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Decontamination of drinking water by direct heating in solar panels

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A.J. FJENDBO JØRGENSEN, K. NØHR, H. SØRENSEN 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 An adjustable thermostat valve prevents water below the chosen temperature from being withdrawn.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* to contaminated 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 50 l of decontaminated water per m^2 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 products 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 (Jorgensen 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 (Jorgensen and Nohr 1995) and this method of pasteurizing water was further studied by using internationally recognized microbiological procedures for the detection of indicator bacteria 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, Hedehusene, 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 233545; Roerslev Smedie).

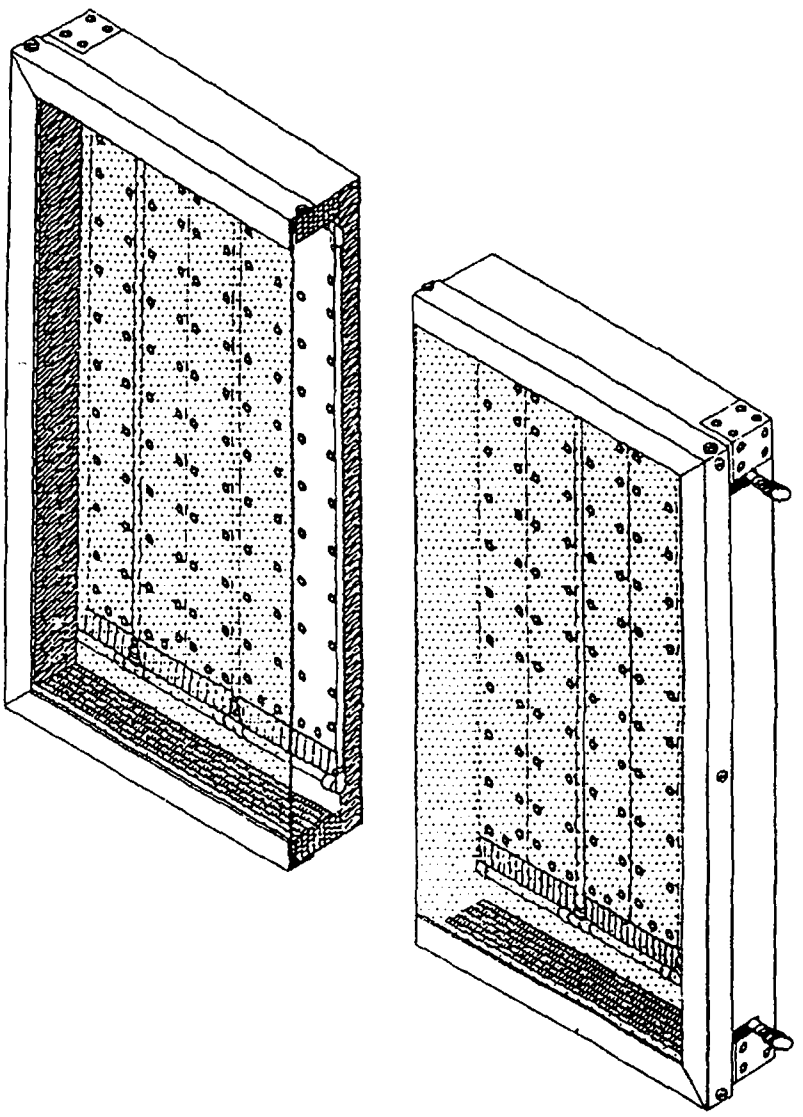

Fig. 1 The solar flat-plate decontaminator with its copper tubes covered by aluminium plates in a box insulated with Rockwool and covered by a double layer polycarbonate plate. The raw water is let in at the bottom, heated and let out at the top through a thermostatic valve

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; MLK FYN Laboratory, Odense, Denmark), *Streptococcus faecalis* (originating from ATCC no. 4533, Rockville, USA) and *Escherichia coli* (no. 4; MLK FYN Laboratory) were added to the raw Mlalakuva River water. The test organisms, after testing for impurities, were transported from MLK 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 (Difco) for 20 h. Then 0·74 ml of the three individual culture media were transferred to 10 ml phosphate buffer and finally added to 75 l 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 thermotolerant 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 thermotolerant 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 (TSJ 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 MLK 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), Mn_2SO_4 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 on Petrifilm aerobic count plates (APC). The heat resistance of the bacterial spores was tested by determination of the Decimal Reduction Time at 160 °C (D-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 $2{\cdot}5 \times 10^4$ and $9{\cdot}7 \times 10^4$ ml^{-1}. This number was reduced to values between $2{\cdot}8 \times 10^2$ and $1{\cdot}0 \times 10^1$ 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, $9{\cdot}6 \times 10^3$ to $> 2 \times 10^4$ l^{-1} (not all results shown in the tables). Coliforms were not detected in any of the samples after treatment of the water. The thermotolerant coliforms were also eliminated after heat treatment of the water in all cases (Tables 1 and 2). Before treatment the content varied between $1{\cdot}3 \times 10^3$ and $9{\cdot}6 \times 10^3$

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

	Unheated river water	Heated water from decontaminator at different temperatures									
	30 °C	62 °C	72 °C	75 °C	78 °C	82 °C		84 °C		85 °C	
Total viable count at 37 °C (ml^{-1})	97 000	190	280	55	70	100		80		39	
	42 000		230	43		65				43	
	25 000		230			120	140*	69	83*	38	26*
	95 000									45	
Coliforms 100 ml^{-1}	1755	0	0	0	0	0		0		0	
Thermotolerant coliforms 100 ml^{-1}	380	0	0	0	0	0		0			
Test bacteria added to river water											
Escherichia coli 100 ml^{-1}	400	0	0	0	0	0					
Streptococcus faecalis 100 ml^{-1}	830 000	0	0	0	0	0					
Salmonella typhimurium	Present	0	0	0	0	0					

* 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 flate-plate decontaminator was fitted with a heat exchanger which could double the production of drinking water

	Raw unheated river water	Heated water from solar decontaminator with heat exchanger		
	30 °C	72 °C	82 °C	85 °C
Total viable count at 37 °C (ml^{-1})	97 000	180	130	10
	42 000			30
Coliforms 100 ml^{-1}	22 000	0	0	0
Thermotolerant coliforms 100 ml^{-1}	830	0	0	0

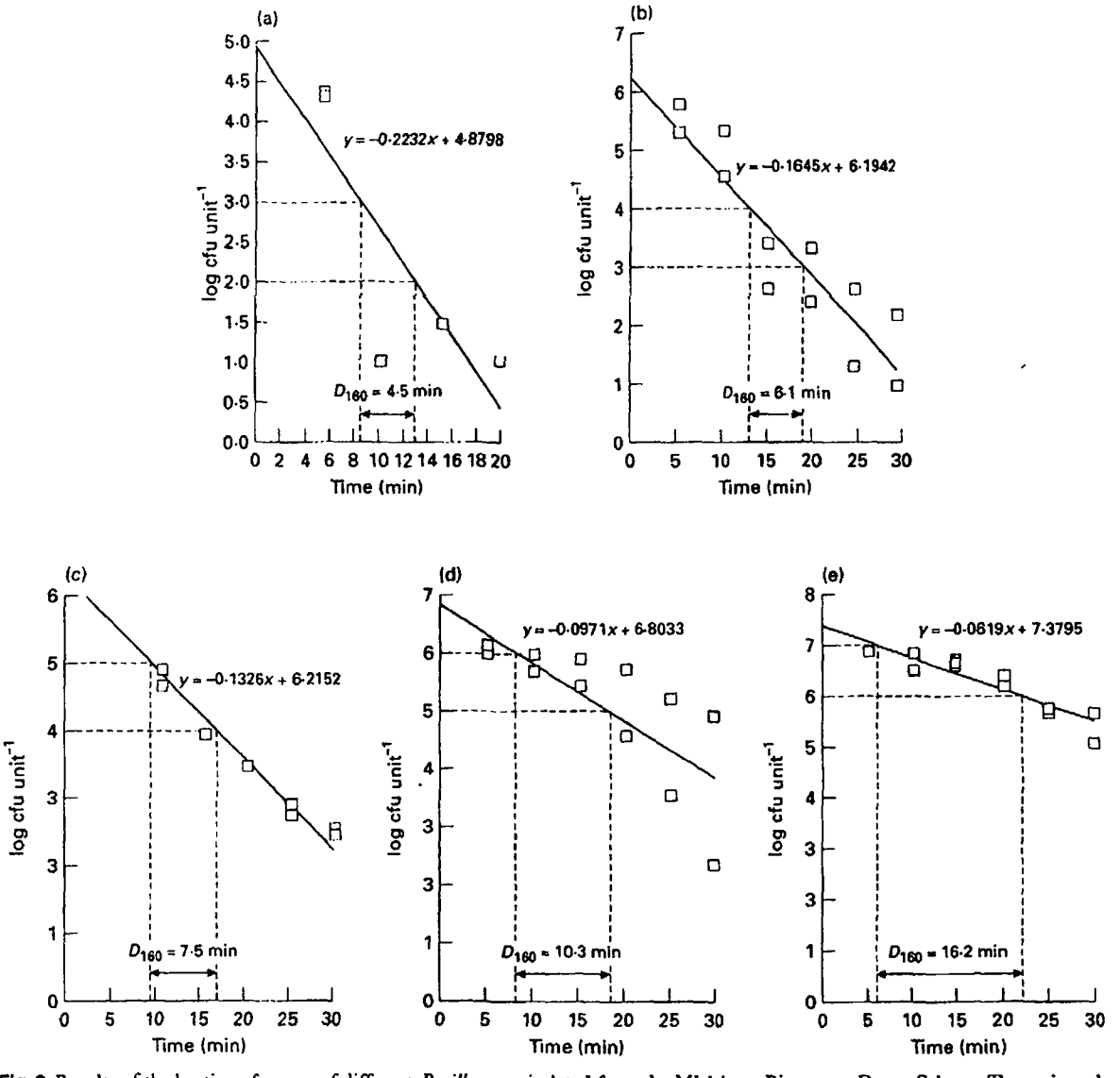

Fig. 2 Results of the heating of spores of different *Bacillus* spp. isolated from the Mlalakuva River near Dar es Salaam, Tanzania and *Bacillus subtilis* var. *niger* (ATCC 9372). The samples were heated for different periods at 160 °C and the decimal reduction times (D-values) were estimated. (a)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

thermotolerant coliforms l^{-1} (not all results shown). Artificially added *E. coli*, *Strep. faecalis* or *Salm. typhimurium* could not be detected in any samples after heat treatment in the solar decontaminator (Table 1).

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-

sity, Institute for Microbiology, Copenhagen, Denmark. All the bacteria belonged to the genus *Bacillus*. The species were *B. licheniformis, B. sphaericus, B. subtilis, B. megaterium* and *B. cereus*. The D-value at 160 °C for the different strains showed a large variation from 4·5 min for *B. sphaericus* to 16·2 min for *B. subtilis* (Fig. 2). In between these extremes were *B. megaterium* (6·1 min), *B. licheniformis* (10·3 min) and the commercial reference strain *B. subtilis* var. *niger* (7·5 min) (Fig. 2).

During the trial period the maximal output per hour of water at 75 °C was 11·31 m^{-2} flat-plate collector and 551 d^{-1}. For the month of April, which is the month with the lowest insolation, the daily average was 39·51 m^{-2}.

DISCUSSION

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 not possible to eliminate all bacteria by this procedure. The higher the temperature the greater the reduction in numbers of bacteria, but never to a degree of sterility because of the presence of spore-forming bacteria. It was also possible to eliminate artificially added bacteria such as *E. coli, Strep. faecalis*.and *Salm. typhimurium*. We did not test other microorganisms commonly transmitted in contaminated water but, based on previous studies, it can be assumed that *Shigella dysenteriae, Vibrio cholerae, Mycobacterium tuberculosis* and *Salm. typhi* 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). Protozoa, 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 D-values showed that some bacteria in the Mlalakuva River could survive high temperatures for a long period. One of the strains had a D-value of greater than 16 min, which is more than twice that of the D-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.

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