Decontamination of drinking water by direct heating in solar panels

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A. J. FJENDBO JØRGENSEN, K. NOHR, H. SORENSEN AND F. BOISEN. 1998. A device was
developed for direct heating of water by solar radiation in a flow-through system
of copper pipes. An adjustable thermostat valve prevents water below the chosen
temperature from being withdrawn. The results show that it is possible to eliminate coliform
and thermotolerant coliform bacteria from naturally contaminated river water by heating
to temperatures of 65 °C or above. Artificial additions of Salmonella typhimurium, Streptococcus
faecalis and Escherichia coli in polluted river water were also inactivated after
heating to 65 °C and above. The total viable count could be reduced by a factor of 1000. The
heat-resistant bacteria isolated from the Mlalakuva River (Tanzania) were spore-
forming bacteria which exhibited greater heat resistance than commonly used test bacteria
originating from countries with colder climates. To provide a good safety margin it is
recommended that an outlet water temperature of 75 °C be used. At that
temperature the daily production was about 501 of decontaminated water per m² of
solar panel, an amount that could be doubled by using a heat exchanger to recycle
the heat.

INTRODUCTION

Worldwide, it has been estimated that water-borne diseases are
responsible for 3-5 billion infections per year, and for
10-25 million deaths per year, of which 60% are children
(Walsh and Warren 1979). The use of chemicals such as
chlorine to disinfect water is common practice in the
developed world but may be inappropriate for developing
countries or sparsely populated areas. There may also be
adverse environmental consequences of using chlorine.
Therefore, increasing efforts have been put into investigating
methods of decontaminating drinking water and food prod-
ucts by using sustainable energy sources such as solar energy.
Ciochetti and Metcalf (1984) used solar cookers for water
decontamination. Naturally contaminated river water can be
disinfected in solar cookers, but the method is suitable for
only relatively small amounts of water. An even simpler
method was introduced by Conroy et al. (1996) in which
water contained in transparent plastic bottles is exposed to
the sun for a few hours before drinking. This method reduced
the rate of childhood diarrhoea by 10%.

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Surprisingly, the use of ordinary solar water heaters for
pasteurization of drinking water has received little attention.
We used solar cookers in an area which was experiencing a
cholera epidemic (Jørgensen 1995), and were asked if the use
of solar cookers could eliminate cholera from water. This is
possible, but it was considered that the method could be
improved and made more user-friendly by using solar panels,
which are independent of electricity or piped water. The
results of a preliminary trial were very encouraging (Jor-
gensen and Nørh 1995) and this method of pasteurizing
water was further studied by using internationally recognized
microbiological procedures for the detection of indicator bac-
teria for faecal contamination of drinking water. We also
examined the effect on pathogenic bacteria added to polluted
river water.

MATERIALS AND METHODS

Solar heating devices

The solar water decontaminator devices (HS 231545;
Roerslev Smedie, Roerslev, Denmark) heat water by using
solar radiation directly in a flow-through system of copper pipes arranged in parallel with two horizontal ‘header’ pipes and several vertical ‘riser’ pipes (Fig. 1). The water is led into the lower horizontal pipe and from here it rises by thermosiphoning to the upper horizontal pipe. The pipes are connected by soft soldering and covered by aluminium plates. The tubes and plates are painted black, mounted in an aluminium box insulated with Rockwool (Rockwool, Hede husene, Denmark) and covered with a transparent double-layer polycarbonate plate, coated to resist u.v. radiation. An adjustable thermostat valve (Thermostat AVTB 40–80; Danfoss, Nordborg, Denmark) prevents water below the chosen temperature from being withdrawn. From the upper ‘header’ pipe the water flows to a pipe with a larger diameter. Inside this larger pipe a sensor is fitted which is connected via a capillary tube to the valve. When the temperature of the water reaches the selected temperature, the valve opens and the water flows out. When colder water reaches the sensor, the valve shuts within 2–3 s. A similar device was fitted with a heat exchanger (HS 23345; Roerslev Smadic).
Experimental procedure

The tests were done in Dar es Salaam, Tanzania, during September 1995, a relatively sunny period of the year. Naturally, but heavily, contaminated water was collected from the small Mlalakuva River outside Dar es Salaam. The water level in the river was low and the water flow was slow. The water was collected from the middle of the stream in plastic containers and put into a larger dark plastic container placed on a 1.5 m high platform. The water was led from the container to the solar panels by ordinary garden hose pipes. The temperature of the water in the container was consistently 30°C. The water from the devices was adjusted to different selected temperatures between 62 and 85°C. Some of the samples were heated to 98°C in a water-bath in the laboratory to check for heat-resistant bacteria. The holding time in the panels varied according to the selected temperatures and was never less than 4 min. The trials were done using devices with and without a heat exchanger.

Water samples were collected into a specially made sterilized plastic bag after first sterilizing the sampling point with 70% alcohol. The devices were fitted with a special bent tube for sampling purposes. All the samples were processed within 2 h and after the temperature of the sample had cooled to below 37°C.

In order to examine the effect of heating on pathogenic bacteria, *Salmonella typhimurium* (no. 64; M.I.K FYN Laboratory, Odense, Denmark), *Streptococcus faecalis* (originating from ATCC no. 4533, Rockville, USA) and *Escherichia coli* (no. 4; M.I.K FYN Laboratory) were added to the raw Mlalakuva River water. The test organisms, after testing for impurities, were transported from M.I.K FYN Laboratory to Tanzania on plate count agar (PCA). One day before use, the test organisms were grown at 37°C in Brain Heart Infusion media (BHI) for 20 h. Then 0.74 ml of the three individual culture media were transferred to 10 ml phosphate buffer and finally added to 751 raw Mlalakuva River water; the mixture was homogenized by stirring approximately 50 times. After 1 h the samples from the container were taken as pre-treatment controls; the artificially contaminated water was then introduced into the solar panels and heated to the selected temperatures.

Bacteriological tests

Coliform bacteria and thermostolerant coliform bacteria were detected and enumerated by membrane filtration using standard methods (Anon. 1990a). For coliforms the membranes were incubated at 37°C on lauryl sulphate agar (LSA; MM 615; Oxoid) for 20-24 h. Presumptive yellow colonies were verified by growth on MacConkey agar no. 3 (CM 115; Oxoid) for another 20-24 h at 37°C. Red or red-purple colonies were considered coliform bacteria. For determination of thermostolerant bacteria and presumptive *E. coli* the membranes were incubated at 44°C on LSA (Oxoid). To verify *E. coli* the suspected colonies were transferred to FluoroCult ECD agar (no. 4038; Merck) and grown for 18-24 h at 37°C. Fluorescent colonies were tested for indole production on dry slide indol (Difco). Presumptive yellow colonies on LSA grown at 44°C, which were also fluorescent and indole-positive, were considered to be *E. coli*.

A relatively new method of enumeration of aerobic microorganisms is the use of Petrifilm plates (3M, St Paul, MN, USA). The dry agar was rehydrated with 1 ml of the raw sample or a similar amount of diluted sample. Total viable counts of bacteria grown aerobically for 48 h at 37°C were determined by using Petrifilm plates (Anon. 1993).

*Streptococcus faecalis* was isolated and counted by membrane filtration according to standard methods (Anon. 1990a) using m-Enterococcus Agar (no. 5289; Merck). Red colonies were transferred to bile-esculine acid agar (no. 0525; Difco) and incubated for 22 h at 37°C. Brown-black colonies were considered to be *Strep. faecalis*. Salmonellas were qualitatively determined according to Danish Standard Methods (Anon. 1988). After membrane filtration of 100 or 10 ml samples the membranes were pre-incubated in 100 ml of growth buffer for 22 h at 37°C. Samples of 0.1 ml were transferred for selective growth in Rappaport-Vassiliadis medium (CM 866; Oxoid) and incubated for 24 and 48 h at 41.5°C. Subcultures were made on Rambach agar (no. 7500; Merck). Presumptive red colonies were inoculated on trisaccharide iron agar (TSI 0265; Difco) and suspected colonies from red-yellow tubes with air formation and discoloration were put on transport agar, taken to the MLK FYN Laboratory for further examination using polyvalent sera (polyvalent-O, group A-S; Murex, Dartford, UK) and tested for biochemical reactions (API 20E; BioMerieux). Bacteria able to survive high temperatures were transported to the M.I.K FYN Laboratory on PCA for further examinations. The bacteria were grown on a medium for sporulation of *Bacillus* spp. modified after Kim and Naylor (1966), consisting of nutrient broth 0.8% (no. 0003; Difco), yeast extract 0.8% (no. 0127; Difco), MmSO4 10 mg l-1 (no. 5963; Merck), agar 2% and adjusted to pH 7.2. The spores were harvested from the medium, diluted, mixed with a carrier of special fine-grained sand, put into glass ampoules, dried and sealed. The numbers of spores were estimated after 48 h of incubation at 30°C using Petrifilm aerobic count plates (APC). The heat resistance of the bacterial spores was tested by determination of the Decimal Reduction Time at 160°C (S-value) for each of the isolated strains. For comparison, *Bacillus subtilis* var. *niger* (no. 9372; ATCC) was used.

**RESULTS**

An initial trial on 27 August 1995 showed that the water source was heavily contaminated and was a suitable supply...
of raw water for further trials. The next trials were all done in the following days, which had strong sunshine with an insolation of 960 Wm\(^{-2}\) without any interruptions from cloudy weather. These conditions permitted the use of the minimum holding time within the heating units and represented a valid trial of use conditions. After the initial trial, the temperatures chosen were between 62 °C, considered to be the lowest practical temperature for pasteurization of drinking water, and 85 °C, which was the highest possible setting of the thermostatic valves.

As shown in Tables 1 and 2, the total viable counts after culture at 37 °C of the raw water fluctuated between 2.5 x 10\(^4\) and 9.7 x 10\(^4\) ml\(^{-1}\). This number was reduced to values between 2.8 x 10\(^2\) and 1.0 x 10\(^3\) ml\(^{-1}\) with a tendency to a larger reduction at a higher temperature. Some of the samples were cultured in duplicate to give an indication of the accuracy of the methods (the figures are shown together in Table 1). The variability was between 7 and 18% compared with the average. Trials employing the device with a heat exchanger gave higher reductions of total viable count (Table 2).

The number of coliforms was also high in the raw water from the Mlalakuva River, 9.6 x 10\(^1\) to > 2 x 10\(^1\) ml\(^{-1}\) (not all results shown in the tables). Coliforms were not detected in any of the samples after treatment of the water. The thermostolerant coliforms were also eliminated after heat treatment of the water in all cases (Tables 1 and 2). Before treatment the content varied between 1.3 x 10\(^3\) and 9.6 x 10\(^3\) ml\(^{-1}\).

Table 1 Pasteurization of naturally and artificially contaminated river water. The solar flat-plate decontaminator was adjusted to produce a range of output temperatures

<table>
<thead>
<tr>
<th>Unheated river water</th>
<th>Heated water from decontaminator at different temperatures</th>
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<tbody>
<tr>
<td></td>
<td>30 °C</td>
</tr>
<tr>
<td>Total viable count at 37 °C (ml(^{-1}))</td>
<td>97 000</td>
</tr>
<tr>
<td></td>
<td>42 000</td>
</tr>
<tr>
<td></td>
<td>25 000</td>
</tr>
<tr>
<td></td>
<td>95 000</td>
</tr>
<tr>
<td>Coliforms 100 ml(^{-1})</td>
<td>1755</td>
</tr>
<tr>
<td>Thermotolerant coliforms 100 ml(^{-1})</td>
<td>380</td>
</tr>
<tr>
<td>Test bacteria added to river water</td>
<td></td>
</tr>
<tr>
<td><em>E. coli</em> 100 ml(^{-1})</td>
<td>400</td>
</tr>
<tr>
<td><em>S. faecalis</em> 100 ml(^{-1})</td>
<td>830 000</td>
</tr>
<tr>
<td><em>S. typhimurium</em></td>
<td>Present</td>
</tr>
</tbody>
</table>
| *The figures on the same line under the same temperature are results of duplicate determinations of the same sample in order to estimate the variations of the method.*

Table 2 Pasteurization of naturally and artificially contaminated river water. The solar flat-plate decontaminator was fitted with a heat exchanger which could double the production of drinking water

<table>
<thead>
<tr>
<th>Raw unheated river water</th>
<th>Heated water from solar decontaminator with heat exchanger</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>30 °C</td>
</tr>
<tr>
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<td></td>
<td>42 000</td>
</tr>
<tr>
<td>Coliforms 100 ml(^{-1})</td>
<td>22 000</td>
</tr>
<tr>
<td>Thermotolerant coliforms 100 ml(^{-1})</td>
<td>830</td>
</tr>
</tbody>
</table>

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Fig. 2 Results of the heating of spores of different *Bacillus* spp. isolated from the Mlalakuva River near Dar es Salaam, Tanzania and *Bacillus subtilis* var. *niger* (ATCC 9372). The samples were heated for different periods at 160 °C and the decimal reduction times (D-values) were estimated: (a) *B. sphaericut* TN19; (b) *B. megaterium* TN18; (c) *B. subtilis* var. *niger* ATCC 9372; (d) *B. sthembiformis* TN 2; (e) *B. subtilis* TN12

Some bacteria from the Mlalakuva River water were able to survive temperatures as high as 85 °C. To see if the bacteria were able to survive boiling, samples were boiled in a water-bath for 10 min. The total viable count could be reduced further but not eliminated. To examine this phenomenon further, microscopy of the surviving bacteria was done after Gram staining, which showed that all the bacteria were Gram-positive spore-forming rods. These bacteria were transported to Denmark and identified at the MLK FYN Laboratory, Microbiology Department and the Royal Veterinary Univer-

The results show that it is possible to clear heavily contaminated river water of faecal indicator bacteria by heating the water to 62 °C or above in solar flat-plate collectors. It is based on previous studies, it can be assumed that it is not possible to eliminate all bacteria by this procedure. The results show that it is possible to clear heavily contaminated river water of faecal indicator bacteria by heating the water to 75 °C. Most enteroviruses will be inactivated at 75 °C although hepatitis A virus might need as high as 85 °C for 4 min in food products (Anon. 1990b). Eggs of helminths such as Enterobius vermicularis will all be killed after less than 5 s at 75 °C (Jensen 1950). In addition, bacteria that grow in water supply systems, such as Legionella, Aeromonas and Pseudomonas cannot survive at 75 °C (WHO 1996). Prototaxa, such as Giardia lamblia (Ciochetti and Metcalf 1984), Entamoeba histolytica (Bran 1974) and Cryptosporidium (Anon. 1990b), will be killed by heating drinking water to 75 °C. Most enteroviruses will be inactivated at 75 °C although hepatitis A virus might need as high as 85 °C for 4 min in food products (Anon. 1990b). Eggs of helminths such as Enterobius vermicularis are killed at temperatures of 55 °C for a few seconds (Anon. 1990b). Bacteria causing food poisoning, such as V. parahaemolyticus, can be killed by heating to 75 °C (Anon. 1990b), whereas bacteria such as B. cereus and B. subtilis, which can cause food poisoning, produce spores that can survive boiling. On the basis of this information and our findings, we recommend that water treatment in the solar pasteurizer is carried out with an outlet water temperature of not less than 75 °C. Treatment at 65 °C produces water which meets recognized bacteriological standards (WHO 1996). By heating the water to 75 °C the water can be expected to be free of organisms that cause most of the water-borne diseases, but it may contain bacteria which, after being used for preparation of food, can multiply and on rare occasions give rise to food poisoning; the water should not be given parenterally.

Based on the daily average insolation in Dar es Salaam (4.6 kWh m⁻² (Anon. 1997), the daily production is estimated at 48.51 m⁻². This can be increased by 50% when a heat exchanger is used. The single parts of the devices are guaranteed for 10 years and, as the running costs are low, the cost of pasteurized water can be estimated at less than 0.008 US$ per litre. This is competitive with other means of securing safe water.

The results of estimating u-values showed that some bacteria in the Malakula River could survive high temperatures for a long period. One of the strains had a u-value of greater than 16 min, which is more than twice that of the u-value for international standards for dry heat sterilization. These findings might indicate that bacteria in hot climates can survive higher temperatures for a longer period than bacteria isolated in temperate climates. On this basis we recommend that bacteriological testing of drinking water uses raw water from the intended place of application.

ACKNOWLEDGEMENTS

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