PRODUCTIVITY ENHANCEMENT OF STEPPED SOLAR STILL – PERFORMANCE ANALYSIS

by

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Maintaining minimum depth in conventional basin type solar still is difficult, as the area is large. However this can be achieved in stepped solar still in which the area of the basin is minimized by having small trays. Very few works have been carried so far in stepped solar still and constant depth trays are used in the basin plate. In this work, a stepped still with two different depth of trays are used. The basin plate contains twenty five trays with 10 mm depth and twenty five trays with 5 mm depth. To improve the productivity, experiments were carried out by integrating small fins in basin plate and adding sponges in the trays. Theoretical and experimental analyses are made for fin type, sponge type, and combination of fin and sponge type stepped solar still. When the fin and sponge type stepped solar is used, the average daily water production has been found to be 80% higher than ordinary single basin solar still. The theoretical results agree well with the experimental. Also an economic analysis was made. The payback period of this setup is 400 days.

Key words: *stepped solar still, productivity enhancement, sponge, fins*

Introduction

Water is one of the prime elements responsible for life on earth. It covers three-fourths of the surface of the earth. However, over most of earth's water is found in oceans as saltwater, contains too much of salt, cannot be used for drinking, growing crops or most industrial uses. The remaining earth's water supply is fresh water. Most of this is locked up in glaciers and ice caps, mainly at the north and south poles. If the polar ice caps were to melt, the sea level would rise and inundate much of the present land surfaces in the world. The rest of the world's supply of fresh water is found in water bodies such as rivers, streams, lakes, ponds, and in the underground.

Our drinking water today, far from being pure, contains some two hundred deadly commercial chemicals toxins and impurities [1]. So there is an important need for clean and pure drinking water. In many coastal areas where seawater is abundant but potable water is not available. Solar water distillation is one of the many processes that can be used for purification as well as desalination.

Solar still is the widely used solar desalination device. But the productivity of the solar still is very low. To augment the productivity of the simple solar still, several research works are being carried out. A flat plate collector was integrated with a single basin solar still by Badran *et* *al*. [2] and Tiris *et al.* [3]. They found that the maximum increase in productivity of potable water was 52%. A flat plate collector [4], flat plate collector with hot water storage tank [5, 6] was integrated with solar stills by Voropoulos *et al*. It was found that the amount of water produced was doubled that when the still was operated alone. Also the authors designed a hybrid solar desalination and water heating system [7]. It was found that withdrawal of hot water from storage tank reduced the production of distilled water in a specific pattern. Productivity of potable water increases 18% when sponge cubes [8] were used in the saline water. A wick basin type solar still [9] was designed by Minasian *et al*. and proved that the productivity increases by 85%. A Multiwick single slope solar still [10] was designed by Shukla *et al*. Integration of solar still in a multi-source, multi-use environment [11] was studied by Mathioulakis *et al*. Tiwari *et al*. [12] used a multi wick solar still with electrical blower. Nafey *et al*. used black rubber [13] and black gravel [14] for augmenting the productivity of the solar still. The productivity increases by about 20%, when black rubber was used and about 19%, when black gravel was used. Potable water productivity increases by 20%, when a baffle suspended absorber was used by Sebaii *et al.* [15]. A plastic water purifier was designed by Ward [16] and effect of double glass in the still [17] was studied by Yousef. It was concluded that the productivity of the double glass regenerative solar still is more than 20% higher than that for the conventional still. A corrosion free solar collector for sea water desalination was developed by Hermann [18]. The author developed collector with corrosion – free absorbers. The absorbers can withstand stagnation conditions and have a good efficiency at the operating temperature of about 90 °C. For augmenting the evaporation rate of effluent in the flat plate collector, Srithar *et al.* [19] compared the simulated performance of open flat plate collector with the experimental. The authors used open fibre reinforced plastic flat plate collector and spray evaporation system [20] and they have compared the conventional collector with open flat plate collector [21]. Analysis of solar flat plate collector evaporation system [22] and single cover fibre reinforced plastic flat plate collector [23] were studied by Srithar *et al*. The effect of using different designs of solar stills was studied by Hayek *et al.* [24]. Hussaini *et al.* used vacuum technology [25]. The results show that applying vacuum inside the solar still increases the water productivity about 100%. Kalogirou [1] designed a parabolic trough solar energy collector for sea water desalination. Sebaii [26] developed a triple basin solar still for enhancing productivity of the solar still. Velmurugan *et al*. [27] designed a mini solar pond and integrated with a basin type solar still. Results show that the productivity increases by 58% than the ordinary solar still.

The objective of this work is to improve the productivity by means of usage of trays with two different depths, integrating fins at the basin, usage of sponges in stepped solar still and combination of the above. Ward [16] designed a plastic water purifier. In his work, the author used trays of constant depth of 10 mm. Whereas in this work different depth of trays are designed using galvanized iron (GI) material. Twenty five numbers of 10 mm depth trays and twenty five numbers of 5 mm depth trays are used. By increasing the area of the basin plate, productivity can be increased. This can be done by using sponges and integrating fins at the exposure surface of the base plate. Initially experiments are carried out with simple basin stepped solar still. In the next setup, 200 sponges are added to increase exposure area of the free surface of water and tested. Then the basin plate is modified by providing 250 fins at the basin plate and tested. Again to enhance the productivity of the stepped solar still combination of both 250 fins and 200 sponges are used. Though sponges were already used by Hijileh *et al*. [8], for comparison purpose they are used in this work. Theoretical analysis is also made by solving energy balance equations and compared with experimental results.

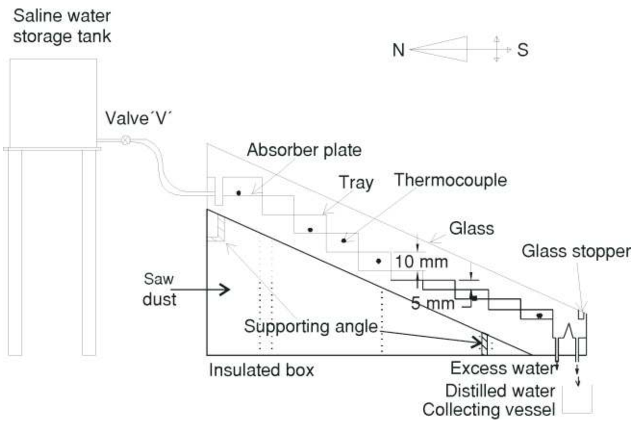

Figure 1. Schematic diagram of the stepped solar still

Experimental setup

Still only

The experimental setup consists of a saline water storage tank and a stepped solar still as shown in fig. 1. The absorber plate in the still is looking like a stepped structure. Material used for absorber plate is GI steel sheet because of its easy availability and low cost. The size of the absorber plate is 1000 by 500 mm. There are totally 50 trays in the absorber plate. Each individual tray is of 99 by 99 mm cross-section but of different depths. Totally the absorber plate has fifty trays. As shown in fig. 2, the first twenty-five trays have 10 mm and the next twenty-five trays have 5 mm depth. The thickness of the tray is 1 mm. It is coated with black paint to increase the absorption. The black absorber sheet is a rectangular shaped structure with the array of shallow, square section trays. The absorber plate is placed inside a wooden box of size 1000 by 500 mm. The space between the wooden box and basin plate is filled with saw dust for insulation purpose.

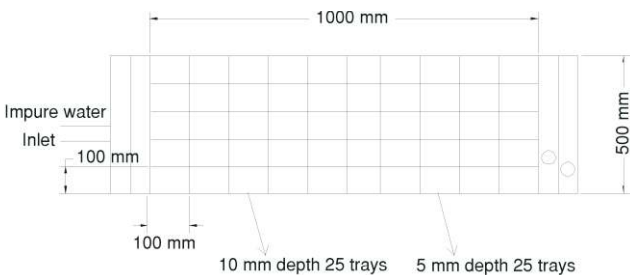

Figure 2. Schematic diagram of the top view of the stepped solar still

The saline water is supplied to the stepped solar still from the saline water storage tank through polyvinyl chloride hose. Once the trays are filled, the excess water comes out from the stepped solar still and collected for reuse. When solar radiations fall on the glass, water evaporates and condenses in the glass. The condensed water is collected through a pipe, provided at the bottom of the still. As evaporation takes place, the saline water level in the solar still decreases. To compensate the loss of water, for every half an hour, the make up water is added to the still from the storage tank. This stepped solar still system has been fabricated and tested at Thiagarajar College of Engineering, Madurai, India, during December 2005 to October 2006. The average sunshine in Madurai is 600 W/m^2 during the above said period.

The errors occurred in the measuring instruments were calculated. Thermocouples, collecting vessel, Kipp-Zonan solarimeter, and vane type digital anemometers are used for measuring temperature, distillate collection, solar intensity and wind velocity, respectively. The minimum error occurred in any instrument is equal to the ratio between its least count and minimum value of the out put measured. The accuracies of various measuring instruments used in the experiments are given in tab. 1.

Table 1. Accuracies and ranges of measuring instruments

Sl. No.	Instrument	Accuracy	Range	% error
1.	Thermocouple	±1 °C	0 to 100 °C	0.25%
2.	Kipp-Zonen solarimeter	±10 W/m^2	0-5000 W/m^2	0.25%
3.	Anemometer	±0.1 m/s	0-15 m/s	10%
4.	Collecting vessel	±10 ml	0-1000 ml	10%

Still with sponges

To increase the free water surface area, sponges are used as shown in fig. 2. In this experimental setup, 200 sponges are used. The dimenssions of the sponges are 35 by 35 by 20 mm. Hijileh *et al.* [8] proved that the maximum productivity would occur when the volumetric ratio between sponge and water is 20%. So, in this work, the volumetric ratio between sponge and water is maintained as 20%. Due to capillary action, water raises to the exposure area of the sponges and thus free water surface increases. There is no side effect of sponges and the taste of water is observed. However, everyday the sponges are cleaned before they are used in the stills.

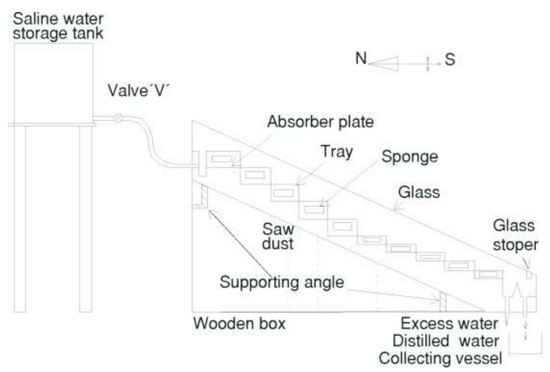

Figure 3. Schematic diagram of the sponge type stepped solar still

Still with fins at the basin

To increase the absorber plate area, circular rods are used as fins as shown in fig. 3. The bottom of the rod is welded at the top surface of the trays. The diameter and length of the fins are 1 and 35 mm, respectively. Five fins are used per tray. Totally 250 fins are used. Half portion of the fin is placed inside the saline water and remaining half portion is exposed to air.

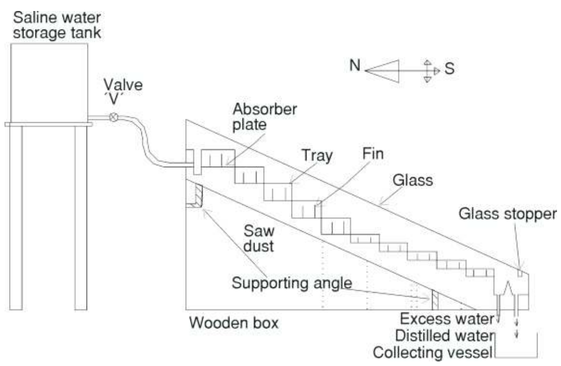

Figure 4. Schematic diagram of the fin type stepped solar still

Still with fins and sponges

For augmenting the productivity of the stepped solar still, an attempt is made with both sponges and fins. In this experimental setup 200 Sponges and 250 fins are used. The schematic diagram of the fin and sponge type stepped solar still is shown in fig. 4. Both the top surfaces of the sponges and fins are exposed to air. The size of the fins and sponges are shown in fig. 5.

Mathematical model

Still only

The various energy transfer in stepped solar still are shown in fig. 6. The energy balance equation for the absorber plate, saline water, and glass of the solar still can be written as follows.

Energy received by the basin plate is equal to the summation of the energy gained by the basin plate, energy lost by convective heat transfer between basin and water, and side losses:

$$I(\mathrm{t})A_{\mathrm{b}}\alpha_{\mathrm{b}} = m_{\mathrm{b}}c_{\mathrm{pb}}\frac{\mathrm{d}T_{\mathrm{b}}}{\mathrm{d}t} + Q_{\mathrm{c\ b\text{-}w}} + Q_{\mathrm{loss}} \tag{1}$$

The absorptivity of the still α_{b} is taken [19] as 0.95.

I(t), the total solar flux on an inclined surface is obtained from [19, 23]:

$$I(\mathrm{t}) = (I_{\mathrm{g}} - I_{\mathrm{d}})\frac{\cos\theta_{\mathrm{i}}}{\cos\theta_{\mathrm{h}}} + I_{\mathrm{d}}\frac{1+\cos\beta}{2} \tag{2}$$

The convective heat transfer between basin and water is taken as

$$Q_{\mathrm{c\ b\text{-}w}} = h_{\mathrm{c\ b\text{-}w}}A_{\mathrm{b}}(T_{\mathrm{b}} - T_{\mathrm{w}}) \tag{3}$$

The convective heat transfer between basin and water is [17] 135 W/m^{2}K. The heat loss from basin to ambient is taken as:

$$Q_{\mathrm{loss}} = U_{\mathrm{b}}A_{\mathrm{b}}(T_{\mathrm{b}} - T_{\mathrm{a}}) \tag{4}$$

where U_{b} is taken [17] as 14 W/m^{2}K

Energy received by the saline water in the still (from sun and base) is equal to the summation of energy lost by convective heat transfer between water and glass, radiative heat transfer between water and glass, evaporative heat transfer between water and glass, and energy gained by the saline water:

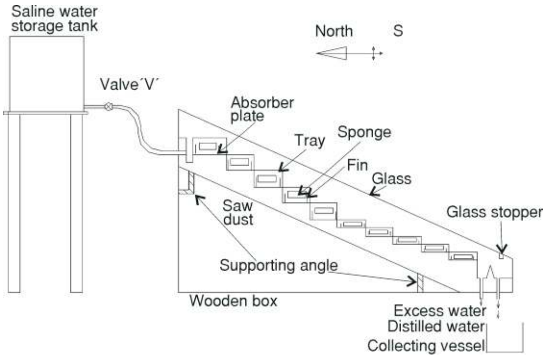

Figure 5. Schematic diagram of the fin and sponge type stepped solar still

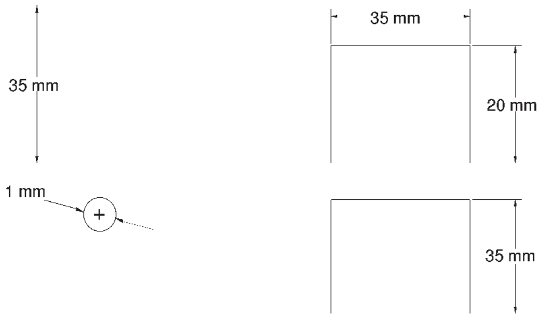

Figure 6. Schematic diagram of the fin and sponge

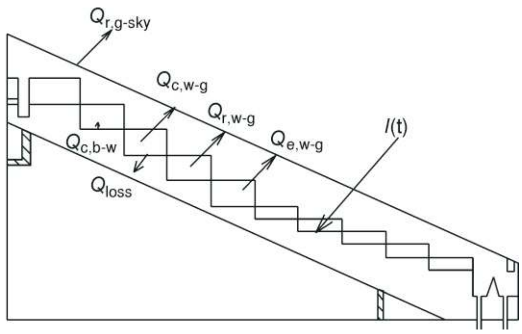

Figure 7. Energy analysis in stepped solar still

$$I(\mathrm{t})\alpha_{\mathrm{w}}A_{\mathrm{w}} + Q_{\mathrm{c\ b\text{-}w}} = Q_{\mathrm{c\ w\text{-}g}} + Q_{\mathrm{r\ w\text{-}g}} + Q_{\mathrm{e\ w\text{-}g}} + m_{\mathrm{w}}c_{\mathrm{p\ w}}\frac{\mathrm{d}T_{w}}{\mathrm{d}t} \tag{5}$$

The mass of water in the still is taken as 3.75 kg and the absorptivity of the water α_{w} is taken [17] as 0.05. The specific heat of the saline water $C_{\mathrm{p\ w}}$ is calculated from [23].

The convective heat transfer between water and glass is given by:

$$Q_{\mathrm{c\,w\text{-}g}} = h_{\mathrm{c\,w\text{-}g}} A_{\mathrm{w}} (T_{\mathrm{w}} - T_{\mathrm{g}}) \tag{6}$$

The convective heat transfer co-efficient between water and glass is given by [17]:

$$h_{\mathrm{c\,w\text{-}g}} = 0.884 \sqrt[3]{T_{\mathrm{w}} - T_{\mathrm{g}} + \frac{(P_{\mathrm{w}} - P_{\mathrm{g}})(T_{\mathrm{w}} + 273.15)}{268.9 \cdot 10^3 - P_{\mathrm{w}}}} \tag{7}$$

The radiative heat transfer between water and glass is given by:

$$Q_{\mathrm{r\,w\text{-}g}} = h_{\mathrm{r\,w\text{-}g}} A_{\mathrm{w}} (T_{\mathrm{w}} - T_{\mathrm{g}}) \tag{8}$$

The radiative heat transfer co-efficient between water and glass is given by [10]:

$$h_{\mathrm{r\,w\text{-}g}} = \varepsilon_{\mathrm{eff}} \sigma [(T_{\mathrm{w}} + 273)^2 + (T_{\mathrm{g}} + 273)^2](T_{\mathrm{w}} + T_{\mathrm{g}} + 546) \tag{9}$$

where

$$\varepsilon_{\mathrm{eff}} = \frac{1}{\dfrac{1}{\varepsilon_{\mathrm{w}}} + \dfrac{1}{\varepsilon_{\mathrm{g}} - 1}} \tag{10}$$

The areas of glass (A_{g}) and basin (A_{b}) are taken as 1 by 0.5 m which is the size of the basin. The area of saline water (A_{w}) is the total area of the trays, taken as 0.49 m^2.

Energy gained by the glass cover (from sun and convective, radiative and evaporative heat transfer from water to glass) is equal to the summation of energy lost by radiative heat transfer between glass and sky, and energy gained by glass:

$$I(\mathrm{t})\alpha_{\mathrm{g}} A_{\mathrm{g}} + Q_{\mathrm{c\,w\text{-}g}} + Q_{\mathrm{r\,w\text{-}g}} + Q_{\mathrm{e\,w\text{-}g}} = Q_{\mathrm{r\,g\text{-}sky}} + m_{\mathrm{g}} c_{\mathrm{p\,g}} \frac{\mathrm{d}T_g}{\mathrm{d}t} \tag{11}$$

The evaporative heat transfer between water and glass is given by:

$$Q_{\mathrm{e\,w\text{-}g}} = h_{\mathrm{e\,w\text{-}g}} A_{\mathrm{w}} (T_{\mathrm{w}} - T_{\mathrm{g}}) \tag{12}$$

The evaporative heat transfer co-efficient between water and glass is given by [10, 17]:

$$h_{\mathrm{e\,w\text{-}g}} = (16.273 \cdot 10^{-3}) h_{\mathrm{c\,w\text{-}g}} \frac{p_{\mathrm{w}} - p_{\mathrm{g}}}{T_{\mathrm{w}} - T_{\mathrm{g}}} \tag{13}$$

The radiative heat transfer between glass and sky is given by:

$$Q_{\mathrm{r\,g\text{-}sky}} = h_{\mathrm{r\,g\text{-}sky}} A_{\mathrm{g}} (T_{\mathrm{g}} - T_{\mathrm{sky}}) \tag{14}$$

Under clear and cloudy skies, the difference between ambient temperature and effective sky temperature is taken as [17, 22, 23] 6 °C. So, the effective sky temperature is taken as:

$$T_{\mathrm{sky}} = T_{\mathrm{a}} - 6 \tag{15}$$

The radiative heat transfer co-efficient between glass and sky is given by [10]:

$$h_{\mathrm{r\,g\text{-}sky}} = \varepsilon_{\mathrm{eff}} \sigma [(T_{\mathrm{g}} + 273)^2 + (T_{\mathrm{sky}} + 273)^2](T_{\mathrm{g}} + T_{\mathrm{sky}} + 546) \tag{16}$$

where

$$\varepsilon_{\mathrm{eff}} = \frac{1}{\dfrac{1}{\varepsilon_{\mathrm{gi}}} + \dfrac{1}{\varepsilon_{\mathrm{go}} - 1}} \tag{17}$$

In eq. (17) terms $\varepsilon_{\mathrm{gi}}$ and $\varepsilon_{\mathrm{go}}$ indicates the emissivities of the inner and outer surfaces of the glass, respectively.

The time interval is assumed as 5 s and for first iteration, the water temperature, glass temperature, and plate temperature are taken as ambient temperature. The change in basin temperature (dT_b), glass temperature (dT_w), and increase in saline water temperature (dT_g) are computed for every 5 s by solving eqs. (1), (5), and (11), respectively. For evaluating, the above said temperatures in the simulation, the experimentally measured values of solar radiation and ambient temperature of the corresponding day and hour were used.

The total condensation rate is given by [17]:

$$\frac{\mathrm{d}m_c}{\mathrm{d}t} = h_{\mathrm{c\,w\text{-}g}} \frac{T_w - T_g}{h_{\mathrm{fg}}} \tag{18}$$

For the next time step, the parameter is redefined as:

$$T_\mathrm{w} = T_\mathrm{w} + \mathrm{d}T_\mathrm{w} \tag{19}$$

$$T_\mathrm{g} = T_\mathrm{g} + \mathrm{d}T_\mathrm{g} \tag{20}$$

$$T_\mathrm{b} = T_\mathrm{b} + \mathrm{d}T_\mathrm{b} \tag{21}$$

The iteration is performed for 8 hours duration from 9 a. m. to 5 p. m. with a time interval of 5 s. The metrological parameters, namely air temperature and solar intensity are taken from the actual measured values in hourly intervals.

Still with fins at the basin

There are 5 fins used in each tray. Totally there are 50 trays and 250 fins were used. For the simulation study of still with fins at the basin, eqs. from (1) to (21), can be used except the area of the basin plate and free water surface. They are taken as 0.527 and 0.499 m^2, respectively, by taking the account of the exposure area of the fin.

Still with sponges

Here, the area of the free surface water is taken as 0.57 m^2 including sponge exposure area. The equations and other parameter remains constant.

Still with fins and sponges

The mathematical model of the simple basin still is used for this modification. But the area of the basin plate and free water surface are taken as 0.527 m^2 and 0.552 m^2, respectively, by taking into account the increase in exposure area due to addition of fins and sponges.

Results and discussion

For comparison purposes, the ordinary stepped solar still is tested without any modification and the average water productivity is found to be 1.01 litres per 8 hour.

Variation of productivity in fin type stepped solar still

Fin type absorber plate absorbs more thermal energy due to increase in exposure area and increases the sensible heat in saline water, which in turn increases the distilled water productivity. It increases by 76% when fins are used in the stepped solar still. The experimental result agrees well with the theoretical results. The deviation is 10%. Figure 8 shows the hourly variation of productivity for fin type stepped solar still.

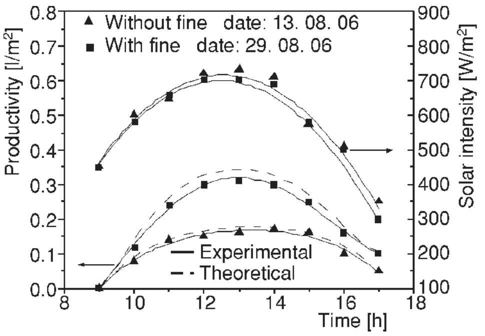

Figure 8. Variation of productivity in fin type stepped solar still

Variation of productivity in sponge type stepped solar still

When sponges are used, the water surface area increases and productivity increases. For constant solar intensity in the days of experiments with and without usage of sponges in the stepped solar still, the average productivity obtained is 1.62 litres per 8 hours. Which is 60.39% more than the productivity of the ordinary stepped solar still. This effect is shown in fig. 9. The deviation between theoretical and experimental result is 8.1%.

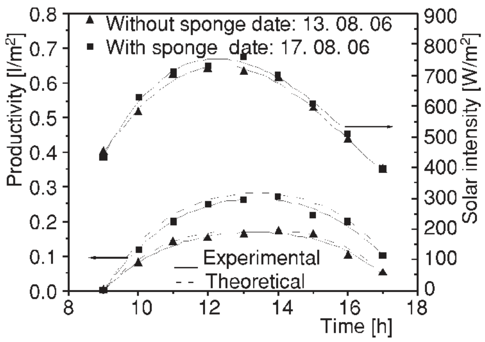

Figure 9. Variation of productivity in sponge type stepped solar still

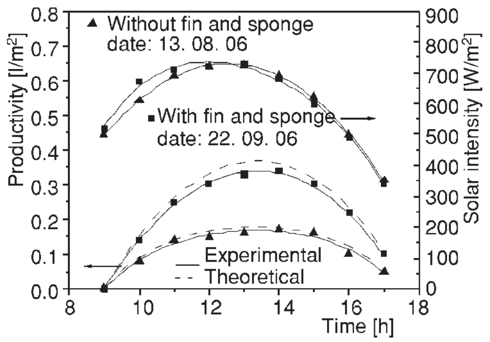

Figure 10. Variation of productivity in fin and sponge type stepped solar still

Variation of productivity in fin and sponge type stepped solar still

When sponges and fins are used, the productivity is 1.98 litres per 8 hours. It is 96% more than the productivity of ordinary stepped solar still. As shown in fig. 10, the solar intensity for the days of experiments with and without the modification does not vary much. The maximum deviation between theoretical and experimental rezults is 9.2%.

Economic analysis

The payback period of the experimental setup depends on overall cost of fabrication, maintenance cost, operating cost, and cost of feed water. The overall fabrication cost is Rs. 8000 ($ 160). The maintenance cost and the cost of feed water is negligible.

Overall cost to be considered = Rs. 8000 ($ 160)
Cost per litre of distilled water = Rs. 10 ($ 0.2)
Average productivity of the stepped solar still = 2 l/m^2

Cost of water produced per day	= Rs. 20 ($ 0.4)
Payback period	= 400 days

Conclusions

The performance characteristics of basin plate with two different depths of trays, fin type, sponge type, and combination of fin and sponge type stepped solar still are analyzed in terms of productivity. Production of water increases for 80% when fin and sponge type stepped solar still is used than ordinary stepped solar still. Result shows that integration of fin in the basin plate gives more evaporation rate than adding sponges. Maximum productivity occurs when both these effect is combined. Theoretical as well as experimental analyses are made. The performance of stepped solar still with fin, sponge, and combination of both fin and sponge were analyzed in terms of productivity. Experimental results show that productivity increased by 76%, 60.3% and 96% when fins, sponges, and combination both fins and sponges is used, respectively. Theoretical analysis was made. It gives very good agreement with experimental result. The maximum deviation between experimental and theoretical is less than 10%. Economic analysis is also made. The payback period of the setup is 400 days.

With some more modification in the stepped solar still, work is in progress to produce potable water from industrial effluent as feed.

Nomenclature

A – area, [m^2]
c_p – specific heat, [Jkg^{-1}K^{-1}]
g – glass
h – heat transfer coefficient, [Wm^{-2}K^{-1}]
h_{fg} – enthalpy of evaporation at T_w, [Jkg^{-1}]
I(t) – solar flux on an inclined collector, [Wm^{-2}]
I_d – diffuse radiation intensity on a horizontal plane, [Wm^{-2}]
I_g – global radiation intensity on a horizontal plate, [Wm^{-2}]
m – mass, [kg]
m_c – condensate, [lm^{-2}]
P_g – partial vapour pressure at glass temperature, [Nm^{-2}]
P_w – partial vapour pressure at water temperature, [Nm^{-2}]
Q – heat transfer, [W]
T – temperature, [°C]
t – time, [s]
U – side heat loss coefficient from basin to ambient, [Wm^{-2}K^{-1}]

Greeks letter

α – absorptivity
β – collector surface inclination, [deg]
ε – emissivity, [–]
θ_i – incidence angle on an inclined surface, [deg]
θ_h – incidence angle on an horizontal surface, [deg]
σ – Stefan-Boltzmann constant, (= 5.6697·10^{-8}), [Wm^{-2}K^{-4}]

Subscripts

a – ambient
b – basin
c – convective
e – evaporative
eff – effective
g – glass
i – inner
loss – side loss
o – outer
r – radiative
s – surface
w – water

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