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Design, development and performance evaluation of non-tracking cooker type solar water purifier

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ABSTRACT

In remote areas of arid region in India, people often use stored rainwater in surface water reservoirs, for example, ponds, tanks, etc. as drinking water where supply of fresh drinking water is not available. Before using the pond water for drinking purpose, it should be cleaned from the presence of any harmful bacteria to avoid contamination. The stored rainwater in pond may be made bacteria-free by heating the water at a specified temperature using solar thermal technology. Considering this, a solar water purifier was designed and developed that can purify 30 L of pond water in a day. Thermal performance of the developed device has also been evaluated. Length to width ratio of the solar water purifier has been kept 2.5:1 to eliminate the tracking requirement. Average maximum stagnation temperature inside the chamber of solar water purifier was observed to be 147.5°C while ambient temperature was 37.5°C. Overall efficiency of the solar water purifier was observed to be 29%. Microbiological examination indicated that pond water contained ~1×10^7 cells mL^{-1} in contrast to the colony count of 1×10^{-1} cells mL^{-1} in treated water by the solar water purifier which indicated a significant improvement in quality of the drinking water. Thermal performance of the solar water purifier was tested as per different test procedures as standardized by the American Society of Agricultural Engineers (ASAE) and the Bureau of Indian Standards (BIS). Experimental evaluation showed the first figure of merit (F_1) as 0.122 $m^2\,°C\,W^{-1}$ under no load condition and second figure of merit (F_2) as 0.418 under water load condition, which indicates that the developed non-tracking cooker type solar water purifier falls under category 'A', as per ASAE and BIS standards.

Keywords: Solar water purifier; Pond water; Bacteria; Stagnation temperature; Water boil test

1. Introduction

Water is a basic necessity for human civilization along with food and air, therefore the importance of supplying hygienic potable or freshwater can hardly be over stressed. Billions of people on the earth have been dependent on rivers, lakes and underground water reservoirs for domestic consumption and use in agriculture and industry. However, the use of water from such sources is not always feasible due to presence of salts and harmful organisms beyond the desirable limits. Impact of many diseases afflicting mankind can be drastically reduced if fresh hygienic water can be provided for drinking purpose. But still there are few places in the world today where majority of the population are lacking fresh drinking water [1]. The availability of clean freshwater is one of the most basic conditions for achieving sustainable development in the 21st century [2]. Contaminated drinking water poses a major health threat to human beings worldwide. The problem is particularly significant in developing countries and in arid areas where water sources are scarce. Unsafe drinking water, along with poor sanitation and hygiene, is the main contributor to an estimated 4 billion cases of diarrheal disease annually, causing 1.8 million deaths, mostly among children less than 5 years of age [3]. In India alone, more than 450,000

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deaths per year are due to diarrheal disease, representing 9.1% of all deaths in children less than 6 years of age [4].

Drinking water is scarcely available in western arid region of India and people use surface water from ponds and open wells for daily consumption and often depend on rainwater collected from rooftop, which is too little to meet their drinking water demand [5]. The impact of waterborne infectious diseases can be drastically reduced if fresh hygienic water is provided for drinking. Generally in summer season, villagers travel miles away from their home in search of freshwater. It is observed that at least one or two family members are always busy in bringing freshwater from distant sources. The worst situation occurs when water resource become unavailable and villagers are forced to consume highly saline underground water containing nitrate and fluorides or pond water contaminated with pathogenic microbes [6]. This normally leads to diarrhea and similar diseases as well as physical disorder of various kinds.

Conventional methods of disinfecting the drinking water are chemical treatment, heat pasteurization and filtration, but these methods require facilities, materials and fuel that may not be readily available or feasible to attain. An alternative treatment option is to utilize solar energy, which has been shown to inactivate pathogens through solar water purifier. In arid part of Rajasthan, solar irradiations are available in abundance and almost 300 clear sky days are observed annually. Amount of solar irradiation received in the region is about 7,600–8,000 MJ m^{-2} per annum, whereas in semi-arid region it is about 7,200–7,600 MJ m^{-2} per annum and in hilly areas it is about 6,000 MJ m^{-2} per annum [7]. Therefore, solar water purifier seems to be a good substitute for conventional methods, which include boiling water by burning firewood. The little work has been done on use of solar energy for water disinfection. Lawand et al. [8] found that small quantity of water can be pasteurized within 2–4 h by exposing water to solar radiation with minimum intensity of 500 W m^{-2}. Andreatta et al. [9] described different methods for pasteurization of water using solar energy. Studies carried out by Brandão et al. [10] using water that presented turbidity of 110 nephelometric turbidity units (NTU) and initial total fecal coli forms concentration of 106 UFC per 100 mL demonstrated that 100% decontamination can be achieved in an exposure time of 2 h and water temperature of 50°C. Based on the above studies, it is observed that a solar water purifier can make the pond water drinkable. Considering this, a solar water purifier has been designed, developed and evaluated for its thermal performance. Experiments were carried out at Jodhpur, Rajasthan, India, with the developed solar water purifier in which different standard test parameters recommended by the American Society of Agricultural Engineers (ASAE) and the Bureau of Indian Standards (BIS), for example, first figure of merit (F_1) and second figure of merit (F_2) were evaluated [11–13].

2. Materials and methods

2.1. Design of solar water purifier

A double glazed non-tracking solar water purifier with reflector was designed and fabricated at the workshop of ICAR-Central Arid Zone Research Institute, Jodhpur, India. The solar water purifier is based on the principle of hot box solar cooker. The outer box was made of galvanized steel sheet (22 SWG) and inner box was a double-walled tray made of aluminum (22 SWG). The dimensions of outer box were 1,300 × 590 × 200 mm and of the inner box were 1,200 × 490 × 100 mm with 80 mm height (Fig. 1). The space between the outer box and inner box was filled with glass wool insulation to eliminate the heat loss. The top side of the inner tray was painted black using black board paint to absorb maximum amount of radiation. Two clear window glass planes of 4 mm thickness were fixed on top of the box with an openable wooden frame fixed on hinges. The spacing between two glass cover was 15 mm to avoid thermal losses. A rubber gasket is provided between the tray and the openable frame to make it leak proof. A 4-mm thick plain mirror reflector was fixed at the back edge of the device and aligned vertically facing south. The tilt of the reflector can be varied from 0° to 120° depending upon the season and its tilt is fixed once in a fortnight. The reflector can be folded on the water purifier while the device is not in use. The aperture area of the solar water purifier is 0.60 m^2 and 20 glass bottles each of 750 mL can be kept inside it for purification of water. The solar water purifier is fixed on an angle iron stand. The length to width ratio of the solar water purifier has been fixed as 2.5:1 to capture maximum amount of reflected radiation by the vertically aligned mirror reflector in addition to direct radiation received on horizontally aligned top glass surface. The portion of the inner box receiving the reflected radiation by the mirror reflector increased from 20% to 33% when length

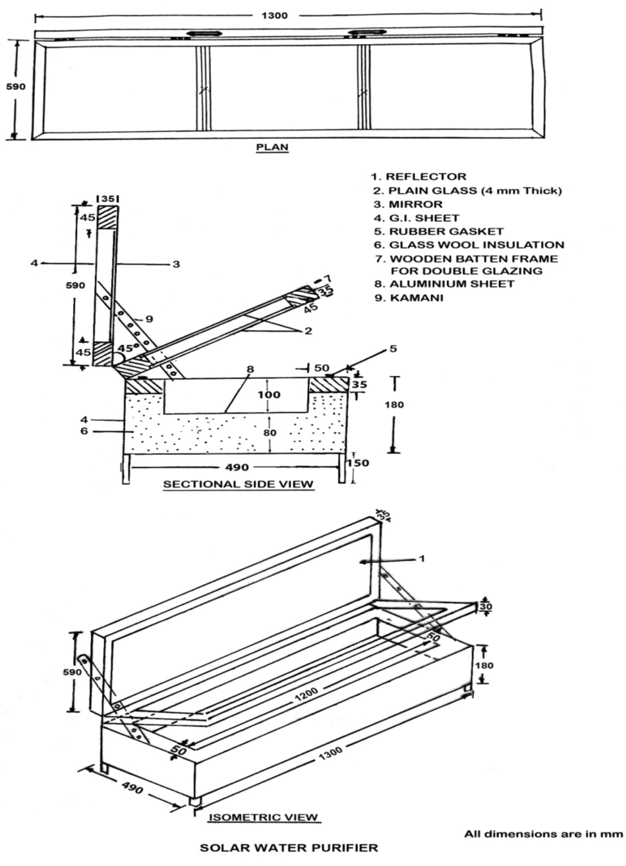

Fig. 1. Design of solar water purifier.

to width ratio of the water purifier increased from 1:1 to 2:1 while at 3:1 it was 40%. Further increase in length to width ratio did not increase the exposed area by reflected radiation within the inner box of the water purifier. Therefore, the length to width ratio of the water purifier was kept 2.5:1, which allowed to receive reflected radiation in 38% area of the inner box of the water purifier [14]. It helped in eliminating the need for azimuthal tracking of the water purifier towards the sun every hour. Actual installation of the solar water purifier is shown in Fig. 2.

2.2. Experimental arrangement and procedure

The on-field experiments at the ICAR-Central Arid Zone Research Institute, Jodhpur, India, (26°18′N and 73°04′E) were performed during May 2016 to evaluate the thermal performance of the developed solar water purifier. In these experiments, the solar radiation intensity (G_s) on a horizontal surface was measured using a thermopile pyranometer. DTM-100 thermometer with point contact thermocouples (accuracy 0.1°C) was used to measure the temperatures at different locations of the water purifier, for example, the base plate and water temperature. Ambient air temperature was measured using a mercury thermometer (accuracy 0.1°C) placed in an ambient chamber. The measurements of temperatures of different regions were carried out on clear sunny days at every 15 min interval for the duration of 10:00 to 14:00 Indian Standard Time (IST). Reflector was used whenever required as per test conditions.

2.3. Thermal performance and testing

A procedure for testing the non-tracking solar water purifier was developed based on existing international testing standards. These standards include three major testing standards commonly employed in different parts of the world: (i) ASAE Standard [11], (ii) BIS Testing Method [12,13] and (iii) European Committee on Solar Cooking Research Testing Standard and others [15]. Based on the existing international testing standards, two tests were performed on the solar water purifier: (i) first figure of merit, F_1 and (ii) second figure of merit, F_2. The first figure of merit is determined by conducting the no-load test, whereas second figure of merit

Fig. 2. Solar water purifier.

was determined by load test in which known amount of water is sensibly heated in solar water purifier. The efficiency of the solar water purifier has also been obtained by measuring the rise in temperature of a known quantity of water in a specified time as proposed by the method of calculation of efficiency (η) of the solar cooker [16–19]. The solar radiation, ambient air temperature, base plate temperature and water temperature were taken at a 15 min interval in order to determine the first figure of merit F_1 and second figure of merit F_2 of the solar water purifier and compared it with the standard. Reflector was not used as per the test protocol and shrouded with black cloth to determine F_1 and F_2.

2.3.1. First figure of merit (F_1) without water load (stagnation test)

The first figure of merit (F_1), of solar water purifier is defined as the ratio of optical efficiency, (η_0), and the overall heat loss coefficient, (U_L). A quasi-steady state (stagnation test condition) is achieved when the stagnation temperature is attained. High optical efficiency and low heat loss are desirable for efficient cooker performance. Thus the ratio η_0/U_L which is a unique parameter which can serve as a performance criterion. In stagnation test initially temperature of base plate increases and after some time it became stagnant. Higher values of F_1 would indicate better performance of the water purifier:

$$F_1 = \frac{\eta_0}{U_L} = \frac{(T_{ps} - T_a)}{G_s} \tag{1}$$

where F_1 is first figure of merit (m² °C W⁻¹), η_0 is optical efficiency (%), U_L is overall heat loss coefficient of the cooker (W m^{-2} °C^{-1}), T_{ps} is maximum plate surface temperature (°C), T_a is ambient temperature (°C), and G_s is global solar radiation on a horizontal surface (W m^{-2}).

2.3.2. Second figure of merit (F_2) with water load (sensible heat test)

The second figure of merit, F_2, of solar water purifier is evaluated under full-load condition (water load), without reflector and can be defined as the product of the heat exchange efficiency factor (F') and optical efficiency ($\eta_0 = a\tau$) [20,21]. It can be expressed as:

$$F_2 = F'\eta_0 C_R = \frac{F_1 (MC)w}{A(t_2 - t_1)} \ln \left[\frac{1 - \frac{1}{F_1}\left(\frac{T_{w1} - \bar{T}_a}{\bar{G}_s}\right)}{1 - \frac{1}{F_1}\left(\frac{T_{w2} - \bar{T}_a}{\bar{G}_s}\right)} \right] \tag{2}$$

where F_2 is the second figure of merit, F' is heat exchange efficiency factor, η_0 is optical efficiency, $(MC)_w$ is product of the mass of water and its specific heat capacity, A is aperture area of the solar water purifier (m²), F_1 is first figure of merit (m² °C W^{-1}), t_1 is initial time (s), t_2 is final time (s), T_{w1} is initial temperature of water (°C), T_{w2} is final temperature of water (°C), $\bar{G}_S$ is average global solar radiation (W m^{-2}), and $\overline{T_a}$ is average ambient temperature (°C).

2.4. Efficiency of the water purifier (η)

The efficiency of the non-tracking solar water purifier was carried out by measuring stagnation plate temperature and rise in pond water temperature filled in the bottles in known interval of time. The stagnation plate temperature was measured by putting number of thermocouples on the plate and on air inside water purifier chamber and temperature of each was measured by the portable digital thermometer with suitable sensor (accuracy 0.1°C) and average of initial and final was taken. The initial temperature of cold water was measured and when it reached near the boiling point temperature of water, the final temperature of hot water was measured and time interval was also measured. The efficiency of the solar water purifier has been found by the following relations proposed by Nahar [16–19]:

$$\eta = \frac{\left(MC_w + M_1C_u\right)\left(T_{w2} - T_{w1}\right)}{CA\int_0^t G dt} \quad (3)$$

where A is the absorber area (m^2), C is the concentration ratio, C_u is the specific heat of bottle (J kg^{-1} °C^{-1}), C_w is the specific heat of water (J kg^{-1} °C^{-1}), G is the solar radiation (W m^{-2}); M is the mass of water in bottle (kg), M_1 is the mass of bottle (kg); T_{w1} is the initial temperature of water (°C), T_{w2} is the final temperature of water (°C); t is the time interval (s) and η is the efficiency of solar water purifier.

3. Results and discussion

The stagnation temperature experiment test revealed that the plate temperature increased up to 105°C within half an hour from the start of experiment at 10:00 h and stagnated at about 145°C at around 13:15 h. The increase in stagnation temperature corresponding to the solar radiations is shown in Fig. 3. The highest temperature attained by plate was 147°C when the ambient temperature (T_a) was 37.0°C and global solar radiation was (G_s) 901 W m^{-2}.

Fig. 3 illustrates the changes of plate and ambient temperature with the variation of insolation. The stagnation temperature varied between 128°C and 147°C with the insolation variation from 893 to 914 W m^{-2}. The first figure of merit F_1 was calculated using Eq. (1) as per the stagnation thermal performance test. The first figure of merit (F_1) of the solar water purifier was found to be 0.122 °C m^2 W^{-1} whereas, as per standard F_1 test, if the value of F_1 is greater than 0.12, the device is marked as A grade while value less than 0.12 is marked as B grade [9–10,20]. Therefore, the developed solar water purifier is marked as a A-grade solar water purifier based on the F_1 test. Higher values of first figure of merit indicate good thermal performance of the solar device [22].

During the full load test of the solar water purifier, initial water temperature (T_{w1}) and final water temperature (T_{w2}) were considered 61°C and 95°C, respectively. The temperature profile of water, ambient condition and insolation during test are shown in Fig. 4. The trend of the water temperature curve shows that as time of day progresses water temperature increases with increasing solar insolation. The value of second figure of merit (F_2) using Eq. (2) was found to be 0.418 using the value of F_1 as 0.122 °C m^2 W^{-1}, which was determined previously. Other parameters of the test were as follows: M = 9.5 kg, C = 4,186 J kg^{-1} °C^{-1}, A = 0.60 m^2, $t_2 - t_1$ = 150 min (9,000 s), T_{w1} = 61°C, T_{w2} = 95°C, $\bar{G}_S$ = 945 W m^{-2}, $\overline{T_a}$ = 37°C. Calculated value of F_2 of the developed solar water purifier was found within the recommended standard value in the range of 0.254–0.490 [20]. Higher values of F_2 indicate good heat exchange efficiency factor F' with number of pots and low heat capacity of the cooker interiors and vessels compared with the full load of water [23]. It is found that F_2 increases with load and this is because of an improvement in heat capacity ratio, as mass of water in the pots increases [22].

Quality of the treated water by solar water purifier was also evaluated by observing the colony count. In general, temperature of pond water filled in 20 glass bottles, which were kept inside the solar water purifier reached to 95°C at 13:30 h during summer condition while it reached to 78°C at 13:30 h during winter. All microbes, including fecal indicator bacteria such as *E. coli,* waterborne pathogenic bacteria such as those responsible for cholera and dysentery, and certain viruses and protozoal parasites are destroyed at temperature more than 70°C, therefore, pond water treated by the solar water purifier is considered suitable for drinking [6]. Fig. 5 depicts nutrient agar plates plated with untreated pond water and solar water purifier treated water after incubation for 5 d at 30°C. Microbiological examination indicated that pond water

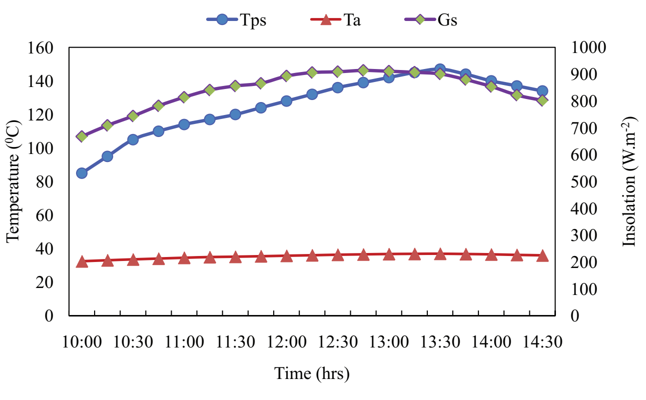

Fig. 3. Stagnation temperature test of solar water purifier for first figure of merit (F_1).

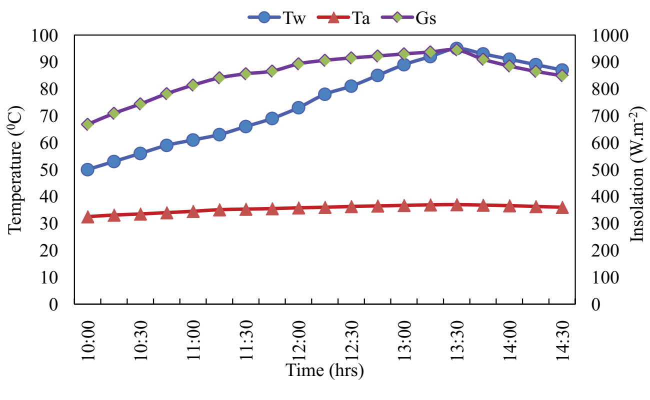

Fig. 4. Water heat-up test of solar water purifier for second figure of merit (F_2).

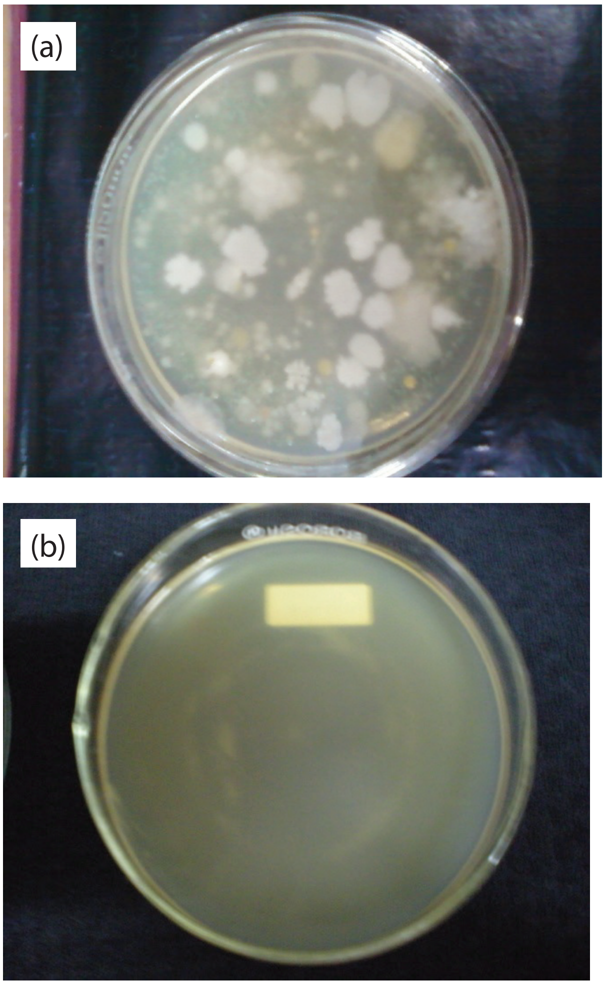

Fig. 5. Microbiological examination of raw pond water with bacteria (A) and solar water purifier treated water without bacteria (B).

contained ~1 × 10^7 cells mL^{-1} in contrast to ~0.1 × 10^1 cells mL^{-1} in treated water by the solar water purifier. Therefore, the results clearly indicate that highly contaminated pond water can be purified by the developed solar water purifier. The developed solar water purifier is capable of purifying 30 L of pond water per day which is sufficient for a family.

The efficiency of the solar water purifier was calculated using Eq. (3) and it was found to be 29.0%. As compared with this, efficiency of hot box and large size non-tracking solar cookers, design of which were similar to the solar water purifier, were found to be 24.5–27.5% and 24.9–27.5%, respectively [16–19]. Thus, the efficiency of solar water purifier was observed slightly higher than similar type of solar thermal devices, which were almost similar in design with solar water purifier. Thermal efficiency of the solar water purifier depends on several factors, for example, solar insolation, mass of the loaded water, time t taken to boil the water, control of the reflector, etc. So, future experiments may be needed to fully understand their effects on thermal efficiency. The present solar water purifier showed the best performance and highest efficiency for the maximum load condition, which is an indication of better heat retention ability of the solar water purifier as compared with others found in the literature [16–19].

4. Conclusion

A non-tracking type solar water purifier was designed and developed to treat the pond water for making it suitable for drinking purpose in rural arid areas of Rajasthan, India. The solar water purifier was designed with a top double-walled glass surface and a mirror reflector. The length and width ratio of the purifier was kept 2.5:1 so as to receive maximum amount of direct radiation and reflected radiation within the inner box of the purifier. Thermal performance of the developed solar water purifier was evaluated by standard test procedures. Stagnation temperature inside the developed solar water purifier without any load was found maximum 147°C while the ambient temperature and solar insolation was 37°C and 901 W m^{-2}, respectively. Temperature of pond water filled in glass bottle and kept inside the purifier with full load of 20 bottles was found maximum 95°C during summer and 78°C during winter. The first figure of merit (F_1) and second figure of merit (F_2) were found to be 0.122 °C m^2 W^{-1} and 0.418, respectively, which were found within the suggested ranges in literatures and thus can be considered as 'A'-grade solar device. Microbiological evaluation of treated water also indicated the destruction of pathogens and harmful organisms, which makes the pond water suitable for drinking purpose. Thermal efficiency of the developed solar water purifier was found 29%, which is slightly higher than the similar type of solar thermal devices as reported in literature. Thus, the developed solar water purifier may be a useful device to rural population in arid areas of India as well as in other arid parts of the world where availability of clean drinking water is scarce. The developed solar water purifier also promotes the use of renewable energy and has a potential to reduce the consumption of conventional fuels and CO_2 emission, which will further help in combating desertification.

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