) is provided to cover it in the night so that water remains warm till next morning.

Fig. 1 – Solar Water heater with glass (left) and PVC (right) as cover glazing.

Both solar water heaters were filled with water daily at 8.00 AM and following tests were carried out.

1. Whole water was drained at 16.00 hrs
2. Whole water was drained at 8.00 hrs next morning. (Heater was covered by an insulating cover in the night)

Second test was carried out because local inhabitants require hot water in early morning hours for taking bath, the solar water heater containing hot water was covered in the night with an insulating cover so that water remaining warm till next morning. The daily collection efficiency was worked out by following relation

$$\eta = \frac{\int_o^\theta q_u \, d\theta}{A \int_o^\theta H \, d\theta}$$

where η = collection efficiency

q_u = rates of heat absorption by water

A = Area of absorber

H = total solar insolation on the collector W/m^2

θ = Period of test

Table 1 shows the maximum temperature reached at 14.00 hrs and retained till next morning at 8.00 AM for both types of solar water heaters along with their efficiency. From this table it is clear that performance of both these water heaters are similar. Therefore, we can replace glass sheet by PVC film of 0.2 mm thick.

CONCLUSION

The cost of solar water heater with glass is Rs. 550/- while it is Rs. 450/- (one U.S. \$ = 8.5 Rs.) with PVC as glazing material. There is approximately 18 percent reduction in cost by using PVC as glazing material for low cost collector-cum-storage type solar water heaters. Therefore, glass can be replaced by PVC film of 0.2 mm thickness is solar water heater so that cost is reduced considerably.

ACKNOWLEDGEMENTS

Authors are grateful to Dr. H.S. Mann, Director and Mr. B.V. Ramana Rao, Head of the Division of Wind Power & Solar Energy Utilization, Central Arid Zone Research Institute, Jodhpur for providing necessary facilities for the present study. Thanks are also due to Shri B.L. Tak, Photographer for taking nice photograph.

Table 1. Performance of solar water heaters

Solar water heater type	Maximum temp. reached at 16 hrs. (^oC)	Temperature retained till next at 8.00 hrs. (^oC)	Efficiency: Whole water was drained at 16.00 hrs. (per cent)	Efficiency: Whole water was drained at next morning 8.00 hrs. (per cent)
Solar water heater with two cover glazing (ordinary window glass 3 mm thick) and aluminium reflector cum insulating cover	65.0	41.5	71.5	47.5
Solar water heater with two cover glazing (PVC film of 0.2 mm thickness) and aluminium reflector cum insulating cover.	65.2	41.0	72.1	47.1

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BHEL'S SOLAR ENERGY RESEARCH AND DEVELOPMENT PROGRAMME

by

T.V. BALAKRISHNAN and R.K. SURI

1. INTRODUCTION

During the past decade the total global consumption of conventional fuels like coal and oil has reached such an alarming level that the danger of dwindling reserves has become a reality. To reduce the consumption of coal and oil and at the same time, to meet the energy demands of rural India, one of the most promising sources of energy from the point of view of availability, cleanliness and ecology is the tapping and utilization of solar energy.

With the increasing cost of commercial forms of available energy in the country and the financial and physical constraints on the erection of conventional power plants and distribution network, it may be worthwhile to manufacture and instal small sized solar power plants to be located in villages and small towns where there is no likelihood of the availability of conventional power for the next decade or so. These power plants could either produce mechanical/electrical energy only or else, they could form a part of an Integrated Energy System (IES).

Bharat Heavy Electricals Limited (BHEL), a fully-owned Government of India Enterprise, has been working in the area of Non-Conventional Energy Sources for the past five years, with institutional responsibility towards developing the Integrated Research and Product Development (RPD) programme on behalf of the Department of Science and Technology, Government of India. Under this programme, a number of projects are being investigated by BHEL in the priority areas; given in the text to follow:

2. RESEARCH & PRODUCT DEVELOPMENT PROGRAMME

BHEL's Research & Product Development (RPD) programme in Non-Conventional Energy Sources covers the following major priority areas:

- Solar Collector Development
- Solar Heating, Cooling & Refrigeration
- Solar Water Pump
- Solar Power Generation, and
- Integrated Energy Systems.

In each of these areas, a number of projects are being investigated, which are briefly described in the text to follow:

2.1: *SOLAR COLLECTOR DEVELOPMENT*

The collector development programme has been given special attention. This programme ensures that while the solar based products are being developed, the collectors will be available for different temperature and fluid applications through this independent continuing activity. The different kinds of collectors being developed are briefly described as under:

2.1.1: *FLAT PLATE COLLECTORS*

Flat plate collectors with extruded aluminium frame, roll-bond aluminium absorber and using single or double glass covers have been developed for water heating applications from 60°C to 95°C. These collectors which use aluminium foil faced fibreglass insulation are being commercially manufactured. For raw water applications, a steel collector with mild steel absorber panel has recently been developed. Figure: 2.1.1 shows the thermal performance of commercially manufactured flat plate collectors, using roll-bonded absorber panel.

The developmental activity for advanced flat plate collectors includes design of self boiling models for freon and ammonia applications.

In a number of demonstration-cum-experimental projects at various locations in the country, over two thousand square metres of commercially manufactured collectors have been installed for water heating, space heating, power generation and for cooling systems.

2.1.2: *CONCENTRATOR COLLECTORS*

In cooperation with the Punjab Agricultural University in Ludhiana, BHEL has developed the engineering design of Winston type of concentrator collector. These collectors have been developed for low pressure steam generation and for boiling organic fluids to operate prime movers.

A tracking parabolic trough collector is under fabrication. The collector has a FRP construction with reflecting surface consisting of small glass mirrors (glued to surface). The line focussing absorber is an internally finned copper tubing to achieve high thermal performance.

Development work is in progress for two different designs of tracking paraboloid dishes of 4.5 to 5.5 meter diameter. One of the dish design consists of segmented FRP construction with faceted mirrored (small size) surface. The second design uses foam glass blocks mounted on steel structure with thin large size mirror segments glued to the foam glass blocks. The first design is being done in collaboration with Messerschmit-

Bolkow-Blohm (MBB) of West Germany and the second with Jet Propulsion Laboratory of U.S.A.

2.1.3: *COLLECTOR MATERIALS DEVELOPMENT*

A number of smaller projects have been taken up to evolve better materials like glass glazing, insulating materials, anti corrosive coatings for steel frames and chemical inhibitors for closed systems using demineralized water as the energy transport fluid with aluminium absorber collectors. A study is also being conducted for development of selective coatings. Another area in which special attention is being given, is the development of manufacturing and fabricational techniques for new collector designs.

2.2: *SOLAR HEATING, COOLING & REFRIGERATION*

The direct use of solar energy as thermal energy has a wide range of domestic and industrial applications. A number of activities are in progress in this field, which are briefly described, as under.

2.2.1: *SOLAR HEATING*

In the initial stages, the major emphasis was to develop well engineered water heating systems for various applications. Under this programme, the following three types of systems have been developed and installed in a number of places:

- Small Size System
- Medium Size System, and
- Large Size System.

Under the small size system, a production oriented design has been developed for domestic solar water heater of 150 litres capacity, using approximately two square meters of collector area (pressed steel absorber) and working on thermo-syphonic principle.

The medium size system consists of forced convective closed cycle system using ten to fifty square meters of collector area (aluminium absorber). The system has automatic operation, using a differential temperature controller. Such systems can be used for guest houses, small hotels and hospitals where the solar system can help save conventional fuel expense to a fairly large extent.

The large size systems consist of over hundred square meters of collector area. These systems, which normally have a closed loop operation, are generally installed as 'retrofit' to existing hot water facility at the user's end. These solar installations, thus act as supplementary source of energy to conserve conventional fuels to as large an extent as possible. The commercial applications of such large size solar water heating systems include installations for process, dairy, chemical, textile, silk and hotel industries. These systems have a great deal of promise for being economically attractive when compared to electric or oil fired units of equivalent capacity. The economics are justified even today if certain minimum incentives are made available to the users and manufacturer in popularizing solar systems.

A number of projects have been installed as demonstration unit of different sizes (summary given in Table: 2.2.1).

2.2.2: *SOLAR COOLING & REFRIGERATION*

BHEL is working on three different combinations of vapour absorption refrigeration systems for production of $0^{\circ}C$ to minus $5^{\circ}C$ evaporator conditions, using solar thermal energy between $80^{\circ}C$ to $95^{\circ}C$. These systems are:

- Ammonia-Sodium Thiocyanate
- Ammonia-Water, and
- Freon-DMF

Investigations are still in R & D stages for building ¼ to 1-Ton (Refrigeration) size experimental units. These systems are to be upscaled to 10-Ton (Refrigeration) and higher sizes for rural applications mostly in conjunction with solar thermal power generation units and with bio-gas as supplementary source of energy. Simultaneous effort is also being made to design vapour absorption refrigeration systems for operation with waste heat (either as hot water or hot gases or waste steam) with near $100^{\circ}C$ generator conditions.

2.3: *SOLAR WATER PUMP*

As a part of its rural applications programme, BHEL has undertaken development of Solar Thermal Pumps. One of the pumps is a 1-kW size double acting engine operating with Freon-11 at nearly $90^{\circ}C$. This project which is being executed jointly with Dornier System of West Germany uses heat pipes to transport solar thermal energy to boil freon. The basic system is shown in Figure: 2.3.1 The engine has metal bellow sealed crank arrangement to convert reciprocating to rotary motion for operating conventional high efficiency water pump and also liquid freon pump. The engine has potential for being scaled up to a higher size. The experimental system will be commissioned by the middle of 1981.

BHEL is also working on the development of a 20 kW size Freon-11 Turbine along with the design of other components of the energy conversion unit and the controls. This system will have applications for providing mechanical and electrical energy needs for a rural community, including water pumping. The system will be commissioned by the middle of 1981.

2.4: *SOLAR POWER GENERATION*

As a first step in this sphere of activity, a 10 kW experimental-cum-demonstration Solar Power Plant using flat plate collectors was designed, fabricated and installed at IIT, Madras under the Indo-German Technical Cooperation Programme. The project which was initiated in August, 1976 was successfully commissioned in January, 1978. BHEL - as Project Manager and IIT (Madras) constituted the Indian team and MBB represented the West German team.

This system has basically two cycles; energy absorption and energy conversion as shown in Figure: 2.4.1. The energy collection and storage system utilizes flat plate collectors to absorb thermal energy at a temperature of 95° C and hot water is stored in an insulated stratified reservoir of 35,000 litres capacity.The energy conversion cycle utilizes Freon-114 as the working fluid. The system has all the necessary instrumentation, controls and electrical storage for obtaining technical data. This data is being analysed on short and long term basis for studying the techno-economic aspects of setting up small-sized units in rural areas where conventional electrical energy is not likely to be available for the next 5 to 10 years. The study of this data will also provide sufficient information to determine the optimum size and the best system suitable for rural applications. The efficiency of existing 10-kW experimental installation is approximately 1.5 percent.

The overall efficiency of the system can be improved further to about 2% through adoption of the following:

- Increasing the temperature of the working fluid to about 110° C by applying selective coating on the absorber panels of the collectors and using the system under pressure.
- By providing higher heat transfer area for the heat exchangers, leading to lower pressure drops and consequently lower auxiliary power consumption.
- By employing permanent magnet d.c. motors for auxiliary drives in place of conventional d.c. motors.
- By resorting to forced draft cooling tower instead of natural draft cooling tower.

2.5: *INTEGRATED ENERGY SYSTEMS (IES)*

In order to meet the total energy needs of the rural community, BHEL is working on the development of Integrated Energy Systems. These systems use solar, wind and bio-gas as the basic energies (depending upon availability at various sites) for meeting the electrical and/or thermal energy needs of the rural community. The various activities for which R & D work is going on for designing and implement IES are briefly described as under:

2.5.1: *RURAL ENERGY SURVEYS*

Based on the metereological data (mainly solar energy), the country has been divided into different zones as shown in Figure: 2.5.1. These zones have been further sub-divided into a number of regions from the point of view of availability of solar and wind engines and potential for generation of bio-gas from cow-dung.

A number of villages were then identified in each region to obtain details of energy needs and other socio-economic data for defining various Integrated Energy System designs. Typical load pattern of a village is shown in Figure: 2.5.2.

2.5.2: *SUB-SYSTEM DEVELOPMENT FOR INTEGRATED ENERGY SYSTEMS*

The development of sub-systems is a separate activity under which a number of projects have been initiated; some of which are:

- Development of solar hot water assisted bio-gas generator
- Development of 2 HP bio-gas engine for coupling to conventional water pump
- Low cost windmill for water pumping
- 1-kW Vertical Darrieus type wind generator.

Besides the above, R & D work is being done for the development of oil-pebble and chemical (PCM) thermal energy storage systems to operate in conjunction with paraboloid dish and parabolic trough at 300° C and 200° C respectively.

2.5.3: *INTEGRATED RURAL ENERGY DEMONSTRATION PROJECTS*

While the sub-systems are being developed, BHEL is simultaneously working on the establishment of an IES (by the end of 1981) totally on its own. This system will have solar thermal energy generation (75 kWh per day), vapour absorption refrigeration system operated cold storage and availability of thermal energy for domestic and small scale industrial applications. The system will use bio-gas as back-up source of energy.

Another large size IES project is being designed for installation by the end of 1982 at a village in Andhra Pradesh - DST's Salojipalli Project. This project, funded by Department of Science and Technology, is being jointly executed by BHEL and CEL with Jet Propulsion Laboratory of U.S.A. as the collaborating agency. The project has plan for providing electrical energy needs of the village (via solar thermal and with photovoltaic conversion) and for meeting the thermal and mechanical energy needs for this essentially 'high irrigation' demand villages.

3.0: **COMMERCIAL ACTIVITY**

Since the objective of all developmental work is to provide commercially-viable products, BHEL has initiated activities to establish infrastructure for the commercial production of such products. Initially, the solar products to be covered under this programme are:

(i) Flat plate collectors for water heating

(ii) Domestic Solar Water Heaters of 150 litres capacity (60° C)

(iii) Medium and Large Size Water and Air Heating Systems upto 95° C applications.

While the specific activities outlined will continue on a long-term basis, efforts are being made to develop new materials, systems and fabrication techniques with necessary software studies to achieve better results in terms of the efficiency, economy and performance of the developed products.

Plans have been prepared for the establishment of a Solar Energy Product Development Centre (SENCE) at one of the major plants of BHEL, with funding from Department of Science and Technology, Government of India. This centre will accelerate the conversion of R & D prototypes in the solar thermal area into commercial models. It will have necessary facilities for the development, design and fabrication of production-oriented prototypes. The centre will be governed by an autonomous body and will cater to the needs of all R & D institutions on a national basis.

4.0: CONCLUSIONS

Within the next few years, the detailed results of the presently-initiated solar energy R & D projects would have been carefully evaluated from the standpoint of technical performance and economic viability in the Indian context. At present, however, the solar energy programmes in the country are at too early a stage to draw any firm conclusions. As in the case of all new technologies developed in the past, efficient and economically justifiable utilization of solar energy can also come about only by passing it through an exhaustive initial stage of experimentation and evaluation as is presently being undertaken.

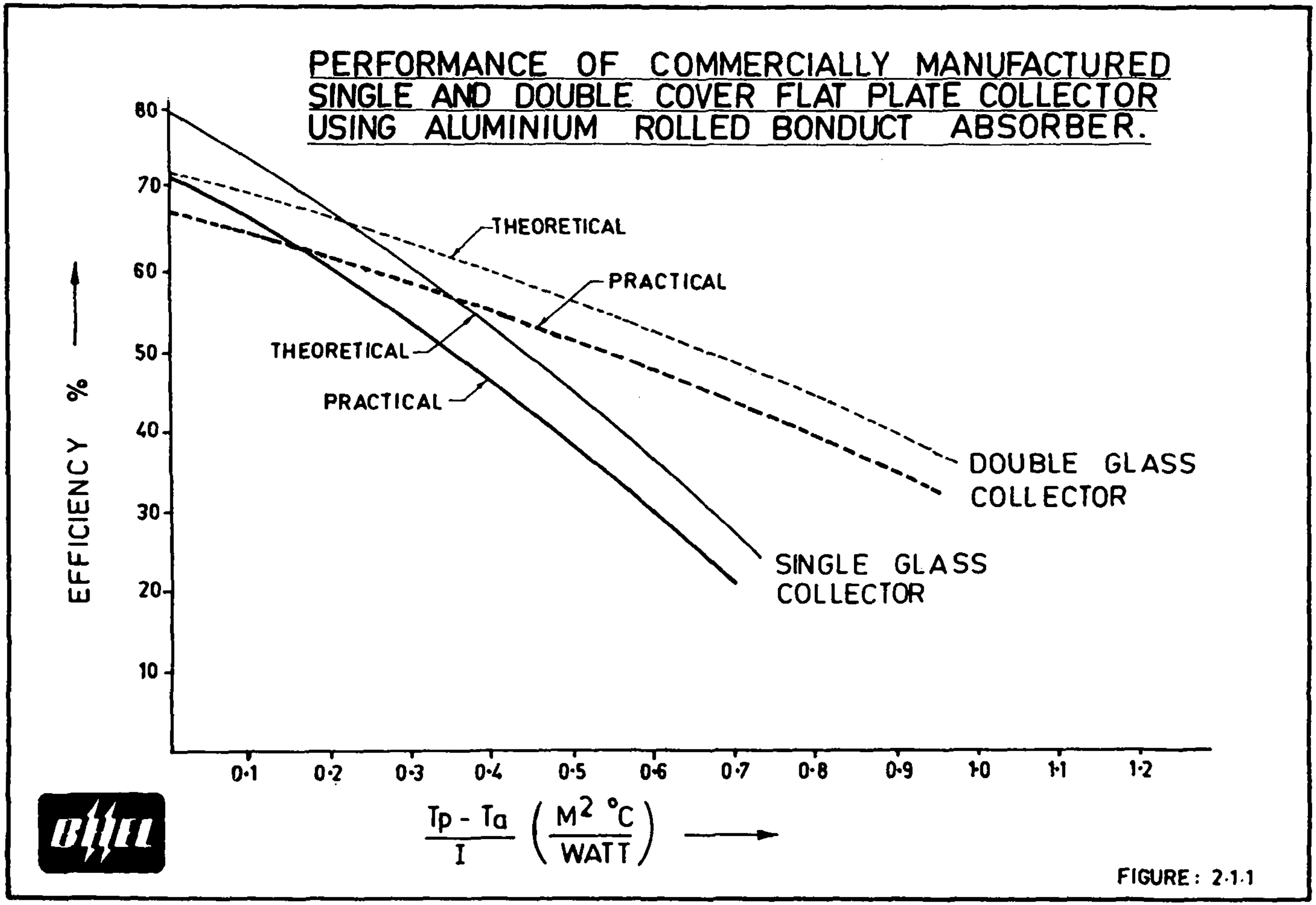
TABLE: 2.2.1: MAIN FEATURES OF SOLAR WATER HEATING SYSTEMS

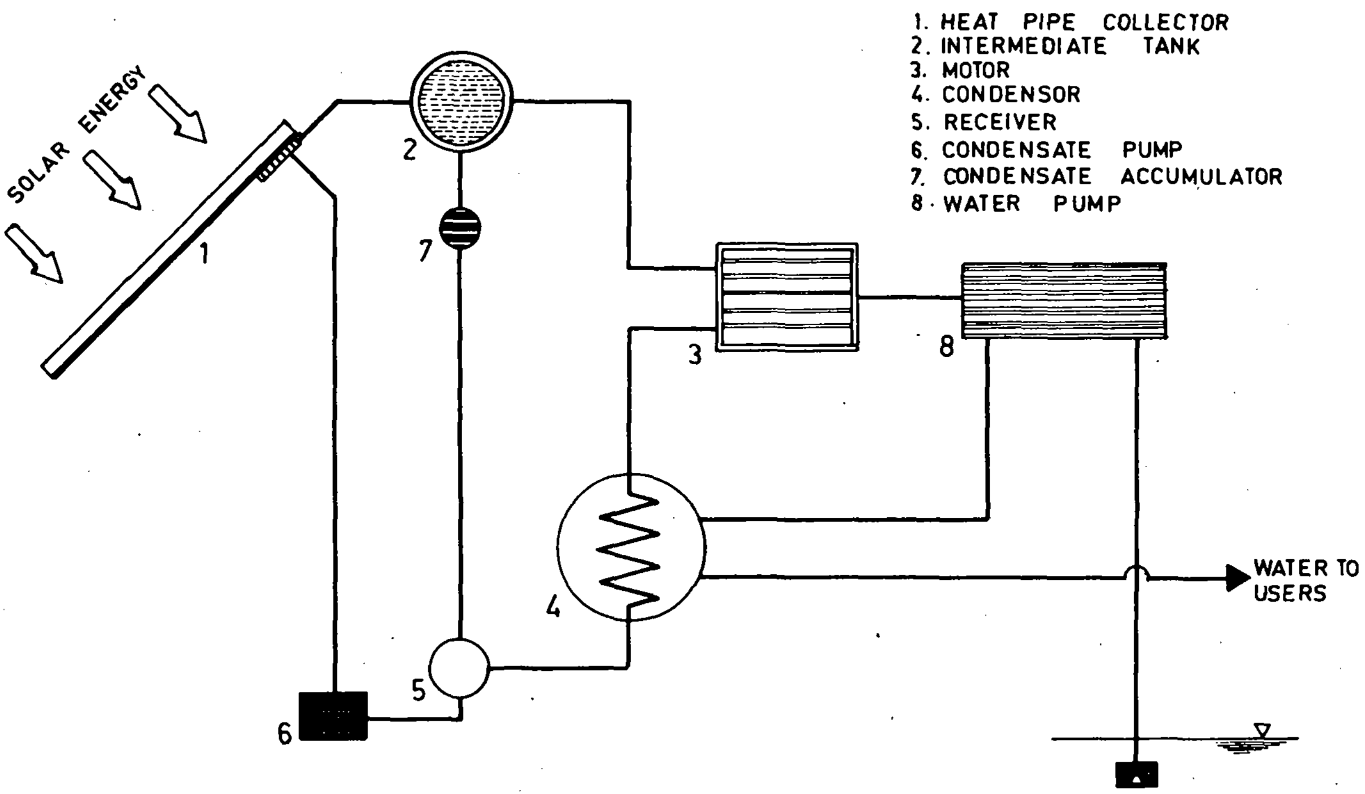
	PROJECT NAME & UTILITY	*ENERGY COLLECTOR AREA*		*OPERATIONAL TEMPERATURE*	*REMARKS*
		COLLECTOR (sq. m.)	*MIRROR BOOSTER (sq. m.)*		
A	SMALL SIZE SYSTEMS				
A1	DOMESTIC SOLAR WATER HEATER				
	150 litres capacity Thermosyphonic system for Household Applications	2 SG	–	50-60	Production Oriented Design; Mass Scale Production to be initiated.
B	MEDIUM SIZE SYSTEMS				
B1	HOUSE PROJECT				
	To Provide Hot Water for Bathrooms and Kitchen	20 SG	–	50-60	Operational Since July, 76
B2	INDO AUSTRALIAN CATTLE BREEDING FARM PROJECT, HISSAR	50 SG	–	50-60	Operational Since Jan., 80
	To Provide Hot Water for Laboratory and Can Washing				
B3	GUEST HOUSE PROJECT, HARDWARE				
	To Provide Hot Water for Bathrooms and Kitchen	50 SG	–	50-60	Operational Since Jan., 80
B4	IIT (BOMBAY) PROJECT				
	To Provide Hot Water for Vapour Absorption Refrigeration System	50 DG	50	90.	Operational Since March, 79

	PROJECT NAME & UTILITY	ENERGY COLLECTOR AREA		OPERATIONAL TEMPERATURE	REMARKS
		COLLECTOR (sq. m.)	MIRROR BOOSTER (sq. m.)		
B5	LEPROSY HOSPITAL PROJECT POONA				
	To supply Hot Water for Leprosy Patients at 35 °C for Bathing, for Operation Room at Higher Temperature and for Kitchen	100 SG 10 DG	– 10	50-60 90	To be Commissioned in Dec., 80
C	LARGE SIZE SYSTEMS				
C1	QUTAB HOTEL PROJECT, DELHI				
	To Provide Hot Water for Bathrooms & Kitchen as a Retrofit System to Existing Hot Water Boiler	217 SG	–	50-60	Operational since June, 78.
C2	10 KW SOLAR POWER PROJECT AT IIT (MADRAS)				
	To Provide Energy Collection Facility with 35 m^3 Stratified Reservoir for Experimental Solar Thermal Power Generation Unit	756 DG	756	95	Operational Since Jan. 78
C3	DAIRY PROJECT, WARANGAL				
	To supply Hot Water for Can Washing and Milking Machines	OVER 400 SG	–	50-60	Being Designed (Dec., 80)
C4	CANTEEN PROJECT, HINDUSTAN MACHINE TOOLS LIMITED, BANGALORE				
	To supply Hot Water for Dish Washing Both Manual and Automatic and also For Kitchen Usage.	OVER 300 SG	–	50-60	Being Designed (Dec., 80)

SG: Single Glass Cover; DG: Double Glass Cover

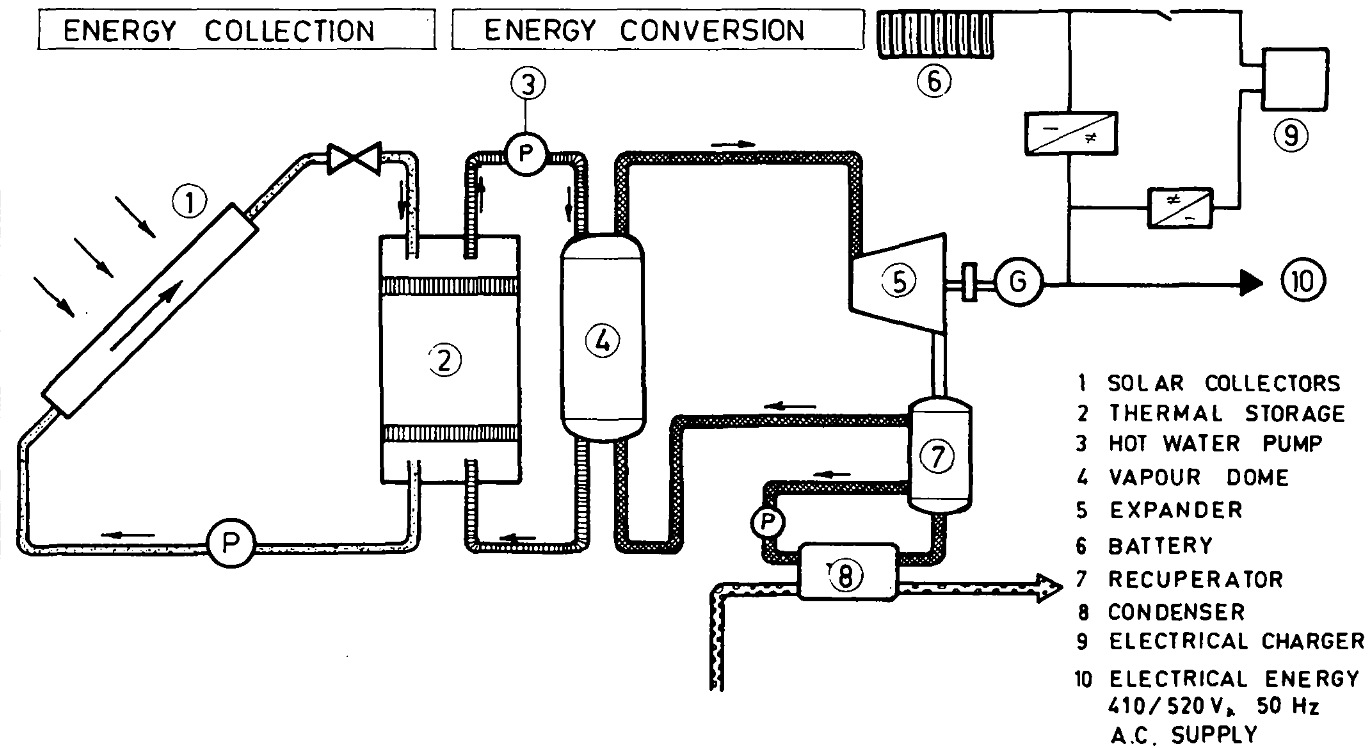
Except A1, C3 and C4 All other systems Are Closed Cycle Arrangement Using Demineralised Water As Energy Carrier Media.


PERFORMANCE OF COMMERCIALLY MANUFACTURED SINGLE AND DOUBLE COVER FLAT PLATE COLLECTOR USING ALUMINIUM ROLLED BONDUCT ABSORBER.
EFFICIENCY %
80
70
60
50
40
30
20
10
THEORETICAL
PRACTICAL
THEORETICAL
PRACTICAL
DOUBLE GLASS COLLECTOR
SINGLE GLASS COLLECTOR
0·1
0·2
0·3
0·4
0·5
0·6
0·7
0·8
0·9
1·0
1·1
1·2
$\frac{Tp - Ta}{I} \left(\frac{M^2\ ^\circ C}{WATT}\right)$
FIGURE: 2·1·1



SCHEMATIC OF SOLAR THERMAL WATER PUMP

FIGURE : 2·3·1



SCHEMATIC REPRESENTATION OF 10 KW SOLAR POWER PLANT

FIGURE : 2·4·1

ZONAL DIVISION OF INDIA BASED ON CLIMATOLOGICAL DATA

FIGURE 2.5.1.

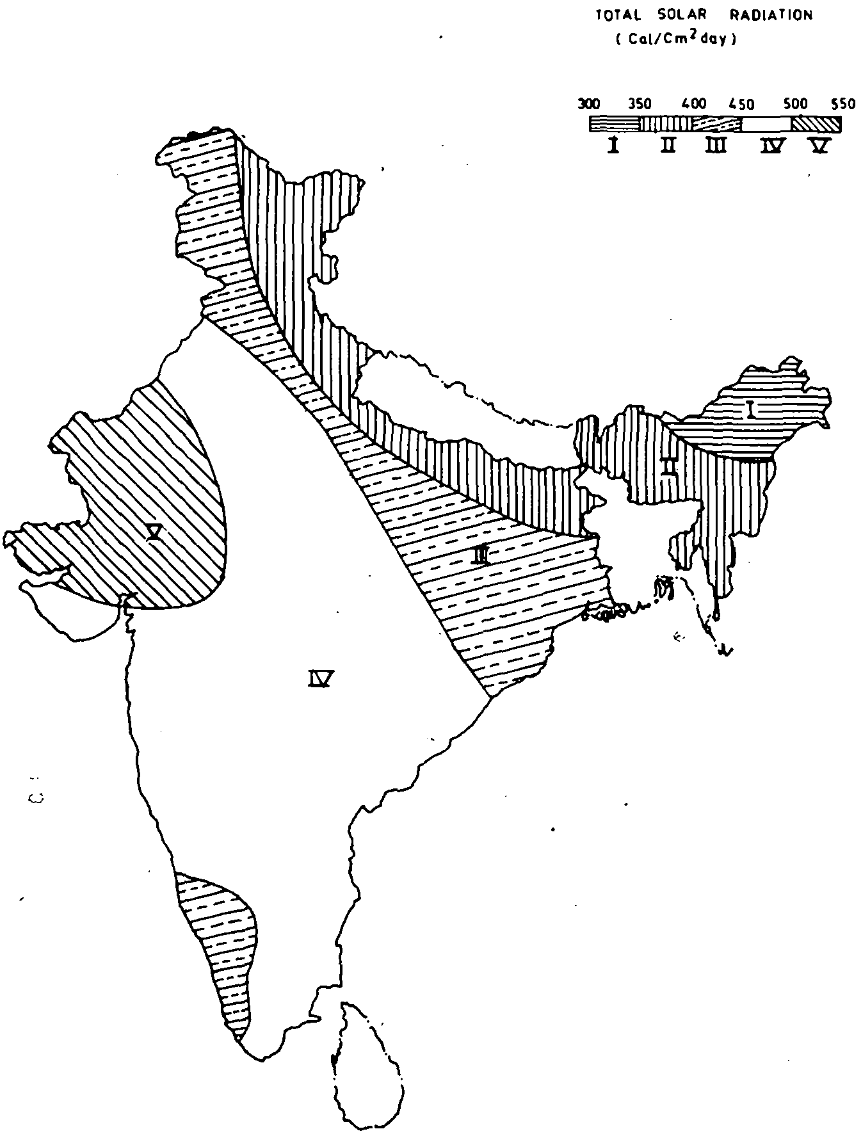
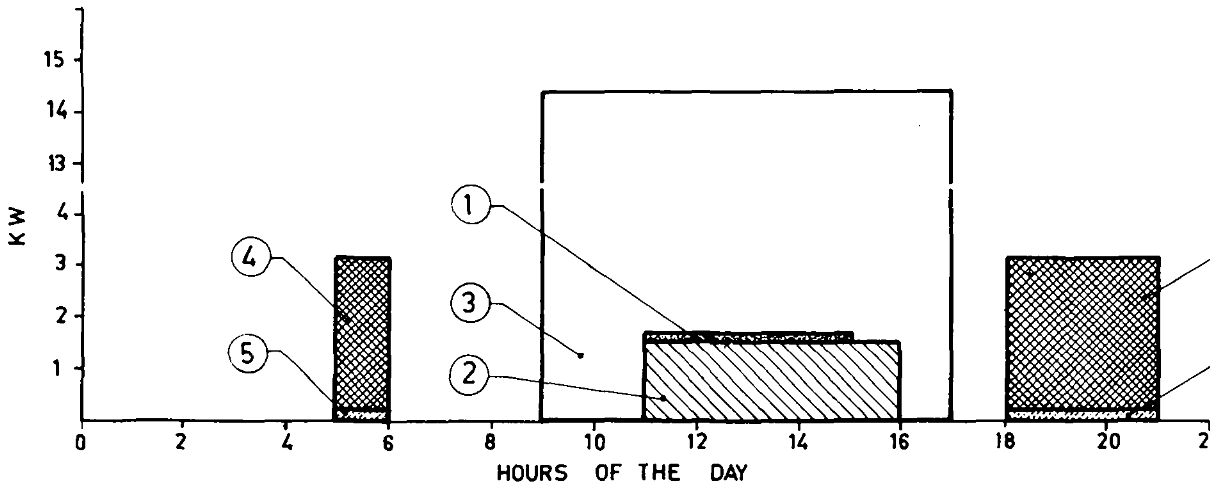


FIGURE : 2·5·2

DAILY ELECTRICAL LOAD PATTERN - SALOJIPALLY

1 P. WATER PUMPING : 0·15 KW
2 COMMON FACILITIES : 1·50 KW
3 IRRIGATION : 14·42 KW
4 DOMESTIC LIGHTING : 3·15 KW
5 STREET LIGHTING : 0·20 KW



CRITERIA FOR COMMERCIAL DEVELOPMENT OF FLAT PLATE COLLECTOR FOR DEVELOPING COUNTRIES

by

SRI R. NAGARAJA

INTRODUCTION

Supplies of fossil fuels which contributed much to the rapid industrialisation of the West and the phenomenal economic boom witness in OPEC, are fast diminishing.[1] With decreasing availability cost of fossil fuels is escalating upwards, causing great strain on economic development of developing and less developed countries which are less fortunate in fossil fuels resources. Above aspects of energy makes us look forward to "SOLAR ENERGY" one of the most attractive non-polluting alternative energy resources and is the right choice for developing and less-developed countries in the tropical belt.

Energy crisis faced by many developed and less-developed[2] countries demands effective and accelerated development of alternative source of energy like 'Solar Energy'. In this context rapid commercial development of techno-economic-viable application of solar energy option like solar water heating system is a must. All out effort are required by industry state, national, and international agency to encourage bulk use of solar energy options to conserve fossil fuels and to mitigate energy crises.

Reviewing the basic options in solar thermal devices in particular for fluid heating we have two options:

1. Focusing type solar collector that can give high temperature has distinct advantage for operating engine or turbo-machinery for power generation. This type of collector needs direct sun light. The collector must be movable in order to track the sun in to and need for movable mount pose problems such as structure has to be larger and sturdier and technology required is to be of advanced level.

2. Flat plate type solar collector uses medium technology and is operational in temperature range up to 100° C. They are not restricted to clear sunny days and can be used in bright cloudy weather also. Normally flat plate type collectors are stationary and are preset to optimum tilt. Energy convertion efficiency of the order 40 to 60% is attainable.

Technology of flat plate collector is available from educational and research institutions but needs commercial orientation to attract investment in production facilities and in deployment of system in bulk as an economic proposition.

CRITERIA FOR COMMERCIAL DEVELOPMENT OF FLAT PLATE COLLECTOR

Flat plate collectors form the heart of solar thermal options in particular for air and water heating application. Commercial development and deployment of flat plate collector is of significant importance to solar industries, in particular to developing energy economy of less developed countries in general in the long run.

Commercial development of any solar energy products needs inter-action between industry and R & D institutions. In particular for Flat plate collector (FPC) system engineering and design refinement to suit economic production is imperative. In order that FPC technology is adopted widely the system economics indicate, demand is not for most efficient product but for a product that can collect maximum energy per unit cost, even at the cost of overall efficient. Key to commercially viable solar FPC technology lies in development of flat plate collector which is simple and of low cost, commensurate with reasonable economic life and performance.

Tungabhadra Steel Products Limited, has made small but committed beginning in commercial development and deployment of flat plate type collectors in India. Product developed, manufactured and marketed is simple, functional and cost effective. Performance and economic life is justifiable. Criteria adopted in development of flat plate collectors is detailed in two phases.

1. Design and performance criteria for the flat plate collector.

2. Commercial criteria for the flat plate collector.

Application of modern tools like ABC analysis, value analysis is illustrated. Typical case study is detailed reflecting energy contribution and economic returns from solar water heating system in particular for industrial application.

DESIGN CRITERIA FOR FLAT PLATE COLLECTOR

Flat plate collector has a vital role to play in solar energy utilisation. In assessing criteria for its commercial development it is essential to review the basic functional requirement of flat plate collector in the system and component of flat plate collector within. The basic function of flat plate collector is to intercept solar radiation and convert radient energy into thermal energy and transfer the thermal energy so generated to working fluid passing through collector, efficiently. Other sub system in solar thermal system are:

1. Thermal storage: Which stores thermal energy over night/over few days to meet demand for energy uniformly.

2. Auxiliary heat source: used to back up, heat demand when solar thermal storage system is unable to meet the demand, made on the system. This makes the system economically viable.

3. Heat Distribution system: This system comprises of piping and fitting together with control system to distribute heat energy to the users point for equipments linked to the solar thermal system.

Detailing the flat plate collector consists of absorber plate normally a blackend metal surface which absorbs direct as well diffuse solar radiation and converts radiant energy into heat. Heat in the absorber plate is transfered to the working fluid, transfers thermal energy from solar collectors to thermal storage system. Other components of flat plate collectors are designed to reduce thermal loss and thereby improve efficiency. A cross section of solar plate collector manufactured at Tungabhadra Steel Products Limited is indicated in figure-1. Functions of the key components going into the flat plate collector is detailed in Table 1 which also indicate desirable thermal radiational, physical and environmental qualities rated to quantify functional requirement. Against the functional requirement, rating of commercial flat plate collector TSP 206A is indicated in Table 2 keeping in view the critical nature of the flat plate collector in the over all solar thermal system, a brief description of the key components[3] going into flat plate collector is given below:

1. *Transperant cover:* Critical function is to transmit radiant energy on to the absorber plate. Other functions are:

(a) Reduces heat loss to a minimum by preventing reradiation from the absorber in the infrared range.

(b) To protect the absorber against environmental influence.

Material property to meet above functions are:

(a) Transmittance to solar radiation in visible range.

(b) Material resistance to fracture/breakage due to impact.

(c) Temperature stability up to 90° C.

(d) Clarity and stability to weathering.

2. *Absorber plate:* Absorber plate is that component of FPC which absorbs incoming solar radiation, transforming radiant energy into thermal energy and transfer thermal energy to working fluid. The critical requirement of the material is high thermal conductivity.

Other material properties are ease in fabrication, low speed gravity and corrosion resistance.

3. *Absorber coating:* Critical function is to absorb radiant enrgy falling on its surface and convert it to thermal energy. Normally flat black paint or varnish is used as a coating. However non-selective black coating has disadvantage of having high emittance

value. Selective coating is useful as it has high absorption value and low emittance value which results in absorber plate being heated up more intensively.

4. *Insulation:* This components is provided to reduce heat loss at the back and sides of the absorber plate. Critical material property being low thermal conductivity. Other desirable properties are low density, good mechanical strength and temperature stability, ease in cutting and installing low moisture absorption.

5. *Housing:* Primary function of this component is to protect absorber plate and insulation against environmental influences. Desirable materials properties are low density case in fabrication and resistance to atmospheric corrosion.

Sizing of the flat plate collector in relation to system requirement depends on the basic design of the flat plate collector, available radient energy and climatic data for the region. Radiation data prevailing in peninsular India is indicated in Tables 3 and 4. The climatic data for peninsular India is fairly different from that of developed countries to the extent of seasonal variation, sunshine hours are predectable due to periodic recurrence of the monsoon. This factor has to be taken into consideration in assessing solar contribution for the month and for annual energy contribution in designing the solar thermal system. It may be noted from weather data presented at table 4 for the peninsular India sub zero temperature are not prevalent as such basic designs do not consider freezing of the working fluid.

Basic design of fluid passage and of absorber material is done keeping in view

1. Long term availability.

2. Cost of material.

3. Methods of fabrication available locally which are labour intensive rather than capital intensive. Another important factor in basic design is one of transporting the solar panels and thermal storage by road transport and rail which necessitates modular design and minimum weight for the flat plate collector.

CRITERIA FOR PERFORMANCE OF FLAT PLATE COLLECTOR

Performance indicates how-far a product meets its functional requirement. Basic function of flat plate collector is to collect solar radiation and convert major portion of it into useful thermal energy transfered to working fluid. To ensure best performance it is critical to examine factors effecting conversion efficiency of flat plate collector in context with radiant energy falling on the surface. Some of the important factors are:

1. *Assessment of radiant energy incident on the surface of collector:* Radiant energy incident on the collector surface has to be optimised. Maximum value of this can occur only by tracking the sun in two directions, for a flat collector orientation and tilt of the collector has to be optimised in relation to solar radiation data available for the

location.[4] Table 3 indicates level of average daily solar radiation per m.sq. on horizontal surface for various locations in penensular India.[5] And Table 2 solar energy available as hourly average radiation per m^2 for a location. It is advisable in the basic consideration of energy input to limit duration of operation of FPC to solar altitude not less than 30° C to the horizontal, as reflection loss from the collector cover glazing will be high for lower altitudes.

2. *Radiant energy incident on absorber coating:* Radiant energy falling on absorber is as on collector surface described above less reflection loss and transmission loss at cover glazing. Transmission loss depends on thickness on glazing clarify dust cover and number of covers opted.

3. *Radiative energy loss from absorber surface in the infrared range:* Radiant energy loss from the absorber in the infrared range can be kept to a minimum by operating at a lower temperature consistent with requirement. This is because emisivity depends fourth power of absolute temperature of the absorber plate and also surface area exposed to sky and nature of coating used. Nor non-selective black it is almost equal to absorption level. For selective surface, emisivity factors is much lower than absorption factor and as such it is desirable to incorporate selective surface for flat plate collector working at high temperature.

4. *Conviction loss due to air in between absorber and cover glazing:* Conviction loss due to air in between absorber plate and cover glazing can be minimised by optimising the air gap and also by use of multiple glazing.

5. *Conductive-loss of thermal energy from back and sides of the absorber:* Thermal energy loss due to conduction is normally reduced by insulating material of suitable thickness at the back and sides of absorber plate.

6. *Operational temperature of absorber plate:* Absorber temperature is an important factor in accounting energy loss by radiation to the sky in the infrared range. It is better to have different absorber plates for different temperature ranges to suit and application. Selective surface is recommended with double glazing for temperature range 80 to 100° C.

7. *Thermal conductivity of absorber material, fluid and CONDUCT material and also thermal bonding:* Thermal conductivity of material is very important in effectively transferring thermal energy to the working fluid. Copper, aluminium and steel are preferable in the order keeping in view thermal conductivity of the material. However considering long term availability and cost it is better to reconcile with steel as a trade off performance against investment.

8. *Thermal capacity of absorber plate assembly:* Thermal capacity of the absorber plate and fluid conduct depends upon the weight of material and its specific heat, volume of fluid contained in the absorber assembly will also increase the thermal capacity of the system. It is desirable to keep thermal capacity to a minimum.

Criteria for best performance of an FPC lies in:

(a) Maximising factors 1, 2 and 7 above.

(b) Minimising factors 3, 4, 5 & 8.

(c) And keeping down factor 6 temperature of absorber to a value sufficient to meet temperature requirement-of the system.

COMMERCIAL CRITERIA FOR DEVELOPING FLAT PLATE COLLECTORS

Commercial product development must have relevance to influences that effects acceptance of the product by the consumer. This may be in the case of solar water heating system.

1. To replace existing energy source like firewood, kerosene, natural gas or electricity by solar energy in order to gain long term economy.

2. Fear of future non-availability of conventional fuels and to mitigate pollution and risk in use of conventional fuels.

3. Desire to adopt new and inovative product concept.

When it comes to make a purchase decision all purchasers irrespective of domestic, commercial or industrial would like to know how much the solar system will cost them and how much solar system will save them before investing their money in the system.

Keeping in view of above basic requirement, commercial factors that effect development of solar industry in general and commercial development of flat plate collector in particular are analysed below. Relevant factors like Market, production, investment and system economics are taken up sequentially, and considered to attain the following:

1. Matching product attributes and performance level to minimise investment, installation, maintenance and transport costs. Also to minimise auxiliary power requirement and spare required for installation.

2. Production economics in relation to fabrication and assembly of flat plate collector and solar thermal system in developing and less developed countries.

3. Lowering the cost in particular with reference to costs basic material labour, transport and installation.

4. System economics to ensure favourable operational features, early return of investment by way of fuel savings and user acceptance for the product both as new and as retrofit into the existing system.

A. *Market factor:-* Market for solar industry in general and for flat plate collector in particular, is substantial and is comparable only to automobile industry and auto spares industry. The product serves the basic need to supplement the energy availability – a key to industrial growth and prosperity of a nation, in particular to less-developed and developing countries facing energy crises which is likely to stun industrialisation of these countries.

Demand for solar water heating system as assessed by Tungabhadra Steel Products Limited from its available market data indicate three well defined market segments for the product:

1. *Domestic:-* Domestic application mainly for residential user, market in this segment is assessed at 20% of the total market potential. Immediate demand as reflected by number of electric geyser units/storage water heating units sold by various companies in India will justify production of solar panels in excess of 50,000 m^2 per annum.

2. *Commercial:-* Commercial application representing use of solar water heating system for hotels, hostels and guest houses represent approximately 25% of total market potential for solar panels.

3. *Industrial:-* Application in particular for, boiler feed water heating system, industrial canteens, process water requirement for textiles, sericulture, diary and food processing is very vast and account for 55% of the total market potential.

The above market potential can sustain a solar industry with a turnover of US$ 24.25 millions at an estimated basic price of panels at US$ 100 per m^2 of collector surface.

Demand is for a product that is simple and functional, for a product, that justify its investment by a level of performance that ensure adequate returns by way of cost of conventional energy saved, to pay itself back within its economic life span.

B. *Production factor:-* Volume production of flat plate collector holds key to economic production of solar panels for solar thermal system. Level of investment in production facilities for fabrication and assembly of flat plate collectors adopting labour intensive methods is very modest. Considering comparatively low cost of labour prevalent in developing and less developed countries, profitability of the product at international price level (US$ 100 per m^2 approximately) is good. Solar industry development in the developing and less developed countries hold immense benefits, in particular to mitigate the enrgy crises faced by many of them and employment generation in relation to manufacture and installation of solar flat plate collector.

Material, equipment and process available indegenously are adoptable for production of flat plate collector in bulk. Use of copper and aluminium for the absorber plate has to be reviewed by the less developed and developing countries keeping inview of scarcity for the material (copper) and energy intensive production methods required (aluminium). Steel absorber plates with non-selective black coating has given satisfactory performance (daily average efficiency 40% and upwards).

C. *Investment and system economics:-* Solar thermal options must be economically viable proposition to attract investment and for adoption in bulk. This can be assured only being minimising investment and maximising returns from the solar system. Application of A B C analysis to the sub-systems of a solar water heating system in particular for domestic, commercial and industrial application is detailed in table 5 indicates that flat plate collector constituting A item accounts for 67% of the system total cost.

Repeating the process of A B C analysis for components of flat plate collector as detailed in table 6. It is seen absorber and its housing constitute 68% of the total cost of the flat plate collector.

Therefore cost of flat plate collector and in turn cost of solar thermal system in general can be reduced by a review value of these item in relation to performance and cost that is application of value analysis to these component to bring down cost and to improve performance for the cost incurred. Table 7 details a rating procedure adopted in selecting basic material for these high value items of flat plate collector. Table 2 details rating for performance of commercial flat plate collector TSP 206A manufactured by Tungabhadra Steel Products Limited, which compares closely with desirable rating for performance detailed in table 1.

Investment and system economics is analysed in detail for a specific industrial application at Madras (India) location. Salient features being:

1.	Equipment	:	Solar water Heating System 20,000 litres/day at 40-60°C comprising 200 m^2 of Flat Plate Collector and Thermal Storage 60,000 litres.
2.	Location	:	Proposed location Madras (India) latitude 13° Longitude 18° 11' altitude 10 m.
3.	Solar Energy contribution.	:	47% Annual average.
4.	Fuel savings	:	25,000 litres per annum estimated.

Details of energy analysis is at table 8 and economic analysis that is investment and benefit there off detailed at table 9. It is seen from table 8 solar energy can supplement conventional fuel to the extent of 40 to 50% and from table 8 investment can be paid back within 12 years value of fuel saved in 12 year works out to Rs 1,484,250 about 5 times the amount invested. Fuel savings 300,000 litres during the same period. Average system efficiency being 40%. Domestic Water Heating System is illustrated figure 2 and domestic installations in India indicated at figure 12.

CONCLUSION AND RECOMMENDATION

Basing on criteria for commercial development of flat plate collectors detailed in preceeding paragraphs, key to wide spread use of solar equipments and in turn growth of solar industry lies in commercial development of flat plate collector which has justifiable performance in relation to the price tag attached to it.

Government and international agency must support and nourish solar industry in developing and less developed countries to encourage wide spread use of solar thermal equipment in particular for all low grade heat applications.

First recommendation is a national/international revolving fund from which interest free loan are made available through recognised bank of the country to commercial, and industrial investors opting for solar systems may be the right choice at this stage. Government subsidy though desirable may not attract investors as it gives deferred benefit compared to interest free loan which acts as incentive to organised sector to opt for solar equipments.

Second recommendation in this context would be that national and international agency should recognise at state level/national level educational and R & D Institution capable of testing performance of flat plate collectors and to accord recognition to measure factories in the state who are up to the mark (minimum efficiency of flat plate collector as per available national and international standards may be specified).

Third recommendation to encourage solar industry is to make flat plate collector technological achievement of educational and R & D institution to industry.
reimburse duty/taxes paid will be attractive to solar industry and to the consumer.

Fourth recommendation would be simplification of procedures to transfer technological achievement of educational and R & D Institution to Industry.

Lastly it is desirable to establish or fund mobile exhibition of solar energy products and demonstration projects to publicide utility of solar options.

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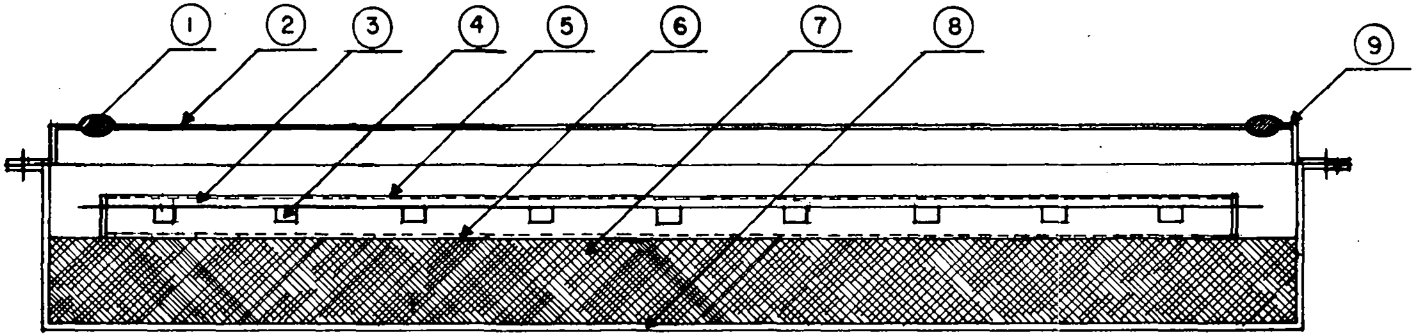
6.	Fig. 1 to 12	:	Courtesy R & D Department Tungabhadra Steel Products Ltd., Tungabhadra Dam, Dist Bellary Karnataka (India) 583225.

FIGURE 1.

CROSS SECTION OF SOLAR PANEL

T.S.P. 206A



LEGEND/PART LIST

1. RUBBER SEALING
2. COVER GLASS (SINGLE)
3. ABSORBER PLATE (STEEL) WITH NON SELECTIVE BLACK SURFACE
4. PIPE GRID (SQ.TUBE) STEEL
5. HEADER PIPE (ROUND) STEEL
6. REFLECTING FILM M.P.E. FILM
7. INSULATION SPINTEX. 300.
8. HOUSING FRAME (STEEL)
9. COVER FRAME (STEEL)

Table 1: FUNCTIONAL REQUIREMENTS OF F.P.C. COMPONENTS

Sl. No.	Component part	Basic function	Thermal conductivity reqt.		Radiation reqts.			Physical reqts.			Environmental reqts.		Preferred rating
			Low	High	Absorption	Reflectance	Transmittance	Low density	Ductility	Easy fabn.	Corrosion res'c	Appearance	
1.	Top Cover (Glazing)	Transmit radiant energy in	1	0	0	0	3	2	1	1	2	1	11
2.	Cover Gasket	Prevent entry of dust and moisture	1	0	0	1	0	1	3	1	2	1	10
3.	Absorber Plate	Transmit thermal energy to working fluid	0	3	2	0	0	2	1	2	1	0	11
4.	Absorber Coating	Absorb radiant energy	0	2	3	3	0	0	1	1	2	0	12
5.	Fluid conduit	Absorb thermal energy	0	3	0	0	0	2	2	2	2	0	11
6.	Insulation	Reduce Loss of thermal energy	3	0	0	0	0	2	0	1	1	0	7
7.	Housing	Protect absorber and insulation from weather	1	0	0	1	0	2	1	2	3	1	11
8.	Back Cover	Protect absorber and insulation from weather.	2	0	0	1	0	2	0	1	3	1	9

RATING

0. NON RELEVANT
1. DESIRABLE
2. IMPORTANT
3. CRITICAL

Table 2: RATING OF A COMMERCIAL FLAT PLATE COLLECTOR

Sl. No.	*Component part*	*Material used*	*Thermal conductivity reqts.*		*Radiation reqts.*			*Physical reqts.*			*Environmental reqts.*		*Rating*
			Low	*High*	*Absorption*	*Reflectance*	*Transmittance*	*Low sp. gravity*	*Ductility*	*Easy fabn.*	*Withstand weather condition*	*Appearance*	
1.	Top cover (glazing)	Window glass 3 mm	2	0	0	0	2	1	0	1	3	2	11
2.	Cover gasket	Natural rubber	2	0	0	0	0	1	2	2	2	1	10
3.	Absorber plate	C.R.C.A. steel	0	1	2	0	0	1	2	3	1	0	10
4.	Absorber coating	Non selective black	0	1	3	1	0	0	1	1	1	0	7
5.	Fluid conduit	E.R.W. sq. section	0	2	0	0	0	1	2	2	1	0	7
6.	Insulation	Spintex 300	3	0	0	0	0	2	0	2	2	0	9
7.	Housing	Steel fabricated housing	1	0	0	1	0	1	1	2	2	1	9
8.	Back cover	C.R.C.A. sheet (painted)	1	0	0	1	0	1	0	2	0	0	7

RATING

0. Non Relevent
1. Tolerable
2. Suitable
3. Indeal

Table 3: SOLAR RADIATION DATA FOR SOUTH INDIAN LOCATIONS.

NAME	*TRIVANDRAM*	*MANGALORE*	*GOA*	*BOMBAY*	*KODAIKANAL*	*BANGALORE*	*HYDERABAD*	*POONA*	*MADRAS*	*VISHAKAPATNAM*
LAT.	$8^{\circ}29$	$12^{\circ}32$	$15^{\circ}29$	$18^{\circ}54$	$10^{\circ}14$	$12^{\circ}58$	$17^{\circ}24$	$18^{\circ}32$	13°	$17^{\circ}48$
LONG.	$76^{\circ}57$	$74^{\circ}51$	$73^{\circ}49$	$72^{\circ}51$	$77^{\circ}28$	$77^{\circ}35$	$78^{\circ}28$	$73^{\circ}51$	$10^{\circ}11$	$83^{\circ}14$
Alt.	*60 m*	*20 m*	*55 m*	*15 m*	*2339 m*	*92 m*	*545 m*	*555 m*	*10 m*	*41 m*
JANUARY	4987	4557	4815	4385	4987	4729	4127	4471	4385	4557
FEBRUARY	5331	5159	5417	4987	4557	4901	5073	5245	5417	5245
MARCH	5589	5503	5847	5589	4643	5933	5245	5761	5847	5503
APRIL	5245	5417	5933	6105	4471	5847	5331	6105	5761	5675
MAY	4643	5073	5933	6191	5073	5589	5761	6191	5589	5761
JUNE	4385	3611	4127	3955	4471	4385	4643	5159	4987	4299
JULY	4127	2923	3267	3869	4127	3525	3353	3697	4471	3955
AUGUST	4471	3525	4299	3439	3955	3697	3525	3783	4729	4385
SEPTEMBER	5675	4127	4643	4557	4127	4041	3353	4471	4815	4385
OCTOBER	4471	4213	4901	5073	3783	4127	3955	4901	4299	4471
NOVEMBER	4213	4127	4643	4299	4041	3869	3439	4385	3611	4385
DECEMBER	4385	4299	4471	4299	4557	4127	3955	4041	3783	4299

All figures in K.cal/sq.m/day.

Table 4: Hourly SOLAR RADIATION DATA (on Horizontal Surface)
For MADRAS LAT 13° LONG 10° 11' HT. 10 m.

		Average Hourly Radiation Kcal/m^2										
MONTH REF.	*AV. TEMP C*	*8 am.*	*9 am.*	*10 am.*	*11 am.*	*12 noon*	*1 pm.*	*2 pm.*	*3 pm.*	*4 pm.*	*5 pm.*	*Total*
January	24.1	–	340	460	570	650	690	650	530	390	200	4480
February	26.3	230	411	570	690	780	790	730	610	450	240	5501
March	28.8	240	430	620	710	790	830	760	630	470	270	5750
April	31.2	250	440	570	710	810	810	770	660	470	270	5760
May	32.5	220	390	540	640	720	750	690	620	460	260	5290
June	32.8	240	410	580	690	720	740	640	510	340	220	5090
July	30.7	190	350	470	580	590	590	500	380	290	–	3940
August	30.3	–	290	430	550	570	580	520	430	350	210	3930
September	30.7	230	400	540	680	690	690	610	490	360	220	4910
October	27.6	–	300	400	480	490	510	450	380	280	–	3290
November	26.9	–	290	390	460	530	500	480	400	310	–	3360
December	24.6	–	300	440	500	530	560	510	440	320	–	3600

Ref. Monthly Bulletin of Metrological Dept. 1958.

Table 5: SOLAR WATER HEATING SYSTEM ABC
ANALYSIS OF SUB-SYSTEM COSTS

Sl No.	*Sub-system description*	*Type 300 lit/day Domestic System % of total cost.*	*Type 1000 lit/day commercial system % of total cost.*	*Type 20,000 lit/day industrial system % of total cost.*
1.	Flat plate collector (Solar panel)	61	74	66
2.	Thermal storage (Tank)	11	9	15
3.	Support structure and piping.	4	4	2
4.	Circulating system	11 *	3	1
5.	Auxiliary system (heating)	6 *	2	–
6.	Installation and commissioning.	7	8	17
	Total costs:	100	100	100

* Offered as optional

A B C Classification	*A*	*B*	*C*
Sub-system	F.P.C.	Tanks	Others
% of total cost (Average)	67	12	21

Table 6: FLAT PLATE COLLECTOR A B C ANALYSIS OF COMPONENT COSTS

Sl No.	*Component description*	*Type TSP 206A % of total cost*
1.	Transparent cover	12
2.	Absorber	32
3.	Insulation	14
4.	Housing	36
5.	Painting and hardware	6
	Total	100

A B C Classification	A items	2 & 4
	% of total costs	68%
	B items	1 & 3
	C items	others

Table 7: RATING FOR KEY FACTORS MATERIAL FOR ABSORBER ASSEMBLY

Sl No.	*Material*	*Thermal conductivity*	*Density (Sp Gr)*	*Corrosion resistance*	*Fabrication factor*	*Availability factor*	*Cost factor*	*Total*
1.	Copper	3	1	3	2	1	1	11
2.	Aluminium	2	3	2	1	2	2	12
3.	Steel (MS)	1	1	1	3	3	3	12
4.	Steel (Stainless)	1	1	3	2	1	2	10

Material suggested – Steel (MS) or Aluminium

Material for Panel Housing

Sl No.	*Material*	*Density (Sp Gr)*	*Corrosion resistance*	*Fabrication factor*	*Availability factor*	*Cost factor*	*Total*
1.	Aluminium	3	2	1	2	1	9
2.	Steel (MS)	1	1	3	3	3	11
3.	Plastic/FRP	3	3	2	2	2	12
4.	Wood	3	2	2	2	2	11

Material suggested – Plastic/FRP.

Rating

0. Non relevant
1. Tolerable
2. Desirable
3. Ideal

Table 8: SOLAR ENERGY ANALYSIS

System: Solar Water Heating System 20,000 lit/day 40-60 °C

Thermal storage: 60,000 litres

Cliant: M/S Indian Molasses Co. Pvt. Ltd., Madras

Location: Madras (India)

Latitude 13 °N

Longitude 18° 11'

Height: 10 m

Month ref.	*Available solar energy K.cal/m²/day*	**Usable energy in area 200 m². K.cal/day.*	*Total energy available per month K.cal/10⁶*	*Energy required £ per month K.cal x 106*	*Solar contribution as % of total energy required.*	*Remarks*
January	4385	350800	10.52	24.42	43.1	
February	5417	433360	13.00	24.42	53.2	
March	5847	467760	14.02	24.42	57.4	
April	5761	436880	13.82	24.42	56.6	
May	5589	447120	13.4	24.42	54.9	
June	4987	398960	11.96	24.42	49.0	
July	4471	357680	10.72	24.42	43.9	
August	4729	378320	11.34	24.42	46.4	
September	4815	385200	15.74	24.42	47.3	
October	4299	343920	10.3	24.42	42.2	
November	3611	288880	8.66	24.42	35.5	
December	3783	302640	9.06	24.42	37.1	
					47.22%	

* System efficiency overall 40%

£ Energy consumed per month equivalent of 17 lit/Hr Furnace oil 240 Hrs per month.

Table 9: ECONOMIC ANALYSIS

Equipment: Solar Water Heating System 20,000 lit/day at 40-60 °C

Cliant : M/S Indian Molasses Co. Pvt. Ltd.,

Location : Madras (India)

Sl No.	*Investment*	*15% interest to IDBI loan*	*Loan repayment in 12 years*	*Depreciation straight line 12 years*	*Maintenance and spares reqt. (10% escalation)*	*Furnace oil rate (20% escalation) Rs ps*	*Value of furnace* oil saved in Rs*	*Net cash flow in + out –*
1.	300,000	45,000	–	–	11,000	1–50	37,500	– 18,500
2.	300,000	45,000	–	–	12,100	1–80	45,000	– 12,100
3.	300,000	45,000	–	–	13,310	2–16	54,000	– 4,310
4.	300,000	45,000	25,000	–	14,641	2–59	64,750	– 19,891
5.	275,000	41,250	25,000	–	16,105	3–11	77,750	– 4,605
6.	250,000	37,500	25,000	–	17,716	3–73	93,250	+ 13,034
7.	225,000	33,750	25,000	25,000	19,487	4–48	112,000	+ 8,763
8.	200,000	30,000	25,000	50,000	21,436	5–37	134,250	+ 7,844
9.	175,000	26,250	25,000	75,000	23,579	6–45	161,250	+ 11,421
10.	150,000	22,500	50,000	75,000	25,937	7–74	193,500	+ 20,063
11.	100,000	15,000	100,000	75,000	28,531	9–29	232,250	+ 13,719
12.	–	–	–	–	31,384	11–15	278,750	+ 247,366
				300,000				+ 262,774

* Amount of Furnace Oil saved per year approximately 25,000 litres.

Net amount after 12 years item (5 + 9) = Rs 562,774

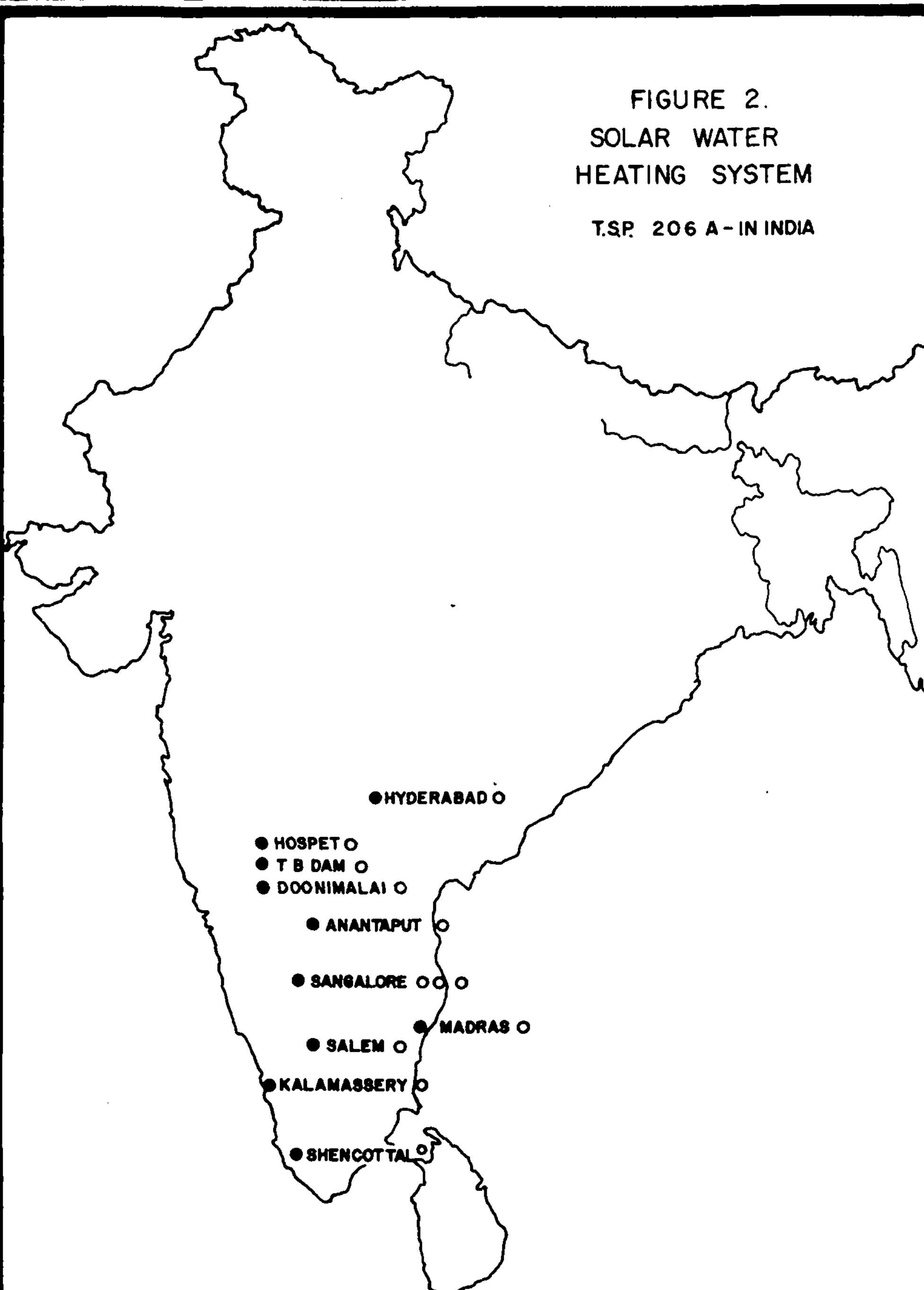


FIGURE 2.
SOLAR WATER HEATING SYSTEM
T.S.P. 206 A - IN INDIA

CORRELATION OF DIFFUSE SOLAR RADIATION DISTRIBUTION WITH CLIMATE CHARACTERISTICS IN INDONESIA

by

PARANGTOPO, A. HARSONO and POESPOSUTIJIPTO

ABSTRACT

By using the total solar energy radiation data collected by the Indonesia Institute of Meteorology and Geophysics it is calculated the diffuse solar radiation, clearness index, and space insolation distribution, daily, monthly and yearly. Clearness index and diffuse solar radiation histograms are constructed on the basis of Manuel Collares Pereira and Ari Rabl method[1] against the expected seasons in Indonesia It is also constructed the graph of space insolation as the functions of the days within the year. Indonesia lies on the equator line, and it is characterized by the three kinds of seasons, rainy season, dry season and in between is the exchange season. From the changes of the histogram features within the year, it may be predicted the circulation of diffuse radiation and clearness index for every seasons. It could also analysed the percentage of the diffuse solar radiation, and evaluated the efficiency of the solar direct radiation.

INTRODUCTION

The diffuse solar energy radition up to 1979 was never detected in Indonesia and even the characteristics of such radiation were never seriously analyzed. The diffuse solar energy radiation is the solar energy radiation scattered by small particles in the atmosphere, buildings, etc. before incident on earth surfaces. The diffuse solar energy radiation was calculated by using the Liu Jordan, Ruth and Chant methods.[2, 3] The data of the global solar energy radiation were measured by the Institute of Meteorology and Geophysics in Jakarta from 1965 up to 1979.

The daily, monthly, yearly total and diffuse solar energy radiation were calculated by using Fortran IV of the Department of Civil Work in Jakarta. The diffuse solar energy radiation was calculated by using Liu Jordan method because Aziz Khan Jahja had calculated it, using Sayigh method and he got a unsatisfactory information about the diffuse solar energy radiation in Indonesia.[4, 5] The average characteristics of diffuse solar energy radiation are quite regular and can be correlated with an effective transmission coefficient of the atmosphere.[1] Several different correlations can be obtained, which depend on the averaging procedure and on the time interval chosen for the insulation (radiation) data, hourly or daily.

A. Clearance index

The present investigation is concerned with the relation between H_d, the daily total of diffuse radiation, and H_h, the daily total of global solar radiation, on a horizontal surface. As a correlation parameter one uses the ratio:

$$K_h = \frac{H_h}{H_o} \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (1)$$

K_h – clearance index.

H_h – daily global solar energy radiation on a horizontal surface (terrestrial radiation).

H_o – daily global solar energy radiation in the absence of any atmosphere (extraterrestrial radiation).

The extraterrestrial radiation is given by formula.[6]

$$H_o = \frac{T}{\pi} I_{o,n} \left[1 + 0.033 \cos\left(\frac{2\pi n}{365{\cdot}24}\right)\right] \cos\lambda \cos\delta$$

$$x\ (\sin\omega_s - \omega_s \cos\omega_s) \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (2)$$

with T = length of day, 24 hr; $I_{o,n}$ = 1353 W/m^2 solar - constant.

n = day of year (starting from 1 January),

λ = geographic latitude;

ω_S = arc cos ($-\tan\lambda \tan\delta$), which is sun set hour angle, and δ is solar declination given by $\sin\delta = 0.3979 \sin\gamma$.

In the approximation of a circular orbit of the earth γ is given by:

$$\gamma = \gamma_o = \frac{2\pi\ (n + 284)}{365{\cdot}24}, \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (3)$$

for greater accuracy the expression

$$\gamma(\text{rad}) = \gamma_o + 0.007133 \sin\gamma_o + 0.032680 \cos\gamma_o$$

$$- 0.000318 \sin 2\gamma_o + 0.000145 \cos 2\gamma_o \qquad \ldots\ldots\ldots\ldots\ldots\ldots \quad (4)$$

is recommended by T.N. Goh.[7]

The data of the hourly global solar energy radiation were measured from 7 Cl early morning up to 18 Cl for 14 years from 1965 up to 1979. The pyranometers were calibrated yearly during measurements. The daily global radiation H_h is equal to the sum of the all hourly measurement for 11 hours and the daily global space radiation H_o is calculated by using the formula (2) and n = 1, ... , 365.

By using the simple formula (1) it can be calculated the daily, monthly and yearly clearance index.

B. The diffuse solar energy radiation

The calculation of diffuse solar energy radiation on the basis of the least square fit with a fourth degree polynomial yield the curve which is shown by the solid line in Fig. (Gb. G1).[2, 3]

$$\frac{H_d}{H_h} = 0.99 \text{ for } K_h \leqslant 0.17$$

$$= 1.188 - 2.272\ K_h + 9.473\ K_h^2 - 21.856\ K_h^3$$

$$+ 14.648\ K_h^4 \text{ for } 0.17 < K_h < 0.8 \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (5)$$

which agrees quite well with the correlations for India, Israel, and Canada.[3]

Until now the correlation between H_d/H_h and K_h has been assumed to be independent of the time of the year. However, since the amount of scattering of the radiation passing through the atmosphere depends on the path length or air mass AM = $\frac{1}{\cos\Theta}$, where Θ being the incidence angle, one might expect a seasonal variation in the correlation for diffuse radiation. The seasonal trend can be seen most clearly at large K_h.[1]

C. Measurements of solar energy radiation

The measurements of global solar energy radiation have been done by the Institute of Meteorology and Geophysics in Jakarta. The Institute uses the pyranometer for measurement and calibrates the pyranometer yearly during the measurement. Due to some reasons the measurement could not be done fully, as daily, monthly or yearly.

The frequencies of the measurements were not equal for every year. The minimum frequency of the measurements was 173 days in 1968 and the maximum frequency of the measurements was 339 days in 1979.

The main reasons of the lacking measurements were related to the climate, like long rainy days, cloudy etc., which is a special feature of the tropical country. Direct solar and diffuse radiations can not be measured in the Institute of Meteorology and Geophysics, because they have no facilities. For the next year the Physics Department of the University of Indonesia will measure both diffuse and global radiation and it will be an opportunity to check the present calculation with the experimental data.

Analysis

A. The Daily Solar Energy Radiation

The daily histograms of K_h during the year from 1965 up to 1979 are shown in Figures Gb. H 1, H 2 . . . . . . H 14, with frequencies above 200 days, except the histogram of K_h of 1968, where the frequency measurement is only 173 days. The average of K_h with maximum frequency measurement during 14 years is about 0,48 as shown in Fig. (Gb. G-5). As indicated, the maximum frequency measurement of K_h seems to shift to the smaller value with the increasing of time except the K_h of 1979, which is probably related to the increasing air pollution in Jakarta. The curve of daily diffuse solar energy radiation as shown in Fig. (Gb. Gf-1) of 1966 and 1974 is slightly correlated with the extra - terrestrial radiation curve Fig. (Gb. G-4) and the values is between 150 cal/cm^2 and 280 cal/cm^2.

The seasons in Indonesia are divided into three seasons, the rainy season, dry season with a changing season in between. To fit to these three seasons on the curve of daily diffuse solar energy radiations, it shows that in the rainy season the diffuse solar radiations is greater than in the changing season, and the minimum one is in the dry season. The minimum value of the diffuse solar energy radiation falls around June and July which is in good agreement with the reality in Indonesia.

B. The monthly solar energy radiation

The total monthly solar radiation during 14 years shows that the smaller total radiation falls between November up to February of the year. However the monthly diffuse solar radiation during 14 years shows that the smaller value falls between June and July. The curve feature of this diffuse solar energy radiation is similar to the form of the extra-terrestrial radiation H_o (see fig. Gb. G-2 and Gb. G-4). Glancing to the equation (5), it can be understood that the calculation of H_d is a function of K_h and the K_h is strongly dependent to the extraterrestrial radiation. One can understand the similar form of the diffuse radiation and the extraterrestrial radiation. The differences of the monthly total solar radiation and the monthly diffuse solar radiation give the monthly direct radiation as shown in the Fig. (Gb. G-6). This monthly direct radiation shows quite significant value from April up to October for every year. It means that, one can use the solar collector effectively during April until October. After that the monthly direct solar radiation drops drastically and utility of the solar collector will be inefficient. According to the curve Fig. (Gb. G-6) the monthly direct solar radiation from November until February equal to 50% up to 60% of the value of the monthly direct solar radiation from April up to October. However the monthly diffuse solar radiation from November until February is about 75%, and the same radiation from April until October is 60% relative to the monthly total solar radiation. The monthly diffuse solar radiation during

14 years in fact is quite large, but we only have adequate value for monthly direct solar radiation around April and October. From November up to February the monthly direct solar radiation is strongly reduced, with the result that the solar energy collection will be extremely not efficient. From February up to April the monthly total radiation will increase but the monthly diffuse radiation is still decreasing, and one can say that this period is the changing season, where the weather is usually unpredictable.. The monthly clearance index is shown in Fig. (Gb. G-7) and the curve of extraterrestrial radiation are in good agreement to each other, as is demonstrated in the curve that the maximum value of the clearance index and the minimum value of the extraterrestrial radiation in Fig. (Gb. G-4) lies on the same months i.e. between June and July.

C. The yearly total radiation and diffuse solar radiation

The yearly total solar radiation during 14 years appears to have an interesting oscillation feature, and the minimum value of the total solar radiation were in 1971 and 1976. With the interval of 5-6 years. Fig. (Gb. G-3). This phenomena is still very difficult to analyze, because we lack for other informations like sun activities and weather information. In 1971 and 1976 we might have had a long rainy season or a very small extraterrestrial radiation due to the less activities of the sun. In 1966 and 1974 there are the larger values of total solar radiation and also the larger values of direct solar radiation (see Fig. (Gb. G-3). There is the tendency of increasing the total solar radiation in 1979, and the maximum value might be predicted to happen in 1980 or 1981. Because the diffuse scattering is nearly constant, we will have a larger total solar radiation, as the direct solar radiation becomes larger. From the rainfalls data of the Institute of Meteorology and Geophysics, it is found that the rainfall of 1971 relatively low compared to the other data. The value of rainfall in 1971 was totally 1853 mm. Similarly the rainfall of 1974 relatively high (2204 mm), and in 1975 it was 1723 mm, and there is no data for 1976. The data for 1977 was 2830 mm and in 1979 was 2233 mm. It seems there is a correlation between the yearly total solar energy radiation and the yearly rainfalls data. The higher yearly total solar energy radiation correlate with the higher yearly rainfalls data similarly for the lower ones. Thus it might be possible that in 1980 or 1981 there will be large extraterrestrial radiation in Jakarta. From the curve of yearly maximum clearance index during 14 years Fig. (Gb. G-5), one can see the tendency of decreasing the maximum clearance index except 1979. This curve shows the tendency of increasing air pollution in Jakarta. However the yearly diffuse solar radiation is not so seriously increasing, and it means that the air pollution in Jakarta is still not a significant phenomena. The air pollution in Jakarta is mainly due to the dust and particles from the dirts and domestic waste materials as well as factories. The curve of diffuse solar radiation is increasing from 1965 up to 1967 to remain to be more or less constant afterwards. It seems that the air pollution in Jakarta is not seriously participating in the process of diffuse solar radiation.

Conclusion

1. The method of Ruth and Chant for the calculation of the diffuse solar radiation has been used in this paper, because the method of Sayigh had been used by Aziz Khan Jahja in 1978 with an unsatisfactory result for Indonesia. In Indonesia there were no significant measurements on diffuse solar radiation, and according to our knowledge, the diffuse solar radiation, like what we have done, has never been calculated. Therefore there is no comparison we can make. Next year the Physics Department of the University of Indonesia will be provided with pyranometer for measuring both total and diffuse solar radiation, and at the end of 1980 it will be possible for us to check the agreement between theory and experiments.

2. If the agreement of theory and experiment will not be satisfying we may modify the empirical method for diffuse solar radiation calculation in Indonesia. After that, the measurements of global solar radiation throughout the country could be done.

3. The measurements and calculations of the diffuse solar radiation throughout the country would be very important. With such informations it will be easier for the decision maker to select the relevant solar collector or solar cell[8] to be of the utmost utility in many parts of Indonesia.

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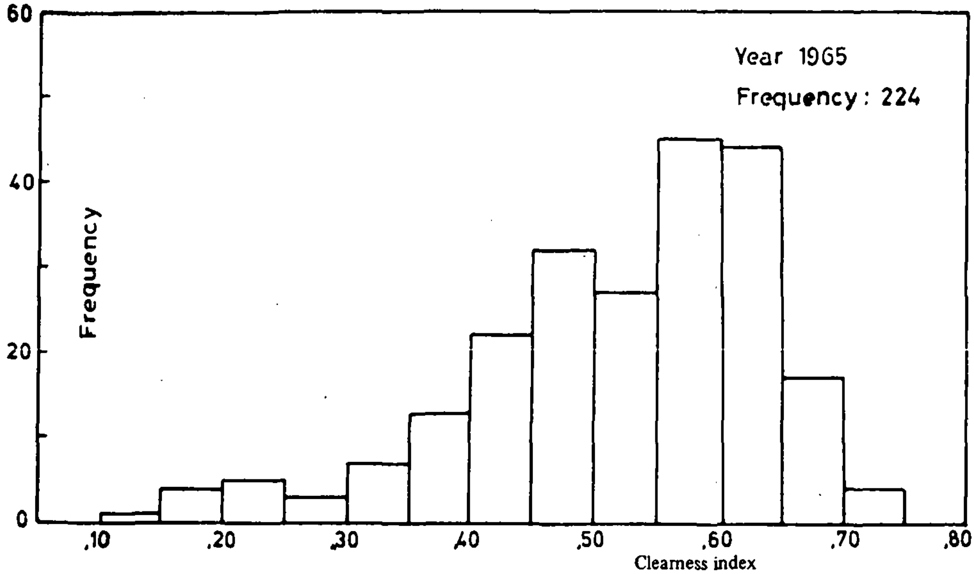
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Frequency
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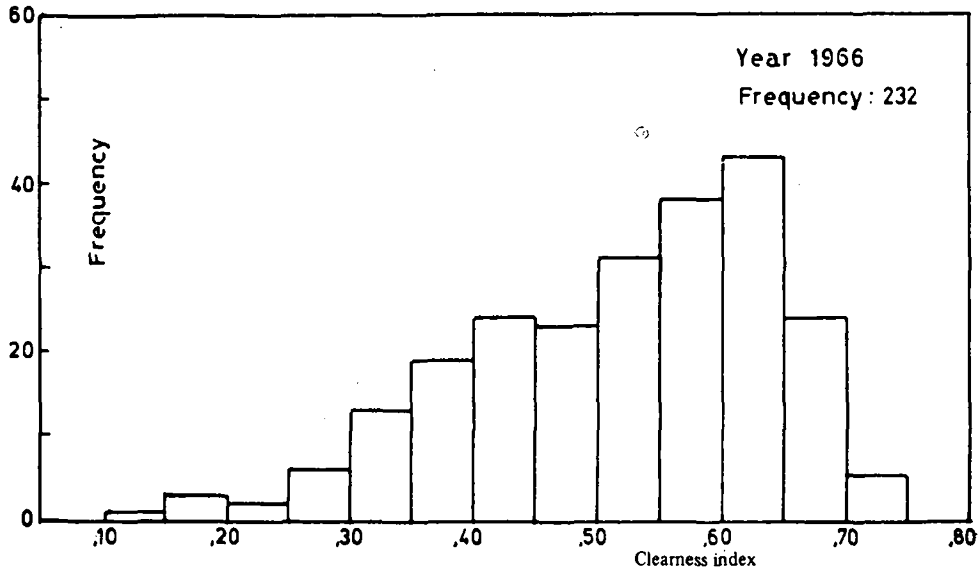
40
20
0
.10
.20
.30
.40
.50
.60
.70
.80
Clearness index

Gb: H – 1


Year 1966
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.40
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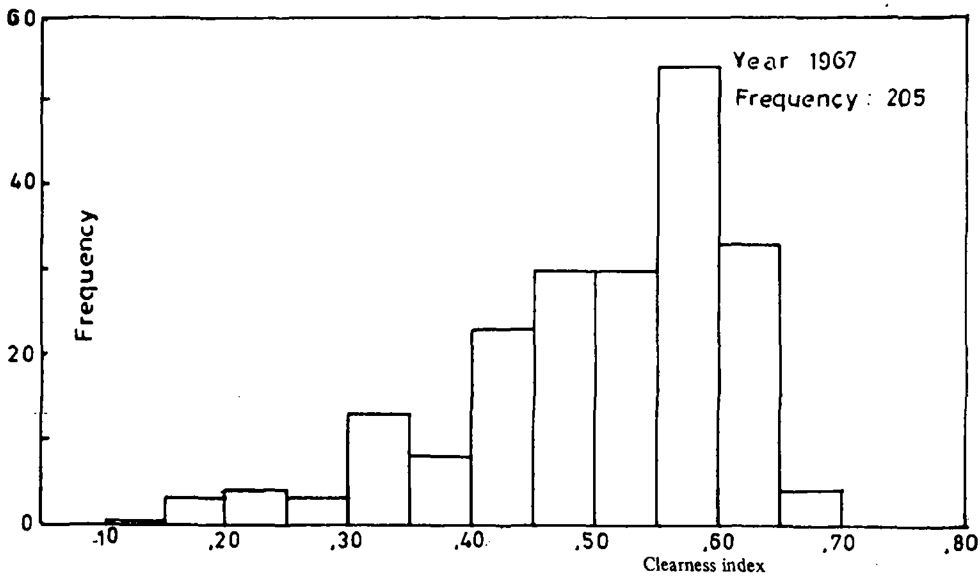
.60
.70
.80
Clearness index

Gb: H – 2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0
Frequency
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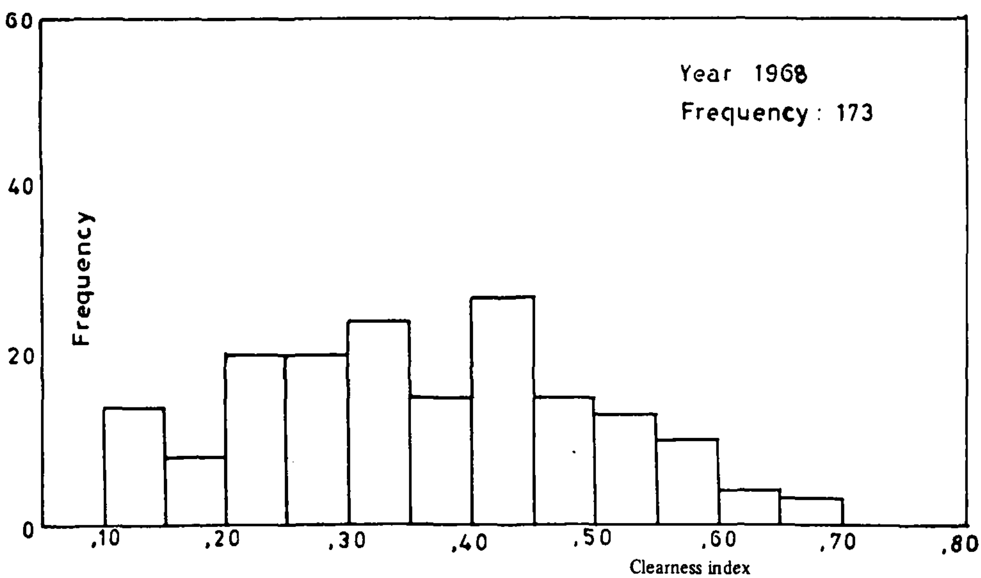
Frequency : 205
.10
.20
.30
.40
.50
.60
.70
.80
Clearness index

Gb: H – 3


60
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20
0
Frequency
Year 1968
Frequency : 173
.10
.20
.30
.40
.50
.60
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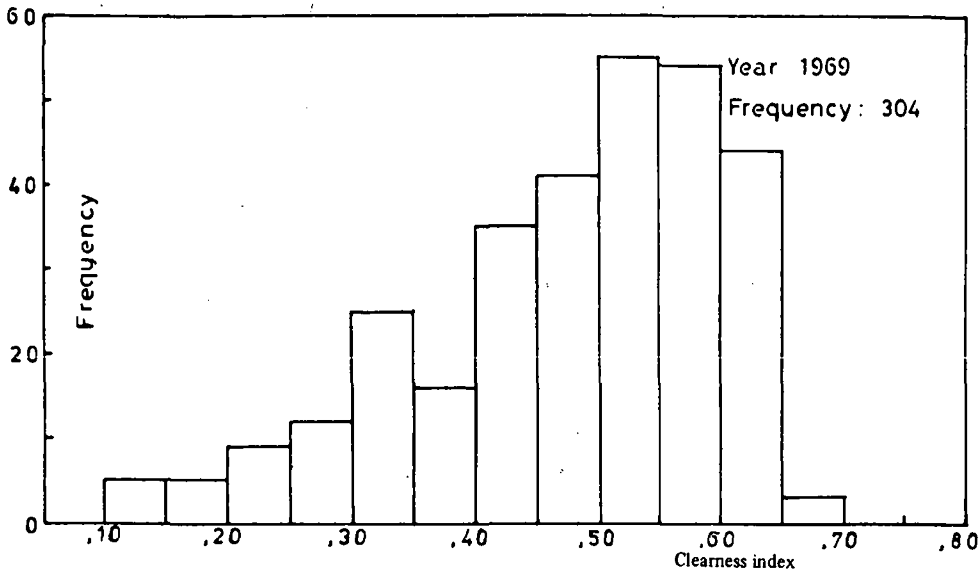
.80
Clearness index

Gb: H – 4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Frequency
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,40
,50
,60
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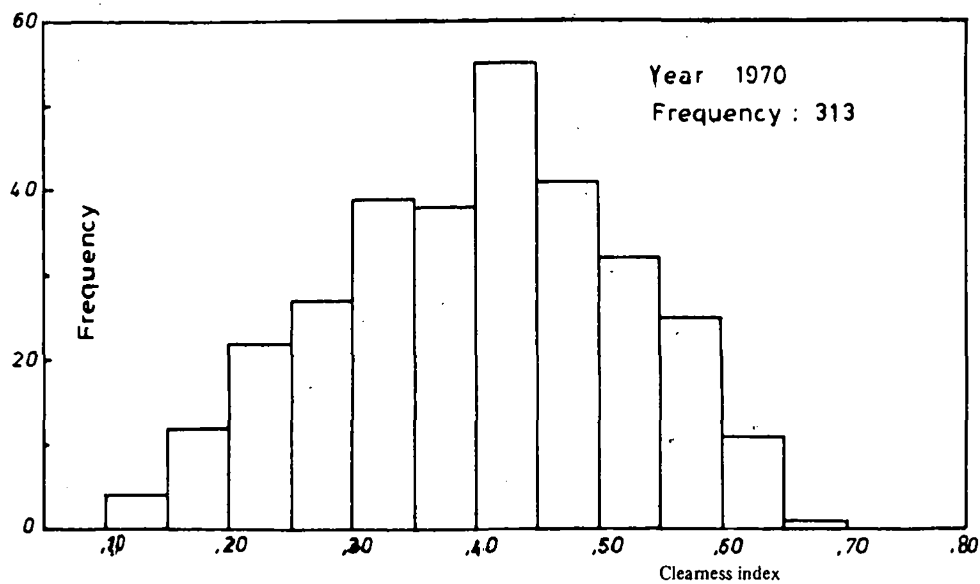
,80
Clearness index

Gb: H – 5


60
40
20
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Frequency
Year 1970
Frequency : 313
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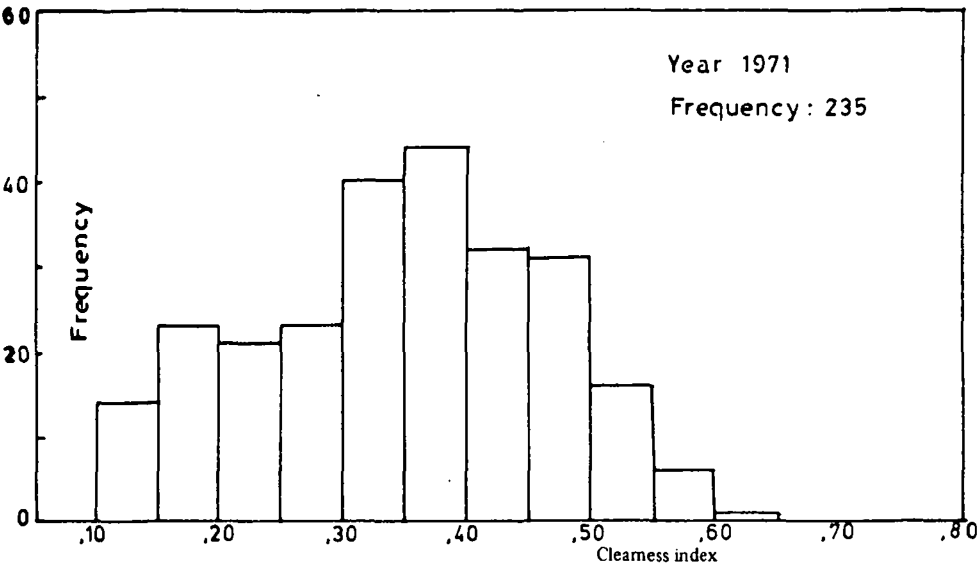
,20
,30
,40
,50
,60
,70
,80
Clearness index

Gb: H – 6


Year 1971
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Frequency
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40
20
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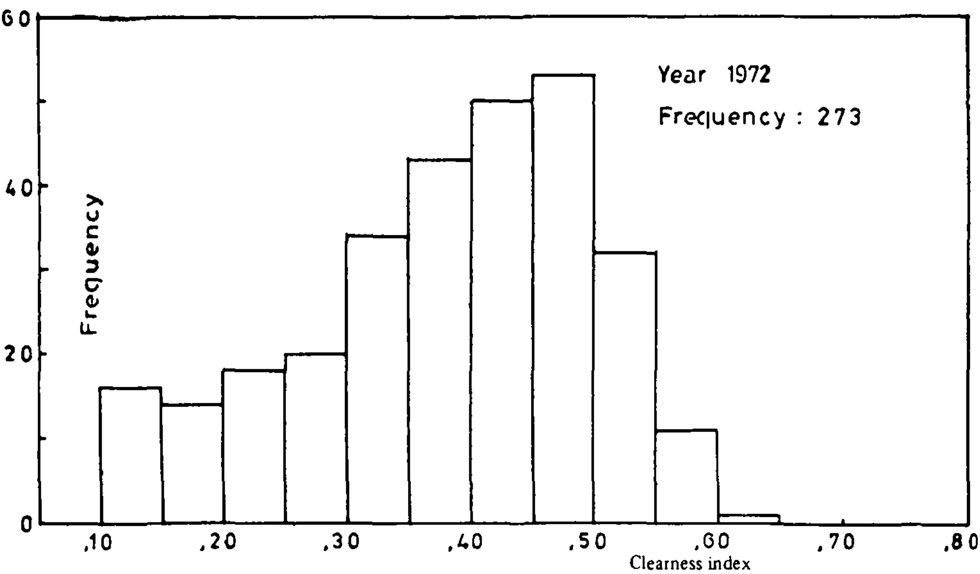
,30
,40
,50
,60
,70
,80
Clearness index

Gb: H – 7


Year 1972
Frequency : 273
Frequency
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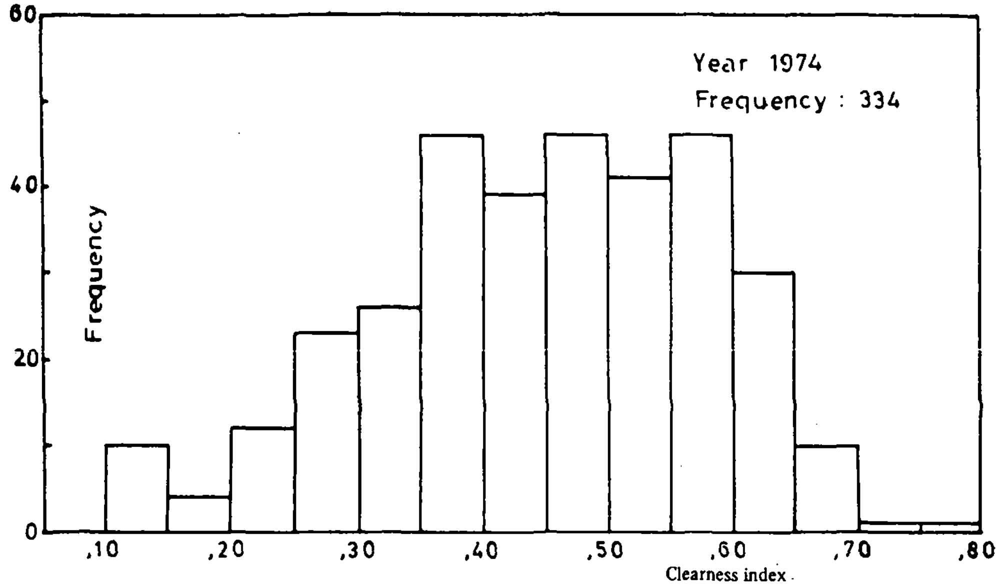
,10
,20
,30
,40
,50
,60
,70
,80
Clearness index

Gb: H – 8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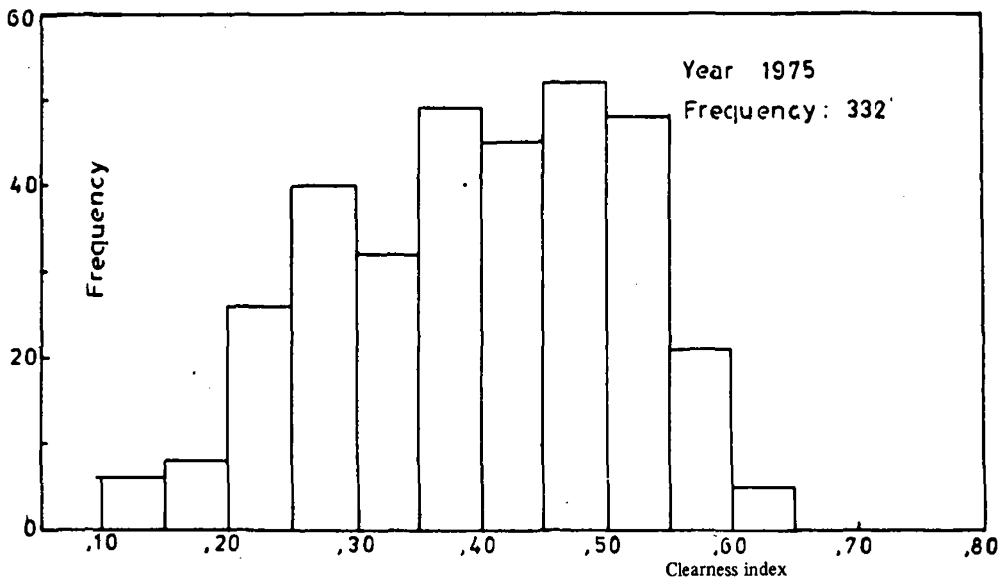
,40
,50
,60
,70
,80
Clearness index

Gb: H – 9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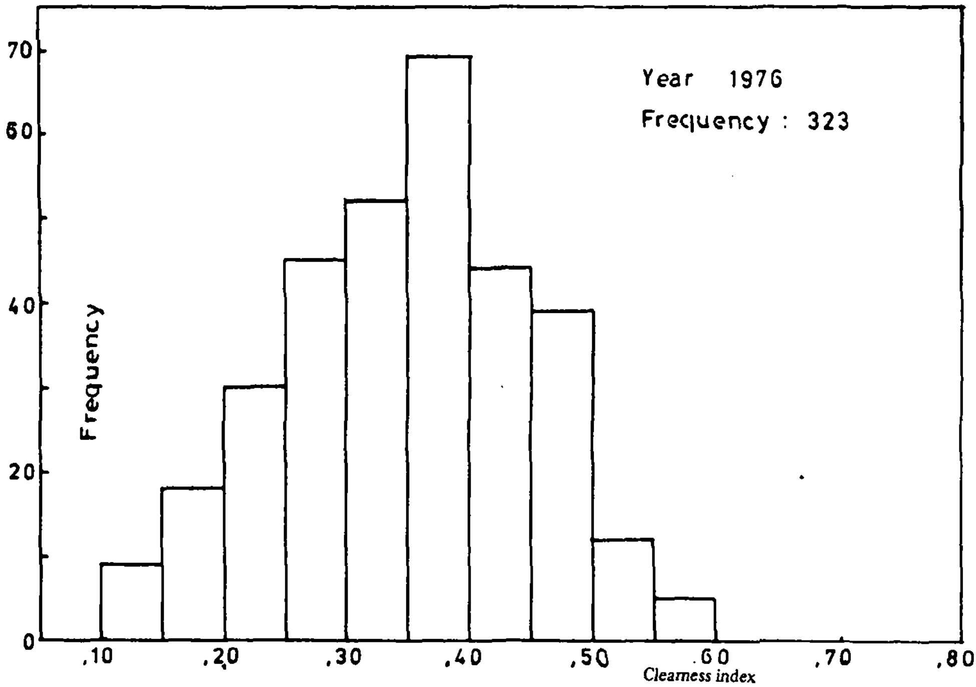
,60
,70
,80
Clearness index

Gb: H – 10



Year 1976
Frequency : 323
Frequency
Clearness index
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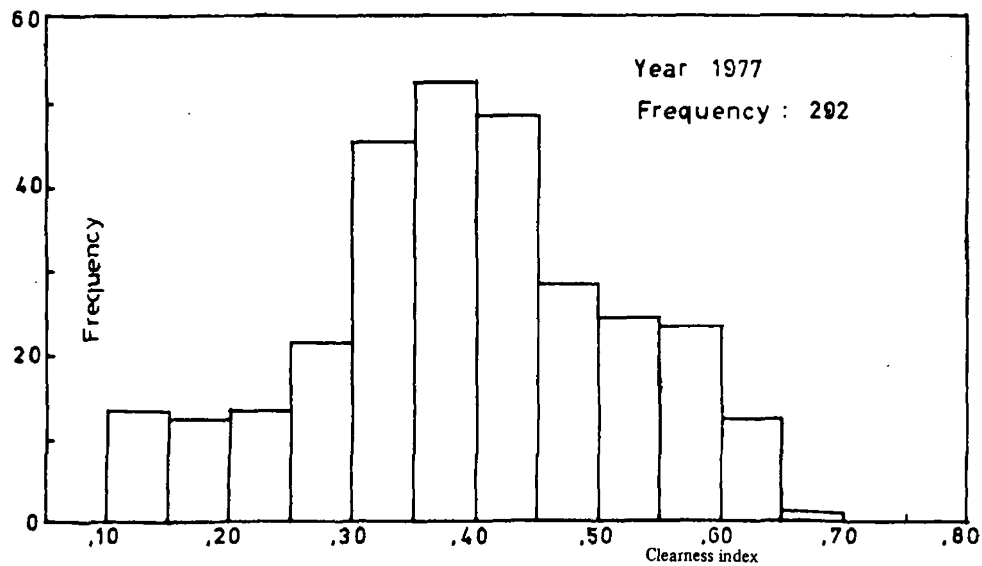
40
60
70
,10
,20
,30
,40
,50
.60
,70
,80

Gb: H – 11



Year 1977
Frequency : 292
Frequency
Clearness index
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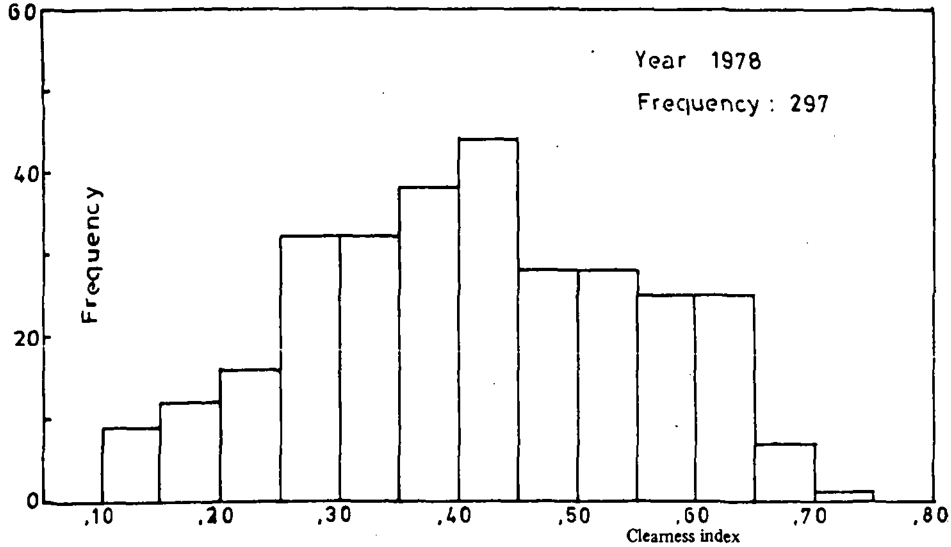
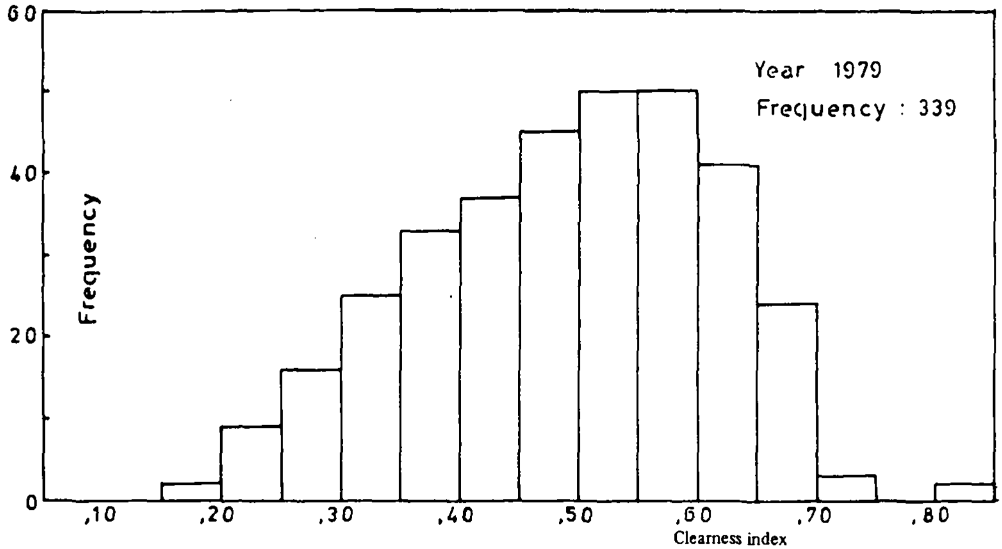
20
40
60
,10
,20
,30
,40
,50
,60
,70
,80

Gb: H – 12


60
40
20
0
Frequency
Year 1978
Frequency : 297
,10
,20
,30
,40
,50
,60
,70
,80
Clearness index

Gb: H – 13


60
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Frequency
Year 1979
Frequency : 339
,10
,20
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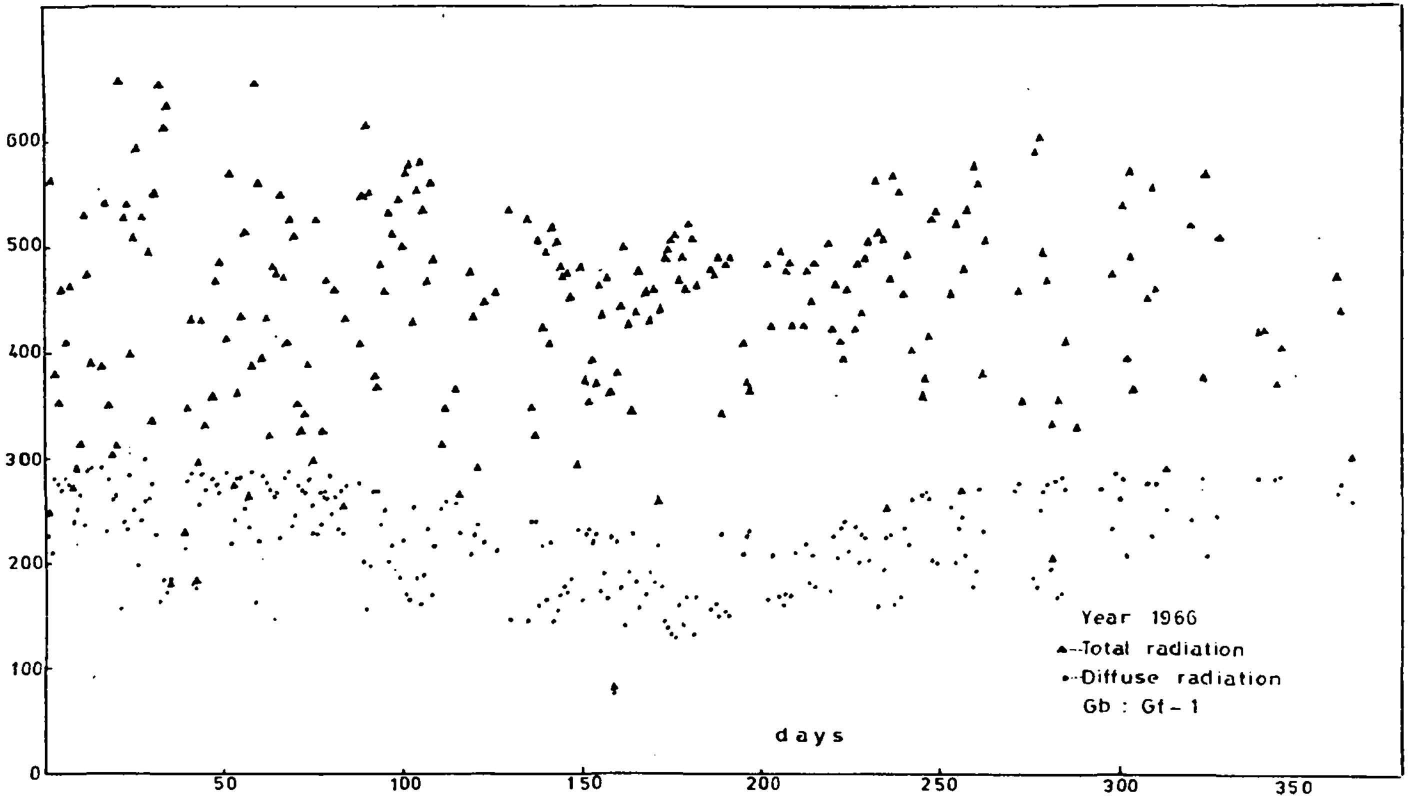
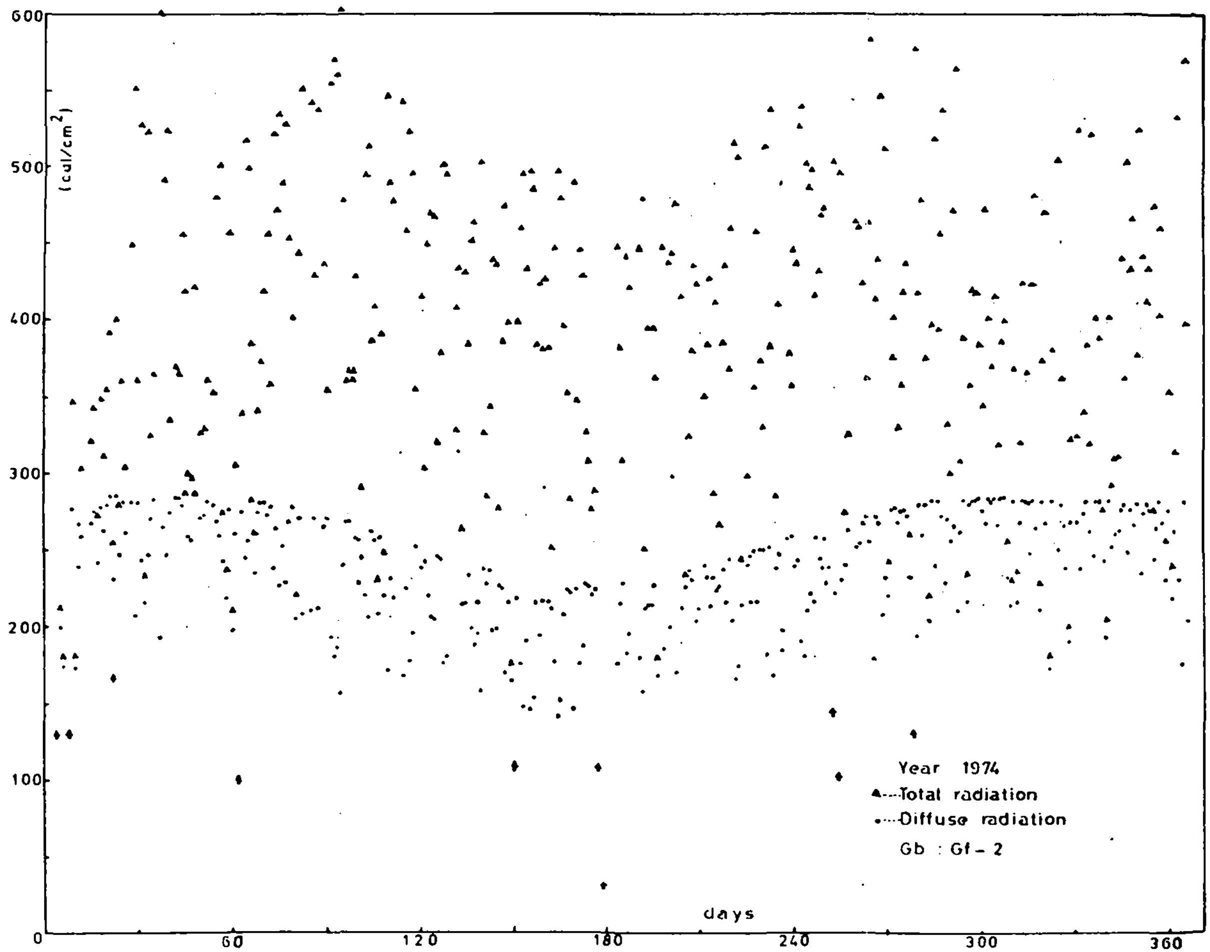
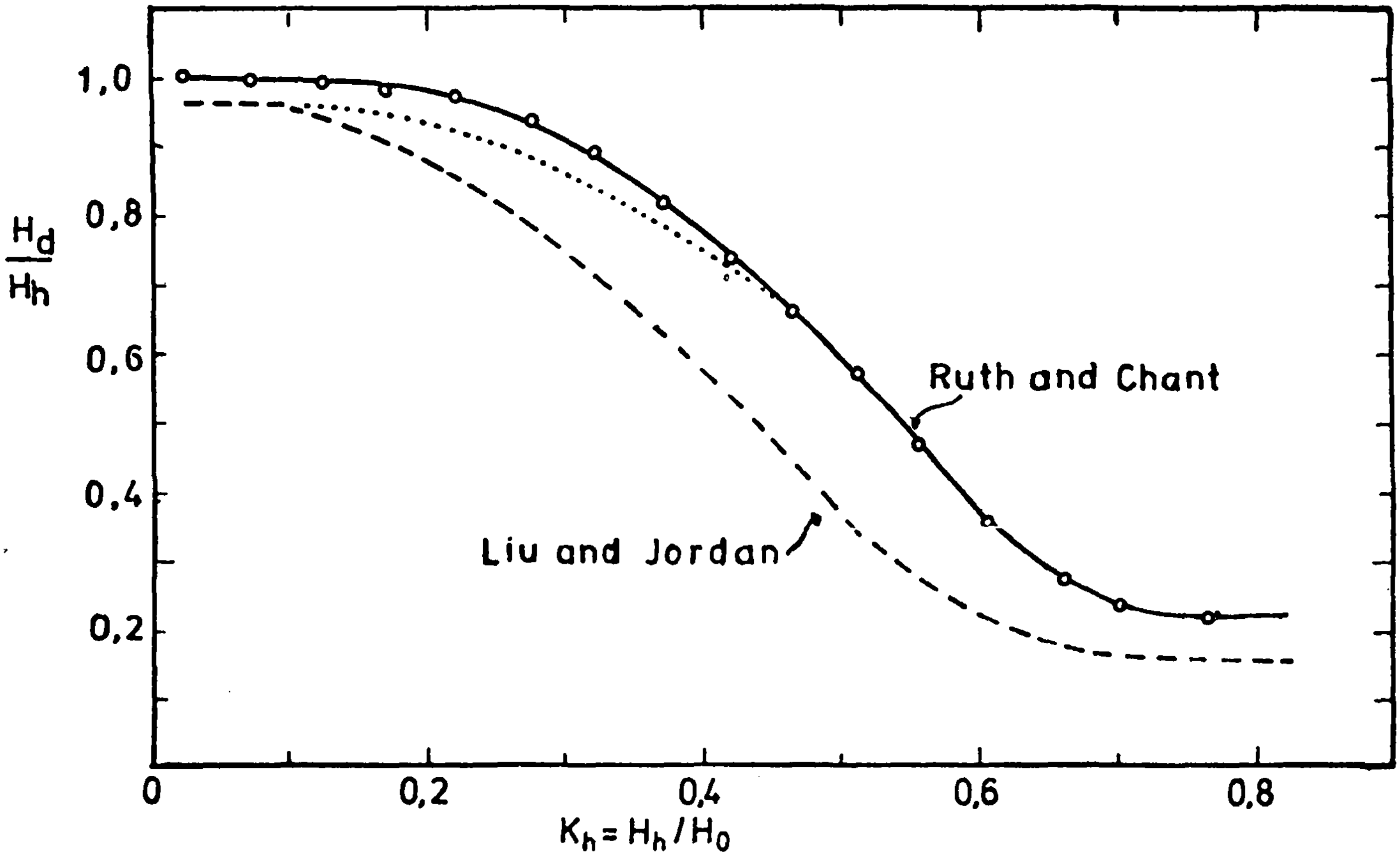
,40
,50
,60
,70
,80
Clearness index

Gb: H – 14

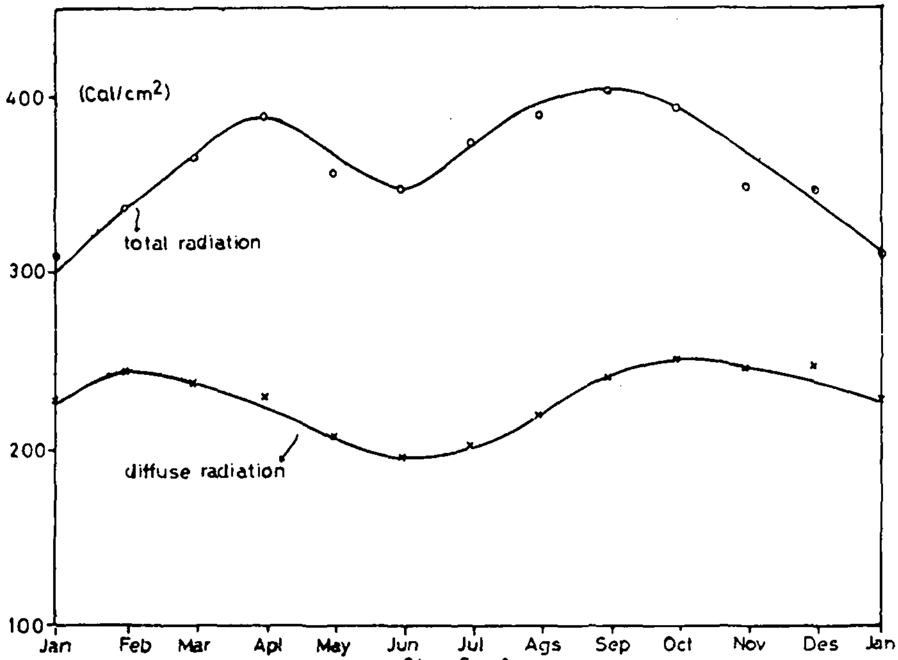

600
500
400
300
200
100
0
50
100
150
200
250
300
350
days
Year 1966
Total radiation
Diffuse radiation
Gb : Gf - 1


(cal/cm^2)
600
500
400
300
200
100
0
60
120
180
240
300
360
days
Year 1974
Total radiation
Diffuse radiation
Gb : Gf - 2

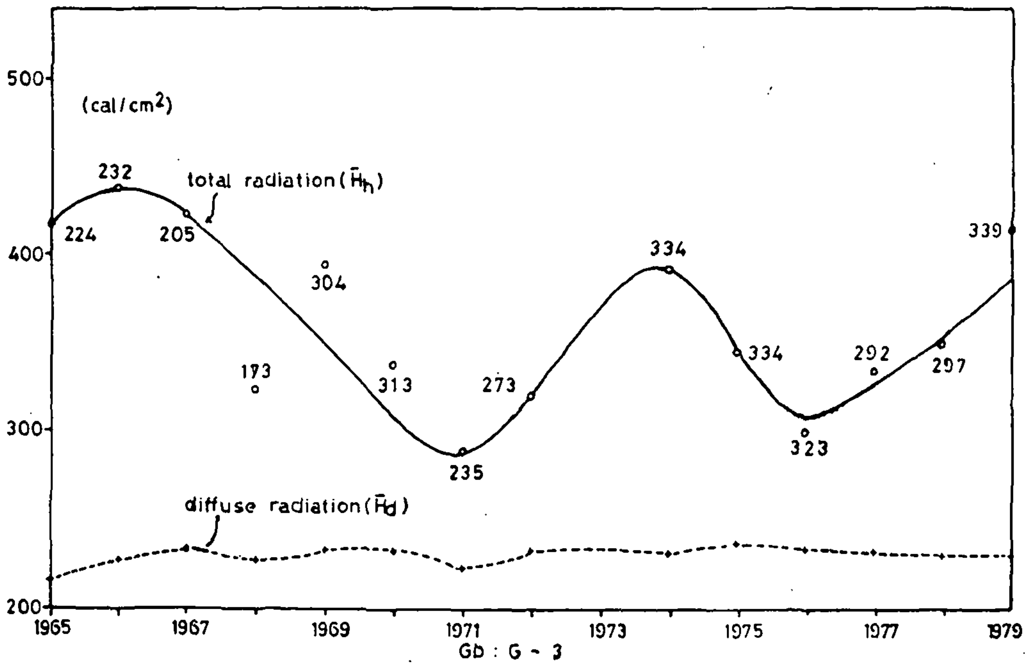


1,0
0,8
0,6
0,4
0,2
$\frac{H_d}{H_h}$
Ruth and Chant
Liu and Jordan
0
0,2
0,4
0,6
0,8
$K_h = H_h / H_0$

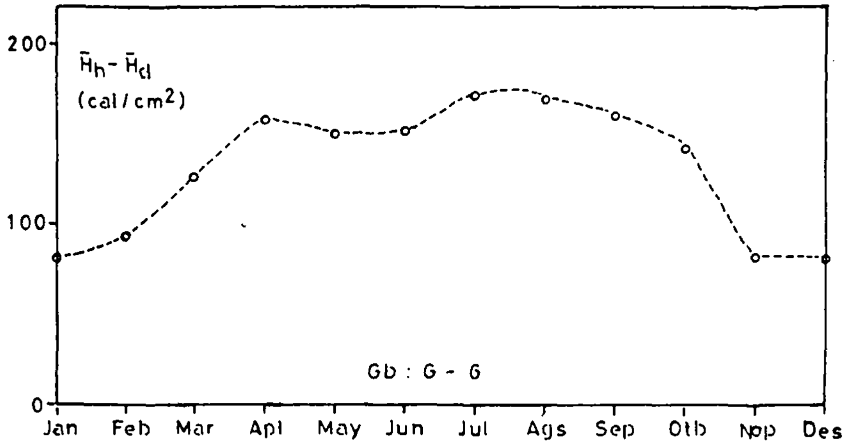
Gb : G - 1


(Cal/cm2)
400
300
200
100
total radiation
diffuse radiation
Jan
Feb
Mar
Apl
May
Jun
Jul
Ags
Sep
Oct
Nov
Des
Jan

Gb : G - 2


500
400
300
200
(cal/cm2)
total radiation ($\bar{H}_h$)
diffuse radiation ($\bar{H}_d$)
232
224
205
304
173
313
273
235
334
334
323
292
297
339
1965
1967
1969
1971
1973
1975
1977
1979

Gb : G - 3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100
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$\bar{H}_h - \bar{H}_d$
(cal / cm2)
Gb : G - 6
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Feb
Mar
Apl
May
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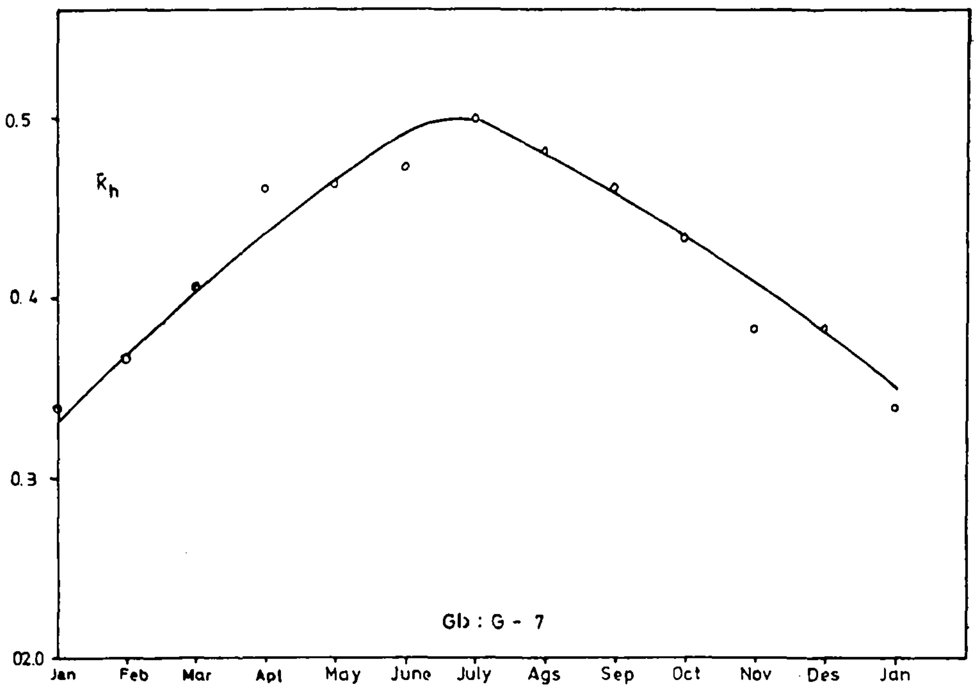
Sep
Otb
Nop
Des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0.3
02.0
$\bar{K}_h$
Gb : G - 7
Jan
Feb
Mar
Apl
May
June
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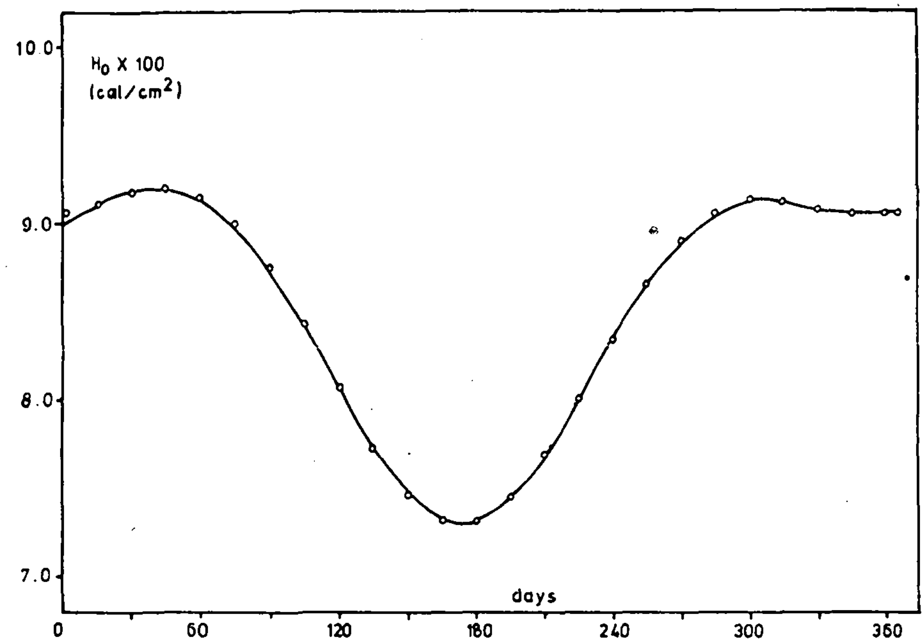
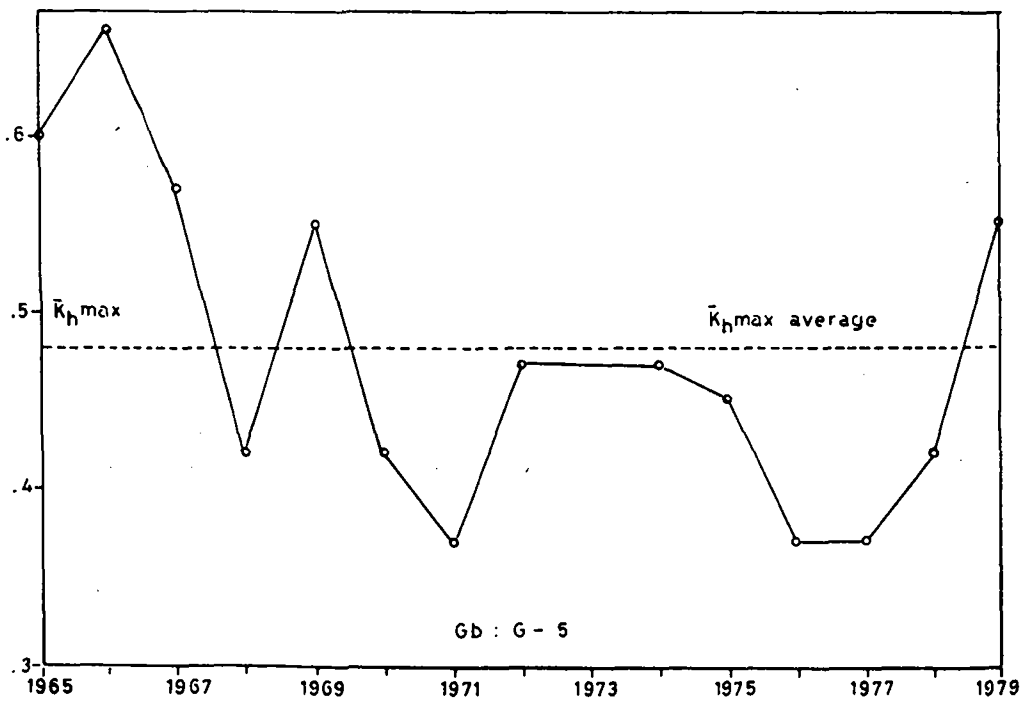
Sep
Oct
Nov
Des
Jan



H_o X 100
(cal/cm²)
10.0
9.0
8.0
7.0
days
0
60
120
180
240
300
360

Gb : G - 4



$\bar{K}_h$max
$\bar{K}_h$max average
.6
.5
.4
.3
1965
1967
1969
1971
1973
1975
1977
1979

Gb : G - 5

Global Solar Radiation (sun and sky) T. cal/cm²/menit

FEBRUARY - 1975 | JAKARTA

Date	06	07	08	09	10	11	12	13	14	15	16	17	18	19	Daily Totals	Remarks
	Hourly totals T															
01		4.2	21.8	45.8	35.6	62.1	55.3	86.7	55.9	48.6	15.7	10.9	5.6		448.2	
02		2.8	10.9	36.7	48.1	55.9	55.9	69.9	74.9	61.5	44.7	22.7	5.0		488.4	
03		-	-	-	-	-	-	-	-	-	-	-	-		-	
04		1.1	2.8	7.8	14.8	22.4	25.8	33.0	18.8	16.0	5.6	0	0		148.1	
05		2.2	15.6	33.6	58.1	67.1	67.1	70.5	67.9	33.6	27.2	10.1	5.6		458.6	
06		4.5	20.2	32.2	41.1	61.8	78.3	48.1	48.3	52.8	48.6	25.2	8.4		469.5	
07		6.5	22.5	41.9	51.7	70.5	70.2	65.1	64.9	65.1	7.8	2.2	0.6		469.0	
08		5.8	20.2	25.8	39.7	51.1	64.3	72.7	55.9	47.8	31.4	31.1	11.2		457.0	
09		2.8	15.0	47.2	43.3	40.0	46.6	78.2	53.6	64.5	37.3	13.7	5.1		477.3	
10		3.2	11.6	22.1	8.1	14.0	32.3	48.4	37.3	19.1	18.8	10.0	4.0		230.9	
11		4.4	2.9	7.8	14.5	36.3	53.8	44.0	43.9	17.5	9.3	7.8	1.1		243.3	
12		4.9	20.1	25.4	39.8	61.0	64.0	61.9	17.0	6.4	2.4	1.8	0.7		305.4	
13		2.2	7.2	19.3	36.7	51.6	56.2	48.0	30.6	25.9	10.8	9.7	3.8		302.0	
14		2.2	7.2	27.2	48.5	43.0	24.8	33.2	72.0	40.5	20.2	19.4	5.4		343.6	
15		3.8	13.9	13.4	32.2	39.7	41.1	36.4	24.9	34.2	16.8	12.0	5.0		273.4	
16		-	-	-	-	-	-	-	-	-	-	-	-		-	
17		-	-	-	-	-	-	-	-	-	-	-	-		-	
18		3.4	17.8	25.2	31.4	30.5	49.2	42.5	39.7	31.4	22.4	10.9	3.1		307.5	
19		4.4	2.9	3.1	4.2	9.8	17.1	25.2	24.6	19.6	9.2	11.2	2.8		134.1	
20		0.3	2.8	9.8	19.9	26.0	33.0	31.4	38.3	30.2	13.4	7.8	3.4		216.3	
21		2.1	14.0	22.4	43.3	71.3	81.7	83.6	59.0	30.5	19.6	34.2	11.8		473.9	
22		4.3	12.6	21.0	23.0	53.1	58.7	67.7	62.1	46.7	25.8	16.5	5.6		397.1	
23		3.1	11.1	32.6	55.0	53.9	49.9	78.2	65.8	70.9	53.2	16.2	7.4		497.3	
24		4.7	22.0	41.5	48.5	67.0	77.7	15.5	44.0	65.0	42.8	15.3	1.1		445.1	
25		3.9	15.5	4.7	40.0	53.4	51.8	42.8	81.7	34.5	35.5	23.3	5.5		391.4	
26		4.6	24.6	36.5	45.4	60.8	75.1	70.1	71.8	58.7	42.3	28.4	4.3		522.6	
27		2.7	15.7	23.8	40.7	63.5	38.8	37.5	30.7	58.5	43.5	23.9	6.5		385.8	
28		3.1	13.3	25.6	42.2	60.9	71.2	69.0	69.0	61.9	32.7	18.7	5.3		472.9	
29																
30																
31																
Monthly totals		87.6	344.2	632.4	905.8	1226.7	1339.0	1359.0	1254.6	1041.4	629.0	383.0	118.3			
Monthly means Q																
Monthly means T		3.5	13.8	25.3	36.2	49.1	53.6	54.4	50.2	41.7	25.2	15.3	4.7			

A COMPUTATIONAL MODEL FOR SOLAR RADIATION PATTERNS IN IRAN

by

REZA HASHEMIAN and ESFANDIAR AFSHARI

1. INTRODUCTION

It is necessary to determine the amount of solar energy actually available on an inclined surface such as flat plate collectors for the design of a solar system. Such energy is received both in terms of beam radiation and diffused radiation. In order to design a passive solar house, specially suitable for the arid zones in Iran, it is also important to obtain the total radiation received by external walls and through the windows of the house. Practically such investigation requires a rather detailed information about the solar insulation through out the country and for a long period of time. As reported [1], there are a total number of 34 locations in Iran providing the basic meteorological data including the mean monthly total hours of sunshine, for a considerable number of years. However, the actual beam and diffuse solar intensity is only available for a few sights, such as Tehran, Karaj, Shiraz, and some others.

To provide the required insolation data for the various location in the country a computer programme based on the theoretical investigations by H.C. Hottel [2] and Bo Leckner [3] is developed. The results of such model are then compared with the measured data obtained in Tehran for the average of two years. The two results are found to be closely match within about 2% of accuracy.

2. THEORETICAL DEVELOPMENT

The theoretical model adopted here in this investigation is based on the physical behavior of the atmosphere surrounding the earth on the solar beam. The model originally developed by Hottel [2] and later presented by Bo Leckner [3], in more precise form.

In a clear sky solar radiation is partly absorbed, partly scattered and the rest transmitted through the atmosphere. Through a layer of dL thickness of the atmosphere the solar intensity i_j, at a wavelength λ_j φ_m, is reduced by di_j such that $di_j = k_j i_j dL$. And for the entire atmosphere we obtain

$$I_j = I_{oz}\, \tau_j \qquad \ldots\ldots\ldots\ldots\ldots \quad (1)$$

and

$$\tau_j = \exp(-k'_j L) \qquad \ldots\ldots\ldots\ldots\ldots \quad (2)$$

where τ_j is the transmission ratio, and L is the atmospheric path length. For normalized atmospheric length.

$$\tau_j = \exp(-k_j m) \qquad \text{(3)}$$

where, $m = L/L_o = 1/\cos z$, is termed as air mass.

Assuming indipendence between the interaction of beam with different atmospheric components, the transmission coefficient k_j (for the wavelength λ_j φ_m) may be written as

$$k_j = k_{rj} + k_{oz,j} + k_{aj} + k_{wj} + k_{gj} \qquad \text{(4)}$$

the coefficients k_r, k_{oz}, k_a, k_w, and k_g represent the Rayleigh scattering, ozone absorption, aerosol attenuation, water reaper absorption, and absorption by uniformly mixed gases such as Co_2 etc, respectively.

(1) The Rayleigh scattering coefficient is given by

$$k_r = 8.623 \times 10^{-6}\ P\ \lambda^{-4.08} \qquad \text{(5)}$$

where P is the actual pressure at ground level in mb.

(2) The ozone absorption coefficient is

$$k_{oz} = k(\lambda)\,\ell \qquad \text{(6)}$$

with $k(\lambda)$ tabulated for different frequencies and is given in Vigroux [4], and ℓ indicates the ozone layer in normal temperture and pressure acquired arround 0.3 cm in this model.

(3) For the aerosol attenuation coefficient we have

$$k_\alpha = \beta\,\lambda^{-\alpha} \qquad \text{(7)}$$

where β and α are turbidity and wavelength factor, respectively. Equation (7) is approximated and averaged by

$$k_\alpha = 2.462\ \beta_o \qquad \text{(8)}$$

with the normalized factor β_o obtained through local measurements. For Tehran location the monthly mean turbodity factor for two years (1978 and 1979) average is given in Table 1. For a choice of α other than the selected

Table 1

Months	Ja.	Fe.	Ma.	Ap.	Ma.	Ju.	Ju.	Au.	Se.	Oc.	No.	De.
β_o	0.2	0.219	0.177	0.195	0.21	0.21	0.2	0.21	0.145	0.16	0.13	0.13

value 1.3 the turbidity factor is replaced by $\beta = \beta_o \times 0.5^{\alpha - 1.3}$.

(4) The coefficients representing the absorption by water waper and the gases is known to be

$$k_m = \frac{0.2385\ \alpha_w\ \omega}{(1 + 20.07\ \alpha_w\ \omega\ m)^{0.45}} \qquad \text{.......... (9)}$$

and

$$k_g = \frac{1.41\ \alpha_g}{(1 + 118.3\ \alpha_g\ m)^{0.45}} \qquad \text{.......... (10)}$$

where, w denotes the local percipitation water vapor in cm. The parameters a_w and a_g are the average values for different wave lengths given in Table 3 and Table 4 of Bo Leckner [3].

To calculate the diffused radiation for the clear sky and on the horizontal plane it is assumed that the scattered irradiance caused by the Rayleigh effect, and aerosol is uniformly distributed and k portion of such scattered radiation is received by the earth surface. So, the diffuse component

$$I_D = k \Delta I \cos z \qquad \text{.......... (11)}$$

and

$$\Delta I = I_o \tau_{oz} \tau_g \tau_w - I \qquad \text{.......... (12)}$$

where I_o, I are the extraterrestrial and ground beam radiation, respectively. And τ_{oz}, τ_g and τ_w are the mean transmission ratio for ozone, gases and water vapor, respectively.

The parameter k is assumed to be 0.5 for the model used. The total radiation is then obtained by the addition of beam and diffused radiation. The programme does not consider the effect of surface reflection for the horizontal planes, as it is negligible for most of the cases.

For an inclined surface with a tilted angle s the total radiation is made of three components, instead of two, which are; beam radiation, diffused solar radiation, and solar radiation reflected from the ground seen by the tilted surface.

(a) The beam solar radiation for an inclined surface with a tilted angle s and surface azimuth angle γ is given by

$$I_s = I \frac{\cos\Theta}{\cos z} \qquad \text{.................} \quad (13)$$

where, Θ is the angle of incidence of beam radiation, and is given in Duffie and Beckman [5].

(b) The diffused solar radiation is reduced for a uniformly distributed case, because, part of the sky dome is replaced by the ground or surrounding objects. Therefore,

$$I_{DS} = I_D \frac{1 + \cos s}{2} \qquad \text{.................} \quad (14)$$

(c) The solar diffused radiation reflected from the ground or surroundings with reflectance coefficient φ is obtained as

$$I_{RS} = (I + I_D)\ \rho\ \frac{1 - \cos s}{2} \qquad \text{.................} \quad (15)$$

with the reflectance coefficient assumed ρ = 0.2 to 0.4 for the most of the cases.

The total solar radiation, therefore, received by the tilted surface is given by,

$$I_T = I_S + I_{DS} + I_{RS} \qquad \text{.................} \quad (16)$$

3. COMPARISON OF THE RESULTS

The model discribed is used to calculate the monthly average hourly total radiation on an inclined surface at Tehran with altitude 35.68°. The surface orientation is due south with the tilted angle s = 35. The measured monthly average turbodity factor is given in Table 1. Other parameters are chosen as; ℓ_{NTP} = 0.3 cm, α = 1.3, k = 0.5, and ρ = 0.2.

The calculated results of monthly average hourly total radiation for every month of a year are given in Figs. 1-12, and the corresponding measured data obtained for a period of two years (1977 and 1978), and on the same inclined plane, are also redrawn on the some figures for comparison. As observed, the two sets of the results closely match in most of the cases with an accuracy arround 1.2 to 2.3 per cent. However, a rather large deviation is seen for the late fall and winter months. Part of the reason for such increase in actual radiation might be the effect of reflection from the snow on the ground in those months.

Similarly, Table 2 and Fig. 13 represent the monthly variation of calculated average daily total radiation on the tilted surface for clear sky in Tehran. The measured data are also provided for comparison. As it is also noticed, in this diagram, the experimental curve is dominantly above the calculated one for the winter months, as discussed before. It is interesting to notice the two picks occuring at the beginning of spring and fall seasons, when the solar beam is quite normal to the plane at the solar noon, when the plane is tilted by an angle equal to the local latitude.

Table 2

Months	*Ja.*	*Fe.*	*Ma.*	*Ap.*	*Ma.*	*Ju.*	*Ju.*	*Au.*	*Se.*	*Oc.*	*No.*	*De.*
Meas. MADT*	16.48	19.59	23.35	24.33	23.64	22.97	22.69	23.29	23.59	21.57	19.17	17.44
Calc. MADT*	14.63	17.39	23.74	23.37	21.92	23.71	22.65	23.06	22.93	20.01	17.44	15.42

* Monthly Average Daily Toltal (MADT) radiation is in MJ/m^2. day.

4. CONCLUSION

Due to lack of sufficient measured data for solar insulation through out the country it is essential to develop a theoretical model for calculating the solar energy received in different locations in Iran. Such calculation needs to be accurate enough, and based on the available geographical, and clinatological information, at the same time. As a first step a computional model is developed here for the spectral distribution of solar radiation on the ground, for a clear sky. The programme is prepared to provide the different components of the solar energy, namely, the beam, diffused, and reflected diffused radiation, as well as, the total solar radiation on an inclined surface with an optional surface azimuth angle.

The model is used for calculating the solar energy received by an inclined surface in Tehran, as an example. The theoretical results are then compared with the measurement data. It is shown that the accuracy of the model is quite acceptable, laying within 2%, for the most of the cases.

5. NOMENCLATURE

a_w, a_g	:	effective absorption coefficients of water vapor, and mixed gases, respectively,
I_o	:	extraterrestrial solar inradiance,
I	:	beam radiation on the horinzontal plane,
I_j, I_{oj}	:	beam on horizontal and extra-terrestrial radiation in wave length λ_j,
I_{DS}, I_S, I_{RS}	:	diffused, beam, and reflected diffused solar radiation on an inclined surface with tilted angle s,
I_T	:	Total solar radiation,
k	:	ground diffused radiation coefficient,
$k(\lambda)$	:	ozone absorption coefficient,
k_a, k_{oz}	:	aerosol, ozone, water vapor, mixed gases, and
k_w, k_g	:	Rayleigh scattering and absorption coefficients,
k_r		
k_j	:	the transmission coefficient for wave length λ_j,
Lo, L	:	The atmospheric path length, normal, and actual,
m	:	The air mass,
P	:	atmospheric pressure in mb,
S	:	the tilted angle,
Z	:	the solar azimuth angle,
α	:	wave length coefficient for aerosol extinction,
β_o, β	:	normalized and actual turbidity coefficient,
Θ	:	the angle of incidence of beam radiation,
τ	:	the transmission ratio for solar radiation.

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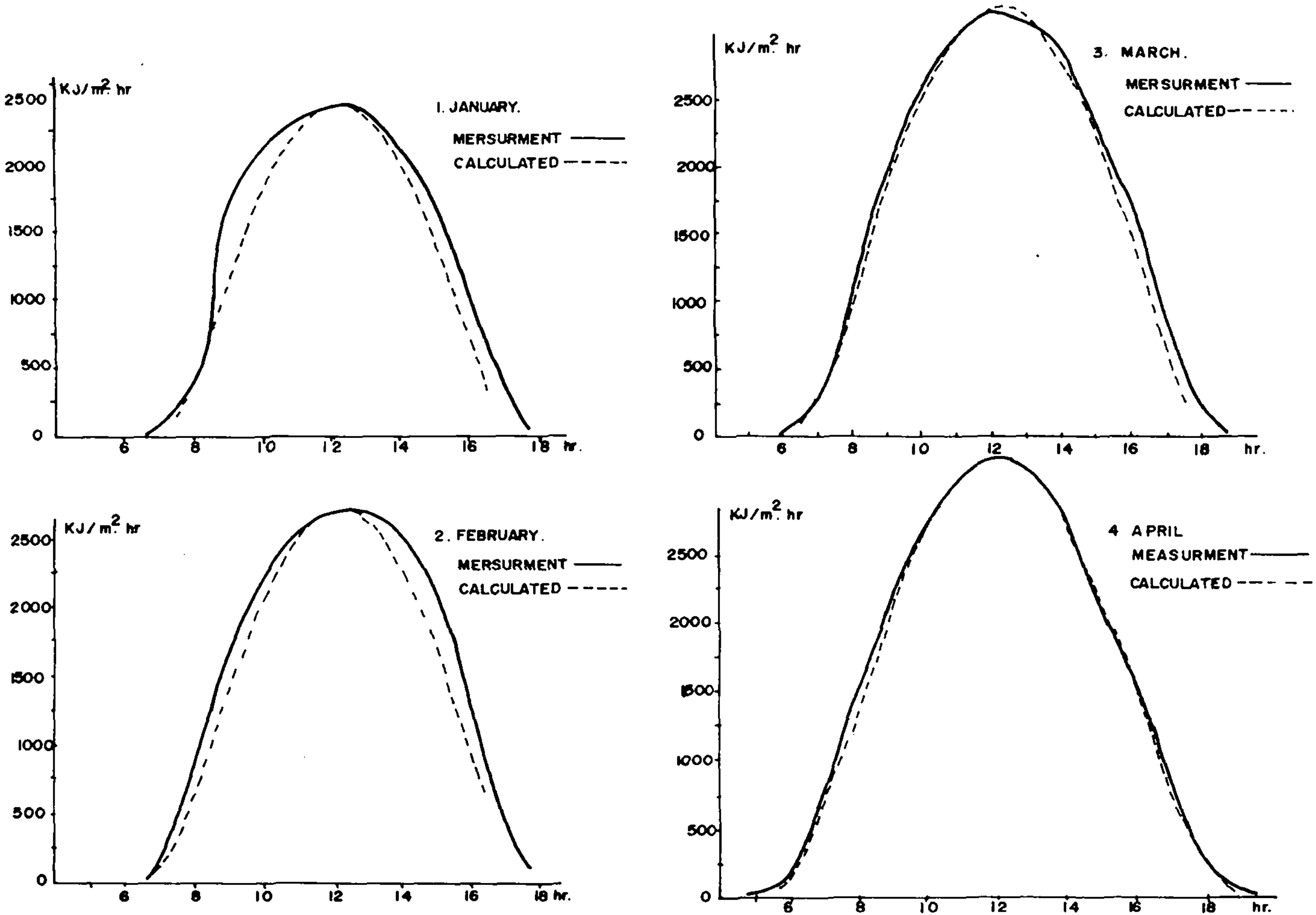
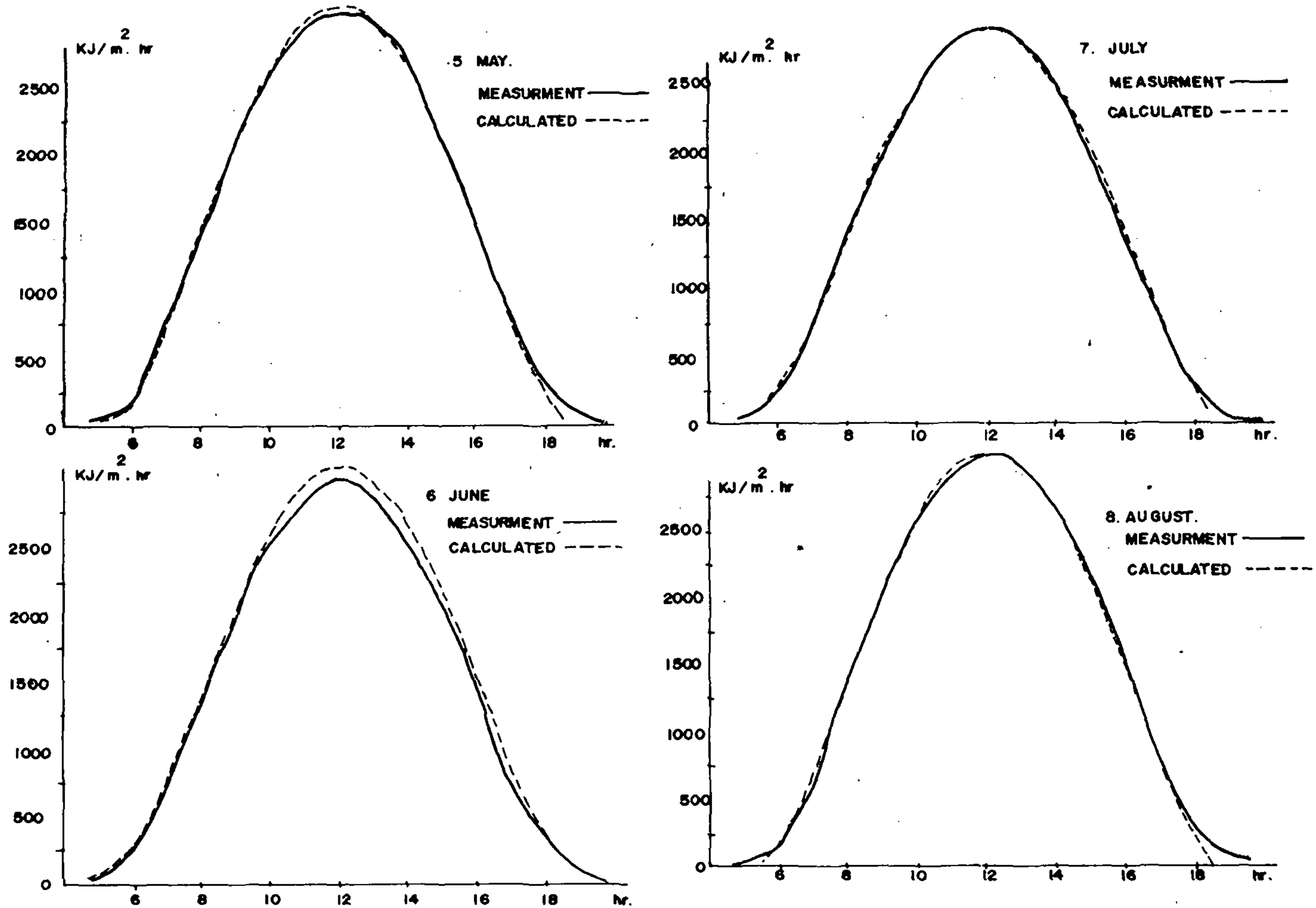
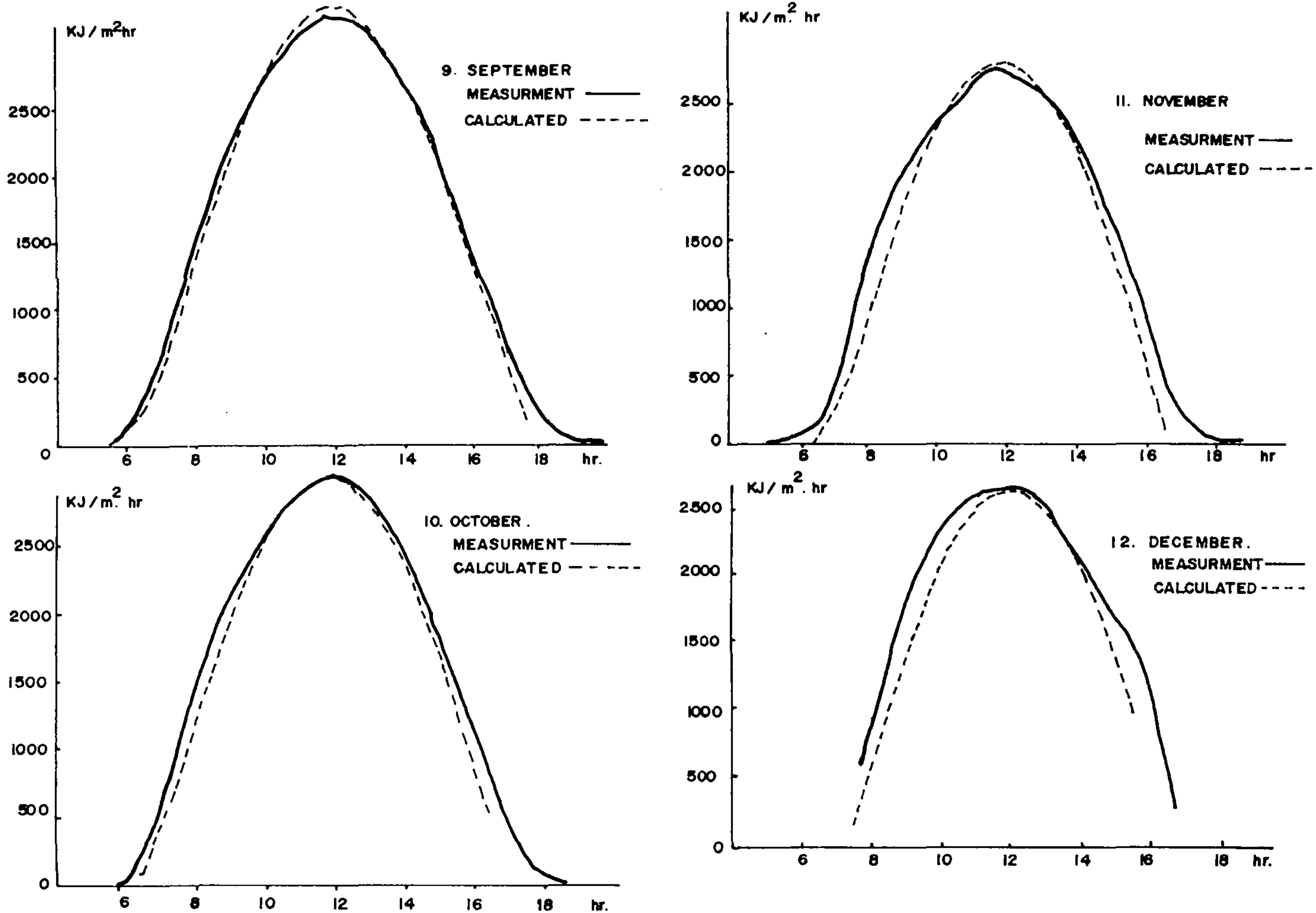


Figs. 1-4. Monthly average of the hourly total solar radiation on an inclined surface in Tehran.



Figs. 5–8 Monthly average of the hourly total solar radiation on an inclined surface in Tehran.



Figs 9-12 Monthly average of the hourly total solar radiation on an inclined surface in Tehran.

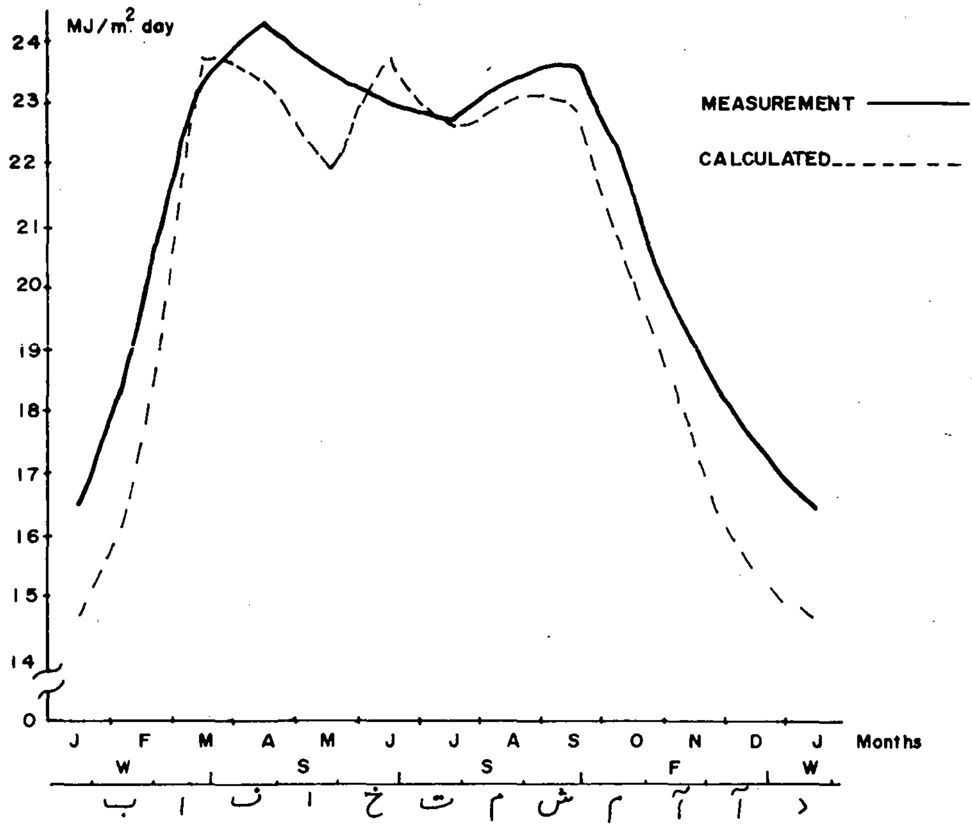


Fig. 13. Monthly average of the total solar radiation on an inclined surface S = 35°, in Tehran, φ = 35.68°

SOLAR ENERGY STUDIES AT THE FACULTY OF ENGINEERING, UNIVERSITY OF MALAYA

by

K.S. ONG

ABSTRACT

Solar energy studies in the University of Malaya began as early as in 1955. Between the years 1956 to 1971 there were isolated studies conducted. It was not until 1972 that a more comprehensive programme on Solar Energy Utilisation in Malaysia was started. Since then numerous studies have been conducted mainly with the aid of the final year Mechanical Engineering students. In 1978, biogas and wind energy studies were initiated. This paper reports on the R & D performed during the period 1972-1979.

Solar energy research at the Faculty of Engineering of the University of Malaya concentrated on water heating for domestic, commercial and industrial applications, air heating for crop and timber drying, distillation of brackish water for human or animal consumption, dehumidification for conditioning of air and selective surface preparation for high temperature solar heaters. The topics selected were mainly based on and geared to, the needs of the country. It was decided not to research into sophisticated systems like solar-thermal power generation and photovoltaics at the moment until the basic and more economically viable applications like water heating and crop drying systems were fully investigated and proven reliable under local environmental conditions. Later studies would be based on improving their efficiencies, reliability and durability.

Biogas studies was initiated in 1978 with the construction of a biogas plant capable of digesting approximately 0.2 m^3 (7 ft^3) of slurry. Initial results using chicken droppings as raw material has shown that assisted by solar heated water, an average gas production of about 0.1 m^3 (3.5 ft^3) over a 30-day period could be obtained. Quality of the gas produced showed a methane proportion of about 70% and a calorific value of 24,200 kJ/m^3 (650 Btu/ft^3). Future work would include the use of other raw materials and the design of devices for the utilisation of the gas produced.

Wind energy studies was initiated in 1978. Data on the availability of wind potential in the country was gathered. Further research is being carried out.

INTRODUCTION

Solar energy research focuses on water heating, air heating, crop and timber drying, distillation, regeneration of silica gel for dehumidification applications, selective surfaces preparation, and use of plastic material in solar collectors.

Investigations on solar water heating began as early as in 1955 when Ward (1) studied the performance of a flat-plate solar heat collector under forced circulation flow. The investigation was carried out in Singapore in the then University of Malaya. Studies by Siah (2) in 1962, Pillay (3) in 1967, and Williams (4) in 1969 followed when the campus shifted to its present site in Kuala Lumpur. However, it was not until 1972 that Ong (5) brought along a revival in the subject with a programme on Solar Energy Utilisation in Malaysia. Since, then, numerous studies were conducted mainly with the aid of the final year Mechanical Engineering students of the Department of Mechanical Engineering.

The topics selected were mainly based on, and geared to, the needs of the country. It was decided not to research into sophisticated systems like solar-thermal power generation and photovoltaics at the moment until the basic and more economically-viable applications like domestic and industrial hot water heating and crop drying system were fully investigated and proven reliable under local environmental conditions. Later studies would be based on improving their efficiency, reliability and durability. The following notes describe briefly the studies carried out at the Faculty of Engineering for the period 1972-1979.

SOLAR WATER HEATERS

Flat-plate solar water heaters operating under thermosyphon flow tural convection conditions have been tested over the past few years. The collector panels were of the conventional tubes bonded onto sheet type and connected to insulated storage tanks by connecting piping. Storage tank capacities were sized according to about 7.35×10^{-2} m^3 for every square meter of absorber area (1.5 gal : 1 ft^2). Typical results obtained (6) on an average fine day for a 0.13 m^3 (28 gal) storage tank connected to a single 1.5 m^2 (16.5 ft^2) copper absorber panel showed that the water in the storage tank could be heated from 28° to 55°C (83° to 130°F) at the end of the day. A mean system efficiency [defined as equal to the ratio of (increase in thermal energy of the water stored in the tank)/(sum total of solar energy incident upon the collector plate surface up to the instant of time considered)] of about 50% could be obtained. This meant that the solar water heater system could convert nearly half of the total incident solar energy into thermal energy. Higher temperature and better efficiencies could be obtained with better insulated storage tanks and absorber panels. Generally, mean temperatures around 50° to 60°C (122° to 140°F) and mean system efficiencies about 50% could be obtained.

There is a wide variety of absorber panel design available – from the simple flat-plate type to the more sophisticated reflector type. In the tropics because of the larger proportion of diffuse radiation, the reflector-type absorber panel is generally felt to be less efficient than the flat-plate type in total energy absorbed and converted into thermal energy per unit area of absorber surface. However, a higher water temperature could be obtained with the reflector type. A direct comparison between the two types would have to be made in order to compare quantitatively, their actual performances under local climatic conditions. What is certain is that the reflector type would be more expensive to operate because of the need to have a tracking mechanism to follow the sun's daily movement.

A cheap and simple flat-plate collector design was attempted in 1973. This was fabricated by spot-welding and soldering together, a corrugated galvanished-iron sheet onto a similar plain flat sheet. The headers were formed by bending the plain sheet around at the top and bottom ends and rolling the edges together. Soft solder was applied at all joints to prevent leakage. Steel brackets were employed to strap down the collector plate onto a wooden box, and also to prevent buckling of the plate. The performance of the system was found comparable with the above type with temperatures of up to 55°C (130°F) and efficiencies of about 40%. However, although cheap to fabricate, this type of collector design was not suitable because of corrosion and buckling. The plate developed leaks and bulged even at the low pressures of 1 m (3 ft) static water head pressure encountered. As a result, further development of this type of collector plate was discontinued.

Investigations on the long-term performances of flat-plate solar water heaters, were also carried out. These studies included the determination of optimum storage tank capacity-collector plate area ratio, night-time heat storage of the system, and the optimum relative height between collector plate and storage tank. The results indicated that for best operating and heat storage conditions, a 1.5 gal : 1 ft^2 capacity to area ratio and at least 1 m (3 ft) relative height between collector and tank rules should be followed.

SOLAR AIR HEATERS

Various solar air heater designs were investigated to provide hot air for crop and timber drying. The simplest of these is the flat-plate collector (7) which consisted of two metal sheets rivetted together to form a hollow section in-between through which air to be heated could be circulated. The collector was fabricated by rivetting and joining together short sections of thin gauge aluminium sheets of trapezoidal profile onto plain flat sheets of similar gauge and size. This formed a sandwich which consisted of several separate hollow channels through which air was circulated by means of a centrifugal blower. The channels were connected by a header formed at the outlet of the collector plate. The supporting framework was so constructed that tests could be conducted with the bottom of the collector left uninsulated or insulated with a combination of 25 mm (1 in) thick fiberglass wool resting on 50 mm (2 in) thick expanded foam polystyrene sheets. Also, the top of the collector could be left exposed or covered with a low-density polyethylene plastic sheet 0.08 mm (0.003 in) thick or with a 4 mm (0.16 in) thick plain glass sheet.

Typical results showed that air temperature rise across the collector and system efficiency depended upon the intensity of solar radiation, air mass flowrate, length of collector plate, whether insulated or not, and also on the type of top cover provided. As expected, best performance figures were obtained when the collector was provided with rear insulation and top glass cover. For this condition, 85 kg h^{-1} (187 lb h^{-1}) of hot air at 90°C (194°F) was obtained at a radiation level of 0.9 kW m^{-2} (284 Btu h^{-1} ft^{-2}) for a 9.76 m (32 ft) long collector. The efficiency [defined as total heat gained by the air/total radiation incident upon the total exposed surface area measured along the perimeter of the trapezoidal profile] was about 60%. It was also found that for optimum operating conditions the collector length and air flowrate should not exceed 7.3 m (24 ft) and 500 kg h^{-1} (1100 lb h^{-1}) respectively. Beyond these values of collector length and air flowrate, there was no appreciable gain in air temperature or efficiency.

Further studies are being carried out to evaluate alternative collector plate designs. The final outcome of the study would be to design an efficient solar air heater to supply hot air for crop and timber drying.

SOLAR OIL HEATER

In order to generate a high temperature heating medium, a force-circulation solar heat collector system with oil as the working fluid was investigated. The collector panels were similar to those used for solar water heaters. A two-stage solar energy collection system was employed. The first stage for low temperature collection, consisted of four single-glass collector panels connected in parallel. These were then connected in series to another high temperature second stage consisting of four double-glass panels. The heat collected was stored in a 0.074 m^3 (16.3 gal) insulated storage tank. This constitute what was termed the primary flow circuit or heat-collection part of the system. It was found that oil at temperatures around 95°C (203°F) could be obtained. In order to recover the energy stored in the tank, a secondary oil flow circuit was incorporated into the system. Here, hot oil from the storage tank was circulated through a finned-tube heat exchanger and returned to the tank. It was found that 340 m^3 h^{-1} (200 cfm) of air at 50°C (122°F) could be obtained from this system for a few hours.

The hot air thus obtained could be used for drying of padi or timber. With the aid of selective surfaces, the temperature of the primary fluid could be increased thus enabling a larger air flowrate or a higher air temperature to be obtained. Further work is in progress to extend the present study to link up with a solar-heated crop and timber dryer, and also to regenerate wet silica-gel.

PADI AND TIMBER DRYING

Numerous studies have indicated that low-temperature solar-heated air can be used in the agricultural sector for the drying of a variety of farm crops, for example, padi (unhusked rice), pepper, cocoa, tobacco, maize, etc., and also for timber and fish drying. However, most of these studies have been on an ad-hoc basis and no distinct or quantitative studies have been made on the individual performances of the solar collector and of the drying characteristics of the products to be dried. Where the latter exists, the required drying parameters such as air flow rates and air temperatures may not be compatible with or not economically achieved by the use of relatively simple low-cost solar collectors. A two-prong approach to the problem of solar drying was initiated. The drying characteristics of padi and timber under intermittent drying conditons were obtained using an electrically -operated drying kiln. In parallel with this, the thermal performances of various solar air heaters were evaluated. An optimum solar crop dryer design could then be evaluated once the initial data are obtained.

The drying kiln consisted essentially of (i) an electric propeller fan at one end, (ii) a heating chamber with three electric heating elements each of 3.6 kW capacity, and (iii) a drying chamber of approximately 60 cm (2 ft) square cross-sectional area. The kiln was fully insulated all round. A removable top section facilitated loading and unloading of the kiln. By varying fan speed and power input to the heating elements, various air flowrates at different temperatures could be circulated once-through the kiln.

Sawn timber (meranti) planks each measuring 2.5 cm (1 in) thick by 15 cm (6 in) wide by 1.20 m (4 ft) long were dried in stacks consisting of 30 planks placed in 3 columns with 2.5 cm (1 in) gap all around each plank for air circulation. The air speed was kept at 1.5 ms^{-1} (5 ft s^{-1}), producing an overall volumetric air flowrate of 19 m^3 min^{-1} (670 ft^3 min^{-1}). The air temperature at inlet to the stack was kept at 50°C (122°F). Drying was carried out for 8 hours each day from 9 a.m. till 5 p.m. Drying times were about 8 to 10 days to obtain final moisture contents of about 14%.

Padi was placed in 15 cm (6 in) deep bins of approximately 54 cm (21 in) square cross-sectional area. The bins were made from plywood and chicken wire mesh with a removable cover for filling and emptying the grains. Altogether up to 5 bins could be placed inside the drying chamber of the kiln. This series arrangement simulated a deep-bed drying design. Successive 15 cm (6 in) layers of grain could thus be removed for determining their moisture contents. Drying runs with air flowrates at 0.48 ms^{-1} (95 cfm) and 0.33 ms^{-1} (65 cfm) and drying air temperatures (at inlet of the drying chamber prior to first bin) of 50°C (122°F) and 40°C (104°F) were attempted. Drying was carried out for 6 hours each day. Results obtained showed that padi could be dried from about 24% to 14% moisture content in about 3 hours.

Yeo (8) investigated the effectiveness of a solar-electric padi dryer in 1974. Drying runs were conducted using air temperature of 40° – 60°C (104° – 140°F) to dry padi from an initial moisture content of 20% to a final 15%. The results showed that a reduction of 60% in electrical energy consumption could be achieved.

Two main types of solar dryers which would be suitable for Malaysia and neighbouring ASEAN countries are:

(i) forced circulation type for co-operative use handling up to 5 tons of padi daily; and

(ii) natural convection type for individual farmer user handling up to 1 ton of padi daily.

Detail proposal plans for studies at the Faculty are outlined in Reference (9). Data on the drying characteristics of padi and timber dried on an intermittent batch drying process basis and the thermal performances of various solar air heaters are available. What remains now is to develop and evaluate some prototype solar crop dryers.

SOLAR DISTILLATION

Small-scale studies (10) of the distillation of water using solar energy was conducted in 1974 using a two-slope glasshouse type of still design. The work was performed to evaluate the performance of small stills operating under local climatic conditions. The results showed that 1.0×10^{-3} to 3.0×10^{-3} m^3 of distilled water per square meter of horizontal still area (0.02 to 0.06 gal ft^{-2}) could be obtained daily. Investigations on the effects of angle of slope of the glass and depth of water in the still and also on a tilted-tray design were conducted in 1977. The results showed that still performance was not significantly affected by varying glass slope in the range of 10 to 40 degrees and that still output increased with decrease in depth of water. The tilted-tray still design required recycling of the heated water to be efficient.

AIR DEHUMIDIFICATION USING SILICA GEL

The dehumidification of air and its subsequent cooling through adiabatic humidification is being studied with possible application in comfort air-conditioning in mind. Silica gel is used as the dessicant. The performance characteristics of a fixed-bed absorber with interbed cooling is being evaluated. With flat plate solar collector in mind as a possible source of low grade heat, regeneration temperatures of the used beds were deliberately kept to below 100°C (212°F).

Preliminary results showed that desired dew-points of 10° – 15°C (50° – 59°F) were obtainable with regeneration temperatures as low as 75°C (167°F), with the silica gel removing about 2 – 3% by weight of moisture. The wet-bulb temperature here did not exceed 15°C (59°F).

An ammonia absorption refrigerator of the von Platen-Munters type is now available and its performance at low regeneration temperatures of about 80°C (176°F) will be investigated soon with solar energy as the energy source.

For both the silica gel beds and the ammonia absorption refrigerator, oil at approximately 100°C (212°F) from the solar collector is necessary, allowing for temperature drop across heat exchangers.

SELECTIVE SURFACE

Black chrome has been prepared on small samples and verified as a good selective surface. The quality control of the bath to ensure consistent plating from day to day is labourious, but effective. A large scale plant to treat up to 0.5 m^2 (6 ft^2) of collector area is ready, subject to obtaining suitable location and 3 phase power supply.

A single glazed V trough collector using black nickel selective surface has been evaluated up to 95° C (203° F) as an initial study for the high temperature programme. Indoor loss testing was first used to estimate the overall heat losses. Outside, the collector was fed on a 'once through' basis from a preheated constant temperature tank over the full range of operating conditions. Flow rate, temperature rise, windspeed, direct and diffuse radiation were all monitored. The large amount of scatter showed that this is an unsuitable method for evaluating focussing collectors where the balance between direct and diffuse radiation is critical. However, the results show that the quality of reflectors used is important, and that double glazing and selective surfaces are justified at these temperatures. The collector has now been modified to include double glazing and improved reflectors and is being tested with a fixed store using an electric water pump. The unit is monitored at 5 min intervals to produce average performance data integrated throughout the day. The information is used to test computer programmes modeling the storage and collection system. To store a given amount of energy at a high temperature, a smaller mass of water is required than at a lower temperature. Combined with the fact that losses increase roughly in proportion to collection temperature the significance of store losses may be expected to increase as the mean temperature rises.

The initial result of the V trough plus store testing programme is that store and piping losses dominate everything else. Standard hot water collector and store design is unsuitable for high temperature focusing systems. Store losses must be reduced by better insulation to become small compared to the thermal capacity of the store. Assuming a practical maximum of 5 cm. (2") polyurethane foam insulation, a minimum store size of approximately 0.07 – 0.09 m^3 (15-20 gallons) is required, requiring a total collector area of approximately 2.3 – 3.7 m^2 (25 – 40 ft^2).

Smaller units do not appear to be practical. The present study is concentrating on finding the optimum store to collector area ratio and on producing a valid computer model for overall system operation, before investigating temperatures above 100° C (212° F) by use of oil and water/glycol mixtures.

HEAT PUMP

The main disadvantage of high temperature solar system is that efficiency drops due to the associated increase in thermal losses. One solution is to use a solar-assisted heat pump. The evaporator of a vapour compression system is used as a solar collector and the heat reject from the condenser is used to heat water or air. The evaporator, operating at a low temperature will be a very efficient collector, whereas the condenser may be heavily insulated – no glass is required – and the heat losses minimised. Previous designs of this system have been tailored to the cold northern winter where evaporator temperatures and coefficient of performance must be low. Malaysia with normal ambient of 25 – 30°C is an ideal climate for a high temperature heat pump working with a large coefficient of performance. A prototype ¼ horse power heat pump using Freon 11 regrigerant is at present under construction. If the compressor is powered from main electricity, a minimum coefficient of performance of 3 is required to show any advantage over the direct burning of fossil fuel. However, if the compressor is powered directly from a heat engine, and heat from the exhaust gasses can be transferred to the heated medium, then the heat pump will be economical at a lower coefficient of performance. Initial studies suggest that coefficients of performance in the range 3 – 5 will be possible.

USE OF PLASTICS

Investigation into the use of plastic as a possible material for the solar collector panels was started in 1976. Two types of collector designs using reinforced plastic were built and tested; viz.

i. a black plastic box in a plastic supporting case was used as a collector-cum-storage solar water heater; and

ii. a corrugated plastic sheet placed over a plain flat plastic sheet and used in forced-circulation solar water heater system.

Results show that system efficiencies of about 60% at temperatures varying from 40°C (118°F) to 77°C (170°F) could be obtained. These results indicate that plastic could be a suitable material for making solar water heaters. Plastic have the advantage of being corrosion-free, easy to manufacture and light in weight.

PASSIVE SOLAR ENERGY DEVICES

The incident solar radiation has a considerable influence on the internal environment of a building. The several strategies that are employed to maintain and improve the comfort standards of the occupants can be classified into 'active' and 'passive' design.

Active designs utilise relatively expensive and sophisticated equipment and controls, and are energy intensive. In contrast, passive designs tend to be elementary, simplistic and lower in cost. They are also energy economical.

The present work is concerned with the thermal design of buildings and the comfort of its occupants, and the passive solar devices that help to achieve these goals. In particular, it is hoped to develop a method of quantitatively evaluating an enclosure in terms of the occupants' comfort and apply this to buildings with alternative passive system components.

BIOGAS STUDIES

Work on Biogas was initiated in 1978 with the construction of a biogas plant capable of digesting approximately 0.2 m^3 (7 ft^3) of slury. The plant consisted of a 585 mm (23 in) diameter digester made of M.S. plate and surrounded by a 64 mm (2.5) thick water jacket which was heated by a flat-plate solar heat collector working under thermosyphon flow. Thermocouples were used to measure the temperature of the slurry at different sections of the digester. An agitator was incorporated in the digester for even mixing of the slurry.

Gas produced was piped off to a floating-type gas collector consisting of a M.S. cylinder with its upper closed and the lower end immersed in water contained in another M.S. tank. Counterweights were attached to the collector, so that the gas pressure in the collector could be varied. Gas production was measured by the vertical displacement of the collector above the water level and its pressure was obtained using a simple water manometer. the gas could be piped off for usage or for analysis. Parameters investigated included the production rate of gas, the pH of slurry and the quality of the gas. Initial results using chicken waste as raw material have shown that assisted by solar heated water, an average gas production of about 0.1 m^3 (3.5 ft^3) per day over a 30 day period could be obtained. Quality of the gas produced showed a methane proportion of about 70% and a calorific value of 24,000 KJ/m^3 (650 Btu/ft^3).

Investigation into the production of biogas using palm oil sludge is currently being conducted. In addition to the above parameters investigated, the B.O.D. of the slurry is also being monitored. Future work would include the use of other raw materials and the design of devices for the utilisation of the gas produced.

WIND ENERGY

Wind energy research was initiated in 1978 [11]. The monthly and yearly wind energy outputs were estimated for the period 1969 – 1973 for a few stations throughout Peninsular Malaysia. Based on these estimates, an economy study of wind-powered electric generation was carried out. It was found that small-scale wind-driven generators with outputs up to a few kilowatts and using batteries for storage would be feasible for supplying electricity to isolated areas, such as islands and fishing villages along the East Coast where favourable wind power is available.

The major setback of wind power is its irregular nature. Some means of storage of energy are needed to provide for periods of calm. A combined wind and solar energy system would be investigated at the Faculty.

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SOME APPLICATIONS USING A PARABOLIC SOLAR CONCENTRATING SYSTEM

by

NOEL JOHN MONERASINGHE

INTRODUCTION

Malaysia receives well over 2000 sunshine hours a year and the mean solar radiation intensity in close on 450 mW-hr/cm^2. Some work on research and development in harnessing and utilization of this energy is in progress in the universities and research institutions of Malaysia. In the search for a rational basis for deciding which concentrator type is best suited for a particular application, this simple focusing cylindrical parabolic collector was investigated to heat water. This paper concentrates on the design and results of the linear concentrator built and tested in the School of Physics, University Science Malaysia, Penang.

Solar Focussing Collectors

To increase the intensity of solar radiation on the energy absorbing surface, focussing collectors utilize optical systems. Higher energy flux on the absorbing surface means a smaller surface area for a given quantity of energy with corresponding reduction of thermal losses. The energy balances, basically similar to flat plate collectors, show that operation at higher temperatures is possible. While thermal losses are reduced, the diffuse radiation is lost as most focussing systems depend on the beam component of solar radiation.

In using the concentrator certain factors must be considered viz. optical characteristics of the concentrator, non-uniform fluxes on the obsorber, wide variation in shape, thermal loss characteristics of absorber and introduction of optical factors in the energy balance.

Tracking the sun for optimum beam radiation is a very vital factor to consider.

Maintenance of the optical system against dust and oxidation has to be considered to retain the quality of the collector.

Before final selection was made, three models with similar concentrating ratio reflectance and absorptivity were considered. *The conical model* with a smaller heat loss will give a higher temperature. It is simple to design and fabricate. However the performance analysis is rather difficult as the energy balance takes into consideration heat loss from the collector in three dimensions. Focussing must be very accurate and a sensitive control system is called for. It is rather difficult to construct.

The Fresnel Model needs a circular shift of the receiver in tracking the sun and is simpler to fabricate needing a thin strip of reflecting surface adjusted to focus on a circular path for all positions of the sun. The performance analysis of this model is difficult. The spaces within the strips, contribute a greater heat loss viz. the effective concentration ratio is reduced.

With the cylindrical parabolic model the performance analysis is much easier and the system is not hypersensitive to the sun's motion. An increase in temperature is possible by an increase in concentrator length.

Engineering Aspects

1. Effective span	–	concentrators width.
2. Rim angle,	–	half the angle subtended by the edges of the reflector at the focus.
3. Reflecting surface area A	–	total surface area of reflecting surface.
4. Acceptance angle	–	angle through which the parallel beams reflected from the reflective surface would be intercepted by the obsorber.
5. Minimum absorber Diameter, 2 rim	–	diameter of absorber corresponds to the acceptance angle.
6. Concentration ratio C	–	ratio of effective area of aperture to area of absorber.
7. Tracking time T	–	time lapse-before concentrator tracking adjustment.

The maximum concentration ratio is obtained for a rim angle of 90 degrees. For a partly insulated receiver the rim angle should be around 70 degrees* where.

$$2 \text{ in angle} = \frac{1 - (\sin\delta / \sin\phi)}{\pi \dfrac{\sin\delta}{\sin\phi} \left(\dfrac{\phi + 90 - \delta}{180}\right)} \tag{2.1}$$

1 = latus rectum of the parabola.

Using a glass envelope

$$C = Aa/Ar \tag{2.2}$$

* Article by S.G. Kandlikar and S.K. Vij – International Solar Energy Congress, 1978.

A parabolic linear concentration of length 150 cm. was built of fibre glass with strips of plane mirrors 1.3 cm. width glued on the surface. The aim is to emphasize the use of readily available materials and the construction within the capacity of local and economical.

The receiver consists of a blackened absorber copper tube with a glass envelope. The diameter of the absorber tube is 4 cm. while that of the glass envelope 5.0 cm. The tracking time is about 14 minutes and the concentration ratio is 10.

For the parabolic model, the equation of the cross section

$y^2 = 4fx$ where f is the focal length of the parabola.

For dimensions of 0.8 m. x 1.5 m. the focal length is about 20 cm.

Latus rectum 1 is from the equation

$$y^2 = 4f.x \tag{2.3}$$
$$= 4 \circ 20x \quad \text{(tanking x as 20 cm.)}$$
$$\therefore 1 = 40 \text{ cm.}$$

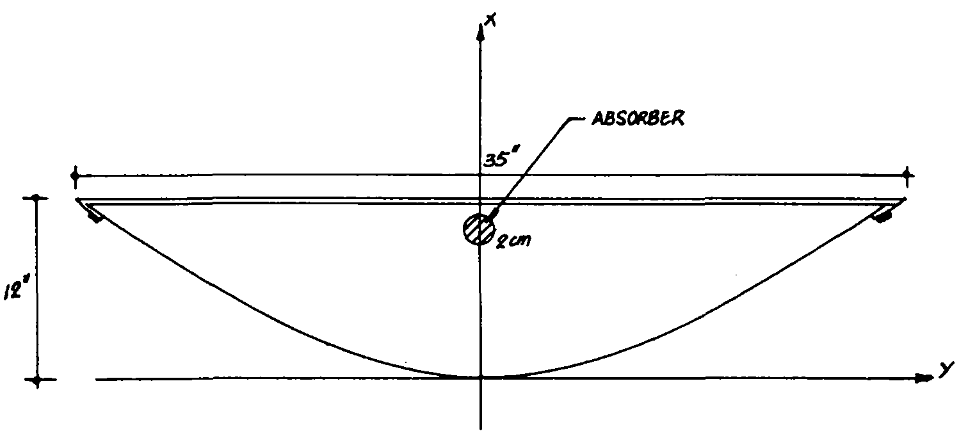
The circumference of parabola

$$2s = 1\,(\mathrm{Sec}\,\phi/2 \times \tan\phi/2 + \ln(\mathrm{Sec}\,\phi/2 + \tan\phi/2) \tag{2.4}$$

For rim angle of 90 degrees.

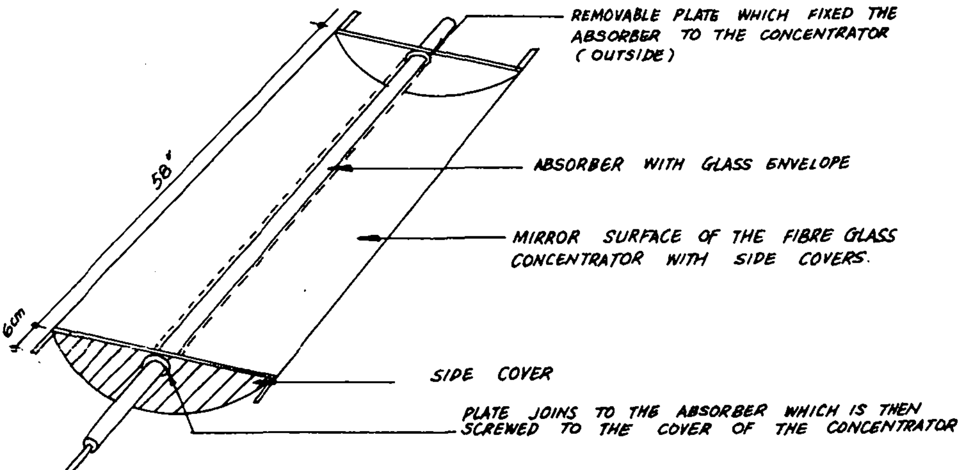
$$2s = 92 \text{ cm.}$$

We fabricated a model 2s = 102 cm. and length 150 cm.

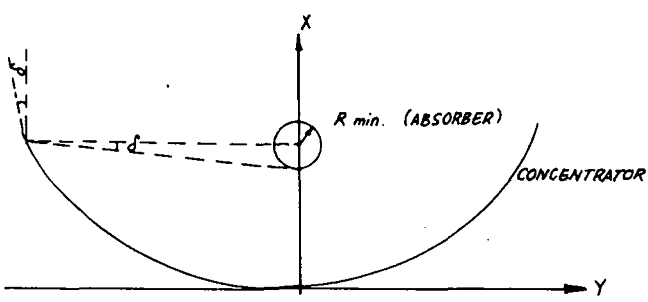


(Fig. 2.1)

The rim angle greater than 90 degrees is to cover the collector sides and reduce lost energy due to error in the angle of tilt of collector to sun.


REMOVABLE PLATE WHICH FIXED THE ABSORBER TO THE CONCENTRATOR (OUTSIDE)
58"
ABSORBER WITH GLASS ENVELOPE
MIRROR SURFACE OF THE FIBRE GLASS CONCENTRATOR WITH SIDE COVERS.
6cm
SIDE COVER
PLATE JOINS TO THE ABSORBER WHICH IS THEN SCREWED TO THE COVER OF THE CONCENTRATOR

(Fig. 2.2)


X
R min. (ABSORBER)
CONCENTRATOR
Y

(Fig. 2.3)

With reference to figure 2.3

R min = 1 tan
= arc tan R min/1
= arc tan 2/40
= 2.8624 degrees.
(rotation 1 degree – 4 minutes)

: Tracking time T = 2 x 4 minutes
T = 23 minutes.

Tracking of sun done every 23 minutes.
R min. is radius of absorber.

Dimensions of Cylindrical Parabolic Concentrator

1. Focal length f = 20 cm.
2. Depth d = 24 cm. distance from vertex to line joining the aims along x-axis
   (the rim angle is about 95 degrees)
3. Effective span 2W = 2(80 x 24)½
   = 88 cm.
4. Circumference of reflecting surface 2S = 92 cm.
5. Length of concentrator L = 150 cm.
6. Reflecting surface area = L x 2S = 13800 cm^2
7. Minimum absorber diam. R min. = cm.
8. Acceptance angle = 2.8624 degrees.
9. Tracking Time T = 23 minutes.
10. Concentration Ratio C = 7

   As defined C = Aa/Ar where Ar = 2 r x 150 and r = R min.
   C = 7

Fig. 2.4. CROSS-SECTION OF THE RECEIVER AND CLASS ENVELOPE.

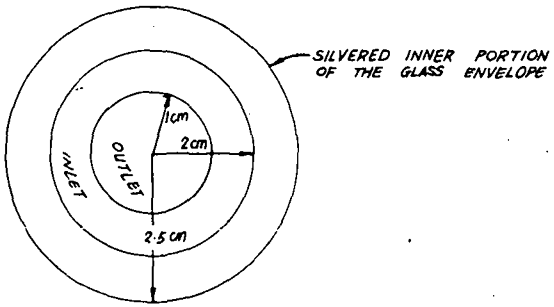
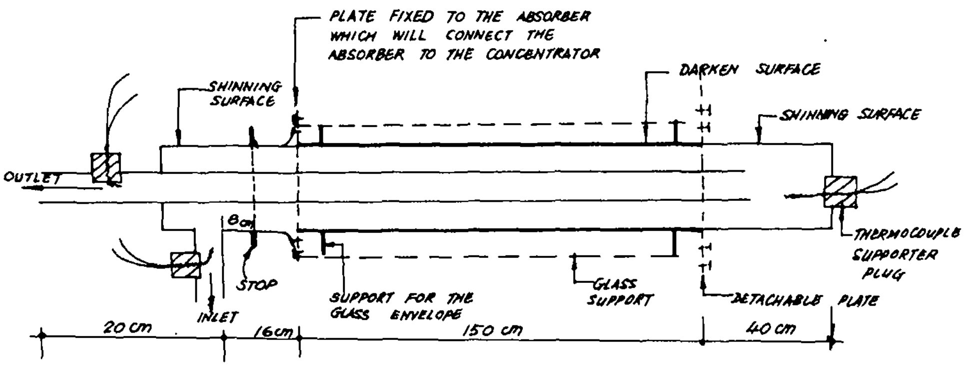


Fig. 2.5. THE RECEIVER AND ABSORBER. NOTE THAT ONLY THE SECTION EXPOSED TO THE CONCENTRATOR IS DARKENED. THE GLASS ENVELOPE SUPPORTERS ARE TO KEEP THE ENVELOPE IN POSITION.



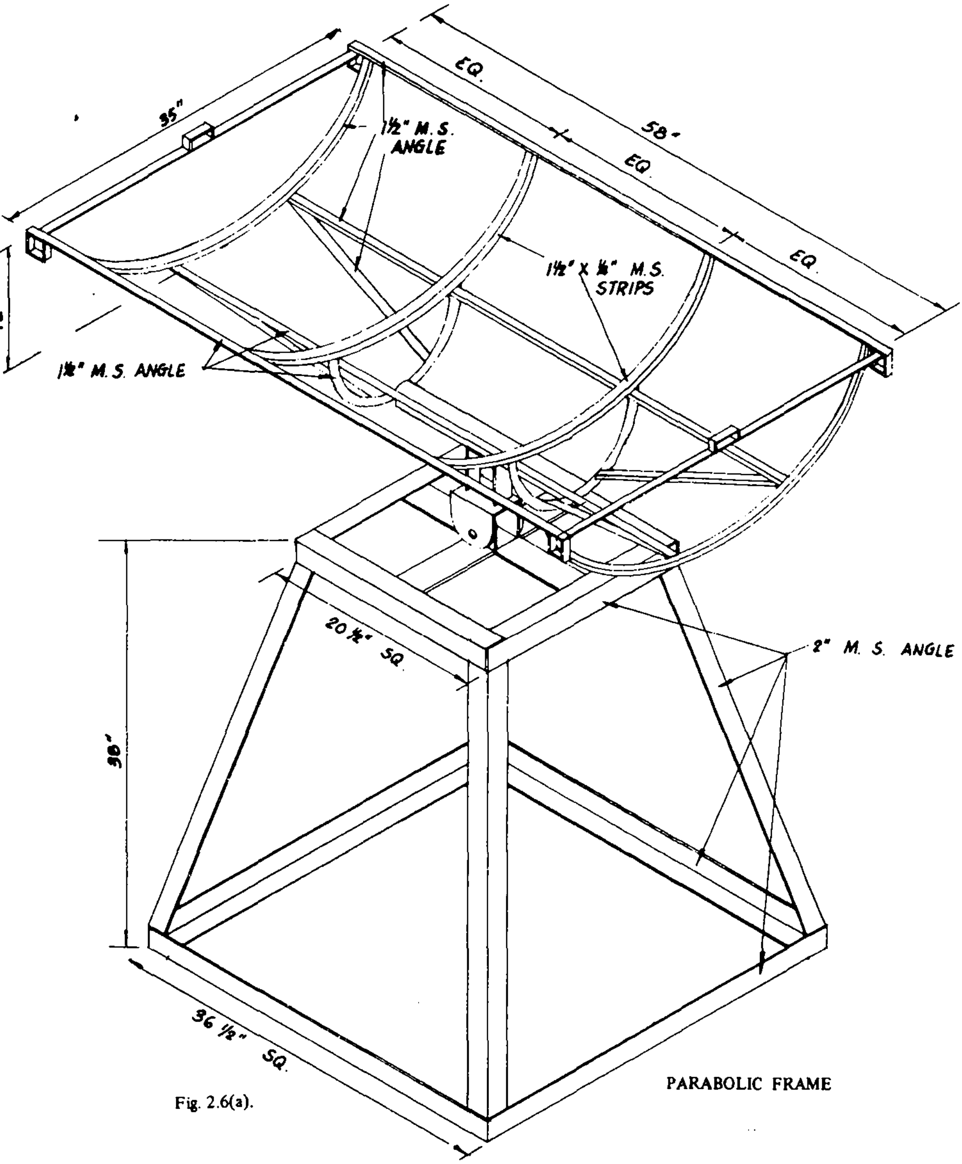


Fig. 2.6(a).

PARABOLIC FRAME

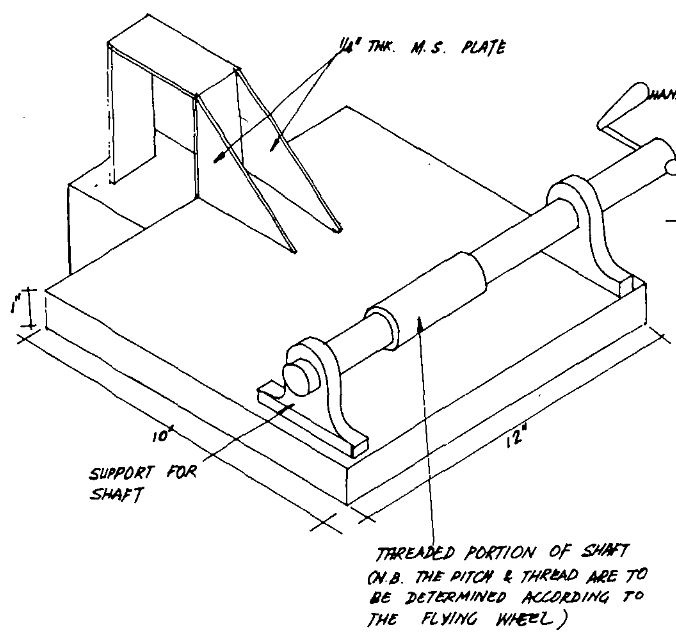
Receiver

The glass envelope is silvered on the upper portion to reduce heat loss through radiation on that portion unexpected to the concentrator. Two plates at end of receiver, fix it to the concentrator so as that they move together during tracking. One plate is detached to facilatate replacement of envelope if necessary in the case of breakage. The envelope supports may be fixed or removed, to hold the envelope in position. The absorber portion within the plates viz. within the concentrator is coated with a heat absorbing black paint. The other sections of the tube are polished to shine. Thermo-couples-plugs are replaceable. The stop between the inlet tube and the plate is permanent, to keep the collection in position on the supporting frame – place this gap on the level of the supporting frame.

The Supporting Frame

Penang is 7 degrees latitude North. The sun moves around 23 degrees North to 23 degrees South during the year. The collector is oriented with respect to the sun's position throughout the year to obtain maximum.

The collector is positioned in a North-South directions with the inlet-outlet end of the receiver in the North. The collector is oriented from 16 degrees North to about 30 degrees, South viz. the collector is tilted 16 degrees to the horizontal and gradually altered in the opposite direction to 30 degrees.



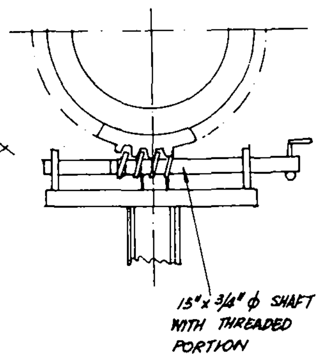


Fig. 2.6(c)

(Fig. 2.6(b))

Section III

Energy Balance

Energy balances are used to described the performance of focusing collector systems.

The thermal performance of a cylindrical parabolic collector can be described in general terms. The energy balance at a location x of our design, consider that the envelope is transparent without the silver coating first (refer Fig. 3.1). By conservation of energy terms,

Energy extracted = Energy input – Energy loss

$$q_u = H_b R_b \rho\gamma\tau\alpha - U_l \frac{A_r}{A} (T_r - T_a) \qquad (Wm^{-2}) \qquad (3.1)$$

We consider that the absorber has a uniform temperature T_r, then the useful gain for the collector.

$$Q_u = A_a H_b R_b \rho\gamma\tau\alpha - U_l A_r (T_r - T_a) \qquad (W) \qquad (3.2)$$

Where,

ρ = specular reflectance of the reflector surface.

γ = the fraction of specularly reflected radiation that is intercepted by the absorber surface is the intercept factor.
(This depend on the accuracy of our tracking system. As we use it manually we can assume that this factor is approx. 0.8)

τ = transmittance of the cover, or envelope.

α = absorptance of the receiver,

H_b = is the incident solar radiation (beam component as this is the only effective component).

R_b = is the ratio of beam radiation on the reflector aperture to that on whatever surface H_b may be measured.
(For beam radiation, some measurement on the surface normal to the direction of propagation are available)
Thus $H_b R_b$ give the beam radiation on the plane of the aperture of the collector.

$\frac{A_a}{A_r}$ = the ratio of the *effective* area of the aperture to area of the solar energy absorber. As defined earlier this is the concentration ratio

Note: A_a is the unshaded projected area of the reflector system only. As calculated c = 7. (We take A_r as the total surface area of the receiver of length 150 cm.)

$U_1(T_r - T_a)$ = Thermal losses per unit area from a receiver at a temperature T_r to the surrounding T_a can often be expressed by this linearized heat loss term.

Thermal losses from the large surface receiver increases with temperature, therefore low useful energy delivery at high temperature results. By increasing the concentration ratio $\frac{Aa}{Ar}$ at constant A_a and U_r, thermal losses are reduced, (equivalent to reducing the diameter of receiver). The method of controlling thermal losses permits collection at higher temperature. But note that our tracking is done manually hence reducing the diameter of the receiver will make work hard and time consuming.

Fig. 3.2 shows the variation of useful heat recovery per unit area of collector aperture A_a as a function of $\frac{Aa}{Ar}$ of am odealized example with constant $H_b R_b$ $\varphi\gamma\tau\alpha$ product and receiver temperature. The useful energy gain and efficiency curves approach asymptoes representing zero thermal losses at zero absorber area (In practice this is also true).

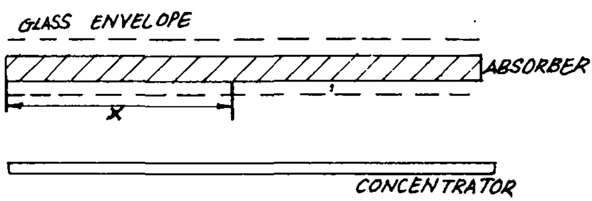


Fig. 3.1 SIDE VIEW OF RECEIVER

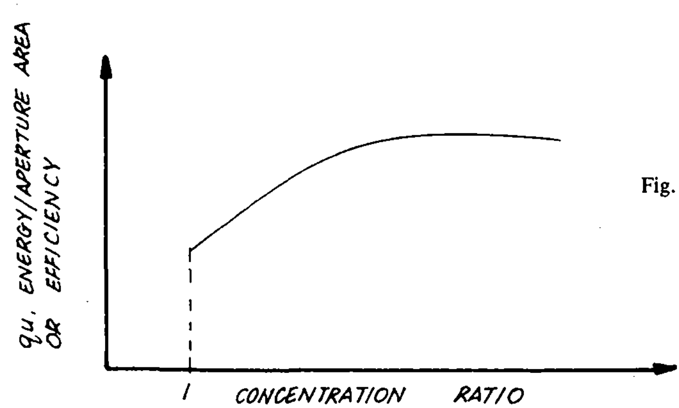


Fig. 3.2 EFFICIENCY OF THE RECEIVER AS A FUNCTION OF CONCENTRATION RATIO

Optical Losses: ρ **and** $\tau\,\alpha$ **and** γ

The specular reflectance φ, is defined as the fractional portion of an incident collimated beam which is reflected such that the angle of incidence = angle of reflection. It is a function of the nature of the surface and of its smoothness. The higher the value of ρ the better the performance will be the collector. For this reason we choose a chromium-plated iron or steel sheet. The average value of ρ is 90%. The transmittance of the glass envelope with reflective index is given by (with normal incidence angle)

$$\tau = \frac{4n}{(n+1)^2}$$

and reflectance

$$R = \frac{(n-1)^2}{(n+1)^2} \qquad (3.3)$$

Note that $\tau = 1$ if no envelope is used.

The absorptance α depends on the kind of coating in the receiver. The greater the value of α the better will be the power of absorbing the radiation but this too corresponds to high emittance. For this reason it is suggested that the receiver be painted with a shinning surface at parts which are not exposed to the concentrator to reduce heat loss. τ and α are dependent on the average angle of incident of the radiation on the cover and receiver also. The angle of incidence of a beam of reflected radiation on the reflector from which the beam is reflected and the shape of the receiver. The proper value of the $\tau\alpha$ product must be arrived at by an integration of the radiation passing through the cover and incident on the receiver from all portion of the concentration. A vigorous analysis of this is very difficult, particularly for low-quality concentrator. For our purpose we can assume $\tau = \frac{4n}{(n+1)^2}$ and depends on the coating only.

γ represents the intercept factor which is defined as the fraction of the specularly reflected radiation that is intercepted by the energy absorbing surface. This factor is a property of the concentrator and its orientation in producing the image, and of the receiver and its positioning relative to the concentrator in intercepting part of that image. Consider the flux distribution of the concentrator as shown in fig. 3.3

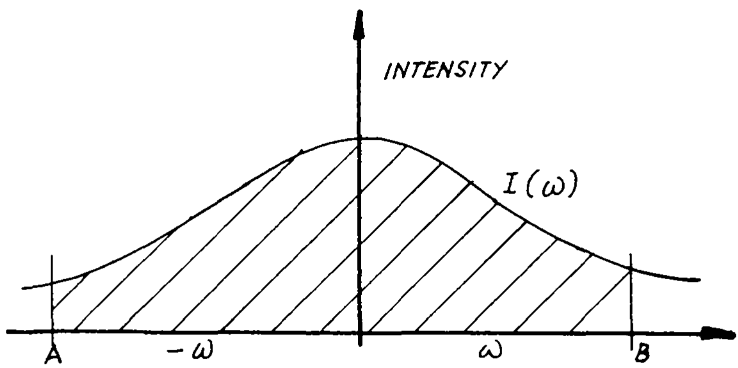


Fig. 3.3. ENERGY REFLECTED.

Area under the curve will be the energy reflected to the focal plane. If the receiver occupies the width from A to B then,

$$\gamma = \frac{\int_A^B I(w)\,dw}{\int_{\infty}^{\infty} I(w)\,dw} \tag{3.4}$$

where w is the distance from the center of the focal area.

Optimum receiver size results in maximum useful energy gain by minimizing the sum of optical and thermal losses; a large receiver results in large thermal and low optical loss while a small receiver means lower thermal loss but larger optical loss. In our case the size of our receiver is restricted because the size of the glass envelope available is restricted and also restricted by the tracking system.

The main causes of the curve in fig. 3.3 are

1. small-scale errors or irregularities on the reflector surface which causes dispersion of the image. This effect could be considered as diminishing of the specular reflectance ρ.
2. macroscopic errors in the reflectors resulting in the distortion of solar image.
3. error in positioning of the receiver relative to the reflector. (This is one major error in the present collector we have).
4. errors in orienting the collector system.

Of all these factor, the second cause is the most significant. Most of the other causes can be reduced by proper design or their contribution is very small.

Assuming that the errors in reflector manufactured are random, a reasonable assumption for distribution of radiation across the focal area is a normal distribution. Then fig. 3.3 represent a normal curve.

For our system, the flux distribution can be written as

$$\frac{I}{I_{max}} = e^{-h^2}\,(w/W)^2 \tag{3.5}$$

$$I_{max} = \frac{1}{\Sigma\sqrt{2\pi}} = \frac{h}{W\sqrt{\pi}} \tag{3.6}$$

where

I	=	radiation flux density	
I_{max}	=	the maximum flux distribution coefficient defined by	(3.6)
w	=	distance from the center of the zone	

W = half-width of the concentrator

σ = standard deviation of the normal distribution curve.

for a symmetrical distribution,

$$\gamma = \frac{2}{\sqrt{\pi}} \int_0^{h(w/W)} e^{-h^2 (w/W)^2} d\left(\frac{hw}{W}\right) \qquad (3.7)$$

Thermal Losses $U_l (T_r - T_a)$

Analysis of thermal losses is not that general and easy. For our cylindrical parabolic concentrator we need to find U_l, the loss coefficient and F, the collector efficiènce factor. Let us consider that there is no envelope and no temperature gradients around the receiver tube first. Also on our receiver tube consisting of two concentric cylinders we consider that there is no temperature difference between the fluid. Let the coefficient of heat transfer between the fluid and the tube be h_i, and the loss coefficient from the outside of the tube is U_l.

$$U_l = h_{wind} + h_r \qquad (3.8)$$

where h_r is the linearized radiation coefficient and is found from

$$h_r = 4 \sigma \epsilon_r T^3 \qquad (3.9)$$

(if only radiative loss, energy loss = $\Sigma \epsilon_r \tau^4$, as in a vacuum surrounding) where T is the mean temperature for radiation and ϵ_r is the emittance of the receiver. Since the heat transfer resistance from the outer surface of the receiving tube to the fluid should include the tube wall. The overall heat transfer coefficient U_o, (based on the outside tube diameter) to the surroundings from the fluid is

$$\frac{1}{U_o} = R_1 + R_2 + R_3 \qquad (3.10)$$

where R_i is the resistance of heat transfer

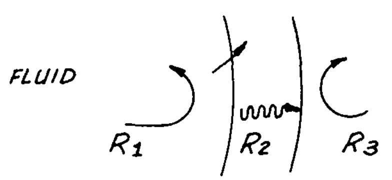


Fig. 3.4 HEAT TRANSFER RESISTANCE FROM FLUID THROUGH THE COPPER TUBE

$$\frac{1}{U_o} = \frac{D_o + D_o \ln D_o/D_i}{h_i D_i \quad 2k} + \frac{1}{1} \tag{3.11}$$

or

$$U_o = \left(\frac{D_o}{h_i D_i} + \frac{D_o \ln D_o/D_i}{2k} + \frac{1}{U_1}\right)^{-1}$$

where D_i and D_o are the inside and outside tube diameters, h_i is the heat transfer coefficient inside the tube and k is. the tube thermal conductivity. Rewriting the energy balance equation (3.2), the useful energy gain q_u per unit of collector length L can be express in terms of the local-receiver temperature T_r as

$$q_u = \frac{A_a}{L} H_b R_b \rho \alpha \gamma - \pi D_o U_1 (T_r - T_a) \tag{3.12}$$

as

$$\frac{A_r}{L} = \frac{D_o \pi L}{L} = D_o \pi$$

and in term of the energy transfer to the fluid as

$$q_u = \frac{1}{R_1 + R_2} \frac{A_r (T_r - T_f)}{L} \tag{3.13}$$

where T_f is the fluid temperature.

$$q_u = \frac{\pi D_o (T_r - T_f)}{D_o/h_i D_i + \dfrac{D_o \ln D_o/D_i}{2k}} \tag{3.14}$$

eliminating T_r

$$q_u = F' \frac{A_a}{L} \left[S - \frac{A_r}{A_a} U_1 (T_f - T_a)\right] \tag{3.15}$$

where $F' = \dfrac{U_o}{U_1}$ (3.16)

and $S = H_b R_b \rho \gamma \alpha$ (3.17)

From (3.14) and (3.15) we can also derived the equations.

$$q_u = A_a F_R \left[S - \frac{A_r U_l}{A_a} (T_{f,i} - T_a) \right]$$

where $T_{f,i}$ is the outlet temperature of the fluid.

with the collector flow factor F" equal to

$$F'' = \frac{F_r}{F'} = \frac{\dot{m}C_p}{A_r U_l F'} \left[1 - e^{-A_r U_l / mC_p} \right]$$

$\dot{m}$ is the fluid flow rate in mass/time and C_p is the specific heat capacity. The same analysis applies to a receiver that is covered, but it is necessary to include the effective transmittance-absorptance product in S and to properly evaluate U_l to account for the added heat transfer resistances.

This method is a way to complete the performance analysis of the cylindrical parabolic concentrator with a glass envelope. We assume that the sum is always being tracked by the system. For total heat transfer refer – "An Introduction to Applied Solar Energy", – Aden B. Meinel & Majorie P. Meinel.

CONCLUSION

It is possible to heat 30 litres of water to 55°C in about 5 hours using a parabolic concentrator. In one set up the outlet temperature of water at a flow rate of 23 ml/s, rose to about 65° C. The quantity of water heated can be increased with correspondingly increased collector area.

The performance however of this system is very sensitive to the position of the sun i.e. the ability to track accurately. It works well when the direct component of solar radiation is high, with little cloud covering.

Here is an attempt to show, within limitations, using locally available materials and expertise, a concentrating system could also be used to heat air for use in agricultural produce and timber drying.

The accompanying eight graphs show the results under various test conditions.

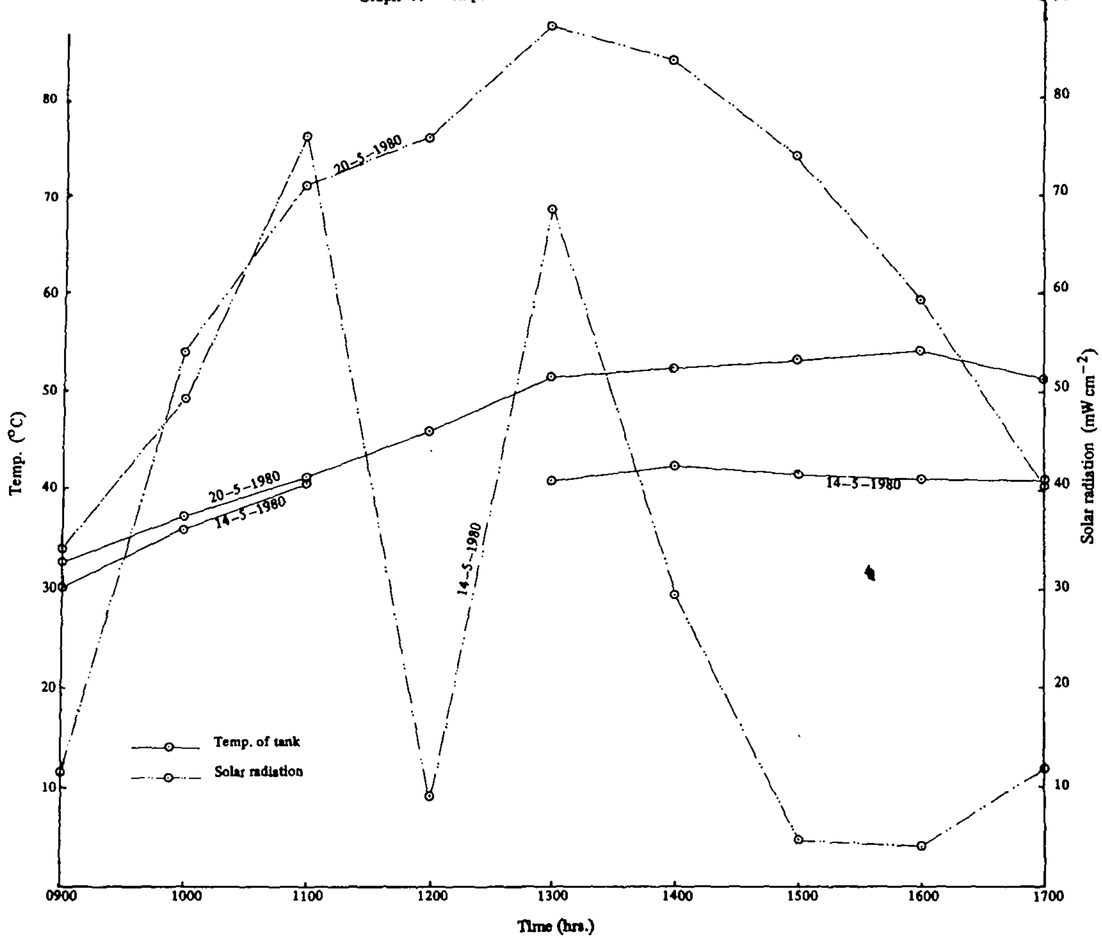
REFERENCES

1. Comparison of Solar concentrators – Ari Rabl. (Solar Energy Vol. 18).
2. Solar Energy Thermal Process – J.A. Duffie and W.A. Beckman.
3. Applied Solar Energy – Aden & Majorie P. Meinel.

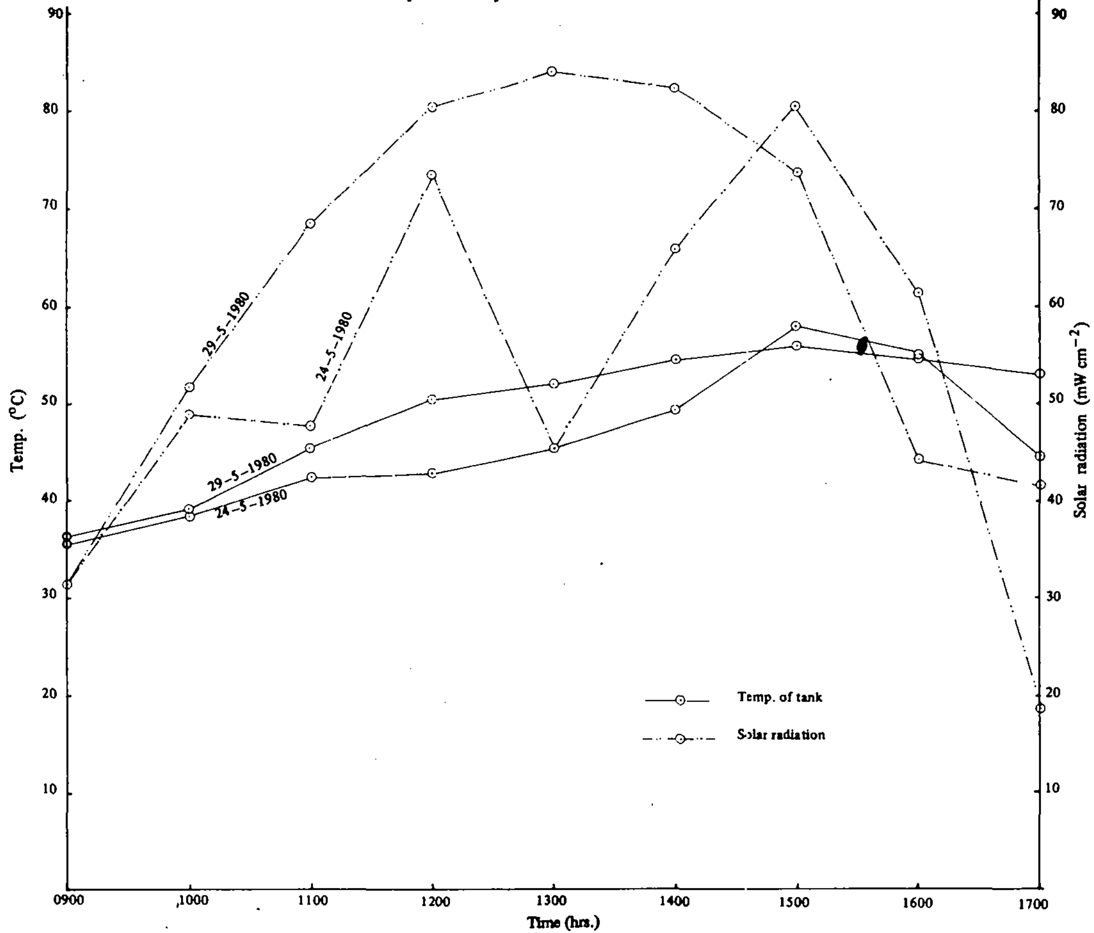
4. Geometrical aspects of cylindrical parabolic collector operated with intermittent tracking – S.G. Kandlikar (International Solar Energy Congress, 1978).

5. Performance analysis of a cylindrical parabolic focussing collector and comparison with experimental results – Michael W. Edenburn (Solar Energy Vol. 18).

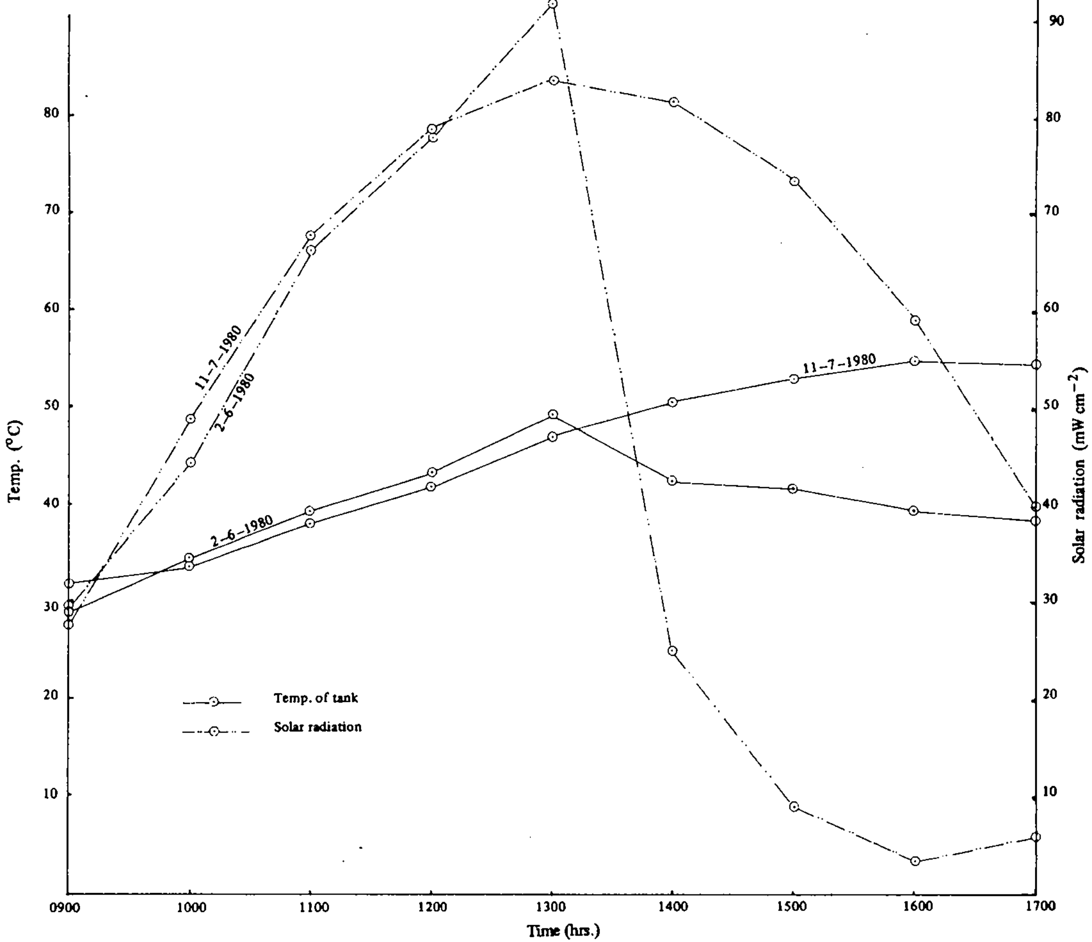
Graph 1. Temp. Rise – Parabolic Solar Concentrator



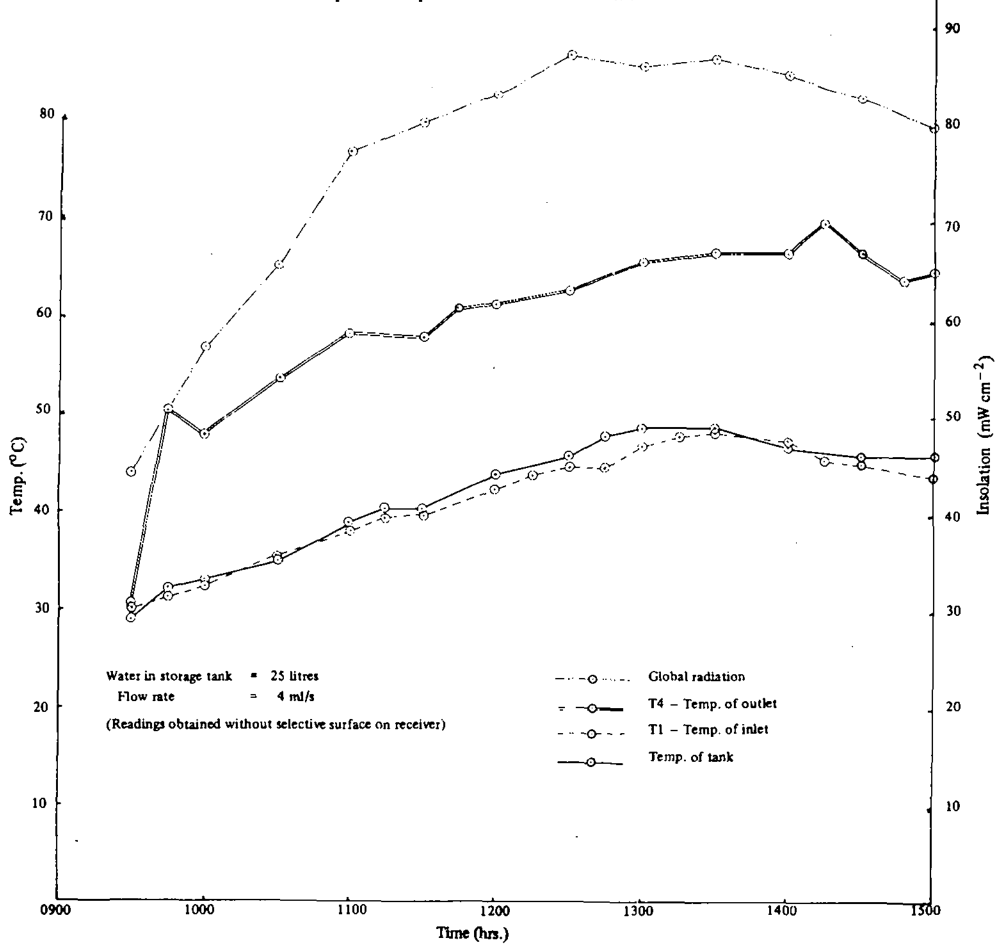
Graph 2. Temp. Rise – Parabolic Solar Concentrator



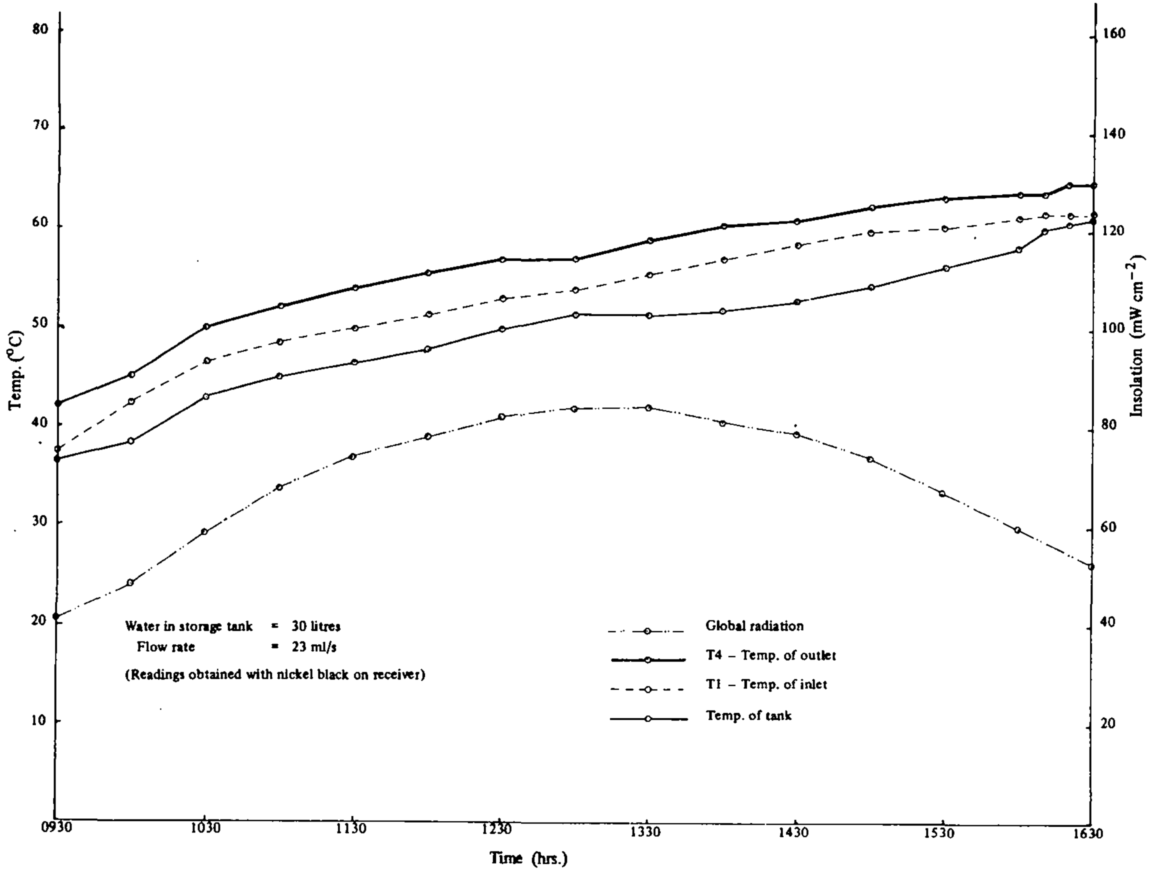
Graph 3. Temp. Rise – Parabolic Solar Concentrator



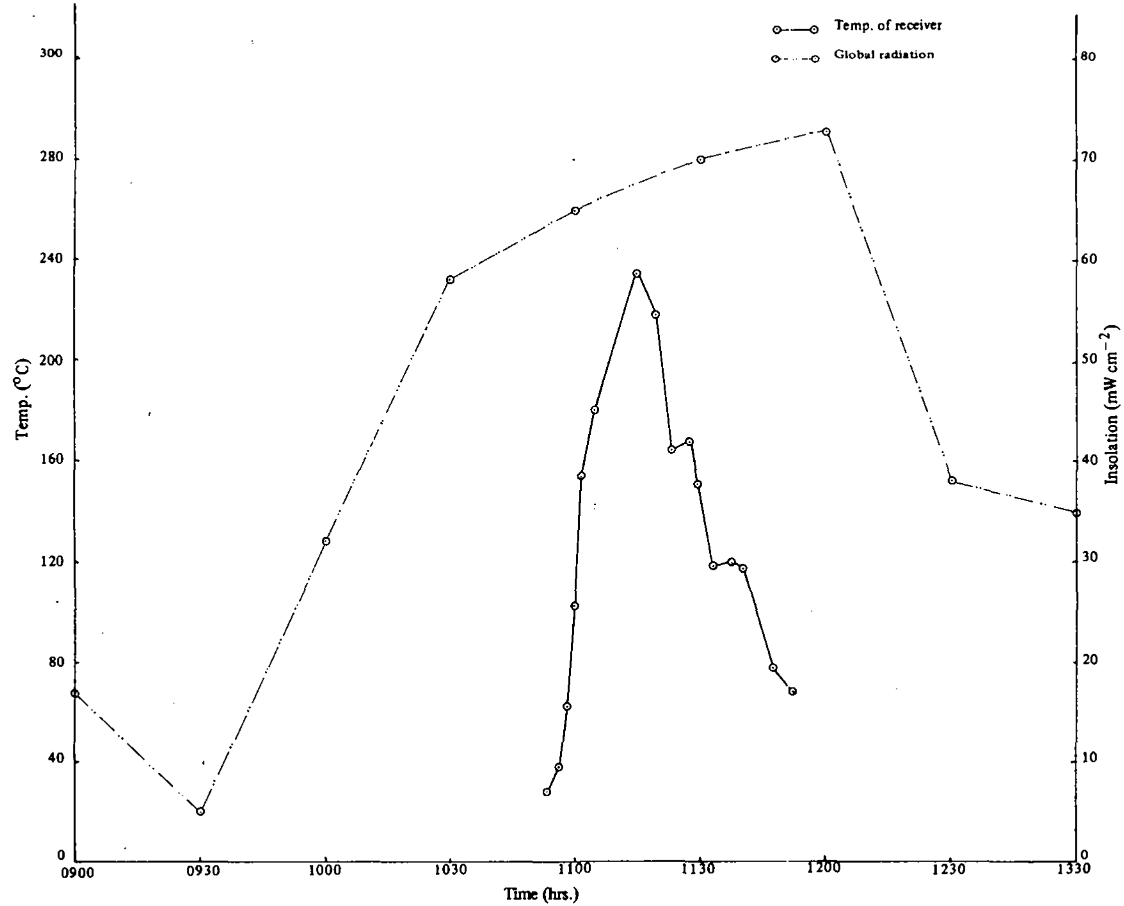
Graph 4. Temp. -- Parabolic Solar Concentrator



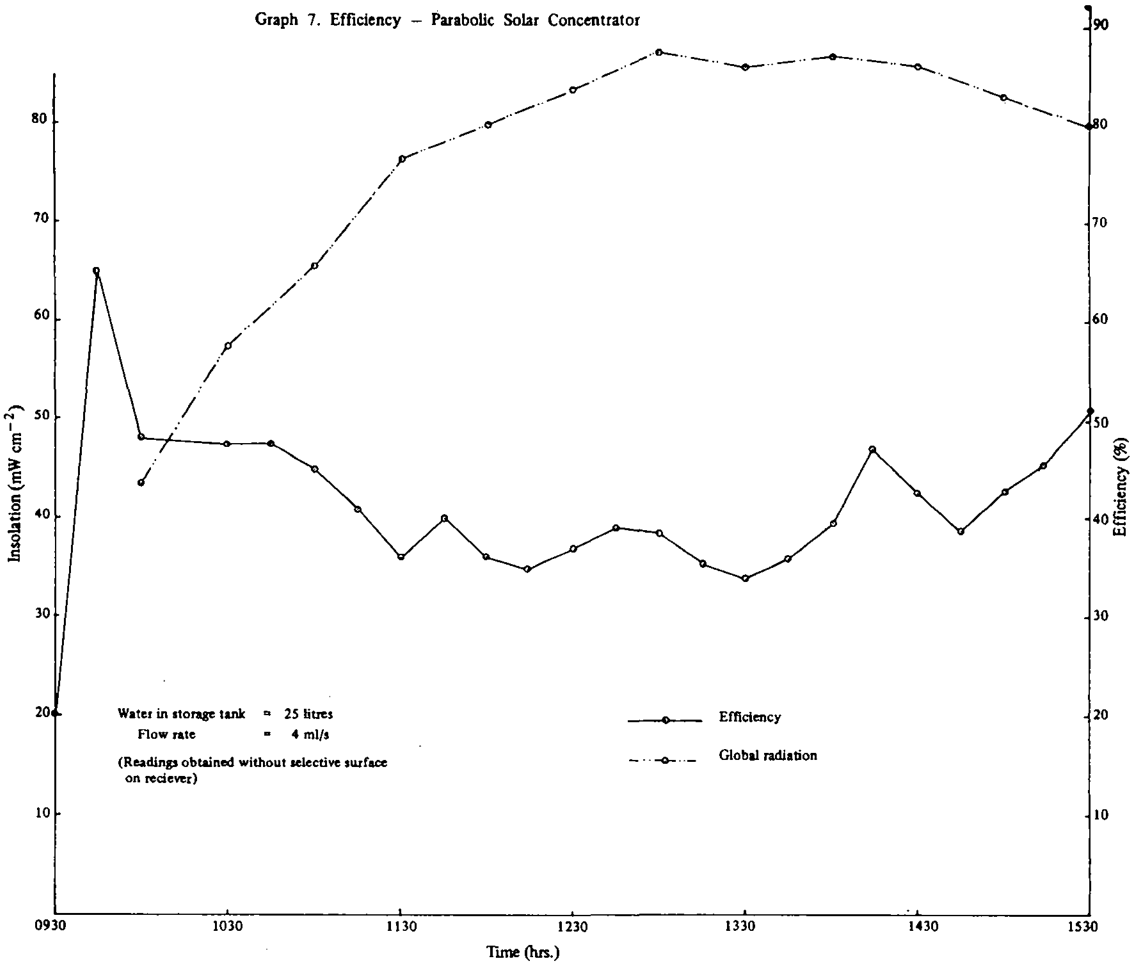
Graph 5. Temp. – Parabolic Solar Concentrator



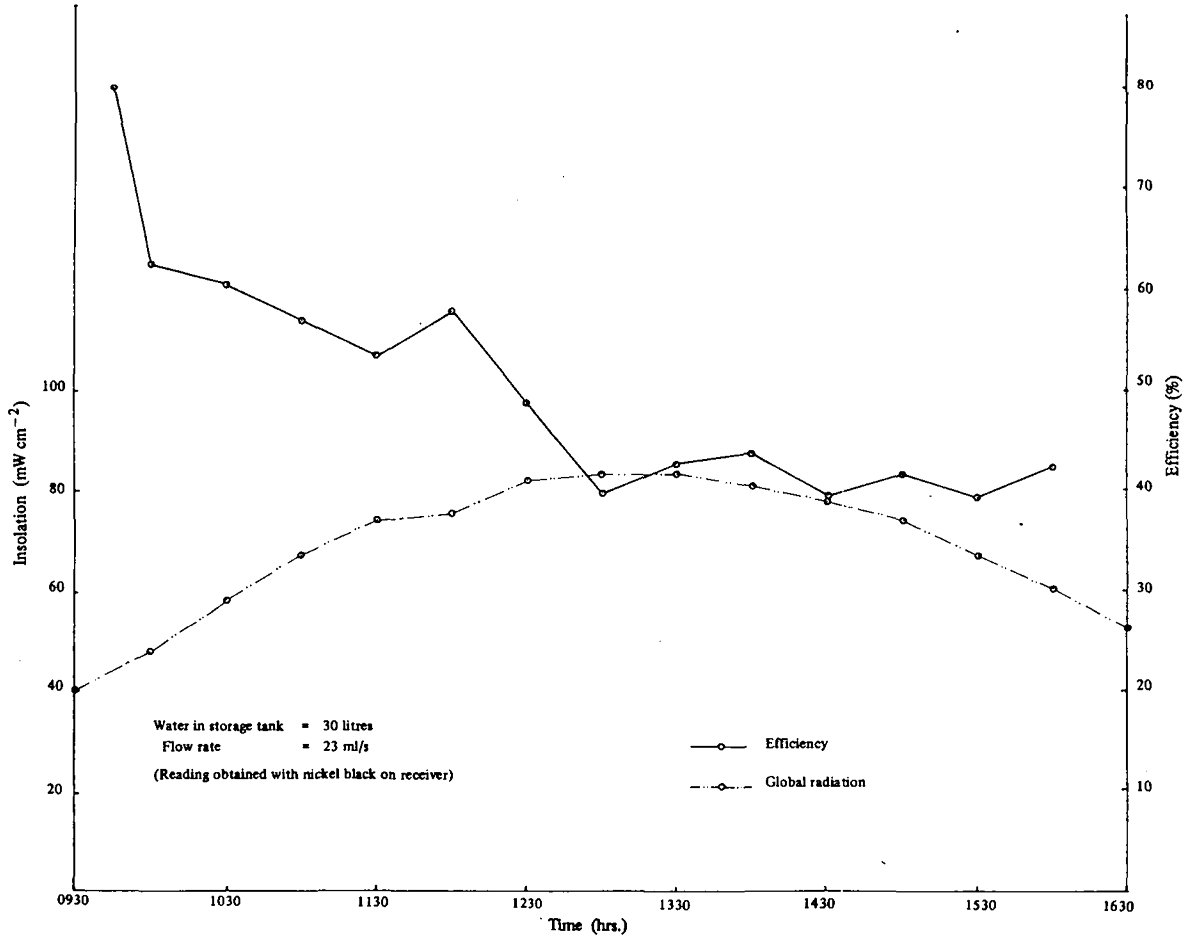
Graph 6. Temp. at Receiver – Parabolic Solar Concentrator



Graph 7. Efficiency – Parabolic Solar Concentrator



Graph 8. Efficiency – Parabolic Solar Concentrator



DEVELOPMENT AND COMMERCIALIZATION OF SOLAR WATER HEATERS

by

GYANI R. SHAKYA and ANDREAS BACHMANN

Nepal is a mountainous country lying between latitudes 26° 20′ and 30° 16′ N and longitudes 80° 15′ and 88° 15′ E. It has enormous potential for hydro-power generation. But due to the giantic investments involved and the long period of completion the country has not yet developed this natural resource to the full. At present the major part of Nepal's energy comes from firewood, vegetable waste and animal manure. And there is no doubt that one of the country's greatest problems – aggravated by the ever increasing population- is deforestation.

Nepal has summer rain and winter sun; the average insolation being between 400 and 600 ly/day. Therefore a lot of solar energy is available for use in the fields of heating and cooling, the drying of agricultural products, photovoltaics and many other applications.

Solar Water Heaters are well accepted as a commercial item nowadays here in Nepal. The first such device produced in this country was made by Fr. B.R. Saubolle of St. Xavier's School in 1967. This was a very successful prototype, which has been working satisfactorily ever since. After that, one or two private parties in Kathmandu tries to make them, but could not popularize them or produce them on a commercial scale. Besides that, a few imports were made from foreign countries like Japan and Israel. In 1974, just after the energy crisis became a crippling fact, the Balaju Yantra Shala- Plumbing Division (at present BYS Sanitary Engineering Ltd.) made one of its first solar water heaters. Since the first successful big installation at Budhanilkantha Boarding School, the development and production of these heaters have continuously advanced.

From the very beginning a modular concept of production was considered, and great care was taken that customers be fully satisfied with the products. Such a modular concept ensures simpler, faster and more accurate and more economical production, and makes maintenance much easier. The solar water heaters produced by BYS Sanitary Engineering Ltd. are of two different systems:

(a) Flat Tank System in which the heating and the storage of hot water are both in the same unit. There is no separate insulated hot water storage tank.

(b) Circulation System in which the insulated hot water storage tank is separate from the collector. With this system a thermostat-controlled electric heating coil can be incorporated as an accessory.

Table 1 shows the standard modular products of this firm. Normally a circulation system of 120-liter storage capacity is supplied with one collector, and a 200-liter size with two collectors. These units may be coupled together or added to as the need for hot water increases. Actually the project should be well studied before deciding on which system to install. If hot water is required only during the daytime or just after sundown, the Flat Tank would be quite satisfactory; but if it is needed in the early morning, then the circulation system with separate insulated storage tank is recommended.

BYS solar water heaters are made for non-freezing areas. Normally the circulation takes place by the gentle natural flow of a convection current without there being any need for a pump. The temperature attained is usually around 60 Centigrades while in constant use, with both systems. The maximum temperature recorded in Kathmandu, again for both systems, is 72 Centigrades.

Fig. No. 1 is a circulation system of 120-liter capacity. Fig. No. 2 shows the relation of hot water temperature in $^{\circ}C$ to the consumption of hot water in liters for a 60-liter Flat Tank unit. On the average about 4000 kcal of heat energy per square meter of collector area is stored per day.

All the materials used for the production of solar water heaters are quite easily available in the local market. Most of the materials are usually in stock. The materials used are:

- Galvanized iron pipes of 1/2", (3/4") and 1" O
- Aluminium sheet 26 G
- G.I. sheet 24 G
- M.S. sheet 2 mm and 4 mm thick
- M.S. plate 10 mm or 12 mm thick (flanges)
- gate valve, safety valve, check valve
  g.i. wire, black paint, anti-corrosive paint, rubber profile, window glass 4 mm, fibre glass insulation, and some other small items.

Production is carried out with simple workshop machines and tools. Of course much depends on the scale and manner of production. The main items are:

- welding machine
- drilling machine
- thread cutting machine
- shearing machine

- folding machine
- pressure testing device
- some special hand tools for sheet metal work
  grinding machine, and other standard simple workshop tools.

Production can also be undertaken without the complete list of tools mentioned above.

The production staff should, at the very beginning, be given preliminary training in solar water heater systems and pipe work. Proper supervision is always essential during the production and installation of solar water heaters. For the production of 60 to 90 units per month, the following approximate numbers of skilled and semi-skilled workers would be necessary: This list of manpower is adequate for the complete production of the units. However it does not include higher technical and administrative staffs. BYS has laid strong emphasis on the quality of its products rather than on quantity.

List of necessary numbers of skilled and semi-skilled workers, approximate:

1.	– Supervisor	1
2.	– Welder	2
3.	– Sheet metal worker	2
4.	– Plumber, fitter	4
5.	– Semi-skilled plumber	6
6.	– Semi-skilled mechanic	3
7.	– Helper	4

Almost all the solar units installed over the past years are still working well. Careful and constant supervision during production is essential, as is also the use of proper and easily available materials. Sophisticated technique has been avoided, to improve quality, and only simple technique has been adopted.

A few points, important for the control of quality, are listed below:

- pressure testing of welded joints,
- proper cleaning prior to painting with anti-corrosive paint,
- proper water sealing,
- good contact of aluminium absorber plate with pipe grid,
- proper connection of collectors with hot water storage tank,

- proper slope gradient of connecting pipes (to avoid air pockets and ensure easy natural circulation flow),
- proper distance of glass from absorber surface,
- proper insulation,
- proper height difference between top collector and bottom of hot water storage tank.

The installation of a solar water heater is every bit as important as its manufacture. This is especially true with the circulation system: any small mistake might render the complete system unworkable. Some points which have to be thoroughly checked are: angle and facing of the collectors, proper height difference between cold water tank (supply system) hot water storage tank and collector, water pressure, fixing of check valve, flow-speed-control valve, safety valve or vent.-pipe, etc. It is by far the best to have the manufacturer do the installation, because he knows all the little points that need special attention. If well trained plumbers with good basic knowledge of solar water heaters are not employed, even the best produced solar units may not work properly!

At present more than 50,000 liters of hot water are being produced daily with solar energy here in Nepal. The cost of a complete solar water heater of 120-liter capacity is about twice the cost of a 50-liter electric heater. The investment for the solar heater system is paid off in appr. two years with the savings in the running cost of electricity, if the cost of the electric heater is deducted from the total investment. The demand for solar water heaters is steadily increasing, and duplication has already successfully started. The future for the market in such heaters is bright. So far heaters have been installed mainly in schools, residential buildings, laboratories, staff quarters, hostels and lodges. And householders in the hills have started to purchase such units here in Kathmandu.

Small scale production could be started in any developing country with a few skilled workers, some standard workshop tools and machines, and a group of trained plumbers for installation. The use of solar water heating systems could be greatly promoted with some facilities in tax laws, government preference for government buildings and government complexes, and with the exemption or reduction of sales tax and other taxes.

We consider the installation of these solar water heaters to be a vital combination of production, successful introduction and application.

INFORMATION AVAILABLE:

- SOLAR WATER HEATERS IN NEPAL, Vol. I: BASIC INFORMATION
- SOLAR WATER HEATERS IN NEPAL, Vol. II: INSTALLATION MANUAL

- DRINKING WATER INSTALLATION AND DRAINAGE REQUIREMENTS IN BUILDINGS IN NEPAL

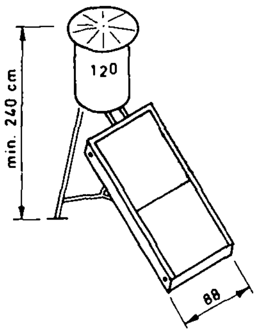
  from: Swiss Association for Technical Assistance, P.O. Box 113, Kathmandu/NEPAL

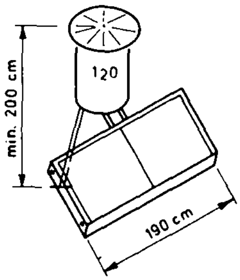
- MINI TECHNOLOGY, FUEL GAS FROM COWDUNG, etc.
  by B.R. Saubolle and A. Bachmann

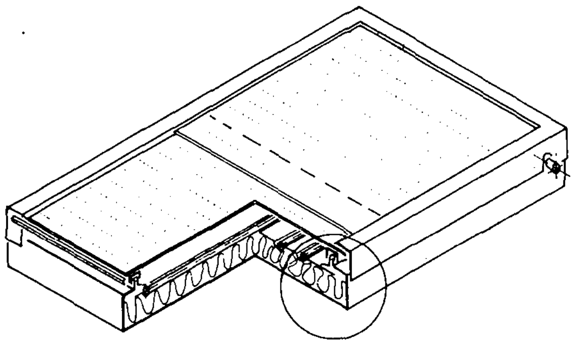
  from: UNICEF, P.O. Box 1187, Kathmandu/NEPAL

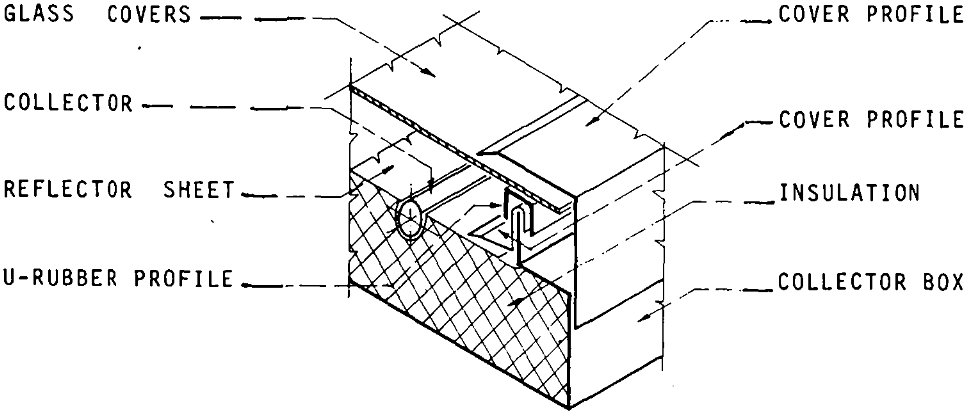
- PUBLICATIONS LIST, Small Scale Renewable Energy Resources and Locally Feasible Technology in Nepal

  from: Sahayogi Press, Tripureshwor, Kathmandu/NEPAL


min. 240 cm
120
88


min. 200 cm
120
190 cm




GLASS COVERS
COLLECTOR
REFLECTOR SHEET
U-RUBBER PROFILE
COVER PROFILE
COVER PROFILE
INSULATION
COLLECTOR BOX

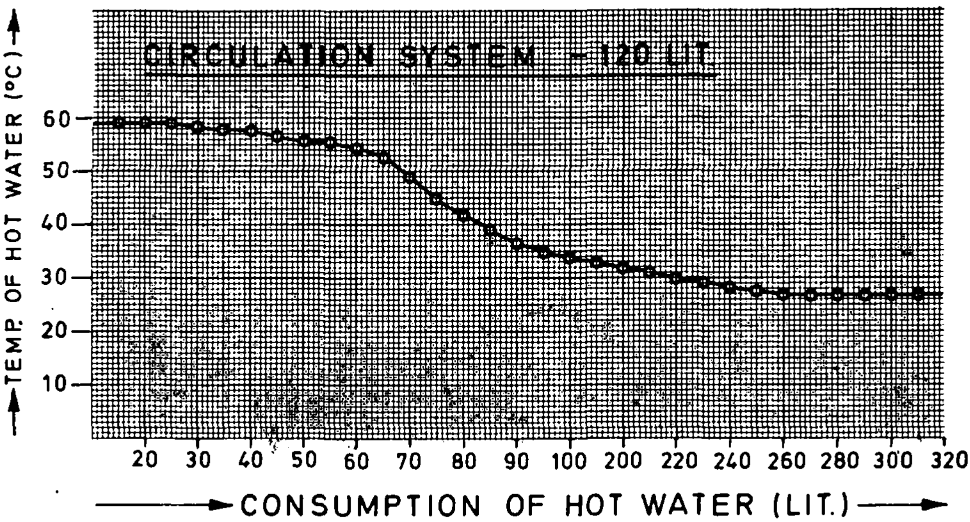


FIG. 1 RELATION OF TEMPERATURE OF HOT WATER (°C) WITH CONSUMPTION OF HOT WATER (LIT.)

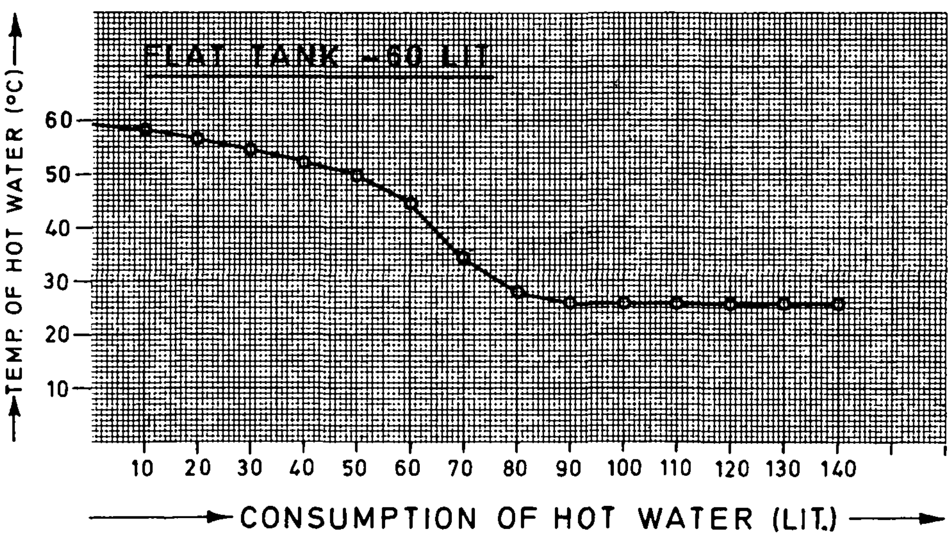
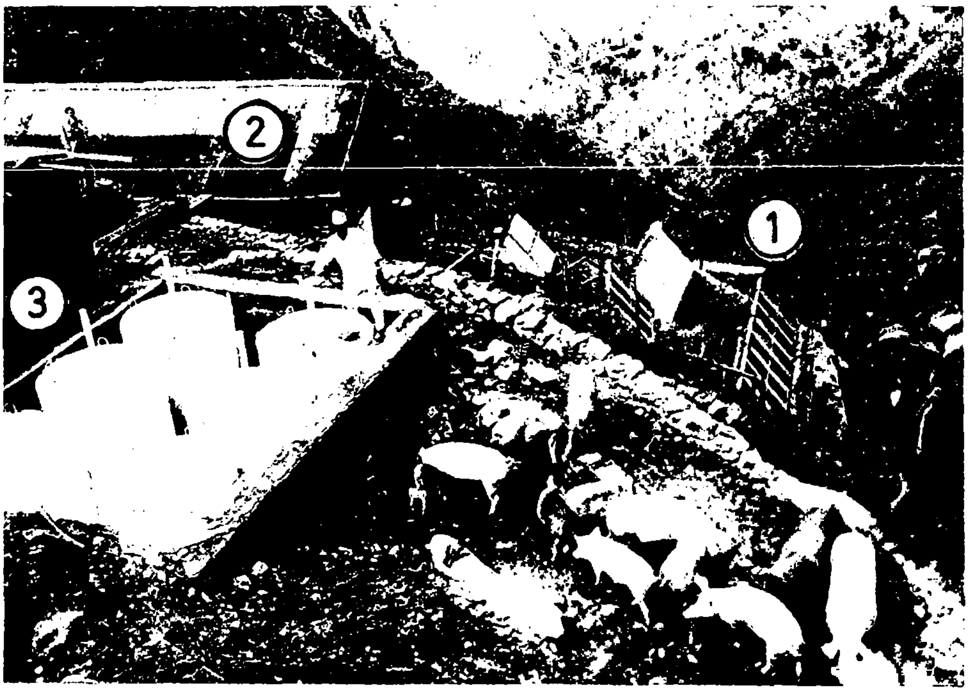


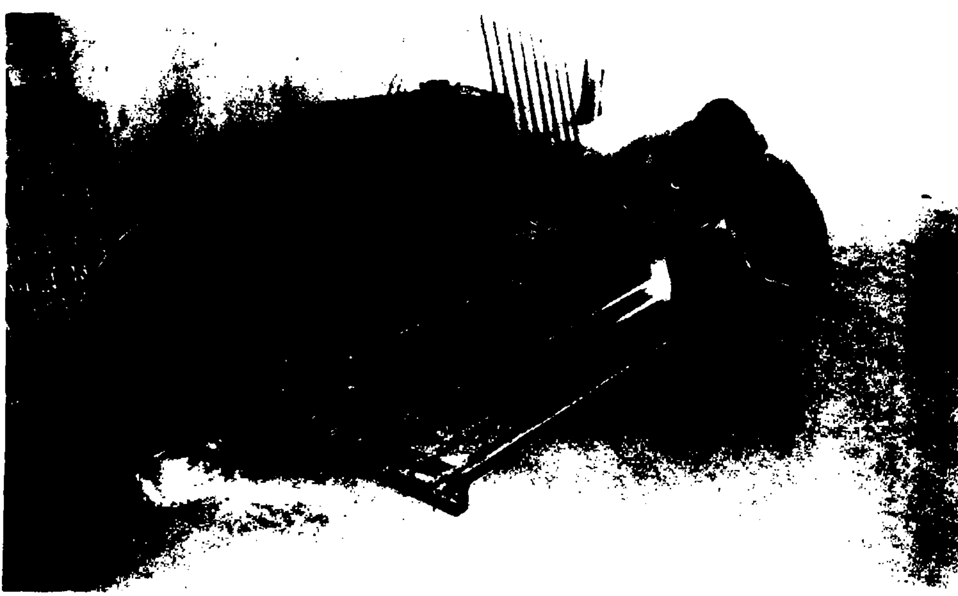
FIG. 2 RELATION OF TEMPERATURE OF HOT WATER (°C) WITH CONSUMPTION OF HOT WATER (LIT.)



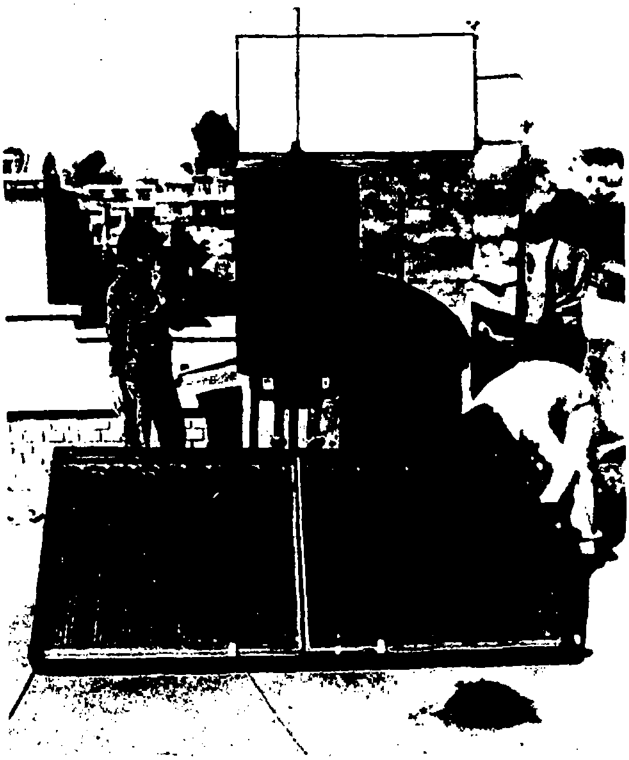
Under construction: Solar heating for biogas plants in colder area, cheese plant in Pauwa, (altitude 1800 mtr.). Biogas is needed for milk processing, whey milk is fed to pigs, dung is used to produce the gas. Solar collectors are heating the insulated house with its three biogas pits.

1 - Solar Collectors
2 - Biogas house, insulated, solar heated
3 - Gas storage tanks

Fixing of glasses can be done with easily removeable cover frames.



Simple workshop facilities will do, moulds for framing of the pipe grid will help.



Circulation System, with a hot-water storage capacity of 120 ltr.

Roof-integrated system (left) and an old system at the right, circulation system at Tiger Tops.

Flat Tank System at Godavari School/Kathmandu-Valley
4 pieces at 140 liters

SOLAR CORN DRYER
(250 BUSHEL CAPACITY)

by

I.H. SHAH and AHMAD MURTAZA

ABSTRACT

A good portion of cereal grains is lost due to birds and rodents while it is being dried in the sun exposed to the environment. Another big part is wasted in the storage because of improper moisture content. These two phenomena are responsible for about 40% loss of the much needed food commodity. If the drying is done in a controlled way these losses can be minimised.

The project design, construction and testing of a solar corn dryer is a step towards this goal. In addition the drying process can be shortened as compared to conventional method of drying. This may allow us the marginal time required for harvesting another crop in between two crops.

Fortunately a significant high potential of solar radiation is available in Pakistan which is lying between latitude 24° N and 36° N. The maximum total daily average solar radiation on a horizontal surface during the month of June is of the order of 27 M joules/ sq. m and to 10 M joules/sq. m in December.

A bin holding 9546 Kilograms (250 bushels) of ear corn was constructed of corrugated galvanised iron sheets. Eight flat plate solar air collector modules have been designed and constructed from locally available materials.

The diffused nature of solar energy precludes the use of high temperature drying. As such a solar dryer based temperature drying has been designed and constructed at the University of Engineering and Technology Peshawar, Pakistan.

The moisture of the corn was reduced to 15.5% based on kernel moisture content (wet basis). This was achieved in 8 to 9 days whereas the conventional method needs 30 to 40 days to dry the ear corn to 20% moisture.

INTRODUCTION

Pretext:

Conservation of energy in the form of fossil fuels (Coal, oil and natural gas) forces those in Pakistan and other less developed countries (LDC's) to think of alternative sources of energy that could be effectively used for day to day as well as long term energy requirements. A similar statement can be made for the more developed countries (MDC's) of the West and also in many LDC's where rapid human population growth is enhancing the pressure on the existing food and energy resources. Under such condition, balancing outputs against inputs is of paramount importance.

Pakistan is basically an agricultural oriented country and a great deal of effort is required to improve the quality and quantity of agricultural products, to conserve the existing produce and to devise methods which could improve its labour oriented technology. Solar energy, an energy source which has been used by man since his existence for his needs, has become an enormously important potential source of energy for our modern society to tap.

The present investigation deals with the design and construction of a solar grain dryer for drying ear corn to obtain a high quality grain, which would be rich in vitamins and nutrients while possessing good colour and texture. A basic criterion is that of reduction in drying time over that currently achieved by conventional method of drying grain on a platform under the direct sun. Grain drying is an energy intensive agricultural operation, increasingly affected by growing fossil fuel shortage. Among the crops requiring drying, corn uses most of the energy. It is harvested with more excess moisture than any other grain crop. It matures in fall and is subjected to extensive field losses if not harvested before winter.

Although crop and grain drying represents one of the oldest uses of solar energy, the proportion of modern solar technology devoted to this application is comparatively small. The crude method of spreading of crops and grains on the ground and drying them in the sun is cheaper as practically no capital outlay for equipment is involved. Considerable labour is required as it needs to be piled up in the afternoon to reduce moisture absorption at night due to respiration of grains at higher relative humidity and front. Further, a high quality product is not often obtained. Today, due to world wide inflation caused by increases in oil prices, labour costs have risen tremendously, even in the LDC's. In the conventional method, overdrying, underdrying, contamination by dirt and insects, damage by granivorous birds and rodents and degradation due to rainfall and hailstorms during long periods of exposure occurs, thereby a considerable portion of the crop is lost.

In view of the increased interest in applications of solar energy and development of other new materials, perhaps greater uses can be made of the sun to hasten agricultural drying and reduce spoiling of agricultural products by control of moisture content which will result in improved quality of the product.

The focus of this investigation is on a method employing solar energy indirectly to heat air and utilize it for drying corn to a safe storage level (i.e. 15.5% moisture wet basis). Any viable method should utilize the locally available resources and technology where ever possible. For this reason a dryer was designed, constructed and studied using locally available materials and the sun which is so abundantly available in Pakistan.

Approximately 18% of harvested corn is lost before reaching storage (Pakistan Agricultural Research Coulcil Report 1976). During 1977-78 about 594 x 10^3 hectares of land was under corn cultivation in Pakistan and a projected yield of 1.71 x 10^6 tons of corn was expected during the fall of 1978. The loss, from harvest to storage, was expected to be about 308 x 10^3 tons, which is worth 4.15 million dollars at the current market price of 13.50 dollars per ton.

It is expected that a reasonable portion of this grain could be saved by mechanical dehydration employing solar heat. This saving will help to increase the total gross national product (GNP) of the country.

Objective Consideration:

Agricultural land holdings in Pakistan are predominatly small, 60% of the holdings are below 4 hectare (small), 31% holdings are 4-20 hectares (medium) and the remaining 9% are over 20 hectares (large). The yield of corn is on the average of 2.87 tonne-hectare, Pakistan Agricultural Research Council Report (1976). Hence relatively a smaller size batch of 65.75 tonnes (250 bushels) has been considered for drying. Besides above facts, the following factors also restricted the size of the batch:

(i) recommendations of Pakistan Agricultural Research Council to fabricate smaller size agricultural produce processing units, so that majority of the farmers possessing small land holdings could be benefited;

(ii) limitations of bank loans to farmers in Pakistan, (about $ 1,500 to $ 2,000 loan can be easily obtained in reltatively short time from agricultural and other banks at comparatively lower rates of interest, usually 6-10 percent);

(iii) an average family of 6 to 8 members would be able to operate and maintain the facility without hiring extra labour;

(iv) recommendations of the Appropriate Technology Cell, Government of Pakistan (1975), attempting to motivate the interest of the average farmer for enhancing the gross national product, wherein smaller agricultural machinery and processing units, which could be maintained and repaired by farmers themselves with minimum of technical skill as well as minimum expenditure, were recommended.

Scope of Present Investigation:

The present study deals with the following specific objectives:

(i) To collect and analyze the solar radiation data for all cities of Pakistan recording solar insolation;

(ii) To design and construct a solar dehydration facility employing locally available materials and technology for drying ear corn;

(iii) To investigate the performance of the dehydration system for drying ear corn in Pakistan particularly at Peshawar (Latitude 34° 00 N, Longitude 71° 31 E, Elevation 359,69 meters).

SOLAR ENERGY POTENTIAL IN PAKISTAN

Since atmospheric conditions are highly unpredictable, even for a few days into the future, it is necessary to rely on the related meteorological data or nearby weather stations and develop the probable solar energy availabilities from these. The determination of solar collector parameters and its optimum orientation are highly dependent on this type of information. Also the thermal performance of any solar system could not be evaluated without necessary solar radiation data for the location where the system would operate.

Solar Radiation Data:

Solar radiation data, for four existing weather stations of Pakistan, namely Karachi, Lahore, Multan and Peshawar, have been obtained from the Pakistan Meteorological Department for a period of about twenty years since 1957. The data provide the monthly averages of daily global solar radiation on horizontal surface.

Figure 1 shows the available solar energy peaks in the month of June. During the May to July period, the difference between the maximum and minimum available solar energy is less than at any other period. The maximum daily average insolatin occurring during June is of the order of 27.00 mega joules per square meter per day. (Mj/m^2 day). A minimum of 10.00 Mj/m^2 day of solar insolation occurs during the month of December and January. The beam and diffuse components of daily total solar radiation for four locations in Pakistan, have been estimated by the method described by Duffie and Beckman (1974).

THEORETICAL ANALYSIS

A solar drying facility essentially consists of a drying bin for deep bed dehydration, solar air heaters, fan and the necessary ducting system (Figures 1 - 4). Theoretical analysis of the system discusses various parameters with regards to the batch size, quantity of water to be evaporatded, heat requirements of the system and computation of the time saved using solar heat based on average meteorological conditions at Peshawar, Pakistan. The solar air collector has also been analyzed to determine its performance.

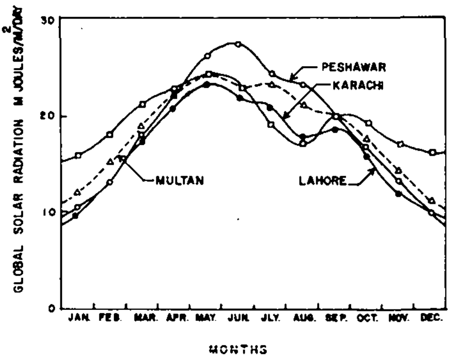


FIGURE I. MONTHLY AVERAGE DAILY GLOBAL SOLAR RADIATION ON HORIZONTAL SURFACE IN PAKISTAN.

Batch Size:

A batch size of 250 bushels of ear corn has been considered for this analysis based on factors described.

Basic Data:

(i)	Hygroscopic material to be dried.	Ear Corn
(ii)	Initial moisture content (kernel).	26.0% (w.b.)
(iii)	Final moisture content of dried product.	15.5% (w.b.)
(iv)	Size of the grain bin	2.28 m x 2.28 m x 3.34 m
(v)	Volumetric capacity of bin.	17.36 m^3
(vi)	Depth of ear corn bed.	3.05 m
(vii)	Volume of ear corn/bushel.	70.79×10^{-3} m^3
(viii)	Quantity of ear corn/batch, considering bin dimensions.	245 bushels.
(ix)	Dry matter in kernel, (15.5% moisture content)	21.45 kg/bushel.
(x)	Dry matter in cobs, (15.5% moisture content).	5.17 kg/bushel.
(xi)	Weight of total dry matter in ear corn at 15.5% moisture content.	26.26 kg/bushel.

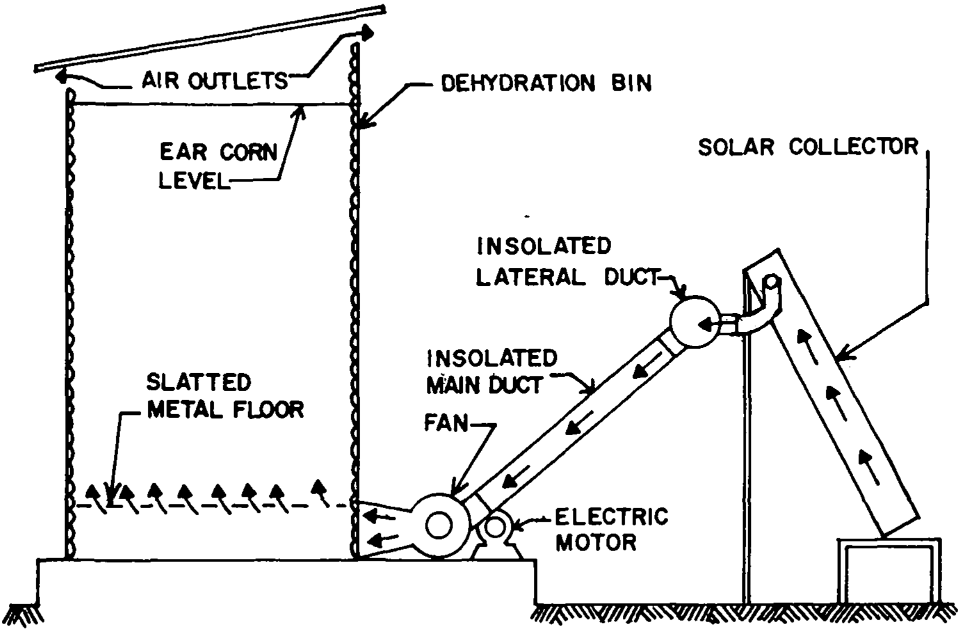


FIGURE 2a: SCHEMATIC OF THE DEHYDRATION SYSTEM

Quantity of Water Evaporated:

Drying 26.0% moisture content wet basis (w.b.) ear corn to 15.5% moisture content (w.b.) requires removal of 7.19 kg of water per bushel, (Harkness, 1961). The total quantity of water to be evaporated is 1763 kg per batch.

Weight of Ear Corn After Reduction in Moisture:

(i)	Weight of ear corn/bushel at 26.0% moisture content (w.b.)	39 kg/bu
(ii)	Total weight of ear corn/batch.	9546 kg.
(iii)	Weight of ear corn after reduction in moisture content from 26.0% to 15.5% (w.b.)/batch.	7783 kg.

FIGURE 2b: ARRANGEMENT DUCTING SYSTEM

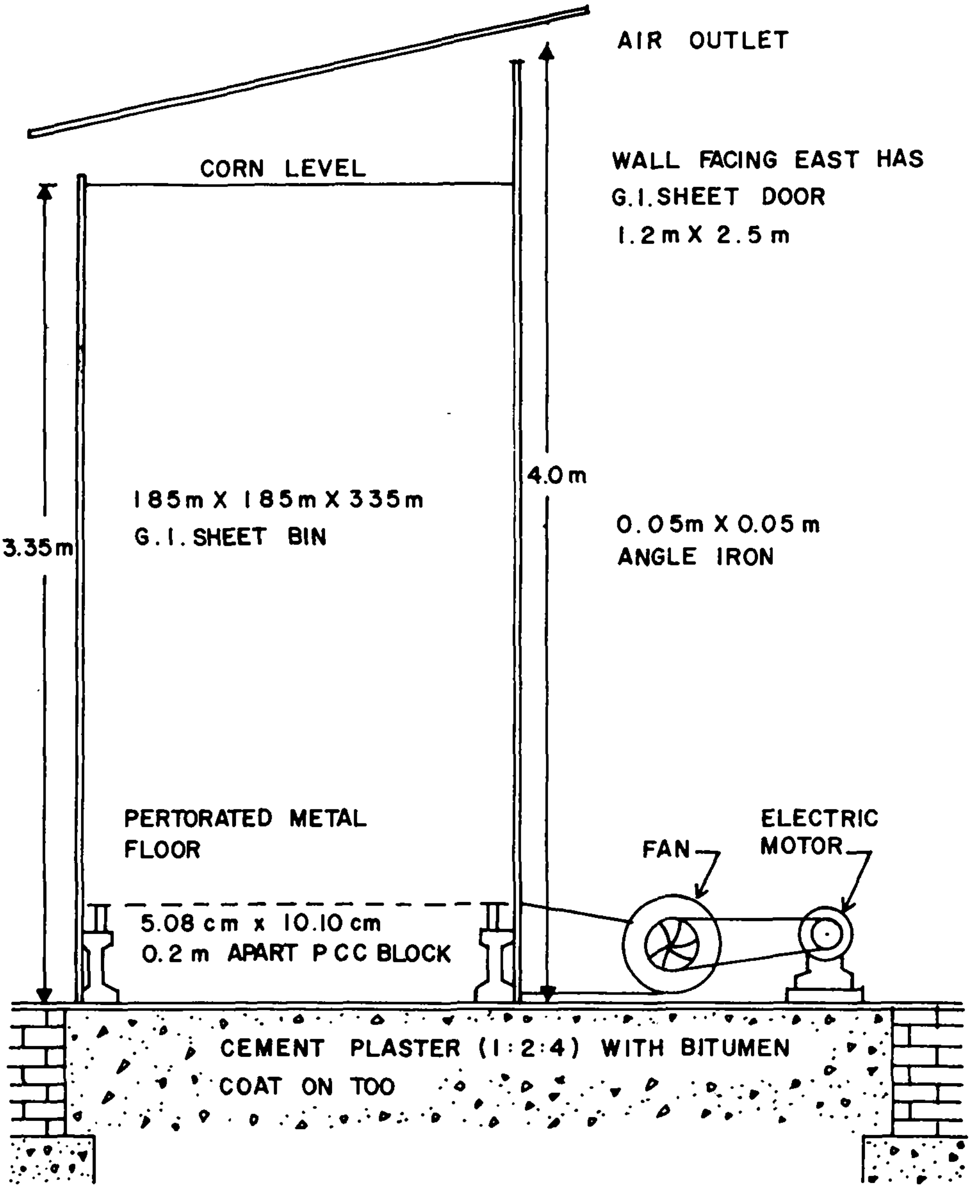


FIGURE 3. SCHEMATIC OF THE BIN

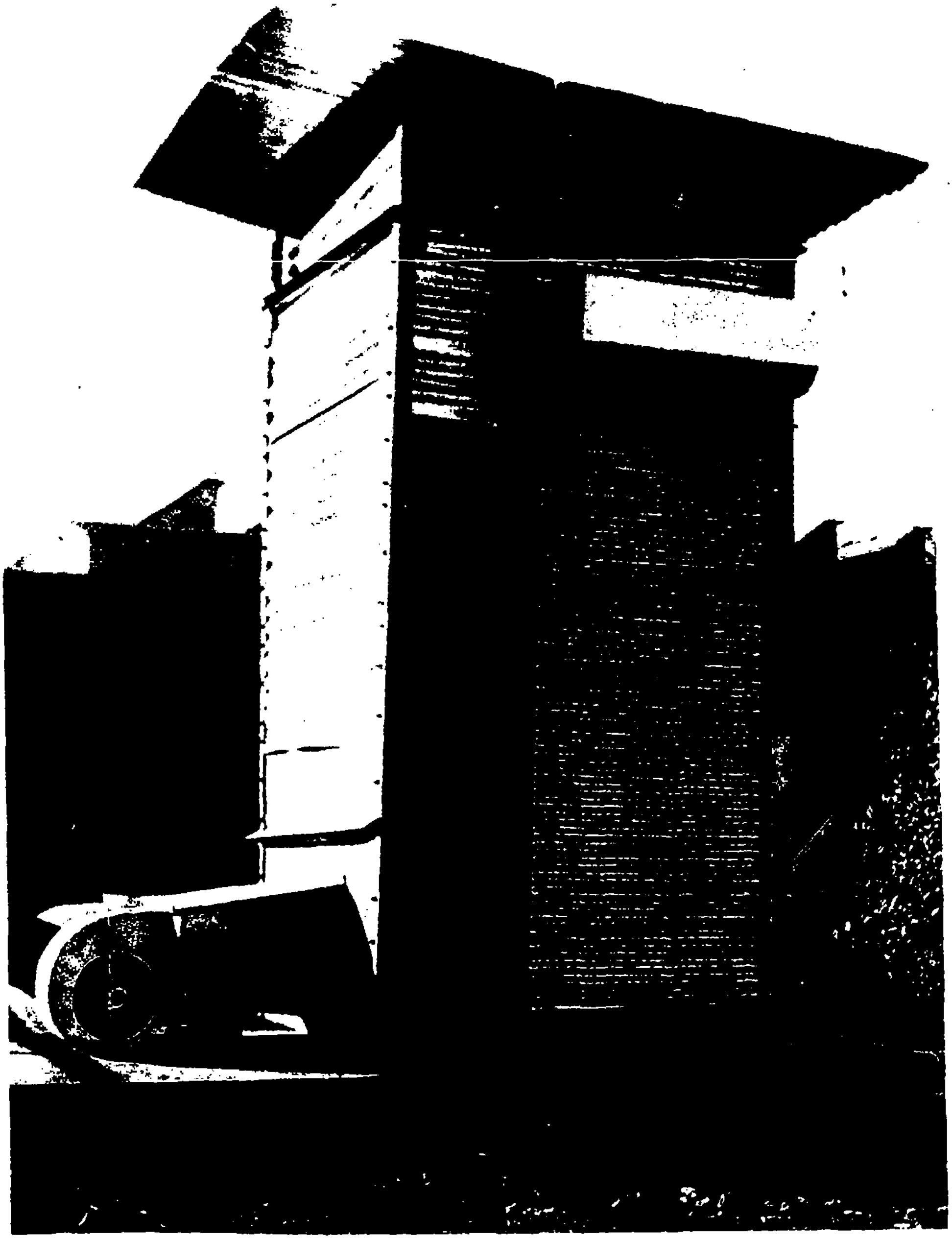


FIGURE 4. THE GRAIN BIN FOR DRYING EAR CORN

Heat Requirements for Moisture Evaporation:

The actual temperature of the product during drying lies above the wet-bulb temperature and approaches the dew point temperature as drying progresses and the rate of evaporation decreases. It is conservatively assumed in the calculations that the product becomes heated to the dry bulb temperature at the entrance to the grain bin. Generally in Pakistan a portion of the corn being dried is used for seed. Therefore the maximum allowable temperature of drying air should not exceed 43.3°C as the germination of most of the corn is severely reduced beyond this temperature, (Hukill, 1947).

As a general rule, the more rapidly the material is dried the better the quality of the product obtained, provided the drying temperature used have not caused any injury like scorching, case hardening etc. The latent heat at drying temperatures may be taken as 2.44 mega joules per kilogram of water evaporated from grains (Hall, 1961).

Heat requirements for moisture evaporation are calculated for average conditions of air during the month of October of Peshawar. The average dry-bulb temperature of air during this month is 21°C and the average relative humidity is about 40%. The temperature of hot air available from the collectors is considered to be 35°C.

Solar Air Collector Analysis:

The type of collector considered for this analysis is a single pass, single glazed, flat-plate solar air collector with an absorber plate of corrugated galvanized iron sheet, coated with black paint. The collector will heat air passing below the absorber plate as shown in the Figures 5 - 8. This collector design is selected keeping in view the problems of rough handling.

(i) *Cover System:*

Single glass cover (low quality);

Size: 1.824 m x 0.912 m and 0.50 cm thick;

emittance, E = 0.8;

Extinction coefficient, K = 0.26/cm.

(ii) *Absorber Plate:*

Corrugated galvanised iron sheet, painted black;

Size: 26 gauge, 1.77 m x 0.90 m;

absorptance, a = 0.9;

emittance, E_p = 0.9;

(iii) *Insulation:*

Locally available loose cotton;

COMPONENT	DIMENSIONS	MATERIAL
COVER	1.84 m x 0.91 m	SINGLE GLASS
ABSORBER	1.77 m x 0.9 m	G.I. SHEETS
FRAME	1.86 m x 0.96 m	WOOD

SCALE 1 cm = 8 cm

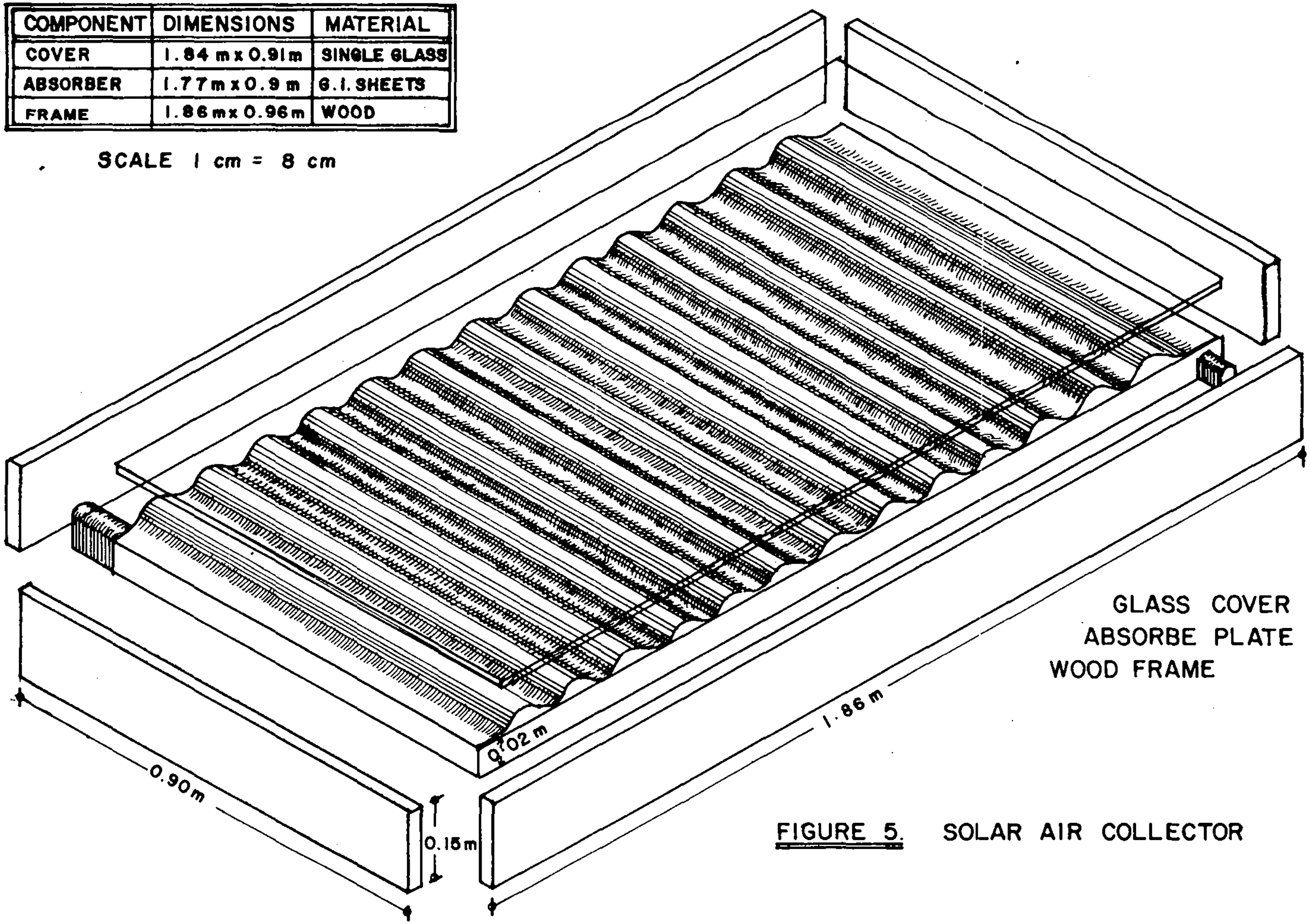


FIGURE 5. SOLAR AIR COLLECTOR

FIGURE 6. THE ABSORBER PLATE

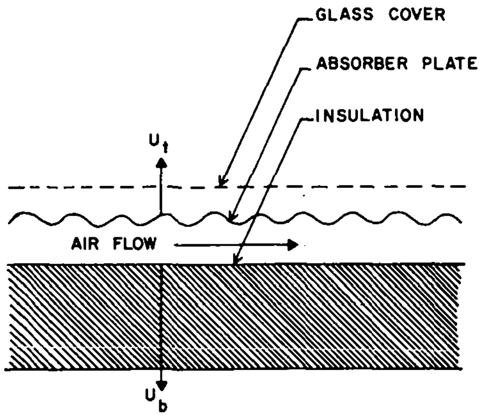


FIGURE 7. LONGITUDINAL CROSS-SECTION OF SOLAR AIR COLLECTOR

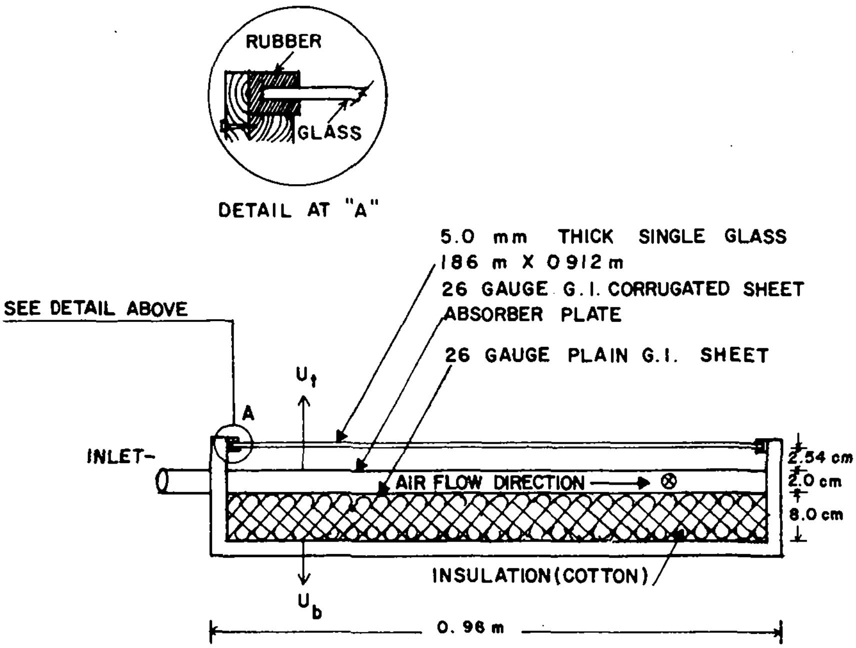


FIGURE 8. SECTION VIEW OF SOLAR AIR COLLECTOR.

insulation thickness at the back of absorber-plate = 0.08 m;

insulation thickness around the perimeter of the absorber-plate = 0.03m;

thermal conductivity, k = 0.06125 W/m°C.

(iv) *Collector Geometry:*

Gross collector dimensions = 1.86 m x 0.96 m x 0.15 m;

Effective collector area = 1.65 m^2.

DISCUSSION OF RESULTS

Out-door tests performed on the single glazed, single pass, flat-plate, solar air collectors prior to their installation in the drying system, revealed that the instantaneous efficiency of the collectors was around 41% during the month of October at Peshawar for an air mass flow rate of 100 kg/hr m^2. It was observed that the instantaneous efficiency of the collectors determined during tests was 18% lower than the theroretical value. The reason may be that a significant part of the energy entering the collector is not available as useful energy, specifically during the morning and evening hours and on partly cloudy days. The part of solar energy during these periods is not sufficient to overcome the losses from the collector. The lower collector efficiency may be a result of the hand tailored design and fabrication of the solar collectors which was the only alternative in Pakistan at the present time.

The test data of the average moisture content of ear corn during the first three days has shown a higher rate of moisture evaporation as compared to the later period which is in accordance with the drying theory (Tables 1 and 2). The rate of moisture evaporation decreases in the later period of drying because diffusion of moisture from the kernels become slower due to relatively lesser moisture content and hardening of the grain crust during drying. Also the result of night drying revealed that during first half of the night the rate of moisture evaporation was higher as compared to the later half. This may be due to the amount of heat stored in the grains during the day time which increases the rate of moisture evaporation during the first part of the night.

Both the drying tests show that the drying time for a single batch of ear corn is about 192 hours where as the theoretical analysis indicate about 73 hours to dry a single batch. The possible factors, besides collector efficiency which may be responsible for a longer drying period, are a lower dry-bulb temperature and a higher relative humidity during the night hours. The average relative humidity at night was about 55% during the first test run. Besides this the drying time of 192 hours using solar dryer was still much shorter then 30 to 40 days required by conventional method of drying.

The values of the average moisture content of ear corn at various depth intervals in the bin, which were observed on October 24, 1978, revealed that the average moisture content was 15.0 - 15.5 percent at the bottom and around 17.0% near the top of the bin. The higher average moisture content of ear corn near the top of the bin may be due to

Table 1: Experimental Values of Average Moisture Content % (Wet basis) of Ear Corn Drying with Solar Heat

Drying Time accumulated Hours	*Average Moisture Content % (Wet basis)*	
	Test Run-1, started October 4, 1978	*Test Run-2, started October 16, 1978*
0	26.40	27.50
6	25.30	26.80
12	24.50	26.10
18	23.50	25.50
24	23.20	25.20
30	22.30	24.50
36	21.60	23.80
42	21.50	–
48	21.20	23.00
54	20.50	22.40
60	19.90	21.90
66	–	–
72	19.00	21.50
78	18.00	20.60
84	17.60	20.10
90	–	–
96	17.20	19.50
102	16.70	19.10
108	16.40	18.60
114	–	–
120	16.00	18.30
126	15.70	18.20
132	15.60	18.10
138	–	–
144	15.50	18.00
150	15.40	17.90
156	15.10	17.50
162	–	–
168	15.10	17.00
174	14.90	16.70
180	–	16.30
186	–	–
192	–	16.10
198	–	15.40
204	–	15.50
210	–	–
216	–	15.00

Table 2: Average Condition of air and Experimental data

No.	*Observations*	*Test Run-1*	*Test Run-2*
1.	Average Dry-bulb temperature of ambient air, (^{o}C).	22.0	21.1
2.	Average Relative Huminity of ambient air, (%).	50.0	52.0
3.	Average initial moisture content of ear corn, % (wet basis).	26.4	27.5
4.	Average final moisture content of ear corn, % (wet basis).	15.5	15.5
5.	Average Dry-bulb temperature of hot air, (^{o}C).	43.0	41.5
6.	Average Relative Humanity of hot air (%).	15.0	14.00
7.	Total drying time (Hours).	204	216

the lower moisture carrying capacity of air passing through the top portion when it passes through the lower portion of the ear corn bed, in the grain bin.

ECONOMIC DETAILS

Capital Cost:

The evaluation of the dryer for drying capacity of 250 bushels of ear corn constructed at Peshawar, Pakistan, showed a total capital cost of Rs. 20,000.00. The break up of the total capital is given as under:

Cost of Materials:

Item	*Unit Cost Rs.*	*Total Cost Rs.*
Solar collector	303.00/m^2	8,000.00
Grain bin	4,000.00	4,000.00
Fan	3,500.00	3,500.00
Electric motor, 1.5 hp	1,500.00	1,500.00
Ducts and insulation	–	1,000.00
Total labour cost	6.00/(unskilled man hour. 12.00/skilled man hour).	2,000.00
Total capital cost		20,000.00

Operating Cost:

The operating cost consists principally of the cost of electrical energy, needed for fan operation and the cost of annual maintenance and repairs of the dryer. The labour costs on loading, unloading and cleaning the grain bin are not considered in the operating costs because these costs are the same as those for drying in the conventional way. Therefore the operating costs are the following:

(i) The electrical energy required for fan motor, to dry a single batch of ear corn including cooling the grain, is 230 kWh whereas the electricity is charged at Rs. 0.30 per kWh according to the present rates in Pakistan (prices as of 1978-79). It is estimated that at least seven batches of ear corn can be conveniently dried during the two and half months of the fall season each year. Therefore the cost of electrical energy consumed per year is Rs. 483.00.

(ii) The cost of annual maintenance and repairs of the dryer are small. Principally this cost consists of the replacement of broken glass and occasional cleaning of the covers of solar air collectors. Further, this cost includes the expenditure involved in controlling the leakage of air at the collector joints, duct joints and the bin walls. The expected annual cost of maintenance and repairs is about 4% of the units total capital cost.

Life of the Dryer:

The stimated life of the dryer is about 8-10 years. This figure is based on the life of various materials used in the construction of the solar air collectors, however the life of fan, ducts and the grain bin is 20-30 years. The annual interest rate on the capital investments in Pakistan is 10% (Pakistan Planning Commission 1978), which could be considered for estimating the return on the dryer.

RECOMMENDATIONS

The facility in the present form for drying can be used for 3½ months per year during the fall season. Since the equipment is capital intensive, from point of view of an average Agriculturist in the developing countries, the investment can only be justified if the equipment can be used for dehydration year round for other major crops, vegetables and fruits. This will necessitate incorporating minor adjustments. If use of the facility is year round it will not only provide a job for a person without land holding, but will also result in intensive savings of food commodities.

The study revealed that the installation should remain in a central location and the crops: cereal, vegetables etc. have to be transported to the installation. The extra labour in transportation will out-weigh the labour in the conventional method of drying.

Availability of the electricity for the fan will pose a problem to locations where it is not available. Further work is needed to devise a chimney or a small horsepower engine (used in spray machines) to replace the electric motor as a primover.

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SOLAR ENERGY UTILIZATION AND MANAGEMENT

by

L.G. TANSINSIN

INTRODUCTION

The Philippines is one of the many countries that is largely dependent on concentrated stock to run its vital industries and transport facilities. In reality, oil is the lifeblood of the country. Without it almost all of the nation's development and economic activities would come to a standstill which could eventually cripple, if not totally incapacititate the economy. Fossil oil has proven to be versatile, all purpose commodity with higher valued competing uses, and that there is hardly any economic sector that does not utilize petroleum or its product in one way or another. The very nature of the industrial system (which is one of the primary sectors considered as a major growth source) and the continuing thrust towards industrial sophistication requires indispensable use and further processing of oil due to the oil bias of most machines and equipment.

The Philippines alone consumed 91.9 MBOE in 1979 and is projected to double in 10 years time (184.62 in 1989). Of this amount, oil constituted 84.9 MBOE, 74.9% of which were imported, representing 27.7% of the total import bill for that year. This amount of energy was consumed by the following users:

Table I
Sectoral Energy Consumption
(In Million Barrels of Oil-equivalent)
1978

	MBOE	*%*
Transportation	32.80	35.7
Industry	39.33	42.8
Commercial	2.65	3.1
Residential	7.71	8.4
Others	9.21	10.0
Total	91.9	100

Source: Ministry of Energy – Ten Year Energy Programme, 1980, 1989.

It was noted that a considerable amount of the energy consumed by the industry sector is used essentially for heating (water, air, or oil). This heating requirement could be done solely or partially, simply by harnessing solar energy from the sun. This source is unexhaustible, abundant and pollution free. It is also free from monopoly and the supply of energy is indefinite. Proper utilization of this natural heat will help dampon the spiralling growth of consumption of fossil fuels. The fact that the nation is almost totally dependent on oil (92.8% of total energy mix in 1979) is not the only problem. This is further complicated by the uncontrolled spiralling of oil prices and the increasing anxiety over supply availability.

In response to this stark reality, a National Energy Plan was formulated way back in 1974, and revised in 1980 for 10 years; but recently reduced to 5 years, to cope up with the impending energy crisis which was building up due to increasing prices and the uncertainty of world oil supply. In this plan, the search for non-conventional sources of energy was emphasized. In fact, prior to the energy plan, the National Science Development Board started a crash programme on energy in 1970 from all sources: conventional and non-conventional. Some of the research results are now the basis of those being implemented by the Ministry of Energy, like the biogas, solar, wind, ocean waves and others.

Earlier, in 1962 the geothermal R & D was started and was proven to be a potential source of energy, however, due to the low cost of fossil oil this was not commercially developed until 1972.

As a result of this, direct solar energy utilization alone is expected to displace 1.1 thousand barrels-of-oil equivalent in 1980. This is projected to increase to 27.9 thousand barrels-of-oil equivalent by 1989. (see appendix A)

UTILIZATION

The sun is the unlimited source of all energy on earth whether as stored or concentrated stock in the form of fossilized fuel, as water power, as nuclear energy and as diffused direct or diffused solar energy.

In general, application of solar energy requires the establishment of scientific feasibilities to fully appreciate the potentials of the new source of energy. The major problem in such application area is to develop systems that are economically competitive with conventional energy sources. To accomplish this, it will require innovative engineering as well as new and improved approaches to collection and conversion of solar radiation and its energy storage and transport also a new system approaches and perhaps most importantly, investigation of new and inexpensive materials to improve system performance, reliability and economic attractiveness. Important problems must also be solved dealing with social, legal and even environmental issues which are identified with widespread implementation of solar energy systems.

Among the non-oil resources, solar energy stands out because it is free and inexhaustible, consequently making it an attractive source of motive power for various uses. Furthermore, solar energy has added advantage of having no critical mass, not being a health hazard, and non-pollutant. Also, the Philippines which is a tropical country receives a substantial amount of solar energy throughout the year. On a global scale, the earth receives from the sun about 745×10^{15} kilowatt-hours per year. World energy consumption at present is only a little about 6×10^{13} kW-hrs annually and is projected to grow to about 3×10^{14} kW-hrs at the turn of the century. Hence, in theory the magnitude of solar energy far exceeds future needs.

However, all efforts aimed at the utilization of solar energy find difficulty in coping with the vast surface areas needed in collecting radiant energy. Sunlight provides a relatively low energy flux density compared to that obtained in power systems using fossil or nuclear fuels. This presents a technological challenge to achieve economical conversion to more useful energy forms. In addition to the problem regarding the collected solar energy which is in the form of low-temperature heat, some forms of solar energy are intermittent and variable due to daily, seasonal and environmental effects. These forms of energy are difficult to store, difficult to transport and difficult to transform into work. Therefore, a technological breakthrough is needed to overcome all these difficulties which is gradually being accomplished by the different scientists and engineers in various countries.

Presently, solar energy find widespread and practical applications in solar evaporation, solar water heating, solar distillation, and solar drying, particularly of agricultural & marine crops products. Researches and experiments are many, some enjoying a degree of technological success, but their economic and social feasibilities have never been fully established. These activities have concerned space (comfort) heating and cooling, refrigeration and ice making, desalination of water, cooking, pumping of water, production of salt, drying, hot-air engines, lighting, solar furnaces, horticultural systems, methane production through bacterial growth, and photochemical conversion.

Other direct solar energy applications that have promising uses are process steam generation, air conditioning and high-level technology electricity generation including photovoltaic cells, solar thermal conversion and ocean thermal energy conversion (OTEC). Of these technologies mentioned, solar water heating and solar drying have been found to be economically viable or close to viability, especially for pre-heating the industrial water for manufacturing and hotels and for drying agricultural crops and fruits. In the Philippines single solar dryers are designed for the rural areas. The design is acceptable especially for those who are engaged in simple food preservation. At least the crops, fishes and fruits dried are assured to be sanitary of high quality compared with the traditional method of drying. The dryer is of the tray type made of wooden frame, painted with black coating and covered with polyethylene plastic sheets.

Indirect solar energy include wind, which can now be viably utilized for water pumping and electric generation; biomass, which finds viable utilization in fuel alcohol, drying of crops, lumber, etc.; process steam generation, and electricity generation using waste thermal and has good potentials in biogas generation, pyrolytic production of charcoal, gas, and oil and electricity generation utilizing dendrothermal and producer gas systems; ocean user, and geothermal energy, the latter already considered or classified as conventional energy.

Solar radiation is diffuse and must therefore be concentrated to convert it to the desired energy or to perform work. Since solar energy collection requires a large portion of land area if this will be totally or partially utilized in industry, it may face some problems in the future. It may or will compete with the other economic requirements of the country. Therefore, a proper mix or balance has to be studied and evaluated carefully by the policy makers. The economies of scale of solar technology is something to be reckon with. This is true when using flat plate solar collectors. However, with the development work being undertaken on photovoltaic cells, the land area requirement may be smaller in area compared with other concentrators. The studies on the utilization of solar energy may be divided into two classification, namely:

1. *Direct Solar Energy R & D*

The National Science Development Board (NSDB) conducted and granted assistance to solar energy projects which aimed at utilizing solar energy for domestic and industrial purposes. In 1974 a project was conceived to conduct R & D studies on the utilization of solar energy and the fabrication of devices/equipment for heating, environmental heating and cooling, and drying for domestic, commercial and industrial purposes.

The results became the basis of future researches while some were found to be commercially adaptable, especially solar water heating, drying and cooking. A similar project was carried out in 1976 to operationalize such results, this time utilizing locally available materials for use as solar panels and energy collectors. A solar dryer was designed and fabricated and investigations were made as to the best method of utilizing collected solar energy in drying agricultural crops, especially palay and corn. The results were favorable and the method was found superior to the traditional sun drying. From these studies, various models of solar dryers were evolved, to suit the various drying properties of different agricultural and even marine products.

Similarly in 1975, a project was conducted to design and fabricate solar collectors using local materials and skills to establish the guiding factors in the design of solar collectors for purposes of producing cheaper and cost-efficient collectors and/or systems. Results showed that the locally fabricated solar collectors using copper performed better than the three (3) imported ones with the following results:

$$\text{Collector Efficiency} \quad + \quad \frac{\text{Heat gained x flow}}{\text{Solar incidence x area}}$$

Local	=	58.5%
$Imported_1$	=	48.7%
$Imported_2$	=	31.2%
$Imported_3$	=	48.2%

Taking advantage of this research, hot water with a temperature of about 100° F has been produced.

Previously, solar energy projects were being conducted without a data base as to the solar radiation that an area has. Hence, in 1977 a solar radiation mapping of the Philippines was conducted to serve as a basis for determining strategic areas for installation of solar devices. A solar map was developed showing the different areas of the Philippines. The average radiant energy (direct and diffuse) that has been recorded by PAGASA from their measuring station in Diliman, Quezon City is 1.575 BTU/cm^2 of horizontal surface area per day. This means that the earth which has a projected area of 13.33 x 10^{15} BTU/hr. of radiant energy. Attached is the solar data.

Recent efforts have been exerted to disperse the application of solar water heaters in Manila, Baguio, Bacolod, Iloilo, Cebu, Legasgi, Dumaguete, Davao, Zamboanga and La Union. This effort is now picking up and people realizes the potential of solar energy as a source of fuel.

Solar stills were installed in a small island to produce *potable* water and at the same salt. In another place, a solar distillation plant was installed to produce distilled water for livestock vaccine production.

Other direct solar projects are devoted to solar crop dryer, solar refrigeration by aqua ammonia absorption system, solar lumber dryer either total or supplemented by biomass – fired furnace.

2. *Indirect solar projects*

Various projects were also made utilizing wind for pumping water for domestic and irrigation purposes and for low power electricity generation (100-150 watt power range). Studies emphasized on the design, fabrication, installation and operation of windmills subject to actual wind characteristics in the selected sites. The following root/winwmill blade designs were studies.

1. Laminated wood blades
2. Wooden and B.I. sheet blades
3. Sail type blades
4. Fiberglass blades

5. Aluminum cups similar to the anemometer

6. Aluminum cups with a combination of replaceable nylon or canvas sails

7. Other locally available materials

The data and results gathered from this demonstration models are now the basis of improving the performance of subsequent windmill designs. Further researches are being conducted to take into consideration wind areas and the occurance of typhoons.

A complementary project was undertaken to construct a surface wind velocity map of the Philippines showing the prevailing wind direction and spread, and duration to serve as a guide as to where wind machines can be installed and operated. The average wind velocity of the country is about 8 mph. In some areas, however, the wind speed is in excess of 10 mph, but these are the areas that are visited by the tropical cyclones or typhoons with centre wind ranging from 100 to 200 mph.

Aside from the wind, projects were conducted to harness the energy from the ocean waves and converting them into other forms of energy. One project utilized the wave energy that impinges against the shore. Another project aimed to design, fabricate and develop an efficient system of obtaining rotary motion from the ocean impulses and converting them into an electrical power. Despite the various problems encountered, a design of a double acting turbine and bouy had been fabricated producing 75 watts of electric power. On further refinements of the model, a commercial model was designed and internationally potented and is now licensed out to a Japanese company and a German firm.

A 30 kW. electric pilot plant using agricultural wastes as fuel was installed in a barrio and this is being administered and serviced by a local electric co-operative.

Biomass, which is another form of solar energy is also being exhaustively studied. Among the projects being conducted are on alcohol from industrial and agricultural wastes, natural man-made forests for generating electricity, production of activated carbon from coir dust and other agricultural products, production of charcoal briquettes from sawmill wastes and low density woods, biogas and others. Most of these projects emphasized on the technical and economic feasibilities, requiring further developmental studies. Biogas R & D has been successful with the determination of suitable models for small and large-scale applications. Various units have been constructed and disseminated in the rural areas for domestic purposes, about 1,000 in number, while large-scale application for industrial uses has been adopted, prominent among which is the Maya Farms in Angono, Rizal, which has replaced about 50% of the oil requirement of the company. Further researches however, has to be implemented to counter emerging problems of maintenance and continuous operation, particularly for small-scale units. Methane gas generation looks simple but complex in nature, thus continuous R & D studies have to be undertaken, including the training of the group to assist in the maintenance of the same.

Studies on geothermal energy was initiated in 1962 and proved to be a potential source of electric power. Presently, about 450 megawatts is being generated from four (4) geothermal areas. Other potential areas are being explored by the NSDB and the UPC.

Marsh gas or low pressure gas is also tapped as a source of fuel and about 6 pilot models have been established. Natural gas deposit at Cebu and Caganyan provinces have been explored. In the former, a 3 kW. power generator was installed.

Another source of fuel in the coconut oil which was processed into coco-diesel oil and as a gasoline – like substitute. In fuel produced are comparable with the commercial one. In order to establish the commercial viability, a pilot plant will be set up soon.

Management

Solar energy utilization has long been the dream by a small group of scientists and technologists in the Philippines. Unfortunately, this was not taken up seriously by the policy makers as a potential source of energy because of the low cost of fossil oil.

However, the National Science Development Board (NSDB) started in a limited way in solar research by having the first solar cooker. the utilization and application was set aside. But in 1972, because of the oil crunch and due to the high price levied on the product, a crash programme on non-conventional source of energy was initiated by NSDB. This covered the solar energy, biogas, marsh gas or low pressure gas or seepages, natural gas, ocean waves, forest energy or dindrothermal, producer gas and others.

The various agencies of the NSDB, the academe and the private groups were involved in this undertaking. The most significant result of this crash programme is the generation of biogas/methane gas, the solar cooker, solar water heater, marsh gas and forest energy. Models have been produced, installed and demonstrated.

Because of the potentials of this non-conventional energy, the Energy Development Board was created in 1974 and later enlarged to the formation of the Ministry of Energy (MOE) taking into account not only the non-conventional sources of energy but the accelerated development of the different conventional sources of energy.

With the creation of the Ministry of Energy (MOE), this only strengthen the research and development efforts of the NSDB and its agencies. In fact, a close working relationship and linkage have been made with the Minister of Energy sitting as a member of the Board of Governors of the NSDB.

To promote broad acceptance in the utilization of non-conventional sources of energy, significant steps have been made by the government, among them the issuance of Presidential Decree (PD) No. 1068, directing the acceleration of research and development and utilization of non-conventional, energy sources. This was followed by another presidential directive, Letter of Instruction (LOI) no. 892, effecting the widespread application and utilization of the non-conventional energy in various regions of the

Philippines, especially in priority areas. At the same time specific agencies were designated to be responsible for the dissemination of the activities, namely: Ministry of Agriculture for biogas, Ministry of Energy on solar water heating and solar crop drying, Farms Systems Development Corporation on wind power relative to waster pumping and irrigation and the National Electrification Administration on small hydro for rural power up to 5,000 kW. while those above 5,000 kW. is the responsibility of the National Power Corporation.

Later LOI no. 933 was issued directing the preparation of an Energy Priorities Programme (EPP) to be included as preferred area of investment in the Board of Investments. Included in the EPP list are manufacturers of solar water heaters, biogas equipment, mini-hydro, turbine generators and windmills. Non-con equipment importation are provided tax importation incentives and deductibility from gross income. Incentives are also granted to the sector that design, fabricate and install their own solar set-up.

In addition, the Centre for non-conventional Energy Development (CNED) was formed under the aegis of the Ministry of Energy. This was followed by the creation on February 1980 of the Philippines National Alcohol Commission (PNAC) which will formulate and define the policies, plans and programme and guidelines for the production and distribution of alcohol for blending with gasoline. The present mixture is 15% alcohol and 85% gasoline.

The relationship of the NSDB and MOE is shown in the attached chart.

It can be observed that on the part of the government, national policies are taking shape-sustained government guidance, promotions, and a combination of stimulating incentive, technical, financial and legal. To make new technology accepted, the accompanying services have been provided in the form of financial assistance (soft loan or an outright grant from NSDB and MOE) to acquire the device and provide working capital and the marketing and distribution network with the accompanying product servicing.

A continuous manpower training is made by MOE and the higher quality manpower by the NSDB on the undergraduate and graduate levels. For awareness in schools a joint project by MOE and the Ministry of Education and Culture (MEC) is on-going with the end in view of incorporating the concept in the curriculum.

Management of energy is further supplemented by having the Energy Conservation (ENERCON) Programme and the Task Force setting rules and regulations for implementation.

The design of houses and building have recently been given importance by the civil and architectural groups (included in the Building CODE) to minimize the use of electric power for air-conditioning and at the same time orient the roof to accommodate the installation of solar collectors in the future.

Another factor that has to be taken into account is the social and environmental aspects in the utilization of solar energy. The acceptability of the system, especially in the rural areas may create some problems as this will surely change the working habits of the people. On the environmental side, more land areas may be used up and this may create an imbalance in the economic needs of a specific place.

Last but not the least is the aspect of cost-efficiency of the system that may be introduced in the future. Presently, entrepreneurs are reluctant to invest in mass production set-ups which would obviously lower unit production because the size of the market is uncertain.

On the other hand, the potential users are discouraged by the high first cost of the systems and thus decide to stick to the conventional route. Not only that, it is the maintenance which they have to build requiring additional investment.

It is generally accepted that the state-of-the-art of solar technologies vary and needs adaptation and further development despite the fact that the country's solar energy resources is immense. Obsiously, R & D is imperative. R & D efforts in this area, in co-ordination with other ministries is maintained by increasing the financial requirements yearly.

Transfer of Technology

A number of models has been transferred to the Philippines from developed countries, and the water pump (Rankine cycle) of France under the sponsorship of UNEP, photovoltaic solar water pump from the Republic of Germany and solar flat plate collectors from Japan and Germany. Another one in the mini-hydro pump from China. All of these models are presently being tested and monitored for their efficiency and reliability.

On the local level, transfer of technology has been achieved by the acceptance of the solar tray dryer for agricultural crops and marine products. Biogas is another R & D results that has been accepted and widely utilized. This is also true for marsh gas utilization, alcohol or alcogas, dendro thermal, producer gas and others.

A breakthrough in harnessing ocean waves has been made and is now licensed to foreign manufacturers. Another important project is the improved mini-hydro presently manufactured locally.

Conclusion

Solar energy finds widespread and practical application in solar evaporation, solar water heating, solar distillation and solar drying, particularly of crops. Researches and experiments are many, however, in some the feasibility has never been established.

It is clear that there is a wide spectrum of potentially interesting methods, focusing solar energy. Some of these have been extensively studied while some are still completely undeveloped. It is not clear at this time to us which of these various processes will find the widest application, or whether several of them will succeed in various climatic zones. The future of these systems is linked to component development. It is also closely interrelated with development in solar heating as the economies of these processes appear to be better than that of either one alone. However, the total application of solar may be hampered by the space requirement which may compete with the other sectors of the economy.

Much work has been done on the subject. And as the old Hungarian saying has it, "the man learns by his own mistakes, but the wise one by the mistake of others". As quoted by S.V. Szokolay, "this is a new field, we are breaking new ground. One day, in the not too distant future, it will become a discipline, a defined body of knowledge. Today we can still enjoy the freedom of pioneers".

The ancient dream of power from the sun may be possible after all.

Recommendations

It is therefore recommended that the following be given due consideration, namely:

1. R & D results that has been proven to be commercially viable should be disseminated among the between countries.

2. R & D work should be continued especially in improving the efficiency of the system and possibly reducing the cost.

3. Exchange of expertise and information should be facilitated and accelerated through the assitance of RCTT and other organizations.

4. A mechanism to link the various countries should be implemented which could be in the form of an advising body or panel of experts and others.

5. Training at different levels of education and maintenance of a core of solar manpower that should support the energy programme of the country including the regional infrastructure should be accelerated.

ENERGY CONTRIBUTION OF NON-CONVENTIONAL ENERGY SYSTEMS*

(In Thousand Barrels-of-Oil Equivalent 10^3 BOE)

Energy Technologies	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989
1. Marsh Gas	1.0	1.3	1.5	1.9	2.2	2.6	2.9	3.3	3.7	4.0
2. Biogas	5.0	5.0	5.1	5.3	5.4	5.5	5.8	6.0	6.2	6.6
3. Wind Energy	0.2	0.2	0.3	0.4	0.5	0.6	0.8	1.0	1.3	2.0
4. Hot Springs	0.1	0.2	0.3	0.7	1.0	1.4	3.4	6.6	13.2	19.7
5. Direct Solar	1.1	1.7	2.2	3.0	4.7	6.8	9.5	13.6	19.4	27.9
6. Producer Gas	0.3	0.7	0.7	0.7	1.8	1.8	3.6	3.6	5.4	5.4
7. Dendro thermal	–	511.9	868.9	1,380.4	1,890.4	2,402.2	2,913.9	3,424.0	3,424.0	3,424.0
8. Alcogas										
Alcogas Production **	138.4	345.4	909.7	1,534.6	2,515.7	3,427.7	4,339.6	5,251.6	5,817.6	5,817.6
Bagasse										
– Used for alcohol	75.5	189.3	495.6	839.7	1,376.6	1,875.6	2,374.6	2,873.6	3,183.3	3,183.3
– Excess	57.3	143.4	375.3	636.0	1,042.6	1,420.5	1,798.5	2,176.4	2,411.0	2,411.0
TOTAL	279.1	1,199.1	2,655.6	4,402.7	6,840.9	9,844.7	11,462.6	13,759.7	14,885.1	14,901.5

* The contribution of already developed and established non-conventional fuels (bagasse, agricultural and sawmill wastes) has been estimated through a survey at about 16 MBOE in 1977 and projected to rise to about 23 MBOE by 1989 rising an average of 3% each year. Charcoal wood production and utilization have been extra-polated from an energy demand survey in 1977. On-going survey analysis indicates that even these extra-polations are conservative.

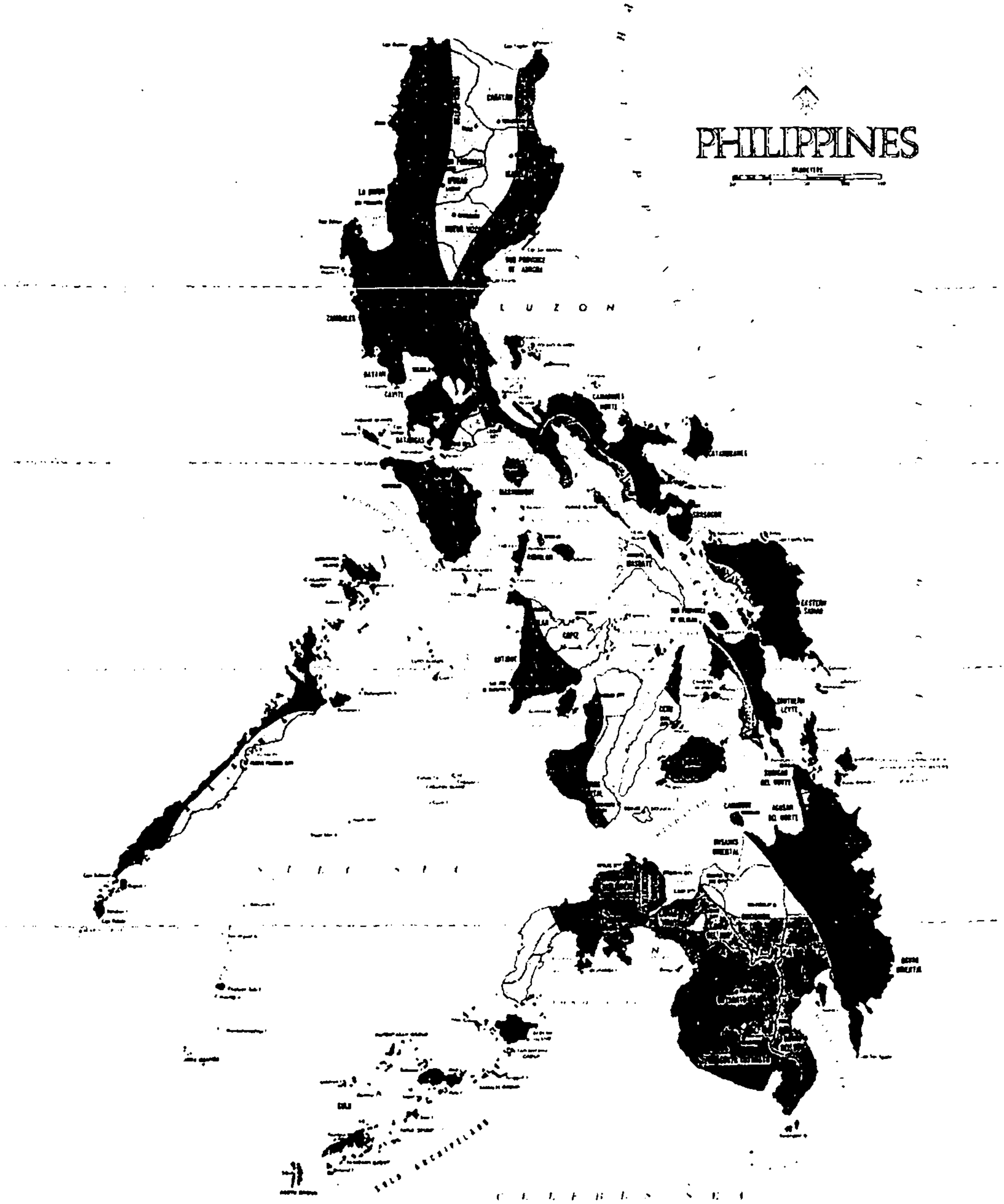
** Represents alcohol barrels. On a per-BTU basis, an alcohol barrel is equivalent to only 0.6 barrel of oil.

Source: Ministry of Energy, Ten-Year Energy Programme 1980-1989.

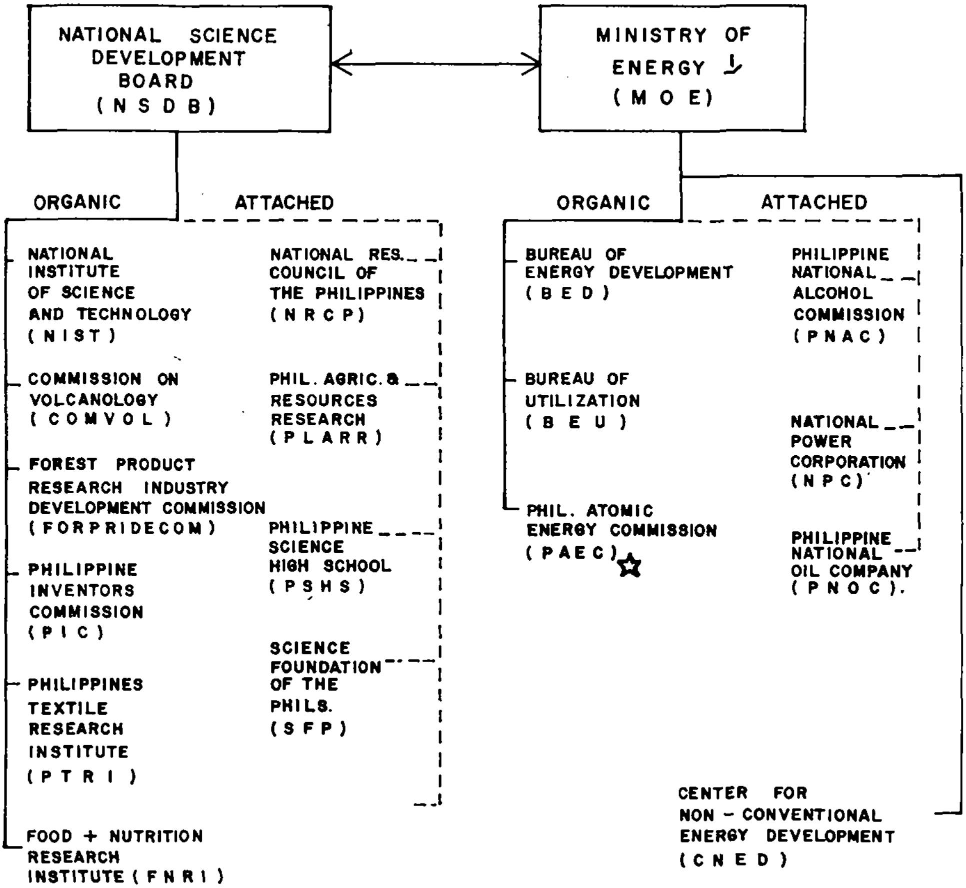
GLOBAL RADIATION DATA (LANGLEYS)

(From Duration of Bright Sunshine)

STATIONS	*JAN.*	*FEB.*	*MAR.*	*APR.*	*MAY*	*JUN.*	*JUL.*	*AUG.*	*SEPT.*	*OCT.*	*NOV.*	*DEC.*	*ANNUAL*
LAOAG	415	505	541	601	579	506	498	423	462	418	416	388	479.33
TUGUEGARAO	294	424	442	543	552	479	479	484	428	397	297	233	421
BAGUIO	389	471	494	524	456	407	364	326	362	395	372	364	410.33
HA. LUISIRA	420	479	503	590	541	444	418	373	404	424	394	377	447.25
QUEZON CITY	378	449	494	551	491	419	403	378	385	367	359	350	418.66
LOS BALOS	356	437	506	574	520	465	423	391	412	386	352	306	427.33
AMBULONG	393	458	503	555	491	459	405	388	390	411	410	340	433.58
CATARHAN	354	410	448	495	529	444	421	445	422	434	371	336	425.75
TACLOBAN	353	400	434	479	480	436	414	434	416	416	376	350	415.66
VICTORIAS	403	446	510	568	505	440	440	445	422	456	409	376	451.66
ZAMBOANGA	460	476	492	509	467	417	436	468	448	441	458	457	460.75
HABACAN	452	426	426	515	487	411	422	442	457	460	442	396	444.66


PHILIPPINES
L U Z O N

ORGANIZATIONAL CHART AND MANAGEMENT LINKAGE



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AN ANALYSIS OF SOLAR PONDS FOR COLLECTION AND STORAGE OF SOLAR ENERGY

by

M.N.A. HAWLADER

ABSTRACT

This paper deals with the performance characteristics of solar ponds under steady state condition. Equations have been developed to predict the optimum depth of the solar pond and the maximum efficiency available from it. The influence of the surface mixed layer and extinction coefficient on the effectiveness of the solar pond have been investigated in detail.

INTRODUCTION

In the tropics, solar energy is available in large quantities but the successful utilization depends on the development of an effective low cost collection and storage system. Solar ponds appear to offer a method of collecting and storing solar energy cheaply. This pond will usually have three layers:

(i) a surface mixed layer, a layer of nearly saltless water in which there is convection due to wind action and evaporation;

(ii) the non-convecting layer (also known as insulating layer), a layer in which salt concentration increases with depth; and

(iii) a bottom mixed layer, a storage layer in which the salt concentration is maintained constant.

A fraction of the incident solar radiation on the surface of the pond penetrates the liquid and falls on the blackened bottom giving rise to the temperature of the storage layer. Thermal conductivity of water is quite low (0.6 W/mK) and hence the presence of an insulation layer on top of a storage layer makes it possible to confine the hottest liquid to the bottom.

The behaviour of the solar pond under non-steady state conditions has been studied by Weinberger (6), Rabl and Nielsen (1), Bryant and Colbeck (2), Akbarzadeh and Ahmedi (10) and Hull (13). An analytical model has been developed by Kooi (3) to study operating characteristics of solar ponds under steady state conditions. Equations developed by Kooi (3) require information on the fraction of the surface radiation reaching different depths of water and an empirical equation has been used which is true for a particular quality of water.

In this paper, equations have been developed to study the operating characteristic of the pond in which the fraction of the incident radiation on the surface of the pond available at different depths of water is expressed in terms of an extinction coefficient, the magnitude of which is dependent on the purity and clarity of the water. The influence of the depth of surface mixed layer on the effectiveness of the pond has also been investigated.

ABSORPTION OF SOLAR RADIATION IN THE POND

A large fraction of the solar radiation incident on the surface of the pond penetrates into salt water. Radiation entering a layer of salt water is gradually weakened by absorption and scattering by salt water and also by scattering and reflection by suspended particles. The absorption of solar radiation in a body of water has been found to be strongly dependent on wave lengths. The long wave and short wave parts of the spectrum are absorbed within a few centimetres from the surface of water. Absorption of solar radiation in particle free salt water is found to be almost same as in pure water (4) although it is also slightly temperature dependant. Measurements of solar radiation absorption with depth in a body of water indicate that initially there is a region of rapid attenuation followed by an exponential decay (5, 6, 7). The following expression for the irradiance at different depth of water was proposed by Dake and Harleman (5).

$$I_h = I_s(1 - F) \exp(-\mu Z) \qquad \ldots\ldots\ldots\ldots\ldots\ldots \quad (1)$$

Above approximation was also supported by measurements (5, 7). The extinction coefficient of extremely clear water of Lake Tahoe has been found to be about one fifth that of turbid water in Castle Lake and about one tenth that of an outdoor solar pond, as shown in Figure 2. This figure shows that the extinction coefficient which is a measure of the quality and clarity of water can vary from 0.05 to 0.5 m^{-1}. Thus, it is essential to include the effect of this variation in an analysis of solar ponds.

MATHEMATICAL FORMULATION

As already mentioned, a solar pond will have three zones, as shown in Figure 1. This pond is intially filled with salt solutions giving a salinity gradient which satisfies stability criteria (6, 8). It will approach a steady state temperature (9) due to solar heating. The time taken to attain steady state temperature depends on the size of the pond and the rate of heating, and for a large pond this may be of the order of two to three years. Heat losses from the wall are small and the ground under the pond acts as a thermal stabilizer (10). This and the large mass of water reduce the possibility of large daily fluctuations in temperature in the storage zone. The temperature in the pond may vary by one or two degree celcius due to the daily load. Since the daily variation of temperature in the storage zone is so much smaller than the seasonal variation, the latter may be modelled as a succession of steady state condition.

When the temperature variation in the horizontal direction for the non-convecring zone of the pond is neglected, it is found that the temperature distribution in the vertical direction for a constant horizontal area of heat flow is governed by the following diffusion equation (5, 12).

$$\frac{\partial T}{\partial t} = \alpha(\partial^2 T/\partial h^2) + I_s\mu(1 - F)(\rho C_p)^{-1}\sec\theta_r \exp(-\mu Z) \quad \ldots\ldots (2)$$

Here, it is assumed that the radiation entering the storage zone is also absorbed there. It may be difficult to ensure that the bottom of a real pond remains unreflecting, but the assumption is robust, since the reflected radiation, which will be of diffused form, would in any case by likely to be absorbed mainly in the storage zone.

When a large pond is operating at or near the steady state temperature $\partial T/\partial t$ becomes negligible, hence equation (2) becomes

$$d^2T/dh^2 = -I_s\mu(1 - F)k^{-1}\sec\theta_r \exp(-\mu Z) \quad \ldots\ldots\ldots\ldots\ldots\ldots (3)$$

This equation is similar to that of Kooi (3) but has an added advantage that the fraction of the radiation reaching different levels of water is expressed in terms of an extinction coefficient. It allows us to study the effect of the extinction coefficient, which is a measure of quality and clarity of water, on the efficiency and the optimum depth of the pond.

A fraction, F, of the incoming solar radiation on the surface of the pond is absorbed in the surface mixed layer but this is dissipated quickly due to convection, radiation and evaporation to the atmosphere above it and hence the temperature of the surface mixed layer is assumed to be maintained at a constant value of T_1. For the storage zone, the temperature variation in the horizontal direction is assumed to be negligible. The temperature of the storage zone is assumed to remain constant at T_2. With these assumptions, the integration of equation (3) between boundaries h_1 and h_2, where the temperature varies from T_1 to T_2, gives

$$\begin{aligned} T(h) = {} & T_1 + I_s(1 - F)(\mu k\sec\theta_r)^{-1}\,[\exp(-\mu h_1\sec\theta_r) - \exp(-\mu h\sec\theta_r)] \\ & + (T_2 - T_1)(h - h_1)/(h_2 - h_1) - [I_s(1 - F)/\mu k\sec\theta_r] \\ & [(h - h_1)/(h_2 - h_1)]\,[\exp(-\mu h_1\sec\theta_r) - \exp(-\mu h_2\sec\theta_r)] \\ & \ldots\ldots\ldots\ldots\ldots\ldots (4) \end{aligned}$$

and the temperature gradient at the boundary, h_2, between the storage zone and the insulating zone becomes

$$(dT/dh)_{h=h_2} = I_s(1 - F)k^{-1} \exp(-\mu h_2 \sec\theta_r) + (T_2 - T_1)/(h_2 - h_1)$$
$$-I_s(1 - F)\,[\mu k(h_2 - h_1)\sec\theta_r]^{-1}\,[\exp(-\mu h_1 \sec\theta_r)$$
$$- \exp(-\mu h_2 \sec\theta_r)] \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (5)$$

When the heat losses from the wall and ground under the pond are neglected, the net energy input to the storage section becomes

$$q_u = I_s(1 - F)\exp(-\mu h_2 \sec\theta_r) - k(dT/dh)_{h=h_2} \quad \ldots\ldots\ldots\ldots \quad (6)$$

Substituting the value of $(dT/dh)_{h=h_2}$ from equation (5) and after rearrangements equation (6) may be put in the form

$$q_u = (\alpha\tau)I_s - U_L(T_2\ T_1) \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (7)$$

where $\alpha\tau = (1 - F)\,[\mu(h_2 - h_1)\sec\theta_r]^{-1}\,[\exp(-\mu h_1 \sec\theta_r)$

$$- \exp(-\mu h_1 \sec\theta_r)] \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (8)$$

and $U_L = k/(h_2 - h_1)$ .... (9)

When incoming radiation is landing normally on the surface of the pond, $\sec\theta_r = 1$ and

$$\alpha\tau = (1 - F)\,[\mu(h_2 - h_1)]^{-1}\,[\exp(-\mu h_1) - \exp(-\mu h_2)] \quad (10)$$

The amount of heat collected from the pond is

$$Q_u = m\,C_p\,(T_{2,out} - T_{2,in}) \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (11)$$

It is a common practice in the study if flat plate solar collector to express useful energy gain in terms of the fluid inlet temperature. Following Duffie and Beckman (11) and Kooi (3), the useful energy gain for the solar pond per unit of pond area becomes

$$Q_u = F_R [(\alpha\tau) I_s - U_L (T_{2,in} - T_1)] \quad \ldots\ldots\ldots\ldots\ldots \quad (12)$$

The heat removal factor, F_r, is defined by the following equation

$$F_R = G C_p U_L^{-1} [1 - \exp(-U_L F' / G C_p)]$$

where the collector efficiency factor, F', is the ratio of the useful energy gain to the useful energy gain if the collector absorbing surface had been at the local fluid temperature. This can be assumed to be unity for a solar pond. Using equation (12), the efficiency of the solar pond can be defined as

$$\eta_p = F_R [(\alpha\tau) - U_L \Delta T/I_s] \quad \ldots\ldots\ldots\ldots\ldots \quad (13)$$

Assuming h_1, T_1, and I_s constant for a particular pond and differentiating equation (13) with respect to h_2 and setting $d\eta_p/dh_2 = 0$ gives

$$[\mu(h_{02} - h_1) \sec\theta_r + 1] \exp(-\mu h_{02} \sec\theta_r) = \exp(-\mu h_1 \sec\theta_r)$$

$$- \mu k \sec\theta_r (T_{2,in} - T_1) [I_s (1 - F)]^{-1} \quad (14)$$

In equation (14), h_{02} is the optimum depth of the boundary, h_2 between the storage zone and insulating zone.

When $\sec\theta_r = 1$, equation (14) simplifies to

$$[\mu(h_{02} - h_1) + 1] \exp(-\mu h_{02}) = \exp(-\mu h_1) - \mu k(T_{2,in} - T_1)$$

$$[I_s (1 - F)]^{-1} \quad (15)$$

For a particular values of h_1, μ, T_1, T_2 and I , equation (14) or (15) can be solved by Newton-Raphson or other methods.

RESULTS AND DISCUSSION

In Figure 3, the variation of η_p/F_R with $\Delta T/I_s$ is shown for a particular pond under vertical irradiation, where μ is used as a parameter. This figure shows that the efficiency of the pond decreases as $\Delta T/I_s$ and the extinction coefficient increase. This suggests that the transparency of the pond, particularly in the surface mixed layer and insulating layer, should be maintained in order to obtain better efficiency. Some typical values of η_p/F_R as a function of $\Delta T/I_s$ for flat plate collectors are also shown in Figure 3. For this case, it is seen that a solar pond is a better collector for $\Delta T/I_s > 0.075$. This has also been pointed out by Kooi (3). Even at $\Delta T/I_s < 0.075$, a solar pond is comparable to a flat plate collector when the extinction coefficient of the pond water is $0.05\ m^{-1}$.

The variation of the optimum depth, h_{02}, as a function of $\Delta T/I_s$ is shown in Figure 4, where the extinction coefficient, μ, acts as a parameter. It is found that the optimum depth, h_{02}, of a pond for $\Delta T/I_s = 0.2\ m^2K/W$ and $\mu = 0.05\ m^{-1}$ is 3.2 m. For the same $\Delta T/I_s$, as the transparency of the pond decreases the optimum depth, h_{02}, decreases e.g. for $\mu = 0.5\ m^{-1}$, $h_{02} = 1.25$. It is thus essential to consider the possibility that it might be highly inefficient to design a pond for $\mu = 0.05\ m^{-1}$ and operate it at $0.5\ m^{-1}$.

The maximum efficiency attainable from a solar pond varies with $\Delta T/I_s$, as shown in Figure 5. The strong influence of extinction coefficient is also evident here.

The variation of the effective absorption-transmittance product and η_p/F_R with depth, h_2, is shown in Figures 6(a) and 6(b). The loss term in equation (13), which is the difference between curves A and B, decreases with the increase of h_2. In Figures 6(a) and 6(b), two values of extinction coefficient, μ, have been considered. These figures show how the optimum depths and the maximum efficiencies are affected by the changes in extinction coefficient. When a pond is designed to operate with $\mu = 0.1\ m^{-1}$, Figure 6(a) shows that the maximum efficiency of 48% can be obtained if the depth, h_2, is equal to the optimum depth, i.e., 2.35 m. For the same pond, it if operates at a much lower value of transparency, e.g. $\mu = 0.5\ m^{-1}$ the efficiency of the pond will be 29%. Figure 6(b) shows that the maximum efficiency of the pond is 32% when $\mu = 0.5\ m^{-1}$ and $h_{02} = 1.2$ m. When these two ponds are compared, it is seen that if the 2.35 m pond, which is designed to operate at $\mu = 0.1\ m^{-1}$, actually operates at $\mu = 0.5\ m^{-1}$, the deeper pond shows a reduction of efficiency of 3% compared with the maximum efficiency of a 1.25 m pond (for $\mu = 0.5\ m^{-1}$). In addition to the loss of efficiency, the deeper pond will also be more expensive.

Figure 7 shows the variation of η_p/F_R and U_L with the depth of the surface mixed layer. It is seen from the figure that the surface heat loss coefficient, U_L, increases rapidly with the increase of the depth of the surface mixed layer. As the thickness of the surface mixed layer increases, the η_p/F_R decreases due to a reduction in the effective insulation thickness. Thus it is also essential to maintain the thickness of the surface mixed layer as low as possible. The efficiency of the pond is reduced by about 15% for an increase of depth of the surface mixed layer by 0.6 m, as shown in Figure 7.

CONCLUSION

A steady state analysis of solar pond has been carried out where equations have been derived to predict operating characteristics of solar ponds. It is seen that the extinction coefficient and the depth of the surface mixed layer have a strong influence on the efficiency and optimum depth, h_{02}, of the pond. It is thus essential to maintain the transparency of the pond and reduce the depth of the surface mixed layer as far as possible.

NOMENCLATURE

C_p	=	specific heat capacity, J/kg K
F	=	fraction of the net incident radiation absorbed in the surface mixed layer
G	=	mass flow rate in the longitudinal direction of the storage zone of the pond, $Kg/s.m^2$
h	=	depth of the pond from the surface, m
h_1	=	depth of the surface mixed layer, m
h_2	=	depth of the boundary between insulating layer and storage zone, m
h_{02}	=	optimum depth h_2, m
I_h	=	irradiance at depth h, W/m^2
I_s	=	net irradiance (incident-reflected) at the surface, W/m^2
k	=	thermal conductivity, W/mK
m	=	mass flow rate through the storage zone, kg/s
T	=	temperature, K
T_1	=	temperature of water in the surface mixed layer, K
T_2	=	temperature of water in the storage zone, K
$T_{2, in}$	=	temperature of the fluid returning from load, K
$T_{2, out}$	=	temperature of the fluid at the outlet of storage zone, K
ΔT	=	$T_{2, in} - T_1$, K
Z	=	the path length of the radiation that penetrates to a depth h in the pond, m
	=	$h \sec \theta_r$
α	=	thermal diffusivity, m^2/s
θ_r	=	refracted angle obtained from Snell's Law (6)
ρ	=	density of fluid, kg/m^3
μ	=	extinction coefficient, m^{-1}

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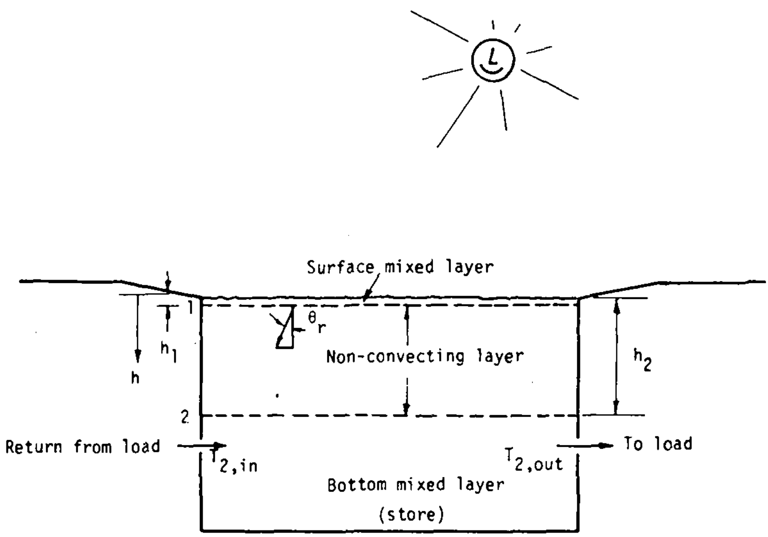

Fig. 1. A diagram of a typical solar pond

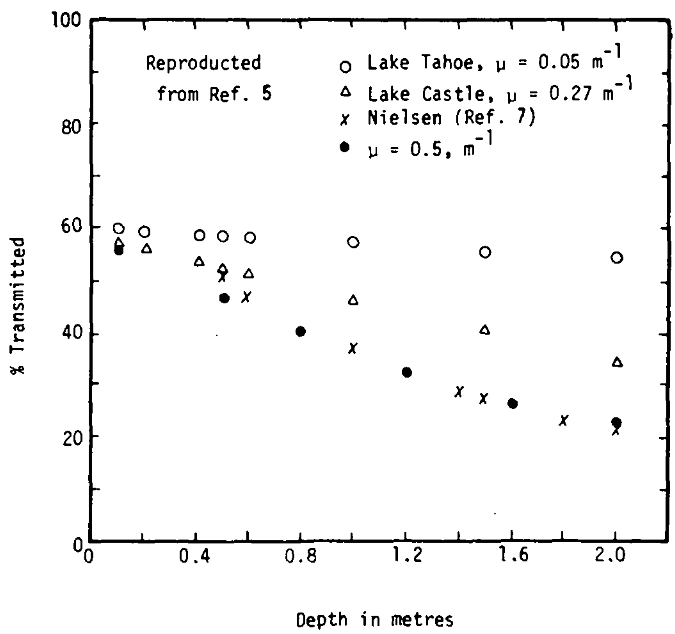

Fig. 2. Absorption of solar radiation in water as a function of depth

water as a function of depth

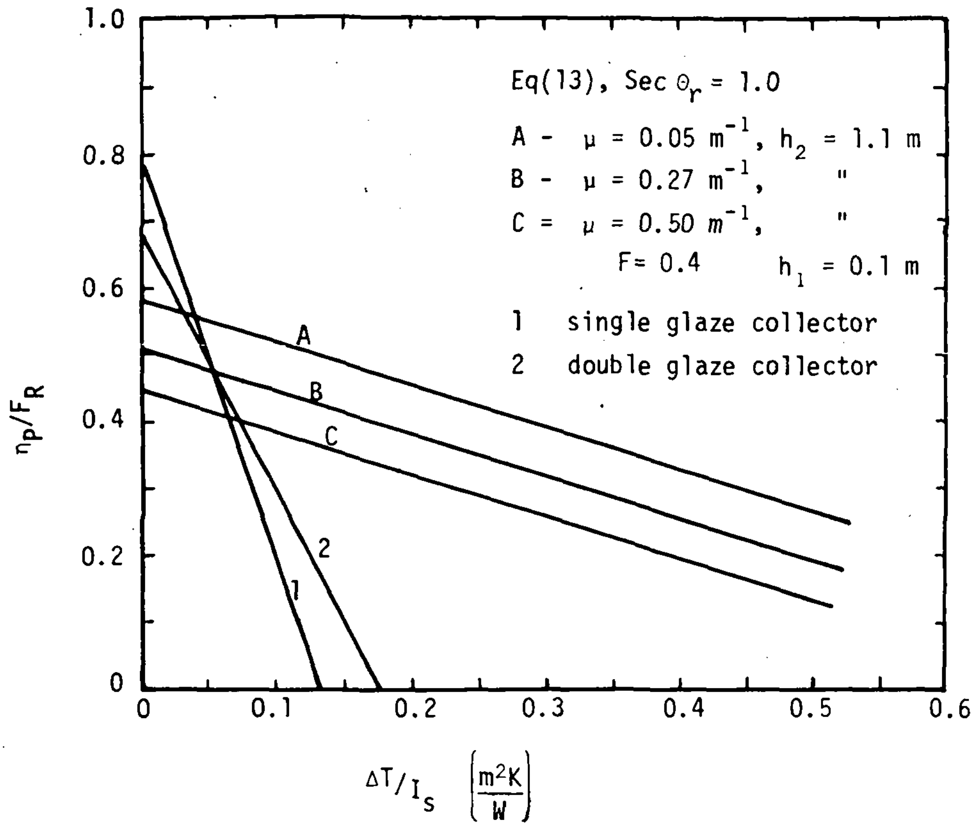

Fig. 3. The variation of η_p/F_R as a function of T/I_s, with μ as a parameter

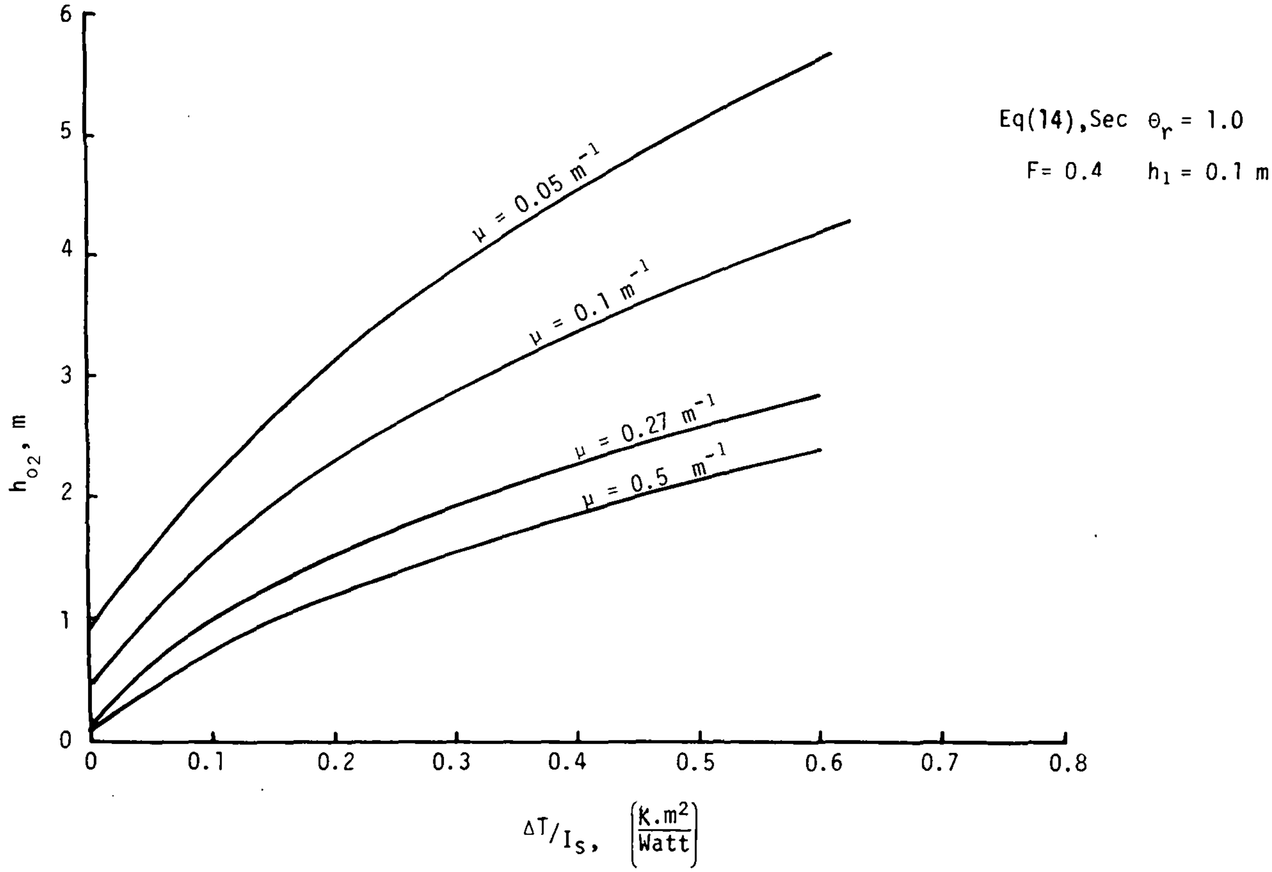

Fig. 4. The variation of optimum depth, h_{02}, as a function of $\Delta T/I_s$, with μ as a parameter

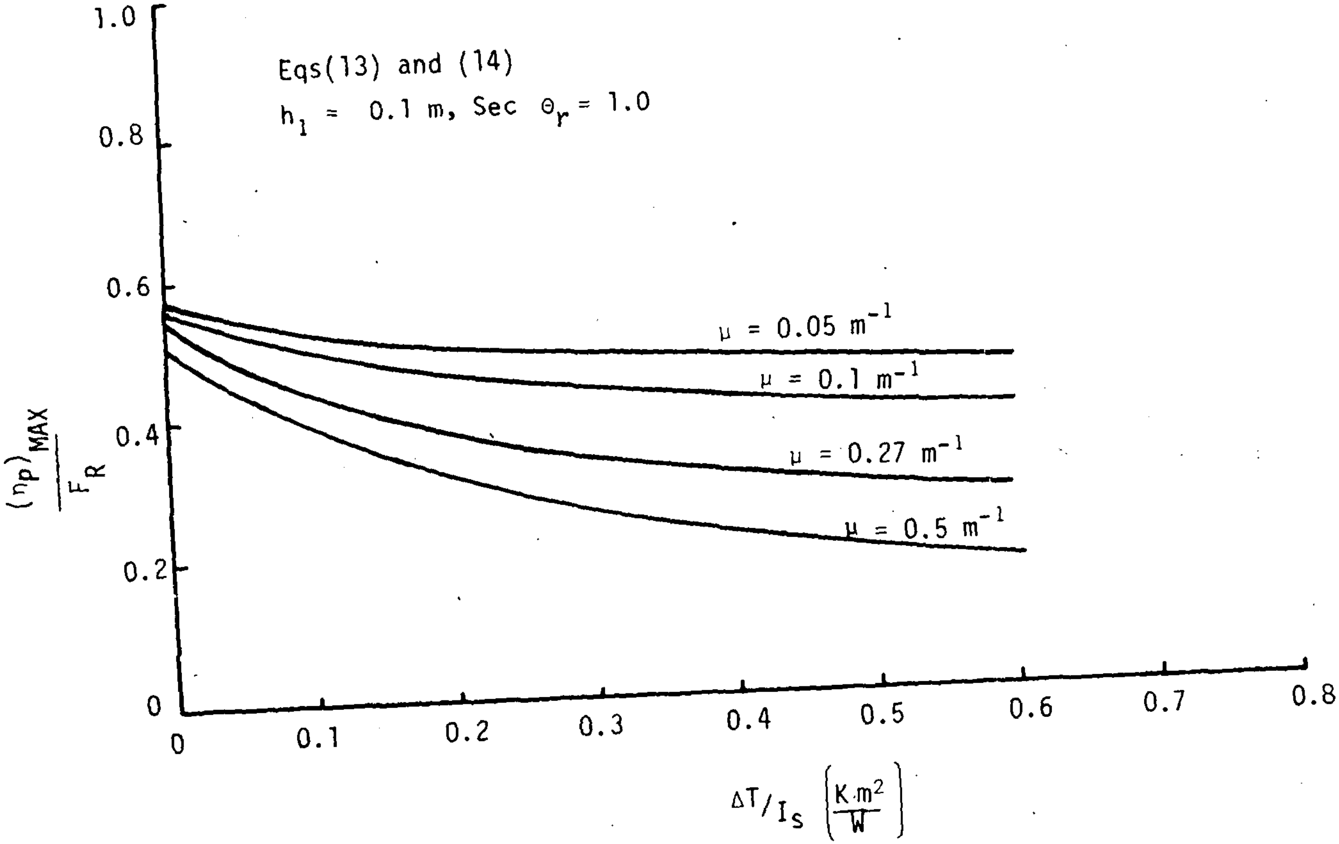

Fig. 5. The variation of $(\eta_p)_{max}/F_R$ as a function of $\Delta T/I_s$, with μ as a parameter

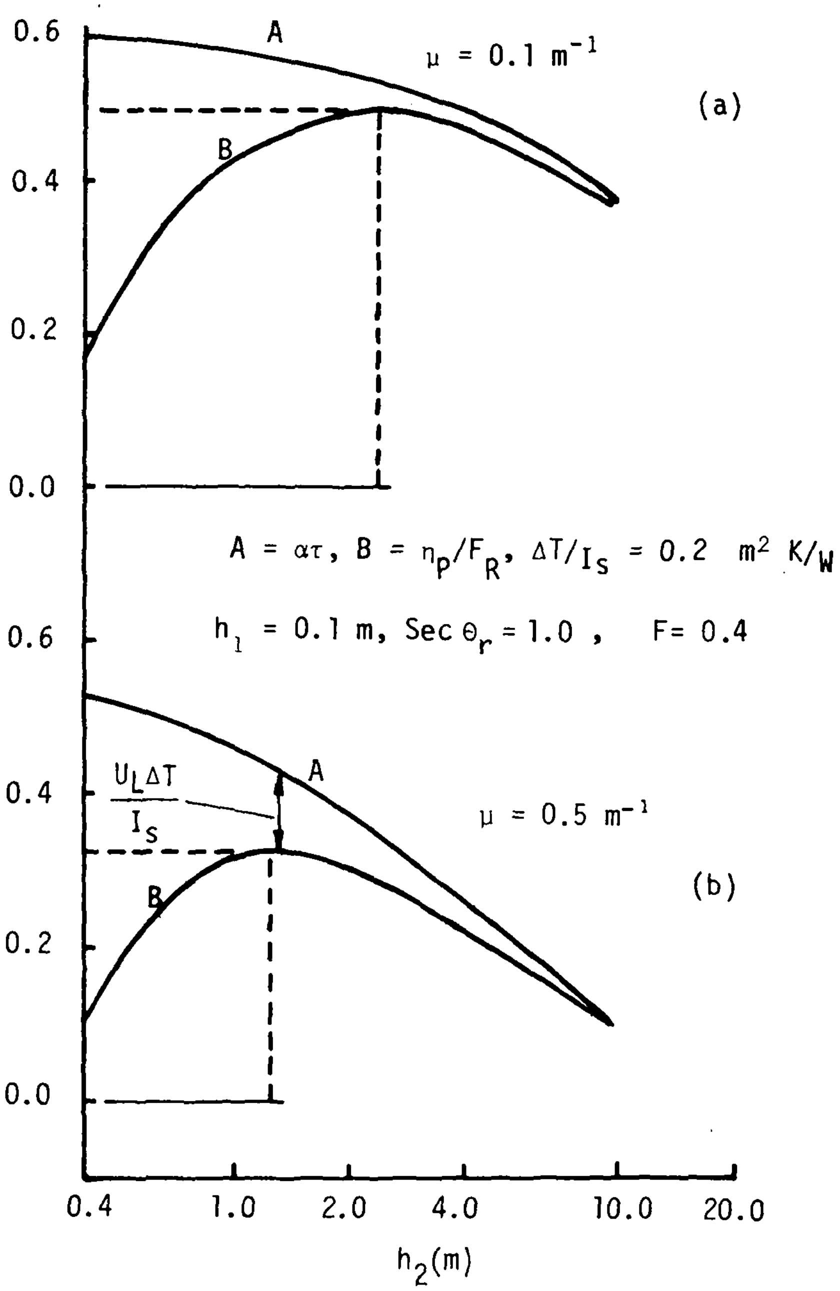

Fig. 6. The variation of $\alpha\tau$ and η_p/F_R as a function of h_2 and μ

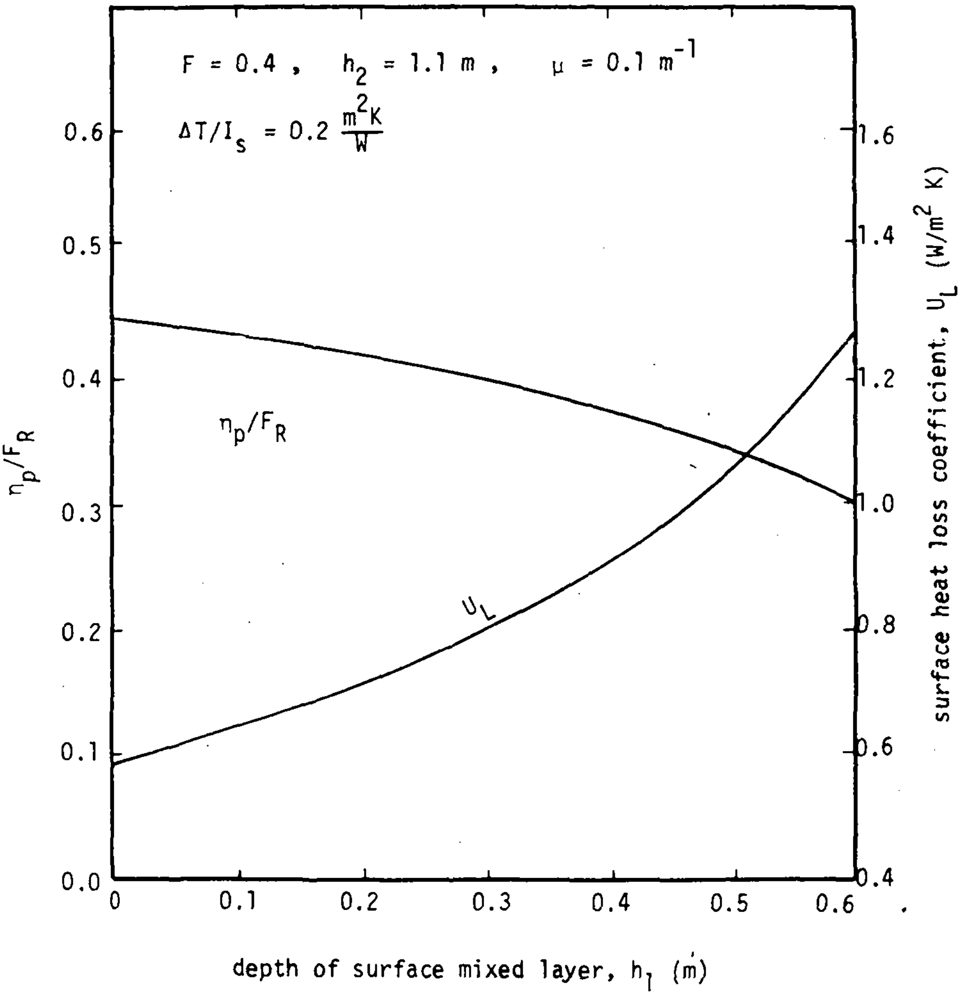

Fig. 7. The variation of η_p/F_R and U_L as a function of the depth of surface mixed layer

RELATIONSHIPS BETWEEN SOLAR RADIATION AND SOME METEOROLOGICAL DATA OF THAILAND

by

K. KIRTIKARA and T. SIRIPRAYUK

ABSTRACT

Solar radiation data and six other meteorological data for Songkla (1963-1967), Bangkok (1972-1976), Nakorn Panom (1963-1967) and Chiengmai (1964-1968) are used to determine correlation coefficients. Simple and multiple linear regression equations are developed to estimate solar radiation from the other meteorological parameters.

INTRODUCTION

The first comprehensive survey of solar radiation of Thailand was prepared by R. Exell and K. Saricali.[1] Detailed maps of the geographical distribution of solar radiation are prepared from data on cloudiness and sunshine duration, and linear regressions relating radiation and sunshine at Chiengmai and Bangkok were made. Relationships between solar radiation and other meteorological data were subsequently studied by K. Kirtikara et al[2] using montly average data from four stations, namely, Songkla, Bangkok, Nakorn Panom and Chiengmai; complete radiation and other meteorological data were available from these four stations. For Songkla, Bangkok and Nakorn Panom correlation coefficients between radiation and sunshine duration are largest compared to those between radiation and other data. The study also indicated that variation in radiation can be explain better by multiple regressions.

In this paper we present the results of the correlation and regression analyses based on the daily total solar radiation and the daily average values of other six meteorological data, namely, the sunshine duration, the cloudiness index, the temperature, the wind velocity and the barometric pressure.

Locations of stations and periods of available data

The locations of the four stations and the periods of which the seven parameters employed in the analyses were available are as follows:

	Location	Altitude (m)	Period
Songkla	7° 11' N, 100° 37' E	9.00	1963 - 1967
Bangkok	13° 44' N, 100° 30' E	2.30	1969 - 1977
Nakorn Panom	17° 30' N, 104° 59' E	140.00	1963 - 1967
Chiengmai	18° 47' N, 98° 59' E	313.13	1964 - 1968

Methodology

Analyses were made with the reported daily values and the dimension less values of data. The parameters used for the scaling purpose are

1. the extraterrestrial daily insolation on a horizontal surface,
2. the day length, and
3. the average values of the other five data over each month interval.

Results

Order of correlation significance

Table 1 shows the orders of significance in correlation between solar radiation and six other parameters, and the correlation coefficients for the reported values and the dimensionless values.

Correlation coefficients between solar radiation and other parameters were also determined on monthly basis. It is found that at Nakorn Panom, where the correlation between the solar radiation and the sunshine hour was highest, there existed uniformly high correlation between these pair throughout the year. The correlation coefficients vary between 0.64-0.92. This is in contrast with the other three stations where the coefficients fluctuate.

Regression analyses

Simple regressions and linear multiple regressions were developed to estimate solar radiation from other six meteorological data. For simple regressions solar radiation is obtained from the sunshine duration, the correlation between the pair is highest at all stations and with both cases of data. Stepwise regression techniques were utilized in multiple regressions using all parameters.

Table 1: Orders of correlation significance and the correlation coefficients between the solar radiation and other meteorological data.

Station	*Order of Correlation Significance*					
	Reported values			*Dimensions-less values*		
	I	*II*	*III*	*I*	*II*	*III*
Songkla	S	C	H	S	P	T
	0.73	– 0.56	– 0.53	0.78	0.67	0.66
Bangkok	S	H	C	S	C	H
	0.46	– 0.39	– 0.38	0.60	–0.53	– 0.47
Nakorn Panom	S	C	H	S	C	H
	0.79	– 0.52	– 0.46	0.85	– 0.69	– 0.60
Chiengmai	S	C	H	S	C	P
	0.54	– 0.39	– 0.35	0.61	– 0.57	0.26

Note: S – Sunshine hour.
C – Cloudiness index.
T – Temperature.
H – Relative humidity.
W – Wind velocity.
P – Pressure.

Table 2 summarizes the multiple R values for the simple and multiple regressions for both cases of data.

Simple and multiple regressions obtained for monthly basis also show consistently high values of multiple R's for the Nakorn Panom Station throughout the year.

It will be noted that

1. The correlation between the solar radiation and the sunshine hour is highest at all four stations for both cases of the reported and dimension-less values.

2. Dimension-less analyses yield higher values of correlation coefficients and multiple R's in regressions study for all four stations. This might suggest using dimension-less parameters in further work regarding solar radiation and meteorological data.

Table 2: Multiple R values for simple and multiple regressions.

Station	*Multiple R values*	
	Simple Regression	*Multiple Regression*
Songkla	0.73 /0.78	0.81/0.89
Bangkok	0.56/0.61	0.61/0.66
Nakorn Panom	0.79/0.85	0.82/0.87
Chiengmai	0.54/0.62	0.58/0.66

Note: The values are presented as those for the reported value/the dimension-less value.

CONCLUSIONS

It is concluded that the best estimation of the daily values of solar radiation at the four stations under study is made with sunshine duration. The preliminary result indicates improved relations between solar radiation and all other meteorological data when dimension-less parameters are used.

ACKNOWLEDGEMENT

The authors are indebted to the Meteorological Department, Ministry of Communications for making available the meteorological data.

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DEVELOPMENT OF SOLAR AUTOCLAVE IN THAILAND

by

T. KIATSIRIROAT, M. MUNGKORNKARN
and S. ASSAWAWIROONHAKARN

ABSTRACT

A solar autoclave was designed and tested. The autoclave consisted of a polished stainless truncated cone with an aperture of 1500 mm., tip angle of 90°, and two black painted concentric aluminum cylinders at the axis of the cone. The autoclave was tracked to follow the sun. The pressure inside the cylinder was controlled to be less than 1.1 bar (gage).

Around 550 – 650 W/m^2 of solar insolation, the warm-up period was about 40 minutes for 3 kg of the instrument load. For the load over this, the warm-up period was too long and the device was not practical to be used in cloudy days.

The solar autoclave is not very expensive, easy to operate, durable and it is developed mainly for applications in rural areas where electricity is not available or too expensive.

1. Introduction

Electric autoclave is widely used for sterlizing medical equipments. The effective sterilization will be done at 121°C around 20 – 30 minutes.

A solar autoclave was constructed to operate on solar energy instead of electricity. The materials used could be obtained in the country. They were durable and not very expensive.

2. Apparatus

The solar autoclave consisted of a reflector which was made of a polished stainless steel sheet in a truncated cone having two coaxial cylinders at the axis.

The cone had a 90° tip angle, 100 and 1500 mm. in diameters at the tip and the aperture, respectively. The black painted coaxial cylinders were at the axis of the cone which was also its focus. The diameters of the outer and inner cylinders were respectively 104 and 100 mm. Both cyliners were 750 mm. long. The gauge pressure inside was controlled not to exceed 1.1 bar by a pressure relief valve at the bottom of the cylinders so that the saturated steam temperature inside would be 121°C. An air eliminator was also placed at the bottom so that the air inside would be rejected from the cylinders.

3. Experimental Procedure

The solar autoclave was shown in fig. 1. The annular spael between the cylinders was filled approximately with water around 0.9 kg. of water and steel pieces which were supposed to be instruments were placed in the inner cylinder. The mass of the steel pieces was varied from 1, 3, 3.9 to 5.6 kg. Test were done in clear days and the warm-up periods, which were the time taken to reach the gauge pressure of 1.1 bar and the temperature of 121 °C, were measured.

4. Test Results

The variation of the warm-up period with solar radiation and mass of steel in fig. 2 shows that for the loads of the steel are over than 3 kg., the warm-up periods are too long especially at low radiations.

The variation of the steam temperature with solar radiation and mass of steel in fig. 3 shows that for the solar insolation of 600 – 700 W/m^2, the required temperature of the steam inside the cylinder at 121 °C is reached in 30, 40, 47 and 79 minutes for the loads of 1, 3, 3.9 and 5.6 kg., respectively.

Fig. 4 shows the warm-up periods of the 3 kg. load at different hours of the day. The suitable working time should be between 9.30 – 15.00 when the solar insolation is over 400 W/m^2 and the warm-up period in this range is about 40 minutes.

The solar autoclave was used for killing some types of bacteria, such as bacillus, and the result was satisfactory.

5. First cost of the solar autoclave

Materials	U.S.	$	120
Valves, gage, air eliminator	U.S.	$	60
Labour	U.S.	$	60
Others (design, blue prints)	U.S.	$	45
Total	U.S.	$	285

6. Discussion and conclusions

For this type of solar autoclave, if its aperture diameter is 1.50 m., it should not be contained the mass of steel over than 3 kg., other wise the warm-up period is too long for practical purposes unless and the solar radiation is very high.

The solar autoclave may be constructed locally in most developing countries. It is durable, easy to move and operate. The cost is not too expensive, it is therefore suitable to be used in the remote areas where solar radiation is good and electricity is not available or too expensive.

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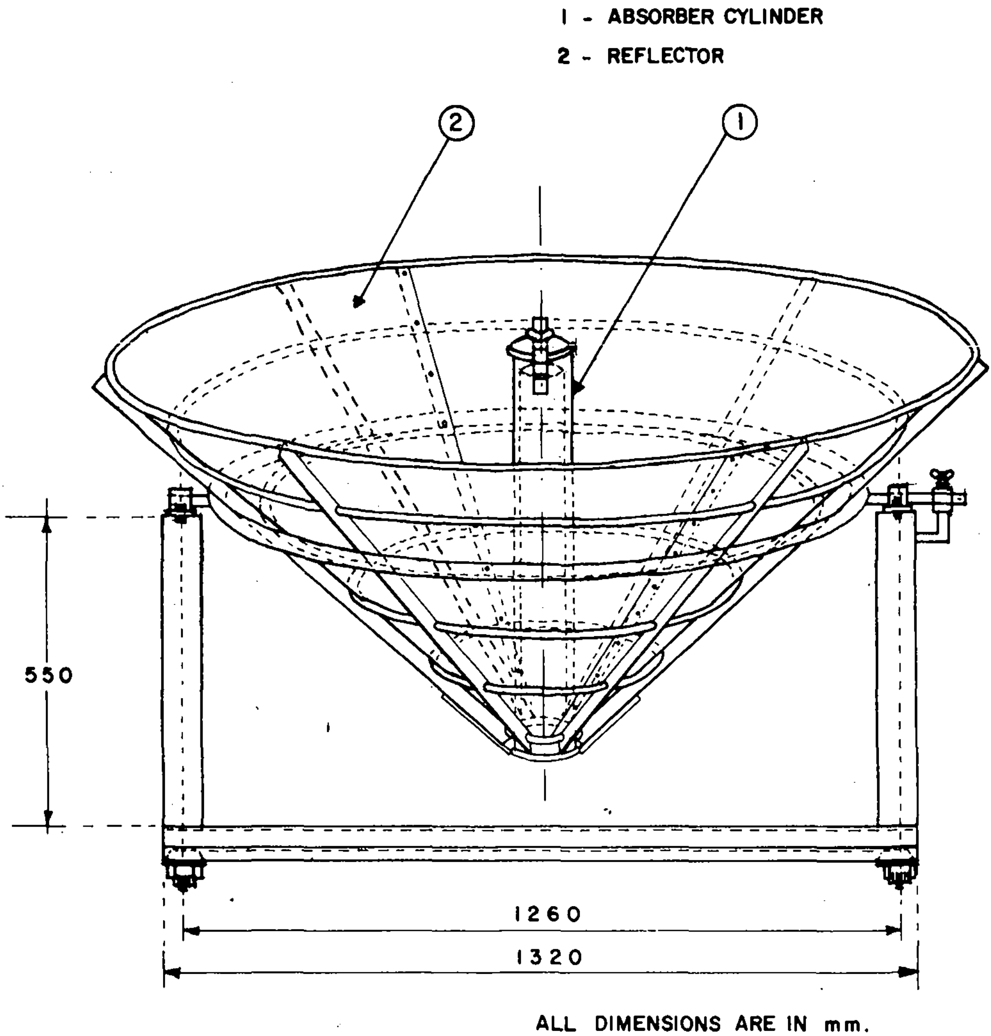

FIGURE 1. THE SOLAR AUTOCLAVE

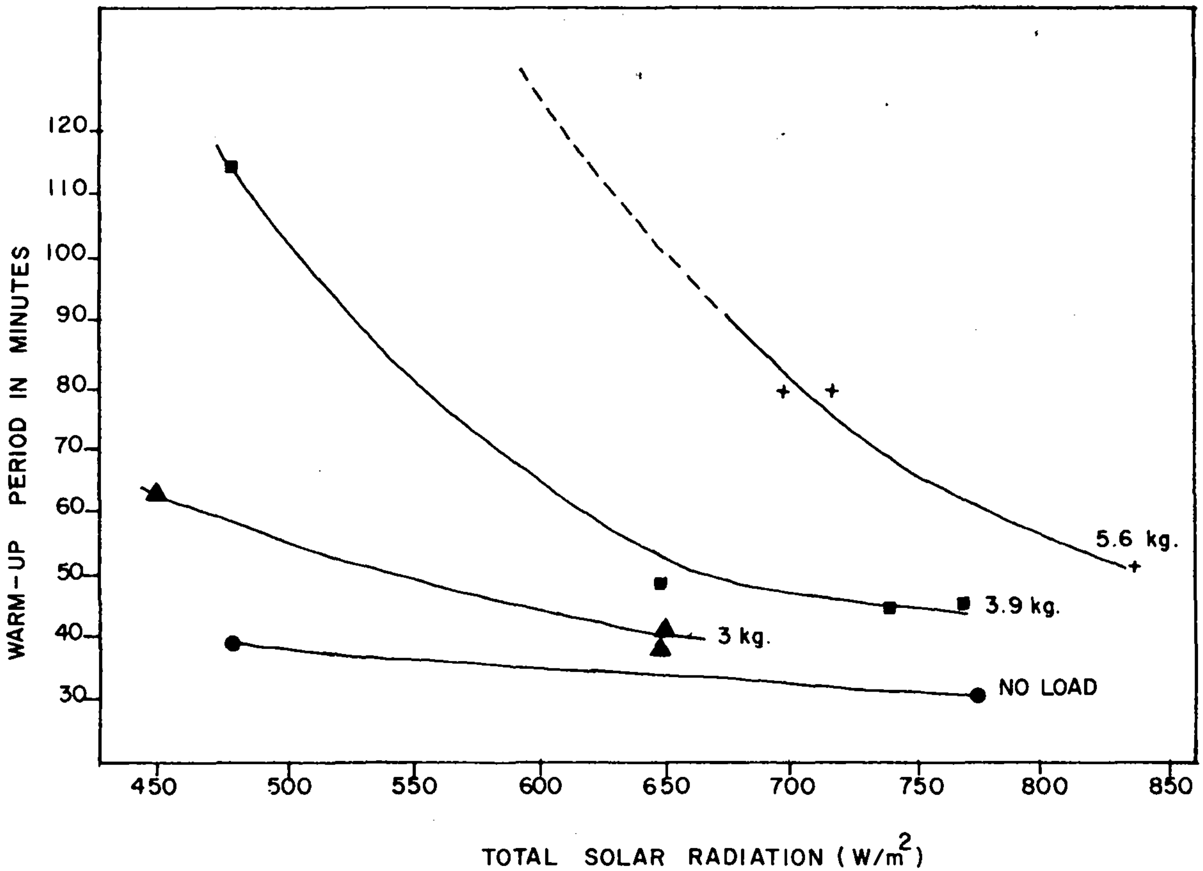

FIGURE 2. VARIATION OF THE WARM- UP PERIODS WITH SOLAR RADIATION AT VARIOUS LOADS OF STEEL PIECE INSIDE THE CYLINDERS

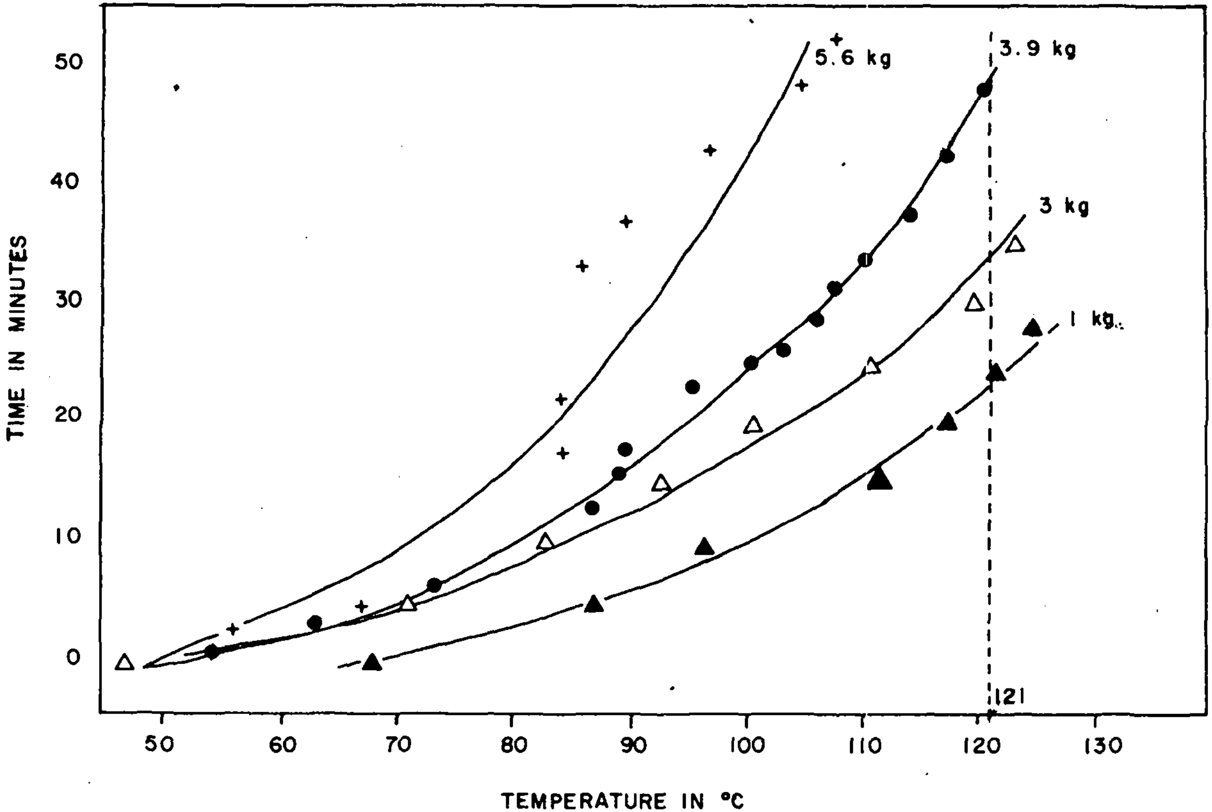

FIGURE 3. VARIATIONS OF TIME IN THE WARM – UP PERIODS AND THE TEMPERATURES OF THE STEAM INSIDE THE CYLINDERS AT VARIOUS LOADS. THE SOLAR INSOLATION 600 - 700 W/m^2

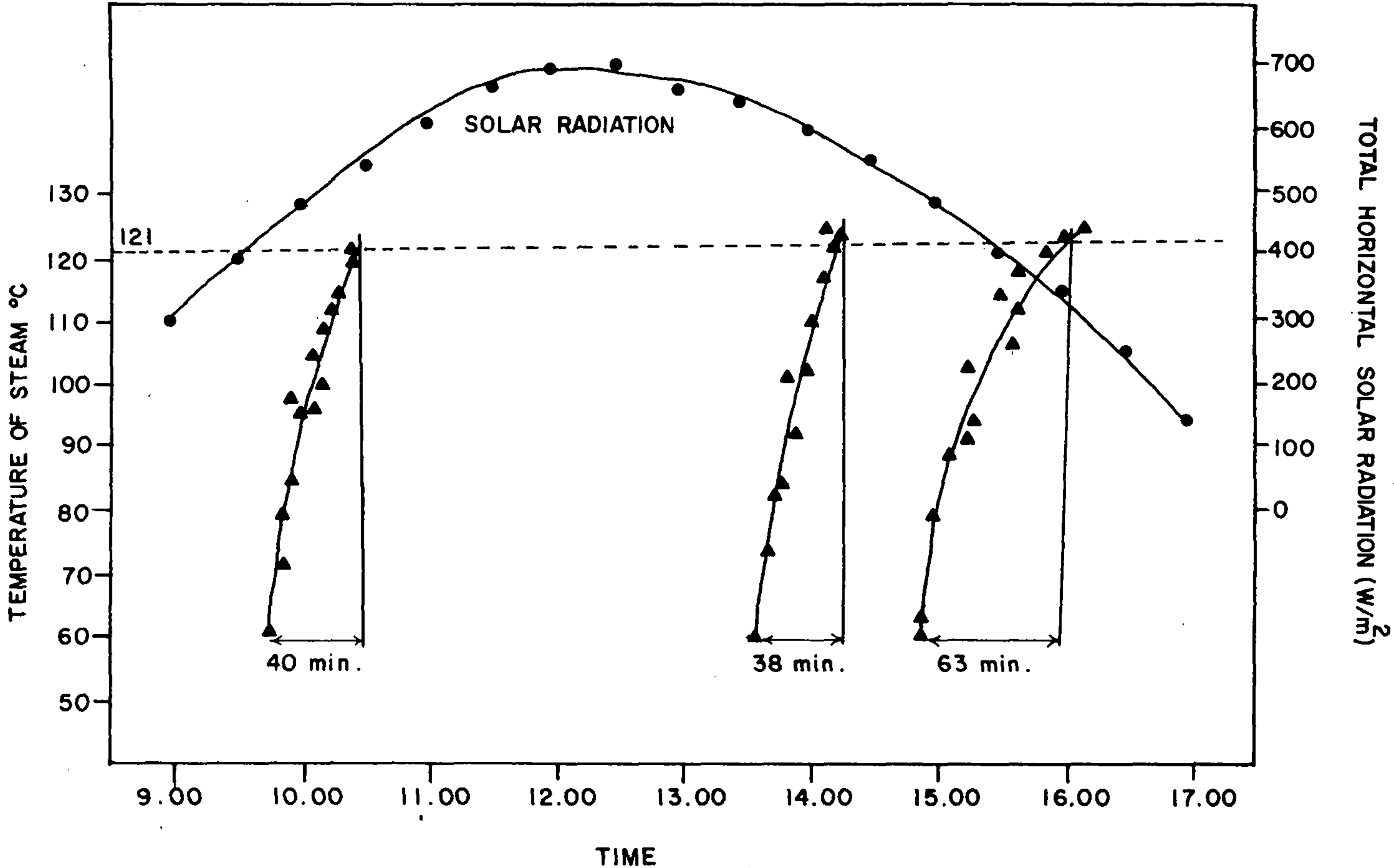

FIGURE 4. THE WARM-UP PERIODS OF THE 3 kg. LOAD AT DIFFERENT HOURS OF THE DAY

A PRELIMINARY STUDY ON RURAL ENERGY CONSUMPTION

by

SURAPONG CHIRARATTANANON

ABSTRACT

It is generally accepted that energy is an essential component in rural development. The recent energy crisis has posed a threat to the Thai rural sector, being dependent on petroleum products and such conventional sources after a decade of transformation in which emphasis has been shifted from traditional sources.

Continuing supply of energy is a prerequisite for rural development, the strategy for such development must invariably provide for the development of alternative energy sources, with emphasis on those available in the rural areas, and the technology which utilize such sources.

To achieve such objectives, an initial step is the study of rural energy resources and consumption. Some results from a preliminary study, based on information obtained from the National Energy Administration, are presented. The result give a reasonable portrait of the rural energy scene. It shows the flow of energy from external sources and rural source to the consumption activities.

INTRODUCTION

The present global energy situation and the political situation has posed a threat to the development of a country in general and rural development in particular. Such a threat involves not only short-term implications such as supply disruption and heavy deficit in balance of payment due to fuel price increase but also long-term implications on the problem of continuing supply of energy, which is as important to livelihood as food. The problem is particularly acute in developing countries which has just begun to achieve initial development, have largely based their energy sources on petroleum and its product, and possess little bargaining power.

In Thailand, the Thai rural scence has been transformed in the last decades from use of traditional fuels and human and animal labour to an increasing use of petroleum fuels. There has been a large increase in the use of farm machineries and chemical fertilizers. As the results of this study will show, the problem is more acute than generally believed, the Thai rural community is presently consuming a large amount of petroleum products. Allowing for the possible errors in the data, the total per capita consumption is much higher than would be expected.

Even though plan for development of renewable energy has been drawn and is being included in the fifth national economic and social development plan (1982-1986), a comprehensive investigation is needed for study on energy resources and consumption, energy need and demand, development of methodology for introduction and promotion of renewable energy technologies, and energy policies and implementation strategies.

This paper present results from a preliminary study based on information obtained from a pilot survey, carried out in 1979 by the National Energy Administration. A more comprehensive survey has already been completed.

Energy Resources and Consumption

Figure 1 shows the flow of energy in rural areas, with all figures in per cent. On left-hand side are shown annual resource requirements per capita. Consumption is shown on the right-hand side with division of consumption into cooking, agriculture, transportation and lighting.

Numerical figures on energy contained in the information released by NEA has all been converted to the S.I. unit of joules. This may be slightly inconvenient for those not familiar with the Thai rural community as it may prove difficult to relate to the quantity of the original fuel, but main features are not difficult to surmise. These features and other interesting information are the followings.

1. The total per capita consumption/year is 7.52×10^9 joules, which is equivalent to 4.4 m^3 of firewood. Rough breakdowns of this consumption figure are:

   56 litter of diesel oil,

   62 litter of gasoline,

   .89 m^3 firewood equivalent of charcoal, firewood and agricultural waste.

2. Most of the energy sources consumed can be described as commercial with 80% of these from established commercial network and 20% locally produced. Non-commercial energy sources account for less than 10% of the total.

3. Major energy resources are:-

   65% petroleum and its product,

   30% firewood and agricultural waste,

   5% human and animal labour.

4. Cooking, agriculture and transportation accounts for almost all of consumption, each taking for about 30%.

5. About half of the liquid fuels, petroleum, are used in agricultural and related activities. Taking the present use of chemical fertilizer and this into account, there is a

large dependence of petroleum and its products. Since agriculture is the main activity and means of livelihood in rural areas there is urgently to focus attention on the problem of providing alternative energy supply and related technological support, if the level of agricultural activities and production is to be maintained.

Implication

Figures 2 and 3 show per capita consumption and resource requirements in terms of income level, here divided into 5 classes. In figure 2 there is a stiff increase in all consumption activities with increase in income from low-income level to the middle level. This pattern suggests a stiff energy demand. To sustain development and increase in income level for the rural community, energy will be the most crucial factor. The similar pattern of resource requirement especially for liquid fuel, in figure 3 supplements this conclusion.

Short term Prediction and Contingency Planning

Figure 4 shows the use of a simple mathematical relation between energy consumption and resources, considering resources as inputs and consumption as output, connected through a transformation matrix. This mathematical model provides utility similar to input-output model used in econometrics. For a minor change in resource composition, say a 10% decrease in diesel supply, the model gives the corresponding change in agricultural activities and production, etc.,.

CONCLUSION

The high level of per capita energy consumption shown in this paper implies high dependence on petroleum products. A comprehensive investigation is needed and effort is needed for finding alternative energy sources.

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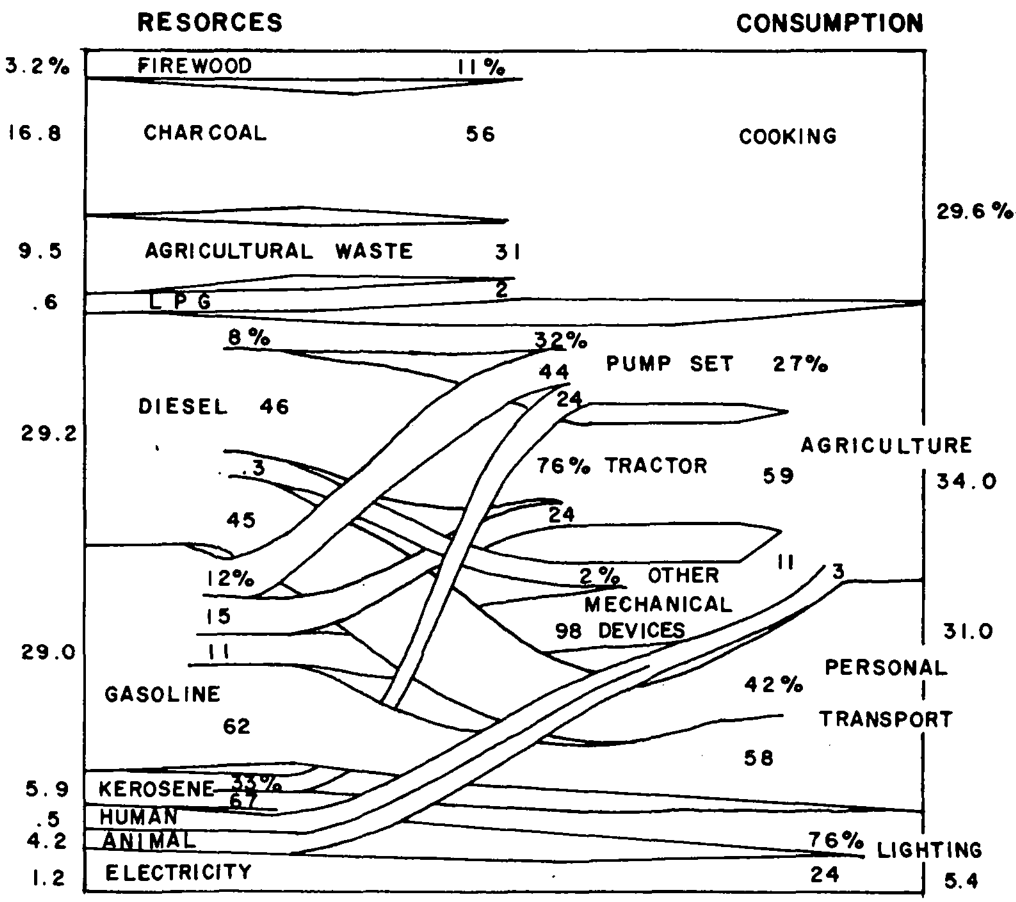
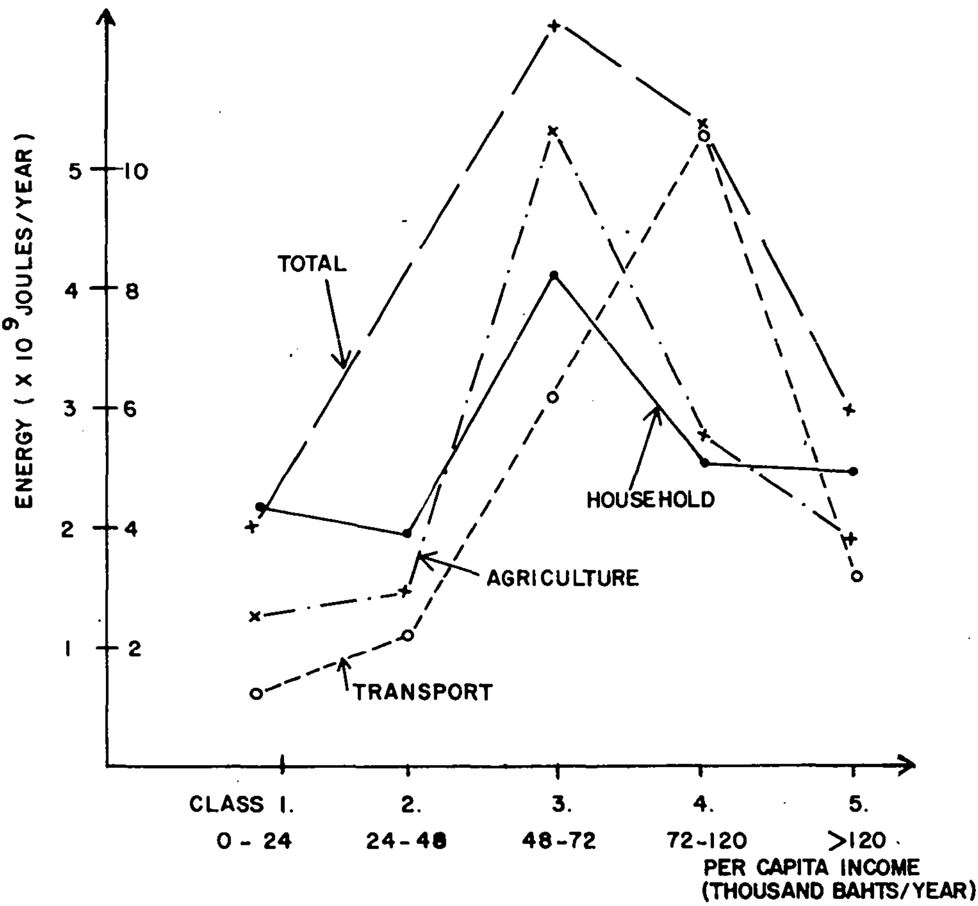


FIGURE I.

RURAL ENERGY FLOW FOR CAPITA CONSUMPTION



(INNER SCALE APPLIES TO TOTAL CONSUMPTION)

FIGURE 2.

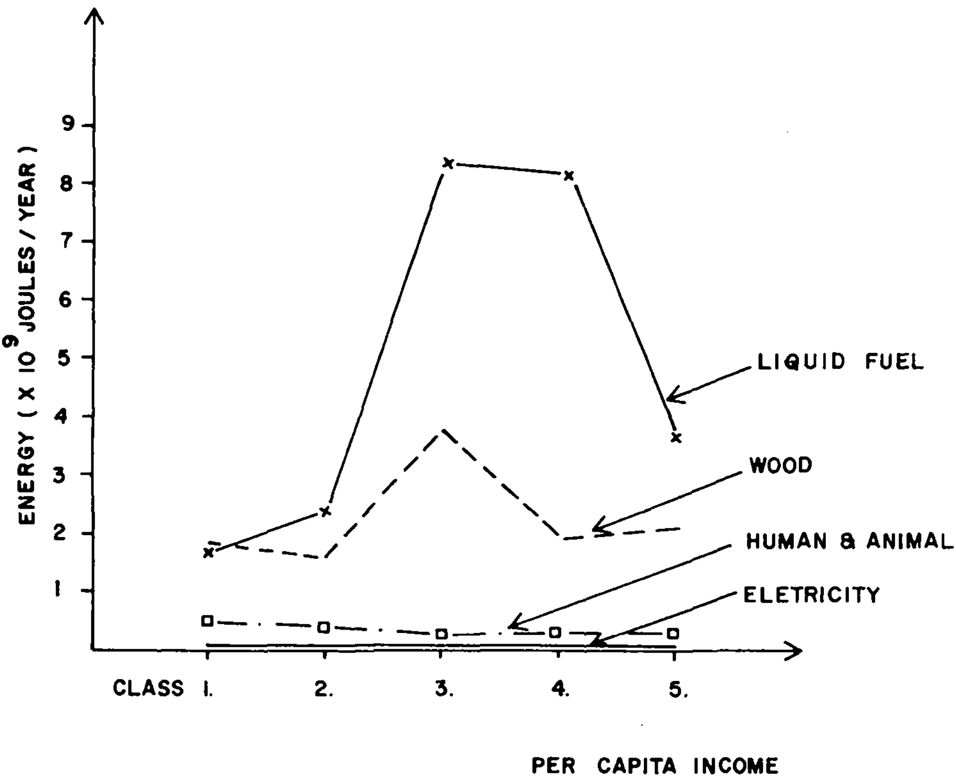

ENERGY (X 10^9 JOULES / YEAR)
9
8
7
6
5
4
3
2
1
LIQUID FUEL
WOOD
HUMAN & ANIMAL
ELETRICITY
CLASS 1.
2.
3.
4.
5.
PER CAPITA INCOME

FIGURE 3.

Consumption *Transformation matrix* *Resources (x 10^9 joules)*

$$\begin{array}{l} \text{Cooking} \\ \text{Agriculture} \\ \text{Transport} \\ \text{Lighting} \end{array} \begin{pmatrix} 2.3 \\ 2.6 \\ 2.3 \\ .42 \end{pmatrix} = \left(\begin{array}{c|c|c|c|c|c|c|c|c|c|c} 1.0 & 1.0 & 1.0 & 1.0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & .55 & .38 & .33 & 0 & 0 & 1.0 & 1.0 \\ 0 & 0 & 0 & 0 & .33 & .62 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & .007 & .0002 & .67 & 1.0 & 1.0 & 0 & 0 \end{array}\right) \begin{pmatrix} .24 \\ 1.4 \\ .71 \\ .04 \\ 2.2 \\ 2.2 \\ .44 \\ .05 \\ .04 \\ 10^{-4} \\ .04 \\ .32 \end{pmatrix} \begin{array}{l} \text{firewood} \\ \text{charcoal} \\ \text{agr. waste} \\ \text{LPG} \\ \text{diesel} \\ \text{gasoline} \\ \text{kerosene} \\ \text{PEA} \\ \text{Loc.Gen.} \\ \text{battery} \\ \text{human} \\ \text{animal} \end{array} \begin{array}{l} \\ \\ \\ \\ \\ \\ \\ \text{Electricity} \\ \\ \\ \\ \\ \end{array}$$

Figure 4

IS PHOTOVOLTAIC SOLAR CELL TECHNOLOGY SUITABLE FOR THAILAND?

by

SOMSAK PANYAKEOW, MANOON ARAMRATTANA,
MONTRI SAWADSARINGKARN, BUNYONG TOPRASERTPONG
and PIERRE BERNOUX

ABSTRACT

The technology to produce the photovoltaic solar cell is highly developed in industrialized countries. The technology has been transferring in many developing countries. Thailand is one of them. However, all out effort to producing solar cells is still lacking due to the reluctancy of energy-policy decision maker.

The paper is presenting the technology and applications of solar cells that are potentially existing in Thailand. The feasibility and benefits by using solar cells are also pointed out. Research and development of solar cell technology at the Semiconductor Device Research Laboratory (SDRL), Faculty of Engineering, Chulalongkorn University, is described. Research and development of appropriate technology is also discussed, e.g. Nickel Electroless Planting, Chemical Vapour Deposition, Paint-on Diffusion.

Finally, the authors propose to have more international cooperation at all levels if photovoltaic solar cells are to be used in large scale energy production and to be commercialized. The proposal emphasizes on short term and long term planning for photovoltaic solar cell manufacturing including the necessary infrastructure of the industry.

1. Introduction

Photovoltaic solar cell technology has been developed since 1954. Unfortunately, little attention was paid to such an important achievement. Subsequently, applications of photovoltaic solar cell were limited. However, the technology was considered too expensive and difficult to be economical at the time. Only special applications utilized solar cells when maintenance-free and weight are the prime concern such as in the space programme.

Due to political situation in the Middle East, the energy problem has been developed into a crisis ever since 1973. Many countries begin to look for new sources of energy rather than the petroleum. Therefore, research and development of photovoltaic solar cell has been increasingly important. In fact, the progress of the solar cell technology has been increased many folds in recent years as compared to that between 1954 to 1973. Solar cell today have better efficiency, rugged and lower cost.

At present technology, much accomplishment were obtained through the use of silicon as the starting material. As can be projected in the near future, silicon will still be suitable starting material. However, the cost-performance of silicon solar cells are not quite satisfactorily. Search for new solar-cell materials has also been a current concern.

Therefore, the main task for research and development of silicon solar cells in Thailand must be to improve the cost-performance of the cells. This can be done through appropriate techniques and utilization of the national resources as much as possible. Some effort on such targets has been originated at the Semiconductor Device Research Laboratory (SDRL), Faculty of Engineering, Chulalongkorn University, Bangkok. In spite of many obstacles, the main concern of the SDRL is to meet the challenging task. The activities of the SDRL is published separately in the introduction of SDRL booklet.

With the present status of research and development of photovoltaic solar cell technology and the experience gained at the SDRL, the authors are confident that if proper planning and continuous support from the government is committed, photovoltaic solar cell technology will certainly developed to be suitable for Thailand.

2. Research and Development on Photovoltaic Solar Cell at Semiconductor Device Research Laboratory (SDRL)

The SDRL was originated in 1975 at the Faculty of Engineering, Chulalongkorn University, Bangkok, Thailand with the principal equipment donated by the Government of France. The main objective of the SDRL is to provide, as a research laboratory and facilities for research and development for educational and training purposes. The other objectives are to research and develop certain semiconductor devices, such as solar cells, power electronic devices and radiation detectors which are also considered to be benificial to Thailand economy in the future.

Among the semiconductor devices mentioned above, solar cells have been the main research and development of the SDRL in the past years. After basic know-how of the processing is understood, Schottky barrier solar cells were fabricated. From then on, various related research topics to solar cells have been conducted at the SDRL. The current studies on solar cells are the concentrated sunlight systems and their applications. In fact, a research contract has been given to the SDRL, by the Electricity Generating Authority of Thailand (EGAT), to launch a pilot project of building a solar cell module.

The fabrication of solar cells at the SDRL is based on the standard planar process for integrated circuits. The brief outline of the process is given in figure 1. Monocrystalline Silicon is also used as starting semiconductor material.

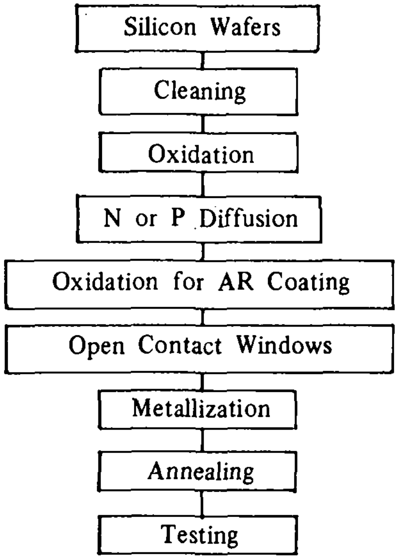


Figure 1. Fabrication process of silicon solar cells at the SDRL.

Typical characteristics measured at 100 mW/cm^2 light intensity of silicon solar cells fabricated at SDRL are as follows.

Open Circuit Voltage	(V_{oc})	=	0.52 Volts
Short Circuit Current	(I_{sc})	=	20 mA/cm^2
Fill Factor	(F.F.)	=	0.76
Efficiency	(η)	=	8%

Many technical problems, such as better quality of gas, water, chemical and cleanliness of the laboratory atmosphere, should be improved in order to obtain higher efficiency of the solar cells with more production yield and reproducibility.

3. Suitability of Photovoltaic Solar Cell Applications in Thailand

Due to geography and distribution of electrical network in Thailand, technological suitabilities from developing solar cell technology are as the following:

1. High average solar radiation per unit area and at longer exposure time.[1]

2. The incomplete rural electrification.

3. The utilization of technological gains as the basis of modern industry development.

With such a high average solar radiation available through out thailand, it is high hopes for technologist to be able to utilize the immense amount of energy from the sun. At the mean time, the need of energy in the rural areas for agriculture has been increasing constantly. Electricity is one form of energy that is convenient, hence, popular energy to consume. Unfortunately, the availability of electricity is not well distributed in Thailand, especially, in the isolated rural areas. The cost of electricity production is also increasing. Therefore, solar cells can be utilized to ease the problems in the areas. A cheap and maintenance-free solar cell power module is a promising system that much of the attention has been paid by the EGAT recently.

In addition, the technical merit gained from the solar cell technology can also be beneficial to other related industries, such as semiconductor assembly plants and the like.

However, in order to back-up the solar cell production in Thailand, there are number of factors that must be improved and created. That is

1. To utilize the more appropriate technology,

2. To create more engineers and technicians with proper education and training to accompany the technology,

3. To create proper infrastructure for the solar cell industry.

The sophistication of the technology has, in fact, slowly been improving. The main obstacles are the availability of technical information and of the sophisticated analytical equipments and instrumentation. To effectively obtain the improvement, a technical information center and a central analytical research laboratory must be established.

At present, universities and various research institutes in Thailand must emphasize the curriculum and policy to produce more qualified personnel in line of the technology, such as Material Sciences, Process Engineering and Device Engineering. In addition, special training are also needed to increase competency of the personnel.

Eventhough a sophisticated technology and competent personnel are available, good quality of the cells cannot be obtained without high quality materials and consumable products. These materials include proper semiconductor wafers, electronic-grade chemicals, and high purity gas and water. Therefore, infrastructure for these consumable materials is also essential.

4. Appropriate Technology for Solar Cell Fabrication at the SDRL

In spite of the availability of sophisticated technology and high quality materials from abroad, it is also vital to self-develop appropriate techniques in order to simplify the process and reduce operating cost. The development has been carried out at the SDRL. These appropriate techniques are

1. Nickel electroless plating[2]
2. Chemical Vapor Deposition (CVD)[3]
3. Paint-on diffusion[4]
4. Anodic Oxidation[5]
5. Life-off Metallization[6]

These techniques were developed in the effort of reducing the operating cost, especially, the electrical energy. Therefore, these techniques are mostly low-temperature operations. Some of the techniques are currently being developed.

However, these techniques will be further developed so that equivalent performance of the solar cells to that of standard process is achieved.

5. Proposal on International Cooperation

The authors would like to put forward a proposal for some possibility of international cooperation on solar cell research and development. This proposal conceived from the fact that the SDRL was originated through the international cooperation between the Thai government and the Government of France. The additional technical cooperation has also been assisted from Japanese research institutes. Such cooperation has proved to be valuable to the SDRL in particular and to Thailand in general. Therefore, a larger scale of cooperation is believed to be qually beneficial for solar cell research and development in this region.

In more specific, the SDRL, French and Japanese research institutes have been exchanging both technical experience and personnel in order to enhance the quality of research at the SDRL. The technical experience received by the SDRL personnel has been the important basis for the development of appropriate techniques in solar cell fabrications. Such techniques are important in order to search for economical way of solar cell production which is suitable in a developing country such as Thailand. The continuing cooperation at the present situation will undoubtedly accelerate in reaching the long range objectives of the SDRL. That is to successfully use the solar cell technology in actual application; such as in telecommunication, portable power generator for agricultural applications and other applications in isolated areas.

From the example and experience at the SDRL, the authors feel that photovoltaic solar cell technology can have sooner and effective impact on life in isolated area if a more extensive and better international cooperation agreement can be set up among countries in this region. It is realized that similar cooperation may not exist in other countries, but it is mostly among developed and developing countries. The proposal here is to set up a better cooperation among developing countries as well as a better support from the developed countries. The cooperation is basically on technical information and personnel exchange. Consequently, appropriate techniques developed by each institute can be learned and developed at the others for suitability. Periodic technical conferences on photovoltaic solar cell technology must be held among developing countries. By doing this, one can save research operating time and cost which will help one's progress faster.

To realize the independent development an solar cell technology in developing countries, developed countries can play another role of international cooperation. That is to assist the research work in developing countries by giving an opportunity for those researchers in developing countries to use the expensive analytical equipments and instrumentation existing in developed countries. Some analytical equipments and instrumentation, which are necessary for solar cell development, e.g. Scanning Electron Microscope, Auger Spectroscopy, Nuclear Magnetic Resonance, Electron Spin Resonance, etc., do not exist in developing countries due to high operating cost and maintenance. Those analytical informations will guide the researchers from developing countries to the most effective direction of research and development for their own suitability.

Last but not least, the infrastructure for solar cell industry is equally essential to the research and development. Beyond the technical area, each institute must have supporting industries so that one can conveniently purchase consumable materials such as electronic-grade chemicals, semiconductor wafers, high purity metals and etc. Such industries may not exist or may exist only some in each country. Therefore, in order to accelerate the progress of research and development of solar cell industry, each government should put forward a national policy to develop such an infrastructure.

6. Conclusion

Suitability of photovoltaic solar cell application in Thailand was discussed. Geographical condition and present situation of technological level are considered in order to answer the question. The establishment of necessary supporting facilities and the improvement of some appropriate technology are required for the independency of solar cell industry in Thailand. Finally, the international cooperations, both among developing countries of the same technological level and between developing countries and developed countries, are proposed to effectively stimulate the regional research and development of photovoltaic solar cell technology in the future. Hopefully, with close cooperation of many countries, solar cells will become a common source of electricity in isolated rural areas.

7. Acknowledgement

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EFFECT OF HEAT CAPACITY ON FLAT-PLATE SOLAR ENERGY COLLECTOR PERFORMANCE

by

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ABSTRACT

In the operation of flat-plate collectors, there are losses in net energy gain because of transient effects. The most severe loss is usually associated with the heating of the absorber plate from its early morning low temperature to operating temperature. This paper shows that commonly used methods for calculating these losses are incorrect at a critical juncture: in the final calculation of loss in useful gain. A revised approach to this final step in the calculations is presented. Examples are used to show quantitatively the error in the previous methods for several cases. The common assumption that the warm-up loss is equal to the gain in stored interval energy in the absorber plate is shown to exaggerate the loss substantially. On the other hand, the assumption that the losses are equal to the difference in plate energy loss between that of a theoretical zero-mass collector and that of the real collector, is shown to underestimate the loss. Both methods are used in the literature. A simple closed solution for losses, utilizing the single-node method, is presented. The equation gives the loss in useful gain as a per cent of the maximum possible loss for simple transient episodes.

NOMENCLATURE

A_c	collector area
F_R	collector heat removal factor
I_c	incident radiation normal to the plane of the collector
I_{th}	threshold value of incident radiation normal to plane of collector
$(mc)_p$	heat capacity of absorber plate and contents
$(mc)_g$	heat capacity of cover
$(mc)_e$	effective heat capacity of absorber $= (mc)_p + \frac{U_c}{U_\infty}(mc)_g$
T_a	ambient temperature
T_p	absorber plate temperature
$T_{p_{th}}$	absorber plate temperature when $I_c = I_{th}$
T_{p_o}	initial temperature of absorber
T_{f_i}	final temperature of absorber plate
t	time
t_o	initial time
t_{th}	time when $I_c = I_{th}$

Greek letters:

$\tau\alpha$	effective transmittance–absorptance of cover/absorber
τ	time constant of collector
η	collector efficiency

INTRODUCTION

In the design of flat-plate solar energy collectors for optimum cost effectiveness, and for predicting the expected contribution of a solar collector array to a given annual heat load, the thermal capacity of the collector components must be properly considered along with other collector and meteorological parameters. The thermal capacity of collectors vary from a minimum of approximately 1 $KJ/m^2 - K$ upwards to 50 $KJ/m^2 - K$. Because of this great range in values of total specific heat, it is important that reasonably accurate estimates be made of effects of transients on collector performance.

The purpose of this communication is to develop a physically valid basis for calculating warm-up losses, and to present this approach as an alternative to methods currently in use. Presently the warm-up loss is taken as the increase in energy stored in the collector system between the moment the incident radiation reaches the threshold value for zero efficiency and the time of shut-down. This approach may appear to have a physically logical basis, but it ignores the interaction of energy losses and energy accumulation in the collector during transients. It is easy to compute from numerical solutions. This method is recommended in [1] and [2]. Alternative methods described in the literature also appear to be incorrect.

However, this paper is not a comment on methods of calculating transient response using models that include the thermal capacity of the collector plate, such as for example the work of Close [3], Morrison and Ranatunga [4], and Klein [5]. Neither is it a comment on transients caused by factors other than thermal capacitance of the absorber. It questions the conclusion of Klein *et al.* [5], that losses due to thermal capacitance of absorber and other collector components have a negligible impact on collector performance, because as will be shown, the formulation for losses and is incorrect and underestimates them.

It is also implied that programmes which do not account for thermal capacitance of the collector components, such as TRNSYS [6] could give misleading results for certain collection systems with unusually high thermal capacitance, such as vacuum tube collectors. In this paper, the loss due to transients is taken to be the difference between the useful energy which a hypothetical zero-mass collectors would realize over a given interval of time, and that realized by the real collector. Both collectors are of course identical in all respects other than heat capacity. For illustrative purposes, a simple transient case is chosen wherein the collector is warmed up to a specified operating temperature and subsequently operates at steady state. The single-node approach is used throughout the paper.

MATHEMATICAL FORMULATIONS AND EXAMPLES

As mentioned earlier, the solution presented here is for the simple warm-up from the early morning low temperature to a presumed steady-state operating condition. For simplicity, the collector temperature is usually assumed to be equal to ambient temperature, at the start of the warm-up episode, and this temperature is assumed to be zero ^{o}C. The one-node model is employed. The differential equation for plate temperature is derived from the first law of thermodynamics and is:

$$[(mc)_p + \frac{U_c}{U_\infty}(mc)_g]\frac{dT_p}{dt} = [(\tau\alpha)I_c - U_c(T_p - T_a)]A_c \quad (1)$$

In this formulation, the assumption is made that there is one cover, and that the collector plate heat loss and cover heat loss are proportional. Integrating T, assuming I_c and T_a are constant, and substituting in the limits

$$\frac{T_p - T_a - (\tau\alpha)I_c/U_c}{T_{p_o} - T_a - (\tau\alpha)I_c/U_c} = \exp\frac{-t}{((mc)_p + (U_c/U_\infty)_c(mc)_g)/U_cA_c} \quad (1a)$$

For the type of transient episode chosen, the threshold value of I_c is of great importance in evaluation of losses. This quantity is the intensity of radiation normal to the plane of the collector which just yields zero efficiency. This value depends on the temperature selected arbitrarily to be the collector inlet fluid temperature. In the analysis that follows, the collector is assumed to start operation without any controls hysteresis, so that the final temperature of all warm-up episodes is T_{f_i} = const.

$$I_{th} = \frac{U_c(T_{f_i} - T_a)}{(\tau\alpha)} \quad (2)$$

or

$$\frac{U_c}{(\tau\alpha)} = \frac{I_{th}}{T_{f_i} - T_a}$$

Substituting this into equation (1a) with T_a set equal to zero yields:

$$\frac{T_p - I_c/I_{th}\,T_{f_i}}{T_{p_o} - I_c/I_{th}\,T_{f_i}} = \exp - \frac{t - t_o}{\tau} \quad (3)$$

Normally, I_c will be given as a function of time. The real variation of I_c with time is approximated by a series of step changes, and equation (3) utilized to obtain the plate temperature as a function of time. The time when I_c reaches I_{th} is assumed known. Th The time when $T_p = T_{f_i}$ is calculated from (3). The warm-up loss is the energy collection of the hypothetical zero-mass collector over interval from the time when $I_c = I_{th}$ to the time when $T_p = T_{f_i}$.

It is instructive to consider first only step change in I_c from zero to some arbitrary value. If I_c increases in this way to a value below I_{th}, the problem is trivial, since there is no useful energy gain possible even with a zero-mass collector. Hence there can be no loss in useful energy associated with such a step change. If I_c increases in a single step to $I_c > I_{th}$, the zero-mass collector responds instantly and begins instaneously to collect energy. The warm-up time of the real collector follows from equation (3) as

$$t - t_{th} = -\tau \, \ell n \left(1 - \frac{I_{th}}{I_c}\right) \tag{3a}$$

The loss in useful gain is

(Energy collected by zero-mass collector)

$-$ (Energy collected by actual collector) $= A_c \eta I_c (t - t_{th}) - 0$

or

$$A_c F_R \left[(\tau\alpha) - \frac{U_c (T_{f_i} - T_a)}{I_c}\right] I_c (t - t_{th})$$

Equation (3a) is used to eliminate the time, and the result is

$$\text{warm-up loss} = -A_c F_R [I_c (\tau\alpha) - U_c T_{f_i}] \, \tau \, \ell n \left(1 - \frac{I_{th}}{I_c}\right) \tag{4}$$

In order to relate this loss to the previously used change in energy storage of the actual collector, an energy balance is written for both the real and imaginary collector during the time interval of the transient process.

Energy balance for zero-mass collector:

$$(I_c A_c (\tau\alpha)) (t - t_{th}) = (U_c A_c) (T_{f_i} - T_a) (t - t_{th}) + q_u'$$

energy balance for the actual collector

$$(I_c A_c (\tau\alpha)) (t - t_{th}) = \int_{t_{th}}^{t} U_c A_c (T_p - T_a) \, dt + \text{energy storage in real collector}$$

The energy storage in the real collector is

$$((mc)_e)\ (T_{f_i} - T_{p_{th}})$$

where $T_{p_{th}}$ is the plate temperature of the real collector at the time the incident radiation reaches the threshold value. For the simple transient episode under consideration, $T_{p_{th}} = T_{p_o} = 0$. Therefore the storage term is

$$((mc)_e)\ T_{f_i}$$

Equating the right-hand members of the above energy balance equations, and solving for q_u, the warm-up loss is

$$q_u' = \begin{matrix}\text{warm-up}\\ \text{loss}\end{matrix} = \int_{t_{th}}^{t} U_c A_c (T_p)\,dt + (mc)_e T_{f_i} - U_c A_c T_{f_i} (t - t_{th}) \tag{5}$$

Since T_p is a known function of t, the first term in the right-hand member of equation (5) can be integrated.

From equation (3):

$$T_p = \frac{I_c}{I_{th}} T_{f_i} \left(1 - \exp - \frac{t - t_{th}}{\tau}\right)$$

Therefore

$$\int_{t_{th}}^{t} U_c A_c T_p\,dt = \int_{t_{th}}^{t} \frac{I_c}{I_{th}} T_{f_i} \left(1 - \exp - \frac{(t - t_{th})}{\tau}\right) dt$$

Integrating yields

$$\int_{t_{th}}^{t} U_c A_c T_p\,dt = U_c A_c \frac{I_c}{I_{th}} T_{f_i} \left[(t - t_{th}) + \tau\left(e^{-\frac{t - t_{th}}{\tau}} - 1\right)\right]$$

Substituting this into equation (5), utilizing the relationship

$$U_c A_c = \frac{(mc)_e}{\tau}$$

the warm-up loss is

$$\text{warm-up loss} = (mc)_e\, T_{f_i} \left[\frac{(t - t_{th})}{\tau} \left(\frac{I_c}{I_{th}} - 1\right) + 1 + \frac{I_c}{I_{th}} \left(e^{-\frac{t - t_{th}}{\tau}} - 1\right)\right] \tag{6}$$

of course equation (4) is simpler to use, but equation (6) shows the loss in terms of the energy stored in the collector.

The warm-up loss as obtained from equation (6) will now be calculated for the following special cases:

case 1: $\quad I_c = \lim_{\delta \to 0} (I_{th} + \delta)$

case 2: $\quad I_c \to \infty$

case 3: $\quad I_c = 5\, I_{th}$

Case 1. From equation (3a), the warm-up time, $t - t_{th} = \lim - \tau \, \ell n\, \tilde{0}$. So the warm-up time increases indefinitely, as the step change in I_c approaches I_{th} in value. When the warm-up loss is solved for using equation (6), the result is zero. (The indeterminant form must be evaluated.) To make this result more meaningful, the time required for the plate to come up to a temperature of $.9\, T_{f_i}$ is calculated. From equation (3),

$$\frac{.9\, T_{f_i} - T_{f_i}}{-T_{f_i}} = \exp - \frac{t - t_{th}}{\tau} \qquad \text{or} \qquad t - t_{th} = 2.3\, \tau$$

Thus, a dwell time of the incident solar radiation at the threshold value for a period of time equal to about twice the time constant of the collector produces a significant effect and largely eliminates warm-up losses.

Case 2. In the hypothetical case of a step increase in radiation to an infinite value, equation (6) in its given form is indeterminant. However, the quantity

$$e^{-\frac{(t - t_{th})}{\tau}}$$

can be expanded in a Taylor's Series, and the indeterminant feature of the equation removed. The quantity in brackets then becomes unity. Thus warm-up loss = $(mc)_e\, T_{f_i}$. In order to obtain a meaningful result for the maximum warm-up losses for the assumed model (obviously, I_c never goes to infinity), we proceed to case 3.

Case 3. A single-cover collector with a selective black absorber will have a loss coefficient U_c near 3.5 W/m^2 °C, and a $(\tau\alpha)$ could be 0.70. With a value of $T_{f_i} = 40°$ C, $(T_a = 0)$,

$$I_{th} = \frac{U_c\,(T_{f_i} - T_a)}{(\tau\alpha)} = \frac{3.5 \times 40}{.7} = 200\ \mathrm{W/m^2}$$

A value of $I_c = 5\, I_{th}$ is close to the maximum intensity realistically possible. The warm-up time for this situation is obtained from (3a) as

$$t - t_{th} = -\tau\, \ell n\, (1 - .2) = 0.22\, \tau$$

and the warm-up loss, from equation (6) is

$$\text{loss} = (mc)_e\, T_{f_i}\, [.22\,(4) + 1 + 5\,(e^{-.22} - 1)] = .9\,(mc)_e\, T_{f_i}$$

Accordingly, in the most severe transient situation likely to be encountered, the loss is 10 per cent less that the increase in energy storage in the plate.

Figure 1 shows a plot of collector loss due to transient effects in simple warm-up episodes wherein the initial ambient and plate temperatures are both equal to zero, and the radiation increases in a single step from zero to some arbitrary value. This figure is representative of losses associated with changing cloud cover, or to shading effects.

During collector operation on clear days without shading effects due to clouds or otherwise, the increase in I_c is gradual, and associated loss in useful gain is less than for sudden increases. As an example of effect of transients in an "average day" situation, the average radiation for the month of January is taken for Great Falls, Montana, and warm-up losses calculated. The collector is assumed to have a constant value of $(\tau\alpha)$ of 0.70, a heat removal factor F_R of .85, a loss coefficient of 3.5 W/m^2 °C, and an effective heat capacity of 50.4 KJ/° C. The water inlet temperature is constant and equal to 60° C. The collector is assumed to be vertical and has an area of 2 m^2. Table 1 gives the incident radiation. The ambient temperature is assumed to be constant at −5° C.

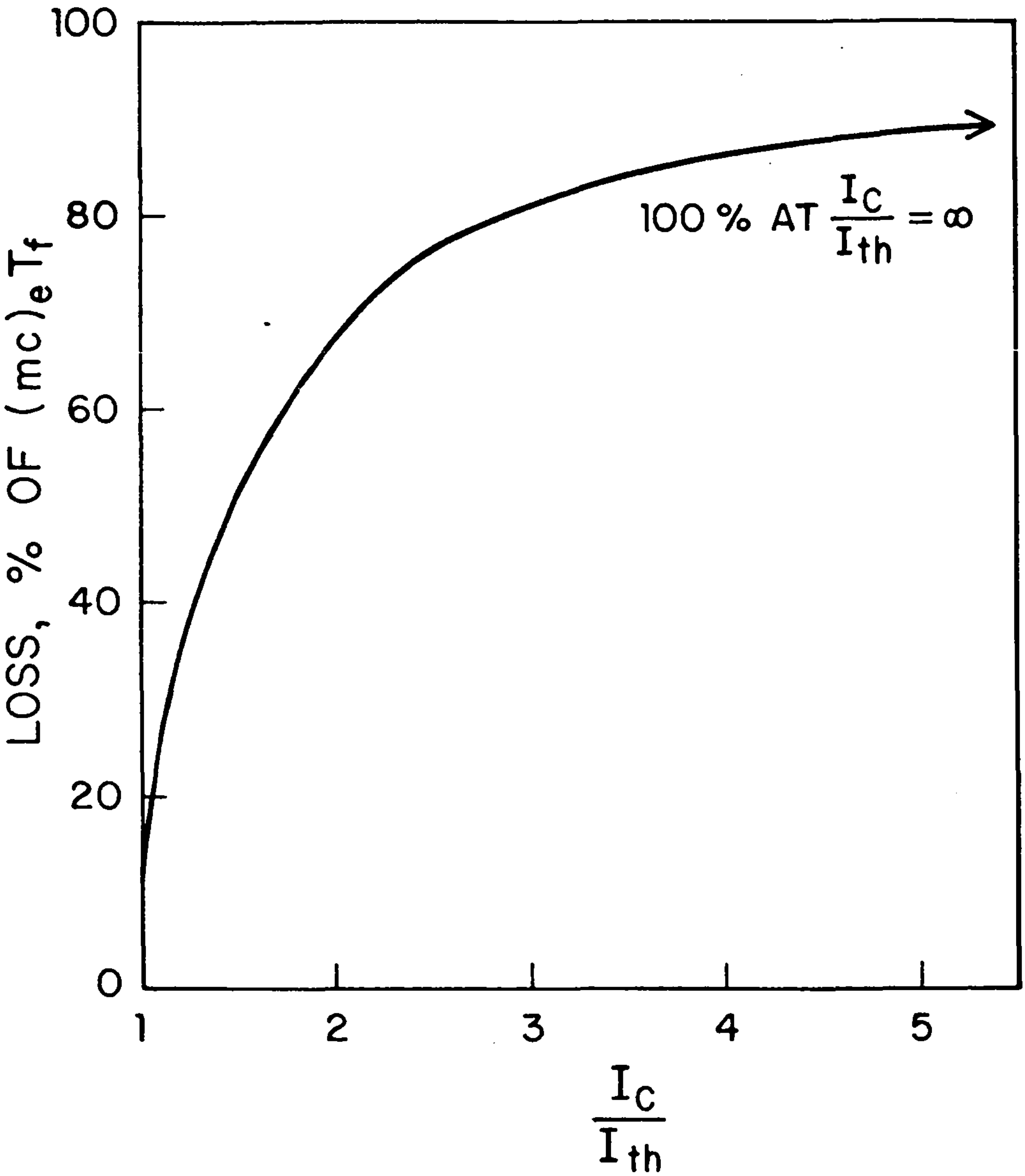

Figure 1. Plot of warm-up loss as a percent of increase in stored energy in the absorber plate, step increases in I_c from zero, initial plate and ambient temperatures zero.

Table 1. Effect of transients on useful energy gain on a clear day.

Time	I_c W/m^2	T_p ^oC	q_u *zero mass*
7	0	−5	–
8	72	0.7	–
9	350	26	30
10	520	55	232
11	615	60	345
12	646	60	382
13	615	60	345
14	520	60	232
15	350	60	30
16	72	–	–
	3760	3291	

The collector has a time constant of 120 minutes. Using equation (1a) for the various step changes in I_c, the temperature of the plate is found to reach 55°C by 10:30. The same equation is used for the 10:30 to 11:30 step change to obtain the time when the collector plate reaches 60°C. The time is found to be 10:40. The threshold value of I_c is 325 W/m^2. The gain for the zero-mass collector is calculated using the steady-state efficiency equation, which is

$$q_u = A \eta I_c = A F_R \left[(\tau\alpha) - \frac{U_c (T_{f_i} - T_a)}{I_c}\right] I_c$$

The reduction in useful energy gain is all the energy collected by the zero-mass collector up to 10:40, or

$$30 + 232 + \frac{10}{60} . 345 = 320 \text{ W–hrs} = 1150 \text{ KJ}$$

The loss in useful gain using the previous method would be the increase in energy storage in the collector plate during the interval of time when I_c is above 325. Since I_c increased through the threshold value at 8:30, and the plate temperature at this time is 0.7°C, the energy storage quantity is

$$50.4\,(60 - .7) = 2989 \text{ KJ}.$$

Accordingly, the previous method leads to an estimate that is about three times greater than that calculated using the correct method. But it is not evident that this formulation, which overestimates effects of transients, has been used in the extensive simulations that have led to f-chart and other correlations. In the often referenced work on transients by Klein *et al.* [3], the transient loss is taken to be the difference between the energy loss from the zero-mass collector plate and that from actual collector. From equation (5)

[Energy loss, zero-mass collector – Energy loss, real collector]

= [Energy accumulation in absorber] – [Actual warm-up loss]

Clearly the difference between energy losses of the zero-mass and real collector cannot be taken as the loss in useful gain.

CONCLUSION

The increase in internal energy of a solar collector "equivalent" absorber, is not a valid measure of loss in useful energy gain during transient operation of a collector. This increase is theoretically correct only for situations wherein the incident radiation increases suddenly from zero to an infinite value. As a maximum, the loss in useful gain is about 90 per cent of the plate internal energy increase. For step changes in I_c to values above but approaching the threshold value of I_c, the loss in useful gain is zero. When I_c increases gradually, losses are less than for rapid changes in I_c between the same end states. A practical consequence is that early morning shading of a collector has a more adverse effect on performance than previously thought to be the case. The loss formulations associated with transient in several texts and also in some of the literature are inconsistent with the physics of the transient process. Except for collectors having high thermal capacitances, the resultant error in commonly available correlation for annual performance of solar systems is small.

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RESEARCH AND DEVELOPMENT ON ALTERNATIVE SOURCES OF ENERGY IN VIET NAM

by

VAN VI TRAN

ABSTRACT

The energy problem is common to all countries. It is the most significant requirement to meet the needs of the developing countries, like Viet Nam. Since the enrgy crisis, Viet Nam is facing the most fundamental problem on energy in which the skyrocketting cost of imported crude oil and its derivative products have drained rapidly her foreign exchange earnings. They are, in turn, to be reserved to purchase machinery and equipment for the reconstruction programmes.

Scientists and engineers of different institutions of high learning in Viet Nam, with the guidance of the State Commission of Science and Technology are conducting fundamental and applied research on alternative sources of energy. The conducive environment and its variations are very suitably and encouraging for such research. The equipment, apparatus and other instrumentations required for fundamental research, training and application assessment are discussed in this paper, in the light of difficulty of procurement, modification and improvisation according to the local conditions.

During the past four years, research on solar energy and biogas has been focusing for applications in agriculture and rural development. This paper outlines also the energy scene, the existing and potential alternative sources of energy and the progress made regarding the applications of solar energy and biogas for serving the needs of cooperative communities. Regional and international cooperation is welcome in the field of such research to be done in Viet Nam. The research infrastructure is available, and because of most suitable reconstruction atmosphere, vast opportunities exist for both basic and applied research in the field of alternative sources of energy. A mutual cooperation in the form of pooling in Viet Nam the research equipment developed overseas will be very beneficial for the developing countries to pursue the goal of saving energy. A list of the main institutions conducting research and development of alternative sources of energy is therefore provided for immediate contact in promoting close cooperation with other countries.

INTRODUCTION

The Socialist Republic of Viet Nam is one of the developing countries in the solar belt. The country has a tropical monsoon climate – equatorial in the South, milder in the North – with warm, wet summer and mild winter.

In recent years, the modernization of an underdeveloped agriculture is being implemented and intensified throughout Viet Nam. Agricultural machines which are being used for cultivation, irrigation, drying and processing of foods, require high capital investment and running cost due to the skyrocketting cost of fuel. Since the energy crisis, Viet Nam is facing the most fundamental problem on energy in which the costs of imported crude oil and its derivative products have drained rapidly her hard foreign exchange earnings. They are, in turn, to be reserved to purchase machinery and equipment for the reconstruction programmes.

The energy problem being the key factor in the economic and social development is common to all countries. Today energy consumption per capita is often considered as one of the most characteristic standards of living in urban and rural areas. Turner[1] had stated that the range of per capita consumption in the six non-OPEC developing country group is 81 kgce for the agricultural non exporters and 1,220 kgce for the industrialized developing countries. The range of combined commercial and non commercial per capita energy consumption varies between 480 kgce and 1,606 kgce for agricultural non exporters and industrialized developing countries respectively. Presently developed and developing countries have more interest in common efforts to promote greater use of alternative renewable energy sources to supplement the commercial ones which are very limited and rapidly depleted. The use of renewable energy sources exists for the last many years, however, not much significant applications have been proposed to solve or ameliorate the present energy shortage.

In considering the potential of alternative renewable energy sources, their development and possible applications in Viet Nam, it is important to determine the energy requirements and the appropriate technology which can be utilized to fit the socio-economic aspects. The supply of energy in urban areas is very well distributed through the existing power plants. It is most difficult and costly in rural areas where energy supply is the most important factor to secure the agricultural production and daily activities.

This paper will outline the energy scene, the natural resources, the potential alternative sources of energy available in Viet Nam and the progress made regarding the applications of solar energy and biogas for serving the needs of cooperative communities.

ENERGY SCENE

The use of energy by human beings since the stone age has been related to control over steady increasing amounts of energy coupled with the growing population. Today, the very large amounts of energy under human control are concentrated in central power stations whether generated by coal, petroleum fuels, hydropower or nuclear energy. In Viet Nam, coal, hydropower and petroleum are the sources to generate electricity which are being used in industries, agriculture and domestic sector. Electricity production had been markably increased from 1955 to 1975 at an average of 17.2 per cent in the north, and from 1960 to 1974 at an average of 12.45 per cent in the south of Viet Nam.[2] The distribution of electricity in the country is, in priority, to the production sectors. Heavy industries get 52 to 54 per cent while the agricultural sector had increased from 17.6 million kWh in 1963 to 110 million kWh in 1973. The table 1, below, shows the distribution of electricity for different sectors in South Viet Nam from 1960 to 1974:

Table 1. Distribution of electricity in South Viet Nam from 1960 to 1974

Year	*Total distribution* %	*Urban domestic and public utilities* %	*Industries* %
1960	100	61.1	38.9
1965	100	56.0	44.0
1970	100	68.5	31.5
1973	100	65.0	35.0
1974	100	57.0	43.0

The other significant source of energy for electricity generation in Viet Nam, has been in the form of hydro-electric power. A small but significant, amount of energy source has been in the form of wood based materials, straw, rice husk and agricultural residues, which are being used in rural areas. In the past and presently, the total electricity production in Viet Nam has not fully satisfied the growing energy demand of different sectors of industries and agriculture. The population, living in rural areas, like other countries, depends on non commercial energy and the electricity supply by thermal or hydro-power plants is not available to them. There are, however, small diesel generating stations to back up for pumping or drainage of water.

Oil is being used to generate steam for power plants to produce electricity and also being used for transportation and domestic sector, in the south part of Viet Nam. Before 1976, the composition of energy consumption by energy forms in both parts of Viet Nam was as shown in Table 2.

Table 2. Compsotion of energy consumption in Viet Nam

Energy form	*North Viet Nam in 1975* %	*South Viet Nam in 1973* %	*Viet Nam in 1976* %
Coal	39	0	40
Oil	12	74.4	26.4
Hydro	4	0.2	1.1
Wood and agricultural residues	45	24.4	32.5

Taking into account of the future requirements in the energy sector for industries and agro-based industries to secure the national development and self sufficiency of food, figures of energy demand forecasts have been made[2] and are given in Table 3.

Table 3. Energy demand forecasts

Primary energy form	*1980* %	*1985* %	*1990* 5
Coal	49.5	49.7	38.3
Hydro	4.0	6.8	11.1
Oil	27.1	28.0	26.8
Wood and agricultural residues	19.4	15.0	21.8

Owing to the increasing demand for energy to meet the energy needs during the reconstruction period, the following steps are being considered to be taken for tackling the energy shortage:

(a) Conserve energy;

(b) Convert thermal power plants operated by fuel oil to coal;

(c) Reduce dependence on oil imports;

(d) Increase the use of renewable sources of energy such as solar, wind, geothermal and biomass;

(e) Emphasize integrated rural development and;

(f) Identify the energy resources and demands in rural and urban areas with respect to the contribution of alternative sources of energy available locally.

NON-RENEWABLE ENERGY

Oil, gas and coal are the most significant non renewable energy sources, which are important as fuels for electricity generation. Oil and gas are not yet discovered in Viet Nam, but their consumption normally depends on the import, and generally used in urban areas. Only kerosene and diesel have been intensively used in rural areas to meet the rural energy demand. Coal is the main source of energy for power generation in Viet Nam. Its production is adequate for domestic uses and for export.

RENEWABLE ENERGY

There are a number of alternative renewable sources of energy available in Viet Nam, which with the present technology are capable of supplying selected energy requirements needed by the rural and urban populace. Since the rate of energy consumed from conventional sources is high and also with the high cost of energy production, any amount of energy contributed from the renewable sources would have economic significance. The incentive in having alternative sources of energy is the saving in foreign exchange if the present energy source continue to be imported or an earning of foreign exchange if the extra source of energy is to be exported. Many energy sources which definitely have great potential applications in Viet Nam, are:

(a) Solar energy;

(b) Wind energy;

(c) Photosynthesis and biomass energy;

(d) Energy from organic waste materials and refuse;

(e) Small scale water power systems;

(f) Geothermal and;

(g) Tidal.

SOLAR ENERGY

Sun provides the earth with some 170,000 million MW of power. For whole of Viet Nam (land area = 329,600 km^2) the total solar energy received is $4{,}812.16 \times 10^{14}$ kcal per year by taking 4,000 kcal per square metre per day, which is the average solar radiation intensity in summer. This would give an idea of the tremendous amount of solar energy available. If we could capture and utilize even a small fraction, it will save a great amount of fossil fuels presently consumed in Viet Nam.

The solar energy can be collected either as heat which may later be transferred into mechanical power, or by direct conversion into electricity or into chemical substances which can store a large amount of it. The sun's energy has been used extensively as heat for a wide variety of applications. Here the most important methods of utilization of solar energy, thermodynamic and photovoltaic applications, will be covered.

Thermodynamic applications of solar energy collectors.

Solar radiation can be collected in two general ways to produce higher temperature: flat plate and focusing collectors.

(i) *Flat plate collectors:* Glass or plastic structures are used to collect both direct and diffused solar radiation and apply it to heat a fluid (air or water) whose stored heat will be used for different applications. This type of collector which can yield a temperature ranging from 40 to 100°C, depending on conditions of the weather and on the use of selective surface coated on the absorber, has been extensively used in many countries of the world. It could be built with local materials by local people in rural areas.

(ii) *Focussing collectors:* In order to obtain temperatures higher than the ones obtained by flat plate collectors, the concentration of solar radiation by lenses, or curved mirrors is necessary. The high temperatures obtained by this type of collector could be used to produce steam for a turbogenerator that produces electricity. This type of collector has not been widely used in rural areas, because the technology involves complex mechanisms to track the sun's path requiring considerable maintenance or a large labour force to focus manually the mirrors to the sun.

It general a solar thermal conversion system comprises of five elements as follows:

1. A concentrator to focus the sun's rays;
2. A receiver to absorb the radiant energy;
3. A means for transmitting the heat obtained to a storage tank or directly to the turbogenerator;
4. A means for storing the heat for use at night;
5. A turbogenerator using steam to produce electricity.

The thermodynamic applications of solar energy that seem appropriate for use in rural areas, are being practised in different less developed countries as follows:

(a) Solar agricultural driers can be used for improving the natural and traditional method of drying agricultural, fish and meat products, and timber.

(b) Solar water heaters can be developed for small and large scale hot water needs for industrial or domestic applications.

(c) Solar stills can convert brackish or polluted water into fresh water for human consumption in rural areas.

(d) Solar sterilizers can be used to sterilize medical instruments in rural clinics.

(e) Solar powered refrigerating systems for storage of perishable agricultural and foodstuffs.

(f) Solar cookers and food warmers.

(g) Solar pumps for irrigation, drainage and rural water supply.

(h) Solar electricity by thermal or photovoltaic conversion.

Photovoltaic conversion.

Photovoltaic conversion systems are based on the utilization of the photovoltaic effect in a semiconductor made of silicon called solar cell. In these solar cells, absorption of light generates an electrical current which can be collected on contacts applied to the surface of the semiconductor. Solar cells are normally made of materials like silicon, cadmium sulfide, cadmium telluride and gallicium arsenide. Their performance and reliability have been established in diverse applications such as remote sensing devices, harbor and buoy lights, highway emergency call systems, railway signal, microwave repeater stations and remote educational television sets. However, because of the very high cost of solar cells, large photovoltaic generators have not been built in rural areas. Some applications of solar cells for pumping and generating electricity have been made in developed countries like U.S.A., France, and Japan. The potential applications of solar cells to produce electricity in rural areas will be increased if the capital cost is sufficiently reduced and economical storage techniques become available. The present price is between US\$ 12.20/W_{ep}. Major research programmes to investigate photovoltaic cells have been conducting in U.S.A., France, West Germany, and Japan. The aim of the American programme is to reduce the price to US\$ 0.50/W_{ep} by 1986 and US\$ 0.10 to 0.30 by the year 2000.[3] If the cost of solar cells is reduced in the near future, people in rural areas will certainly benefit the progress of technology to improve their quality of life and increase agricultural and industrial productivity.

WIND ENERGY

Wind is a free and inexhaustible source of energy. In fact, it can be regarded as an indirect form of solar energy. For centuries, the wind has provided mechanical power for pumping water, milling grain in rural areas, and to propel boats and ships. Windmill had also been used for generating electric power. However, windmills have been out of the style for some time, due to the cheap power produced by centrally generated power plants. In recent years, there have been attempts to construct windmills of larger size to produce greater quantities of electricity in both industrialized and developing regions. In Viet Nam, there are many areas with suitable wind regimes. The average wind speed is ranging from 2 to 4 m/s. Since the wind regimes are irregular, it remains to be seen how much of the total available wind power can really be utilized and stored in batteries for usage when the wind is calm.

PHOTOSYNTHESIS AND BIOMASS ENERGY

Photosynthesis

In the process of photosynthesis solar energy is absorbed by plants and stored in the form of chemical energy. This natural transformation has many advantages:

- It yields high quality concentrated fuels through the production of various types of plant tissue.
- The energy produced is easily stored.
- For the same power, the investment required is much smaller than for other systems.

The chemical energy which accumulate through photosynthesis can be used in different forms: combustion, methane fermentation and pyrolysis.

Methane fermentation

Methane production through bioconversion of agricultural and animal wastes has already been demonstrated in several countries, including Viet Nam. There are to processes available:

1. A discontinuous process which uses vegetable wastes and requires the addition of little of animal manure.
2. A continuous process which is well adopted for animal manures (Biogas plant).

The methane gas produced by these processes is suitable for cooking, heating water, refrigeration (it can be substituted for oil in absorption refrigerators) and for operating farm machinery.

ENERGY FROM ORGANIC WASTE MATERIALS AND REFUSE

Pyrolysis

The phrolysis of organic waste materials consists of heating in a closed vessel or reactor to produce a low grade gas and a solid residue similar to charcoal, which is known as char. Char can be used for fuel and can replace firewood in the traditional combustion. The low grade gas can be burned or used to drive diesel dual fuel engine which in turn produces electricity. The gases produced by this process are mainly hydrogen, methane, carbon monoxide, carbon dioxide. Available organic materials such as animal feedstock, coal, tree bark, waste timber, rice husk, sewage slurry and used tyres, could be used to produce fuels.

Fuels could also be produced from biological materials by chemical reduction in the presence of waste carbon monoxide and catalyst at high temperature and pressure. Under optimum conditions, the process can convert as much as 99 per cent of the carbon content to oil yielding about 290 kg per ton of dry waste. At high temperature, organic materials may be pyrolized with the destructive distillation in the process to provide a wide range of gases, liquids and solid fuels.

The starch and cellulose components of agricultural products can be fermented aerobically to produce alcohol. A mixture of up to 20 per cent alcohol and 80 per cent petrol could be used to fuel the present internal combustion engines, and the performance in terms of fuel consumption and shaft power has been reported satisfactory.

Energy from refuse

It is possible to use the refuse as fuel for electricity generation through incineration. Energy recovery from refuse incinerator has been proven to be feasible and widely accepted in some developed countries. The calorific value of refuse is in the range of between 5,000 kJ/kg to 7,500 kJ/kg as compared with that of coal to be 35,000 kJ/kg.

SMALL SCALE WATER POWER SYSTEMS

Hydropower draws indirectly on solar energy. The kinetic energy of water flowing from a higher to a lower level can produce useful mechanical or electrical power. Traditionally, mechanical power for pumping and milling had been generated with the use of water wheels, turned by the flow of streams or small rivers. The amount of power theoretically available from the flow of water is related to the speed of flow, and the head of water. The actual power obtained is calculated by multiplying the theoretical power by various factors that represent the efficiency of each element of the hydro-electric system. Techniques for the conversion of hydropower to electrical energy have been successfully applied in large scale hydroelectric plants.

Recently, several European countries, China and North Korea have developed low head hydroelectric devices for rural electrification. Hydropower plants which produce 500 kW or less are categorised as small scale plants. For small power outputs around 50 kW, a simplified turbine alternater system could be used. Another types of turbine such as Pelton wheel and Francis turbine are most suitable for hill streams and low heads.

The cost of hydropower investment remains generally high. Several conditions which must be fulfilled, before any installation of mini-hydropower stations could be implemented, are as follows:

(a) regular possible stream flow;

(b) longest possible use of energy all through the year;

(c) absence of abrupt changes in power demand;

(d) presence of a consumption centre near the water source;

(e) simple technology using local materials and no high skilled labour required.

The future applications of mini-hydro-power plants would be of greater potential to developing countries as a source of energy for small rural and agro-industrial centres provided the cost of presently available units be reduced through local enterprise.

Geothermal

Viet Nam has about 150 useful geothermal locations, 46 of them are with hot water at 50° C available at the surface, and the rest are at 3000 m depth at 160° C.

Geothermal energy is not easy to transport, unless converted into electricity. The electricity produced is cheaper than coal, oil or nuclear, since the power plant using geothermal heat requires neither fuel nor boilers. Hence, the capital and running costs of such a plant are from 1/8 to 1/2 those of oil fired plants. The development of such geothermal resources should be encouraged on priority basis in Viet Nam.

Tidal

Tidal power is analogous to hydropower. It is an enormous potential source of energy which could be harnessed from tides – the rise and fall of sea level twice a day. Viet Nam has 3200 km coastline and many small bays estuaries. The average tides of 4 m height have been observed.

Tidal power from global tidal resources was estimated at 3 million MW, only 2 per cent could be exploited by the methods that are 8 to 25 per cent efficient. France is the world's first country which had completed a large scale tidal power installation of 240 MW at La Rance, Brittany.

The above mentioned renewable sources of energy should be fully exploited to assist the rural electrification programmes which had been difficult to realise due to the high installation cost. Since Viet Nam is an agricultural based country, and a majority of the population lives in rural areas where electricity supply from urban centres is not feasible, the renewable sources of energy should be incorporated to any rural development programme.

INTEGRATED RURAL DEVELOPMENT

Industrial-urban or city development has created numerous problems, and at times it has reached nowhere near an orderly or systematic growth. It is, therefore, important and precautionary to think rural development from a different and more suitable view. It leads to the appropriate technology to be appropriate and progressive and develop the rural regions without repeating the mistakes and bottlenecks of urban development programmes.[4, 5]

In order to achieve self-sufficiency in food in a country, the most dangerous part is the cost of production and hence viability of the venture. That is food-producers get poorer due to high cost of production in the name of self-sufficiency and the import is banned. Whereas import at cheaper and lower price will help the food-producers rather than self-sufficiency.

A great deal of efforts and planning and implementation is to be done so that rural people are given a better deal. The uppermost problem is lagging food-production and rural poverty. The chief aim of the world-community should, therefore, be to improve the production, income and living conditions of the rural people who are the disadvantaged sections of the whole community. Many times the conditions of the farmers are fishermen of the cooperative communities are not affected in the agricultural and rural developments and food production programmes. Sometimes, the conditions are superficially improved as an indirect consequence of such programmes, even though they were not meant to be so. Rural poor must be efficiently organised in order to render more effective their relationship to the rest of the society. In other words, integration of rural poor in the development process and promoting self-reliance should be achieved by participating in mobilising resources and in designing and formulating projects at the grass-root level. Rural development is necessary not only for humanity reasons but to avoid scores of social, socio-political and other complexities of both developing and the developed societies. A large majority of the countries threatened with the twin evils of mass-unemployment and mass migration into cities have developed 'dual-economy' which is the basis of all social and socio-political tensions. Rural-development cannot and should not be instantaneous – it is gradual and an evolutionary process. Sudden application of advanced technology in a backward rural area could be disastrous and further develop dual-economy. A technology that recognizes the economic and social boundaries and which is either too high nor too advanced is the one that might help in short and long run without damaging the existing state and norm of the rural society.

RURAL ENERGY REQUIREMENTS

Due to the high cost of basic energy such as kerosene, diesel and lack of electricity supply, the standard of living of rural people has been affected. The government has also tackled these problems by giving high priority to the agricultural production sector by making available the necessary energy needs. The rural electrification is the most important task to the rural development. Since improving the living standard and increasing the agricultural production in rural areas require a large amount of energy, it is at present, extremely difficult to get sufficient energy from the centralized power stations.

In rural areas the basic energy requirements are listed below:

(a) Mechanical power to supplement and/or replace manual labour in operations like pumping water, cleaning, plowing planting, weeding, grinding, harvesting, threshing, drying and transporting people and agricultural outputs;

(b) Heat for cooking and preserving food;

(c) Lighting of homes, schools and hospitals;

(d) Electricity for operating radios, educational television sets and small essential household appliances;

(e) Cooling of perishable foods and;

(f) Fertilizer and chemicals which need to be processed so that they may supplement natural fertilizers.

In most rural areas, the sources of energy used for cooking and lighting are kerosene, firewood, charcoal and agricultural wastes. The above mentioned energy requirements in rural areas could be alleviated if appropriate sources of energy locally available could be used.

RESEARCH AND DEVELOPMENT ON ALTERNATIVE SOURCES OF ENERGY

During the past few years, scientists and engineers of different higher institutions of learning in Viet Nam, with the guidance and cooperation of the State Commission of Science and Technology are conducting fundamental and applied research on alternative sources of energy such as solar, wind energy and biogas.

The research activities of these centres are concentrating on the development of solar, wind and biogas devices which can be used in the rural areas as follows:

(a) Solar drying of agricultural and industrial products;

(b) Solar water heaters for domestic and industrial application;

(c) Solar distillation of sea, brackish or polluted water into potable water;

(d) Solar powered refrigeration systems;

(e) Solar pumps for irrigation and drainage;

(f) Solar electricity by thermal and photovoltaic conversion;

(g) Windmills for generating electricity and lifting water;

(h) Biogas plants using animal and agricultural wastes to produce methane.

A. Some solar devices built and tested in Viet Nam.

1. *Solar Water heaters*

   A solar water heating unit with 10 square metre of collector area which had been designed by the Electric Research Centre and produced by a district engineering workshop, was installed in the northern province of Ha Son Binh to supply 1000 litres of hot water at 50°C. (Photograph 1).

2. *Sea salt production*

   A 6 square metre absorber had been used to produce salt from the brine at 21°C and 18.7° Be, in the Van Ly salt field in northern Viet Nam. The yield of salt by this method was two and a half times more than the tradiational method, and the quality was better.

3. *Sun Raying rice seeds*

   Experiments on the rice seeds output and desease prevention by using solar energy have been carried out. The first experiment on the sun raying method had shown that 82 per cent of rice seeds sprouted after being sun rayed while only 75 per cent of the comparison bath under normal condition sprouted.[6]

4. *Solar dryer*

   Different types of solar driers had been built and tested at the Electric Research Centre. The performance of those pilot units was found to be satisfactory.

5. *Photovoltaic solar cells*

   Preliminary studies and research on the production of solar cells have been conducted by the scientists of Institute of Science & Technology in Ho Chi Minh City. Important consideration is given to the use of local material and appropriate technology so that the end product is suitable and beneficial to rural areas in Viet Nam.

An example of appropriate technology of constructing solar devices using local materials and labour by Vietnamese scientists is shown in photographs 2 to 4.

B. Some constraints facing the research and development

Research and development on alternative sources of energy in Viet Nam are being on the right path to solve the energy crisis. The government has encouraged all scientists and engineers of different institutions to pool their scientific know-how to solve the rural energy demands. However, the procurement of equipments, apparatus and other instrumentation required for research is very difficult due to the lack of funds. On the other hand most of the equipment is manufactured and supplied by the developed countries only to the friendly nations.

C. Regional and international cooperation

Acceleration of research and development effort to the optimum utilization in existing practical problems needs equipment, instrumentation, documentation and funds. This is true not only for any developing country, but even for some of the advanced countries of the world. The fast progress and change in almost every field of scientific research is making some of the present available research tools as obsolete. The regional and international cooperation, therefore, is very important in research and development. There is no sense in duplicating the same work in one country or the other. Energy problem is every-body's and every nation's problem. Since cooperation without any strings is the only hope to solve the alarming energy crisis. The cooperation and coordination mentioned and discussed in this paper does not mean salemanship or profiteering by transferring either the obsolete technology or useful technology in the same of scientific progress.

The author's urgent recommendations are:

(i) To pool the scientific resources in a manner which is useful and profitable to all parties whether donor or receiver;

(ii) Since in Viet Nam, the scientific manpower is highly efficient and easily available, a cooperative attitude on the part of advanced countries will help solving not only ther regional energy problems but on a global scale. The much needed research equipments and instrumentations should be brought into the region and tap the scientific talent which is very suitable for local conditions and environments. Outside scientists can always have joint projects, and mutual interchange of experience and knowledge for the sake of progress and a viable solution to energy crisis;

(iii) As mentioned already, Viet Nam is quite rich in resources, both renewable and non renewable and they are in the process of being tapped for efficient usage. Seminars, shortcourses, symposia and workshops should be organised right in Viet Nam keeping in mind, the availability of the organisational facilities. It will enable scientists all over the world to know each other, each other's problems, how and in what way the work is being done and what more can be done for mutual benefits;

(iv) In order to understand the problems faced by developing countries following are some of the examples of the transfer of scientific and technical information:

– Establishment of documentation center for energy should be decentralised and located preferably in the developing countries and not, like what it is at present, in the advanced countries. Even a single page of information (photostat) costs a lot which an institution or individual scientist in a developing country cannot afford. What is more, the price is in US currency which is much higher if the same photostat is done in the recipient country. Foreign exchange involved is also unbearable for most of the developing countries. It should be clearly understood that transfer of technology means to have a free flow of scientific information. The charge of photostate should not be calculated on the basis of labour charges of an advanced country but be in the local currency and at the same price available in developing countries. It is a well known fact, that the scientists of developing countries are not allowed to have foreign accounts in which to pay for information needed for their research works. The author recommends to have dispersed information centers in the developing countries linked with those in the developed countries. These should have available all scientific documents whether borrowed in orginal for further copying locally – this is much cheaper and easier to distribute – or a spare copy to the local library within the developing country. There are two institutions in the region sending information free of charge: United Nations University (ASSET) and Tata Research Centre (ENERGY UP DATE and DOCUMENTATION).

In order to facilitate the communication in the field of energy in Viet Nam, the following institutions and individuals should be contacted for joint research proposals, research facilities, exchange of scientists and any other relevant information needed in the said field:

NAME OF INSTITUTION	*FIELD OF RESEARCH*	*PERSON IN CHARGE*
ELECTRIC RESEARCH CENTRE MINISTRY OF POWER & COAL 54 HAI BA TRUNG HANOI, SRVN	LOW & HIGH TEMPERATURE APPLICATIONS OF SOLAR ENERGY, WIND ENERGY BIOGAS	MR. TRINH TRONG THUC DIRECTOR
INSTITUTE OF SCIENCE & TECHNOLOGY 1 MAC DINH CHI HO CHI MINH CITY, SRVN	PHOTOVOLTAIC CONVERSION	MR. HOANG AHN TUAN DIRECTOR
POLYTECHNIC UNIVERSITY PHU THO HO CHI MINH CITY, SRVN	SOLAR PUMP SOLAR AIR CONDITION-ING & REFRIGERATION	MR. HUYNH XUAN DINH DIRECTOR

CONCLUSION

Research and development on alternative sources of energy in Viet Nam have been focusing on the applications in agriculture and rural development which has the full support of the government. In order to use them efficiently, it is necessary to know the location of their inputs and the applicability in each situation. Some immediate application of alternative energy sources such as solar energy, wind power, biogas and mini-hydropower are certainly possible.

Implementation and promoting the application of renewable energies to the development of the rural sectors are not an easy task. However, with proper approach and appropriate technology, it could be achieved. It is, therefore, important that in the introduction of new devices using alternative sources of energy for rural environment, the following factors need to be considered:

(i) identification of the energy resources and demands in rural areas (e.g. energy required for daily activities of the rural people);

(ii) Appropriate devices would be built with locally available materials and locally available workmanship;

(iii) Low cost, simple operation and little maintenance required;

(iv) Direct participation of rural people;

(v) Increase awareness, among the rural population, of the benefits of utilizing alternative sources of energy in saving the high cost of conventional fuel.

To achieve this goal, it is necessary that the renewable resource technologies must be acceptable technically, economically and socially. The conditions for acceptability are not yet satisfied due to the cost and non-availability of energy storage systems. For the time being, the most appropriate approach to exploit the renewable resources in rural areas is to promote the applications as soon as they become operational and competitive with the conventional one. In this way, it can be determined which renewable energy technologies can be applied to meet the energy requirements in rural areas and fit into the national energy plan. It is, therefore, recommended that the international and regional organisations should establish co-operation with Viet Nam in research and development of alternative sources of energy. This can be achieved through joint projects sponsored by UN bodies or bilateral arrangements at insitutional or government levels. Some of the devices developed in advanced countries could be brought into Viet Nam for field testing and further modifications to suit local conditions. However, the first step to be taken to solve the problem of alarming shortage and fast depleting energy sources is the conservation of energy and then the development of alternative sources of energy.

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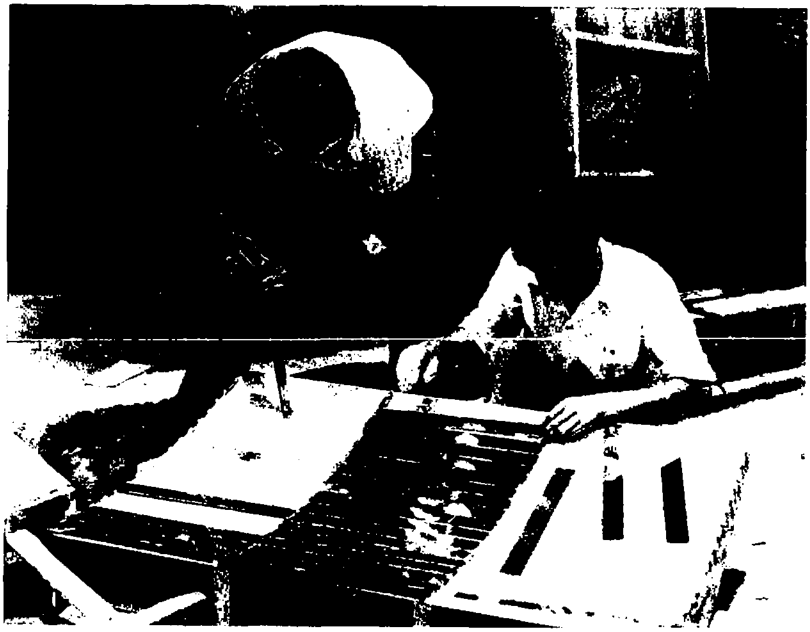
Photograph 1: Solar water heater in Hoa Son Bin

Photograph 2: Solar Energy Experimental Centre at the Electric Research Centre at Hanoi



Photograph 3: Construction of a parabolic solar reflector

Photograph 4: Solar cooker

STABILITY OF ALUMINIUM REFLECTIVE COATING OF SOLAR COLLECTORS UNDER THE ACTION OF ENVIRONMENTAL FACTORS

by

NGUYEN CONG VAN and TRAN QUOC GIAM

I – Introduction

Reflective surfaces being the most important component of solar collectors, the search for a highly efficient method of their manufacture from materials locally available and specifically resistant to the severe conditions of heat and humidity in the tropics has been a problem of widespread interest.

In this paper, we shall describe a number of experimental results obtained at the Solid-state Physics Laboratory, Polytechnical Institute of Hanoi concerning the damp heat resistance of vacuum-deposited aluminium reflective coating on different base materials under the climatic condition of Viet Nam.

II – Some characteristic climatic and radiation date of Viet Nam[1]

Viet Nam is a tropical country situated the latitudes 8° and 23° 5 N and having abundant solar energy resources characterized by long average sunshine durations: 2 600 and 1 700 hrs per annum in the southern and northern provinces respectively, and 6.3 hrs per day in Ho Chi Minh City and 6.8 hrs per day in Nha Trang. The highest absolute and average annual temperature are 42.8°C and 23.5°C respectively in Hanoi and 40°C and 27°C in Ho Chi Minh City.

– Average relative air humidity stands between 81 – 88% with values of higher than 90% accounting for 45% of the total length of the year and average values – 71% of that length.

– Total annual radiation is estimated at 110 – 130 kcal/cm^2/annum and highest direct radiation instensity is 0.6 kcal/cm^2 per day, average UV radiation intensity – 0.1 kcal/cm^2 per day.

– The atmospheric salinity and impurities contents are 1.1 mg Cl^-/m^2 per day in coastal areas and 35.5 mg Cl^-/m^2 per day on island areas.

III – The choice of manufacturing methods and test materials

Silvered glass, polished metals and metal-plated plastics are known to have been used for reflectors.[2, 3, 4] These materials, however, have been developed and tested mainly in the temperate and cold zones and some of them are not always available elsewhere, others are brittle, hard to shape and have low mechanical strength as in the case of glass. The choice, therefore, of an adequate technology permitting the use of various types of indigenous materials is for us a problem of major significance. In this connection, we have found and adopted a process of manufacturing reflective surfaces by vacuum condensation of aluminium vapour on supports of different materials and have tested the obtained products under the climatic conditions of Viet Nam.

a. The process is characterized by the following features: high reflection coefficient, or reflectance (R), of the obtained Al coating in a wide range of wave lengths,[5] namely, for $\lambda = 0.22\ \mu m$, $R = 91.5\%$ and for $\lambda = 20\ \mu m$, $R = 99\%$; possibility of using various materials, electrically conducting or non-conducting; possibility of mass-production on an industrial scale and, consequently; of reduced costs.

b. The tested base materials are of five different kinds, most of which are non-conducting and, thus, unsuitable to electro-chemical polishing, but all are easily obtainable, namely

- Window glass (G)
- Vernished sheet iron (VSI)
- Polymethyl-Metacrylate (PM)
- Polystyrene (PS) and
- Photographic film (photofilm)

c. The supports are heat-treated while being coated, which allow to obtain better-structured coatings and stronger bonds among the Al atoms themselves and between them and the base materials, thus increasing the adherence of the coatings to the supports and their resistance to the severe environmental conditions and service stresses.

Temperature of the supports during deposition (T_s) are given in table. I, but in our experiments only two values are opted for, namely room temperature and 50°C.

Table 1

Materials		*G*	*VSI*	*PM*	*PS*	*Photofilm*
Temperature (°C)	room T°	X	X	X	X	X
	50	X	X	X	X	X
	100	X	X	–	–	–
	200	X	X	–	–	–

d. Two thickness values of the Al coatings, 1 200 Å and 2 000 Å are chosen for heat testing.

e. Experiments are conducted under natural climatic conditions as under the most severe standard conditions,[7] in which the specimens are subjected to.

– Tests in laboratory conditions (room temperatures between 25° C and 35° C, relative humidity η = 60 – 80%),

– Exposures to direct sunshine in natural atmosphere (temperatures from 25° C to 40° C, relative humidity η = 60 – 85%),

– Saturated humidity tests at temperatures of 40° C, 50° C and 60° C respectively,

– Damp heat tests in the PKW-2U device[6] without UV radiation and in the FEUTRON-3001 device[6] under UV radiation by means of the PRK-2 lamp with an intensity three times as great as that of natural radiation, temperature T = 40° C ± 2° C and relative humidity η = 95 ± 3% in both cases.

IV – Test results and discussion

1. Adherence of the Al coatings to the base materials

The adherence of the coatings to their supports was determined by the Heaven-Benjamin method and the ultrasound method. In the first case, 2 000 Å thick coatings were tested on the DB-49/05 equipment and loads required to peel off the coatings were recorded for different base materials as depicted in table 2.

Table 2

Materials	*. G*	*. VSI*	*. PM*	*. PS*
Loads	3.7×10^{-3} Kg	5.5×10^{-3} Kg	2.5×10^{-3} Kg	13.2×10^{-3} Kg

In the ultrasound method, the samples were immersed in a medium of distilled water and subjected to ultrasounds of 50 kHz engendered by a 60 W Banansonic-12 generator. Under the ultrasonic impacts the coatings gradually came off and the denuded areas were periodically measured by means of the MIM-7 metallographic microscope, from which the changes in the coated area were derived with reference to time. The obtained results are shown in figure 1.

The results of the two tests are quite in agreement with one another and their correlation actually shows that the denuded areas are inversely proportional to the peeling loads, that is the harder the coatings are to peel off (in the first test) the lesser their denuded areas (in the second). This is true of on the materials tested as shown in table 3.

Table 3

Materials	*G*	*VSI*	*PM*	*PS*
Loads	3.7×10^{-3} Kg	5.5×10^{-3} Kg	2.5×10^{-3} Kg	13.2×10^{-3} Kg
Denuded areas after first 5 minute (% of total surface)	1.5	1.2	3.1	1

From which it is also clear that polystyrene exhibits the highest coating adherence, followed respectively by varnished sheet iron, window glass and, finally, polymethyl-Metacrylate.

From fig. 1 it can be seen that the destruction process of the coatings was composed of three successive stages. At first, the coating was destroyed rather fast, at spots where the support had not been thoroughly cleansed or where defects in the structure of the coating had not been eliminated by heat-treatment. Next, the destruction rate slowed down considerably, marking the beginning of the second stage which was of variable duration, depending on the material in question. It was, in fact, longest in the case of window glass and polystyrene and shortest in the case of Polymethyl-Metacrylate. The third stage began when the best-structured portion of the coating was broken and the destruction grew as fast as in the first stage.

2. Determination of the damp heat resistance of the aluminium reflective coatings

As a result of the tests carried out to this effect, the degradation of the coating reflectance was plotted against the exposure time of the specimens to environmental factors, respectively for the materials under examination.

Results of environmental test on 1 200 Å coatings obtained with $T_s = 50^\circ C$ are given in fig. 2 and those corresponding to 2 000 Å coatings with $T_s = T_r$ (room temperature) are shown in fig. 3.

– Fig. 2a and 3a represent the diminution of the coatings' reflectance on different support – (G), (VSI) and (PM) – when tested under laboratory conditions: $T_r = 30 - 35^\circ C$, relative humidity $\eta = 60 - 80\%$, test duration 45 days, during which measurements were taken at 24 hour intervals in the first phase and at 5 day intervals in the last one. It can be seen from the graphs that the decrease in the reflectance was rather rapid after the first day, then gradually slowed down and finally levelled out from the

12th day when stability of the coating was reached. The relative reflectance diminution of the coatings is the least on VSI supports (1.9% and higher on G and PM ones 3.4%). For all the tested support materials, thicker coatins exhibit lesser reflectance diminution.

– Fig. 2b and 3b describe the decrease in reflectance of coatings during exposures to natural climatic and radiation conditions with temperatures of 25 – 40° C and relative humidities of 65 – 85%. Like in the laboratory tests, the coatings reached stability after 12 days being exposed to sunshine, their reflectance remaining unchanged ever since and the thicker the coatings the lesser the decrease in their reflectance. For VSI supports, in particular, reflectance of the coatings appeared to have undergone the least changes, from 73% after two days' exposure to 71% by the last (45th) day of the experiment. As for coatings on PM supports, the initial 82% reflectance fell quickly during the first ten days down to 71%, but this value persisted till the end of the test. The decrease in reflectance was the same for the rests of the tests.

– Results of saturated humidity tests are given in fig. 2c and 3c, from which it can be derived that the reflectance of 2 000 Å coatings (fig. 3c) on G supports displayed the lowest degree of degradation. As for the 1 200 Å coatings, those obtained on VSI supports at T_s = 50° C proved to be the most stable, their reflection coefficient droping from the initial 76% down to 68% and remained unchanged afterwards till the end of the tests. Under such severe environmental conditions coatings on PM and G support appeared to be least stable.

– Simulated climatic tests in the PKW-2U standard device without radiation, at 40 ± 2° C and 95 ± 3% relative humidity (fig. 2d and 3d), showed that coatings on VSI support exhibited the lowest diminution of reflectance which, after 21 days under test conditions, dropped from 83% to 77% (reflective diminution – 7.2%) for 2 000 Å coatings, and from 84 to 79% (reflective diminution – 5.9%) for 1 200 Å coatings, whereas the relative diminution in the case of other support materials were, respectively : G – 13.2% and 10%, PM – 16.7% and 12.8%, PS – 21% and 19% and photofilm – 24% and 20.5%.

– Test in the FEUTRON – 3001 device with the same simulated climatic factors as in the PKW-2U device, except for the presence of UV radiation by PRK-2 lamp gave similar results (fig. 2e and 3e). After 21 days, reflection coefficient of coatings on VSI dropped from the initial value of 83% to 74% (relative diminution – 10.8%) for 2 000 Å thickness and to 76% (relative diminution – 8.4%) for 1 200 Å. the relative diminution for other support materials are as follows G – 16% and 12.2%, PM – 22.2% and 18%, PS – 30.8%, photofilm – 33% and 29% respectively.

The above simulated climatic tests permit to conclude that VSI supports ensure the best performance of Al reflective coatings against the effects of rigorous climatic factors,

V – Conclusions

On the basis of the results obtained through five series of different tests, a manufacturing technology of reflective surfaces for solar collectors by vacuum condensation of aluminium vapour can be formulated as follows:

- Vacuum pressure for Al evaporation $p \leqslant 10^{-4}$ mmHg,
- Temperature of the supports during Al vapour condensation for different base materials $T_s = 50^\circ C$,
- Coating thickness 2 000 Å,
- Materials for supports, listed in preference order by reason of damp heat resistance and economic implications:
  - (i) Varnished sheet iron,
  - (ii) Glass,
  - (iii) Polymethyl-Metacrilate,
  - (iv) Polystyrene,
  - (v) Photographic film.

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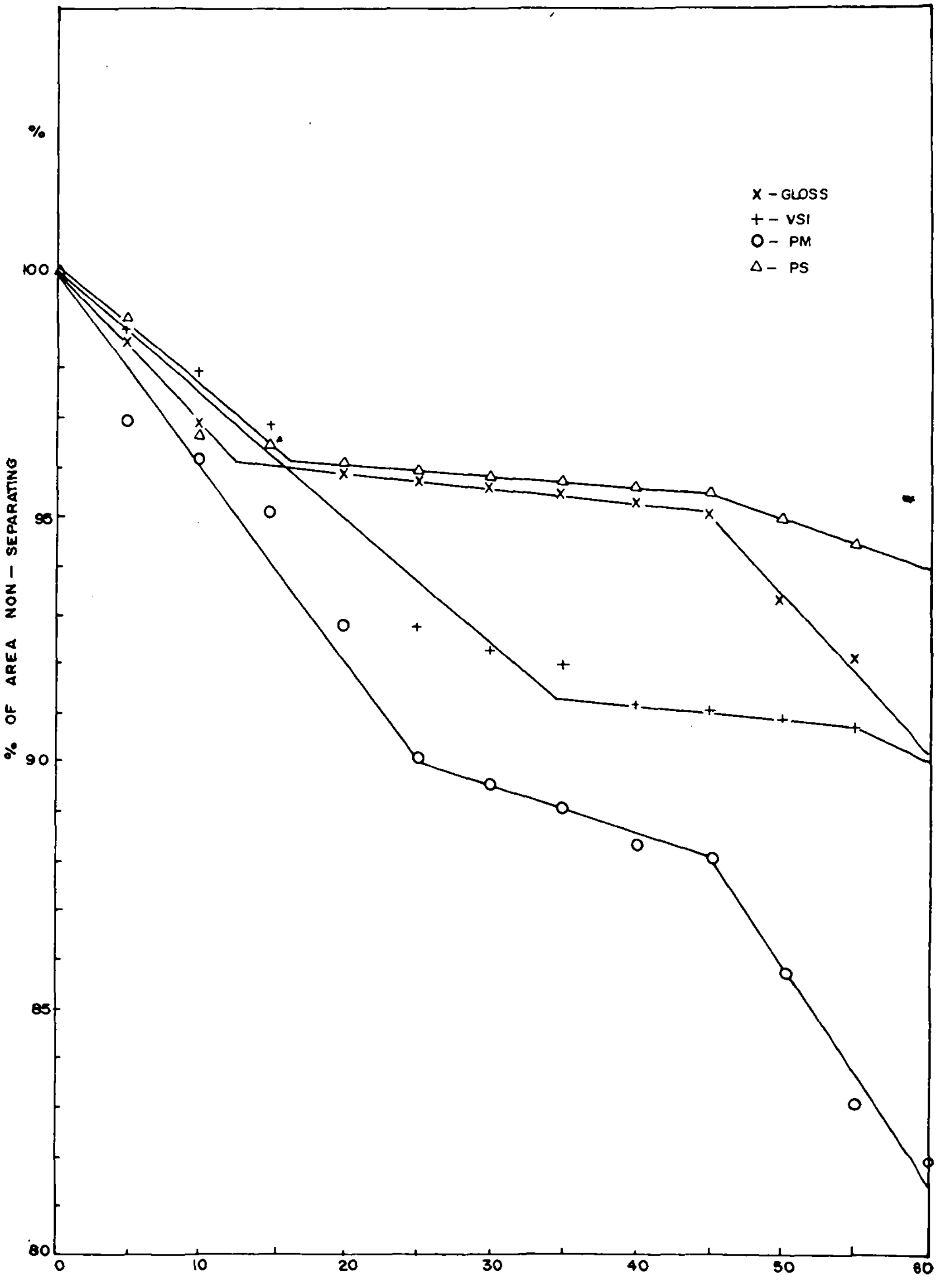
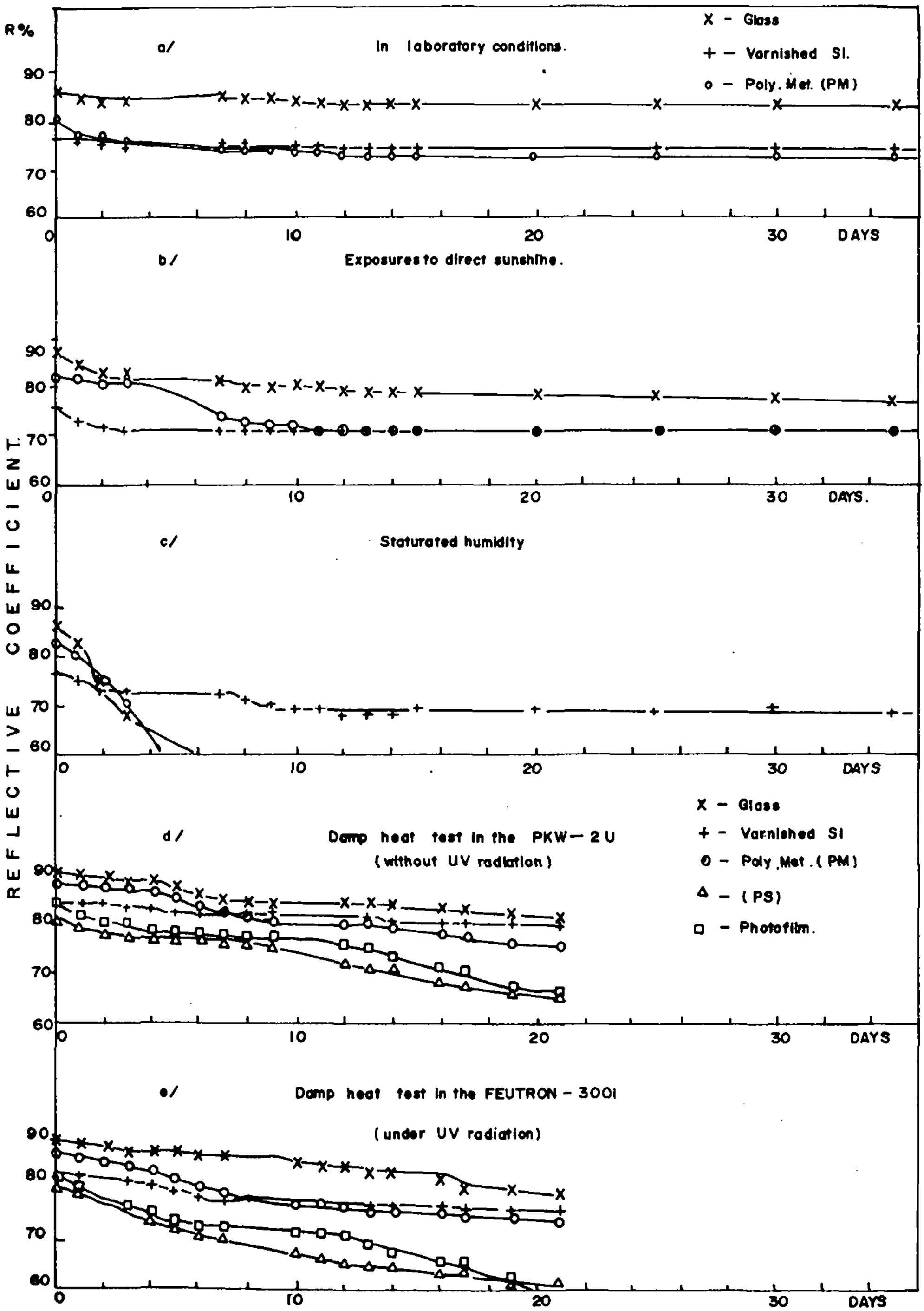
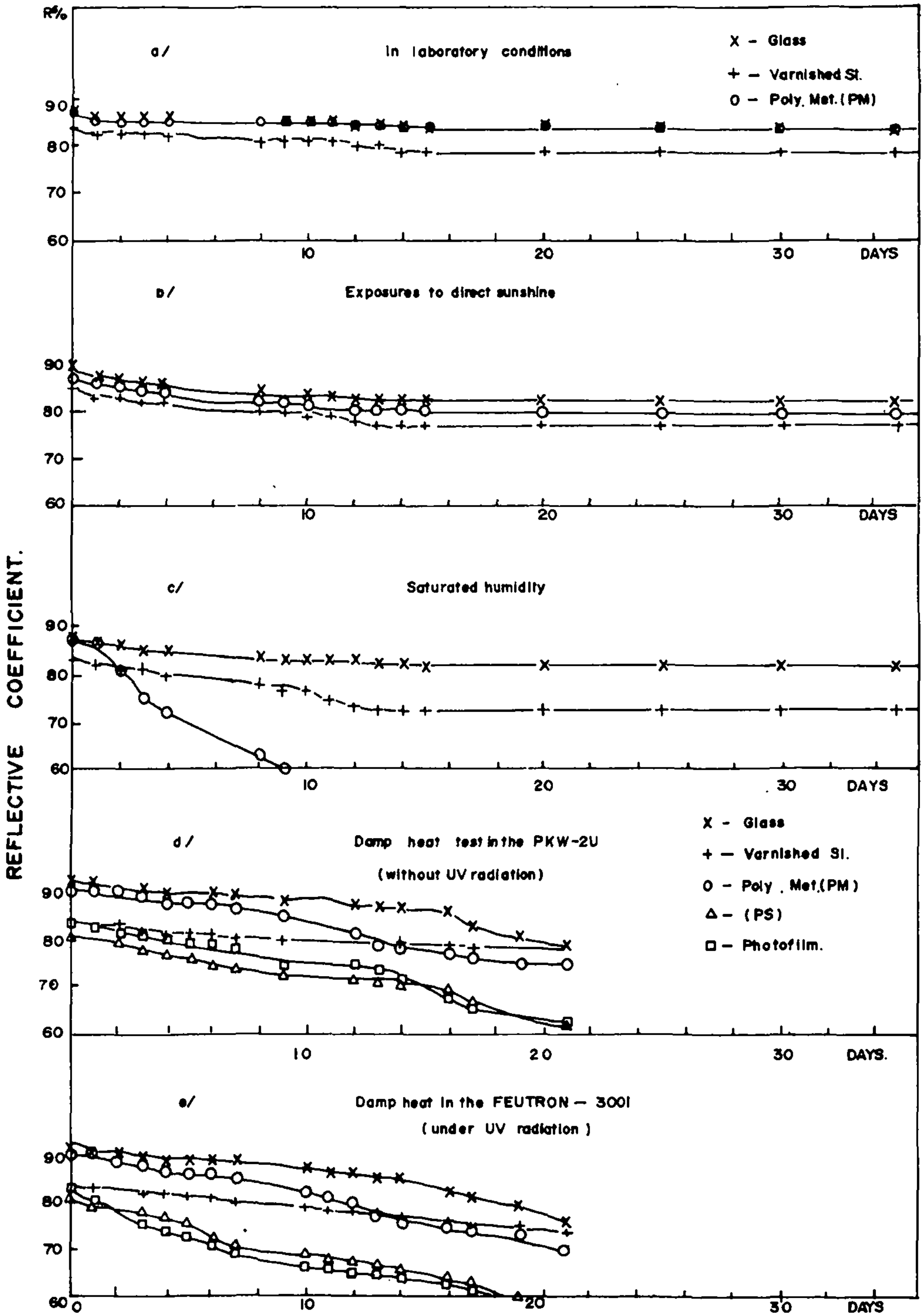

%
X - GLOSS
+ - VSI
O - PM
Δ - PS
% OF AREA NON - SEPARATING
100
95
90
85
80
0
10
20
30
40
50
60


R%
a/
In laboratory conditions.
X - Glass
+ - Varnished Si.
o - Poly. Met. (PM)
b/
Exposures to direct sunshine.
c/
Staturated humidity
d/
Damp heat test in the PKW-2U
(without UV radiation)
X - Glass
+ - Varnished Si
o - Poly Met. (PM)
Δ - (PS)
□ - Photofilm.
e/
Damp heat test in the FEUTRON - 3001
(under UV radiation)
REFLECTIVE COEFFICIENT.
DAYS



R%
REFLECTIVE COEFFICIENT.
a/
In laboratory conditions
X - Glass
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O — Poly. Met.(PM)
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Exposures to direct sunshine
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Saturated humidity
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Damp heat test in the PKW-2U
(without UV radiation)
X - Glass
+ — Varnished St.
O — Poly . Met.(PM)
Δ — (PS)
□ — Photofilm.
e/
Damp heat in the FEUTRON — 3001
(under UV radiation)
60
70
80
90
0
10
20
30
DAYS