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EFFECT OF COVERING BY BLACK POLYTHENE SHEET AND COAL POWDER ON NEAR BY SURFACES OF SAND BED SOLAR STILL: STUDYING HEAT AND MASS TRANSFER

Tiwari Anil Kr.* and Mishra Dhananjay R.
*Author for correspondence
Department of Mechanical Engineering,
National Institute of Technology Raipur,
Raipur, Chhattisgarh 492010,
India,
E-mail: aktiwari.mech@nitrr.ac.in

ABSTRACT

The lack of potable water poses a big problem in the world. Solar stills have long been used as an easy-to-operate and popular water production unit. In present work, the real situation near the seashores where wet sand is available in abundance with brackish water is being simulated and experiments were conducted. The experimental results are helpful for the coastal area where there is abundance of saline water but lack of potable water. The two experimental arrangements were compared for the ***heat and mass transfer*** within the single slope solar still and the ***yield*** in the month of ***March at Raipur (Latitude 21.16N and longitude 81.42 E) India***. It has been observed that the daily distillation yield is more in second case where surrounding mass of sand has been converted as ***heat storage*** that enhances ***heat and mass transfer***. The wet sand top surface temperature that resembles the water temperature of solar still of both arrangements increases slowly as the sun rises up and reaches to its maximum at ***1:30 pm of 1st as well as 2nd day*** by rise of ***231 % and 125 %*** more with comparison to morning temperature respectively for solar still S-1. The same water temperature for solar still S-2 also reaches to its maximum at same time ***1:30 pm of 1st as well as 2nd day*** by rise of ***234 % and 139 %*** respectively. It has been observed that the second solar still S-2 remains always ahead as for as yield is concerned. Finally in two days of observation the second still gives ***12.20% more yield (6.205 litres in comparison to5.530 litres) per m² basin area in 48 hours*** of the basin in comparison to the first solar still S-1 under consideration. This yield can be increased significantly by increasing the area of the basin. One more interesting conclusion is the fact that in still wet sand nearly behaves as a free water surface.

Key wards: Solar distillation; Glazing effect; Earth water still, Sand Bed Solar Still, passive solar distillation

INTRODUCTION

Water is one of nature's most important gifts to mankind. It is essential to life as a person's survival depends on drinking water. The underground water, wherever exists, is usually brackish, saline and cannot be used as it is, particularly for drinking purposes. Renewable resources such as solar energy allow energetic diversification and are inexpensive, pollution-free and available for predictable periods of time. A conventional solar still utilizes direct sunlight to heat and evaporate brackish, saline or unclean water in its basin. The evaporated water touches the transparent and relatively cooler inclined cover and get condensed, trickled down with the slope of condensing cover and get collected in a separate channel as distillate. Solar stills, however, have always been blamed for the low productivity.

Nevertheless, being a sustainable water production method that is especially suitable to remote areas that lack high-tech expertise, the solar still continues to attract wide research attention that is targeted at enhancing its yield. Among the important factors affecting the performance of the solar still are the use of solar energy received, still shape and design, weather conditions, brine depth in the basin, feed water salinity and temperature and the presence of an absorbing material. Anything above that can increase the heat and mass transfer within the still can contribute for better yield from the solar still. To increase the productivity of the simple solar still, several research works are being carried out. Solar still coupled with flat plate collector was studied by Badran et al. [1] and Tiris et al. [2]. A Multiwick single slope solar still [3] was designed by Shukla and Sorayan. Annual as well as seasonal performance analysis for the different water depths in a single slope solar still reported by Tiwari and Tiwari[4]. Experimental study of the enhancement parameters on a single slope solar still productivity was reported by Badran [5] An excellent review on the use of renewable energy in various types of distillation system and a survey of various types of solar thermal collectors and applications were presented by Kalogirani [6,7]. Many theoretical and experimental works conducted on the single slope solar stills for testing. Performance of different enhancement parameters like different absorbing materials were used by Nijmesh et al. [8] and M. A. S. Malik , G. N. Tiwari, A. Kumar and M. S. Sodha and was reported in solar distillation [9]. Effect of various inclination of condensing cover like 15^0, 25^0, 35^0, 45^0 and 55^0 out of which the optimum tilt angle for single slope solar still was found 35^0 for maximum water production [9]. The higher salinity decreases the water production was also reported [10]. Different parameters affecting still design reported by M. S. Sodha. Thermal modeling and characterization of solar still were presented by Tiwari [11], Tiwari and Noor [12] Tiwari and Prasad [13] and Tiwari et al. [14]. A transient analysis of a double basin solar still was studied by Suneja and Tiwari [15]. The daily yield of an inverted absorber double basin solar still increases with the increase of water depth in the lower basin for a given water mass in the upper basin was observed by Tiwari et al.[16], they derived expressions for water and glass temperature , hourly yield and instantaneous efficiency for both passive and active solar distillation systems . Tripathi and Tiwari [17] analyzed the distribution of solar radiation, using the concept of solar fraction inside a conventional single slope solar still by using simulation model for a given solar azimuth, altitude and latitude angles and longitude of the place. Srivastava et al. [18] in their numerical analysis showed that there is a significant effect in the plant water temperature and distilled output due to change in the fraction of solar radiation incident, depth of water, absorptivity of basin and inclination of roof where as the heat capacity of plant has marginal effect on these temperatures and distilled output. A comprehensive mathematical model for single slope solar still reported [19] considering the interactive parameters involved in productivity and efficiency as well. This present work aim to find out the co-relation for the sand bed solar still that includes practical validation along with the comparison of efficiency & performance of sand bed solar still on ground surface.

NOMENCLATURE

$\dot{q}$	$[W/m^2]$	Total rate of internal heat transfer from warer surface to inner surface of glass cover
$\dot{q}_{rw}$	$[W/m^2]$	Rate of radiative heat transfer
$\dot{q}_{cw}$	$[W/m^2]$	Rate of convective heat transfer,
$\dot{q}_{ew}$	$[W/m^2]$	Rate of evaporative heat transfer
h_{cw}	$[W/m^2\,^\circ c]$	Convective heat transfer coefficient,
h_{rw}	$[W/m^2\,^\circ c]$	Radiative heat transfer coefficient
h_{ew}	$[W/m^2\,^\circ c]$	Evaporative heat transfer coefficient
h_1	$[W/m^2\,^\circ c]$	Total internal heat transfer coefficient
P_w	$[N/m^2]$	Partial pressure of water vapor at water temperature.
P_g	$[N/m^2]$	Partial pressure of water vapor on inner surface glass temperature.
T_a	$[^\circ C]$	Atmospheric temperature,
T_g	$[^\circ C]$	Temperature of inner surface of glass
T_w	$[^\circ C]$	Temperature of water surface
δT	$[^\circ C]$	Difference in water and glass temperatures
S		Direction of geographical south
L	$[J/kg]$	Latent heat of vaporization
M_{ew}	$[kg/m^2]$	Distillate output from the still
A_t	$[m^2]$	Basin area of Solar still.
σ	$[W/m^2K^4]$	Stefan Boltzmann constant
ε		Effective emissivity
ε_w		Emissivity of water surface
ε_g		Emissivity of glass surface exposed to atmosphere
Δt	$[s]$	Time interval

EXPERIMENTAL SET UP

The two distinguished experimental setups solar still-1(S-1) and solar still-2 (S-2) are being schematically shown in **Figure 1** and **2** the photographs are shown in **Figure 3** and **4** respectively.

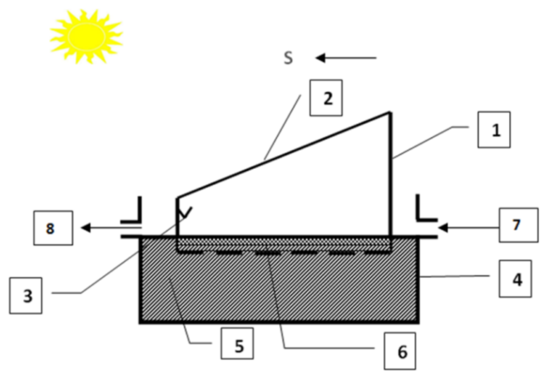

Figure 1 Schematic arrangement of Solar Still -1 (S-1) without black polythene sheet around it.

The names of the parts in both the **Figure 1** and **Figure 2** are as below 1. FRP (Fiber reinforced plastic) single slope solar still with 25 holes of 2.5cms diameter each at bottom for water communication with sand mass 2. Transparent glass condensing cover 3. Drain to collect condensed water 4. Tray made of GI (Galvanized Iron) sheet 5. Wet sand mass 6. Black coal powder spread over upper surface of sand within still. 7. Inlet port for brackish water 8. Outlet port for brackish water 9. Transparent polythene cover spread over wet sand around solar still-2 (S-2) only.

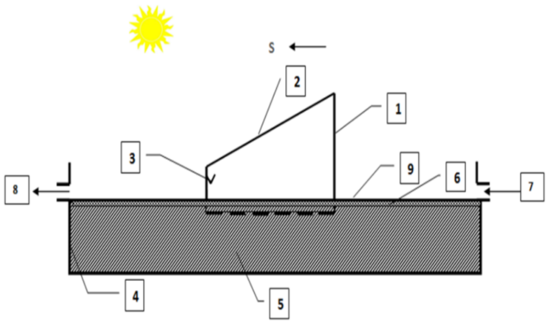

Figure 2 Schematic arrangement of Solar Still -2 (S-2) with black polythene sheet around it.

In construction, solar still S-2 is ***with*** and solar still S-1 is ***without*** black polythene sheet (10 micron thickness) that is spread over the surrounding earth surface. This difference in construction between S-2 and S-1 is in the want of enhancing the heat storing capacity of earth mass of S-2 over the S-1 in which solar still basins are buried. Both experimental setups are identical with only the difference in second case where a black polythene sheet is used to cover the surrounding area of solar still.

Figure 3 Photograph of Solar Still -1 (S-1) without black polythene sheet around it.

In first setup that is being called as still-1(S-1) the conventional single slope solar still partially buried in wet sand is being observed where black charcoal powder is spread over wet sand within the basin and analyzed. In second set up everything is same as first setup with only the difference that the surrounding earth surface was covered with black charcoal powder and also black polythene up to 1m in all four directions. These solar still were fabricated by fiber reinforced plastic (FRP) having basin area $1m^2$ $(1m \times 1m)$.

The bottom of basins in both solar stills was having 25 holes of 25mm each for rising of brackish water through capillary action to fill the space that has been emptied because of evaporation. This ensures top surface of the sand wet all time to keep evaporation continuous and hence give better yield. There is no clear measurable water depth that can be seen but wet sand resembles very thin water depth with very high surface area for evaporation. In first case the surface of wet sand is covered with black coal to enhance heat absorption that is an influencing factor for evaporation of pure water. However in second case the same setup is used with additional coverage of earth surface with black coal and black polythene sheet of the surrounding earth surface. In this new arrangement, storage of solar heat increases within the side by sand of the still that affects as increase in the yield particularly after the sun set i.e nocturnal distillation.

Figure 4 Photograph of Solar Still -2 (S-2) with black polythene sheet around it.

The solar energy received, wet sand surface temperature, and output of potable water from both stills were observed every half an hour for 48 hours in the month of March at Raipur, India. Analytical expressions for water temperature (wet sand surface temperature) and other design parameter like water depth, absorptivity of basin liner, wind velocity, bottom insulation and cover inclination were studied. Both stills are facing due south for receiving best possible solar insolation.
The following are the observations made every half an hour:

- Distillate yield in ml for 48 hours for both stills.
- Solar radiation on horizontal surface (by means by SP-Light Silicon Pyranometer.
- Atmospheric temperature (in shade) by MDTI-039T digital temperature meter.
- Temperature at the inner surface by thermocouple.
- Temperature of top surface of wet sand (S-1) and (S-2) by MDTI-039T digital temperature meter that has been called as water temperature.
- The Grain size of sand used in experiment was also determined by screening the particles on a series of standard wire sieves. The obtained observations are shown in Table 1.

Table 1 Grain size of sand

U.S. Standard Sieve No.	Opening (mm)	% Passing
10	2.00	100
30	0.60	40
50	0.30	10-30 (MAX)
80	0.18	5 (MAX)

HEAT TRANSFER WITHIN SOLAR STILL

There are three modes possible for heat transfer from water surface to condensing cover these are Radiative, Convective and Evaporative heat transfer.

Radiative Heat Transfer Coefficient

The rate of radiative heat transfer ($\dot{q}_{rw}$) from water surface to the condensing cover can be obtained as

$$\dot{q}_{rw} = \varepsilon\sigma\left[T_1^4 - T_2^4\right] \tag{1}$$

where, $T_1 = (T_w + 273)K, \qquad T_2 = (T_g + 273)K,$

Equation (1) can be rewritten as $\dot{q}_{rw} = h_{rw}(T_1 - T_2)$ (2)

$$\text{where, } h_{rw} = \varepsilon\sigma\left\{\frac{(T_w + 273)^4 - (T_g + 273)^4}{T_w - T_g}\right\} \tag{3}$$

$$\varepsilon = \left[\frac{1}{\varepsilon_w} + \frac{1}{\varepsilon_g} - 1\right]^{-1} \quad \text{and} \quad \sigma = 5.67\times10^{-8} W/m^2K^4$$

thus if water temperature and glass surface temperature are known the radiative heat transfer coefficient can be calculated.

Convective Heat Transfer Coefficient

The convective heat transfer coefficient (h_{cw}) can be obtain from

$$h_{cw} = 0.884\left\{(T_w - T_g) + \frac{(P_w - P_g)\times(T_w + 273)}{\left(2.689\times10^{-5} - P_w\right)}\right\}^{\frac{1}{3}} \tag{4}$$

The value of P_w and P_g (for the range of temperature between 10^0C to 90^0C) can be obtained at water and inner surface glass temperature from the relation shown in equation (5) considering P_w and P_g as a function of temperature.

$$P(T) = \exp\left[25.317 - \frac{5144}{T + 273}\right] \tag{5}$$

The rate of convective heat transfer $\dot{q}_{cw}$ in $\left(W/m^2\right)$ from water surface to the inner surface of glass condensing cover can be obtained by

$$\dot{q}_{cw} = h_{cw}(T_w - T_g) \tag{6}$$

Evaporative Heat Transfer Coefficient

The rate of evaporative heat transfer $\dot{q}_{ew}$ from water to inner condensing cover is given by [20]

$$\dot{q}_{ew} = 0.0166 \times h_{cw} \times \left(P_{\text{w}} - P_{\text{g}}\right) \tag{7}$$

The rate of evaporative heat transfer $\dot{q}_{ew}$ can also be given as by the basic approach,

$$\dot{q}_{\text{ew}} = h_{\text{ew}}(T_{\text{w}} - T_{\text{g}}) \tag{8}$$

Thus equation (8) can be rearranged as equation (9)

$$h_{\text{ew}} = \frac{\dot{q}_{\text{ew}}}{\left(T_{\text{w}} - T_{\text{g}}\right)} \tag{9}$$

and by putting the value of $\dot{q}_{ew}$ from equation (7) in equation (9) the evaporative heat transfer coefficient can be obtained as

$$h_{\text{ew}} = 0.016 \times h_{\text{cw}} \times \left[\frac{P_{\text{w}} - P_{\text{g}}}{T_{\text{w}} - T_{\text{g}}}\right] \tag{10}$$

Using Eq. (1), (2) and (3) total heat transfer coefficient h_1 can be written as $h_1 = h_{rw} + h_{cw} + h_{ew}$ (11)

The total rate of heat transfer from water surface to the inner surface of glass cover can be obtained as

$$\dot{q} = h_1\left(T_w - T_g\right) \tag{12}$$

THEORETICAL AMOUNT OF CONDENSATE

The amount of distillate output from solar still during a period mainly depends on evaporative heat transfer and can be obtained in Kg by the following expression [20].

$$M_{ew} = \frac{\dot{q}_{ew}\times A_t \times \Delta t}{L} \tag{13}$$

where $\text{L} = 3.1615\times10^6\left[1 - 7.6160\times10^{-4}T_w\right]$ for temperature higher then $70^\circ C$,and

$$L = 2.4935\times10^6\left[1 - 9.4779\times10^{-4}T_w + 1.3132\times10^{-7}T_w^2 - 4.7974\times10^{-9}T_w^3\right]$$

for operating temperature less then $70^\circ C$ [20]. In our experimental set up the basin area is $A_t = 1\text{m}^2$, and the observational time slot Δt has been kept 30 minutes.

OBSERVATIONS, RESULT AND DISCUSSION

The variation in receiving the solar radiation and ambient temperatures during experimental two days have been shown in **Figure 5** that has been observed during 6 AM of March 15, 2012 to 6 AM of March 17 at Raipur (Latitude 21.16N and longitude 81.42 E) India. The other observational data that has been observed are; inner surface glass cover temperature and the temperature of water /wet sand.

The **Figure 5** proves both experimental days as a shiny solar day because the peak solar radiation of the order of 976 W/m^2 and 983 W/m^2 was received at noon time of both the days that is a good enough amount to be useful for any solar thermal application. Whereas the ambient maximum (38-40 ^{O}C) and minimum (12-13 ^{O}C) temperature was attained at 5pm and 6am of both days respectively.

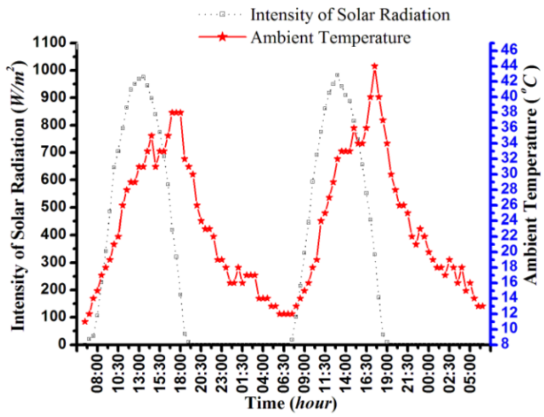

Figure 5 Hourly variations of Solar Radiation incident and Ambient Temperature.

Figure 6 and **7** shows the hourly variation in water temperature and inner surface glass cover temperature respectively for both the solar stills under comparison. It is very clear from **Figure 6** and **7** that **t**he water and glass inner temperatures in both the stills remains almost similar up to 10 pm of both days but after that the same drops down in still S-2 with comparison to S-1. This is because the black polythene covering around the solar still S-2 radiates more heat (being black polythene) to the sky and becomes a reason of heat loss to the ambient. This reason of spreading the black polythene around still that was helping to enhance h_{ew} (evaporative heat transfer coefficient) and ultimately h_1 (total heat transfer coefficient) within still is favorable for yield during day time is becoming a reason for loss in the night.

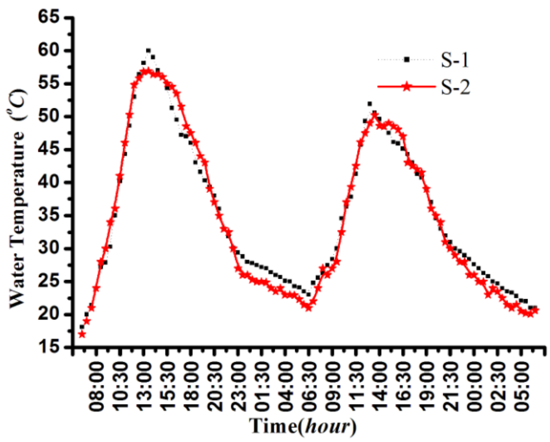

Figure 6 Hourly variations of water temperature of both solar stills.

It is very clear from the equation (13) that the yield is proportional to evaporative heat transfer and equation (8) reveals that this evaporative heat transfer depends on evaporative heat transfer coefficient and equation (10) tells this evaporative heat transfer coefficient depends on the difference of water and glass temperature and also on difference of partial pressures. Up to some extent higher the difference in water and glass temperature the higher will be the yield from the solar still because this difference in temperature affects the numerator as well as denominator of equation (10). The combined effect is to increase the yield if the difference in water and glass temperature increases. The difference in water and glass temperature in a solar still plays a major role to influence the output from the solar still.

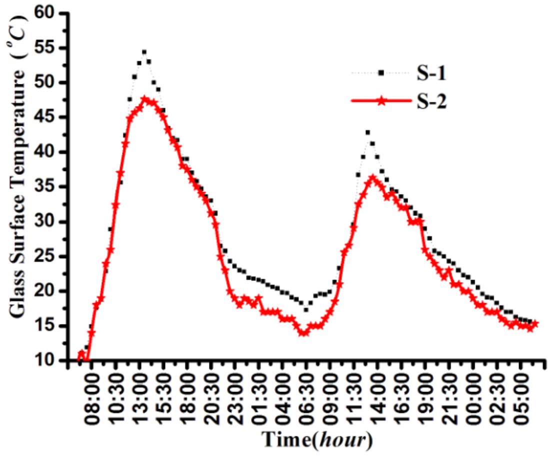

Figure 7 Hourly variations of inner surface of glass temperature of both solar stills

Figure 8 shows the variation in difference in water and glass temperature in short the same will be written as **δT**. It can easily be seen that this difference in temperature δT has been found always greater in case of solar still S-2 that shows the possibility of this solar still to be ahead than solar still S-1 as for as yield is concerned as per theory discussed above. If evaporative heat transfer coefficients h_{ew} and total internal heat transfer coefficient h_1 is being compared as shown in **Figure 9** and **10**, the same are always higher slightly for solar still S-2 with comparison to S-1. This also leads to the theoretical conclusion discussed above that higher the difference in temperature **δT** higher will be evaporative and total internal heat transfer coefficients up to some extent.

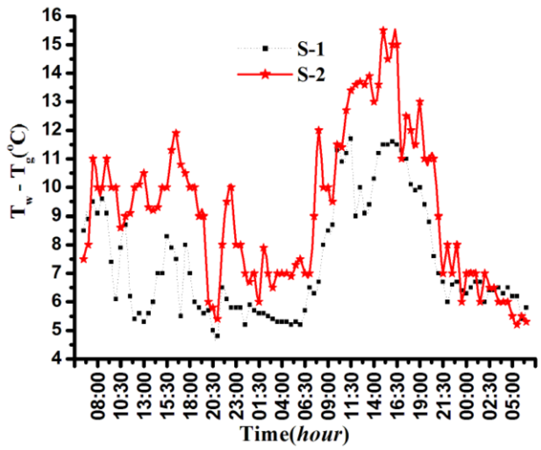

Figure 8 Hourly variations of the difference in temperature of water and glass inner surface **δT** of both solar stills

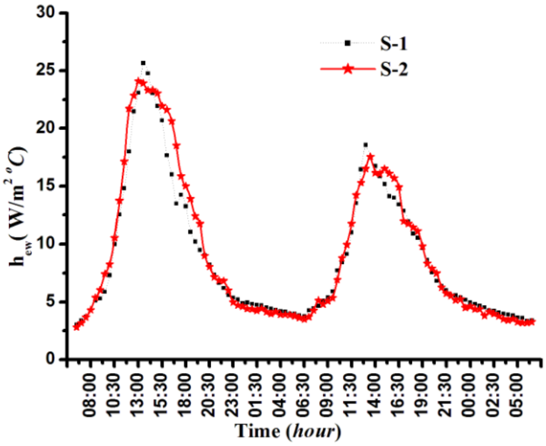

Figure 9 Hourly variations of the evaporative heat transfer coefficient h_{ew} of both solar stills S-1 and S-2.

It is very clear that the δT is higher for solar still S-2 with comparison S-1 and the difference varies from minimum 0.9 ^{O}C to maximum 5.3 ^{O}C that is being encountered at morning 8 AM and evening 5 PM respectively almost on both days However this difference in temperature δT influences every heat transfer coefficient like radiative, convective and evaporative. Therefore the total also is being influenced as can be seen through equation (3), (4), (10) and (11) respectively. Its effect is very complex because at some places it is at numerator and at other place in denominator. But one thing is very clear that it increases evaporative heat transfer as per equation (8) and ultimately the yield as per equation (13).

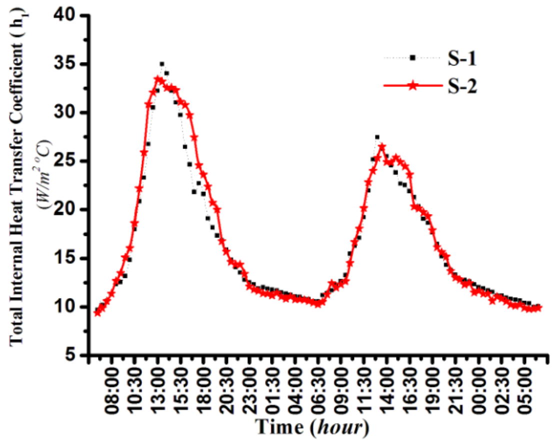

Figure 10 Hourly variations of the total internal heat transfer coefficient h_1 of both solar stills S-1 and S-2.

Figure 11 and **12** shows the variation of actual and theoretical output from solar still S-1 and S-2 respectively with respect to time. The graphs show the similar trend for actual and theoretical yield from both the solar still thus the mathematical model proposed is here by validated. The difference between theoretical and actual yield in both the solar stills have been found little noteworthy during noon time because of unpredictable climatic conditions for short duration like wind velocity presence of clouds etc.

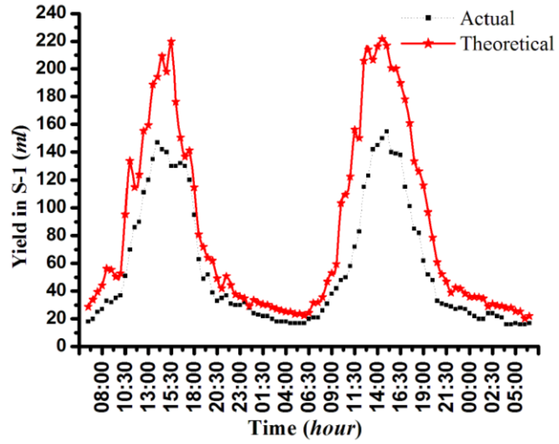

Figure 11 Hourly variations of the actual and theoretical distillate output i.e yield from solar stills S-1

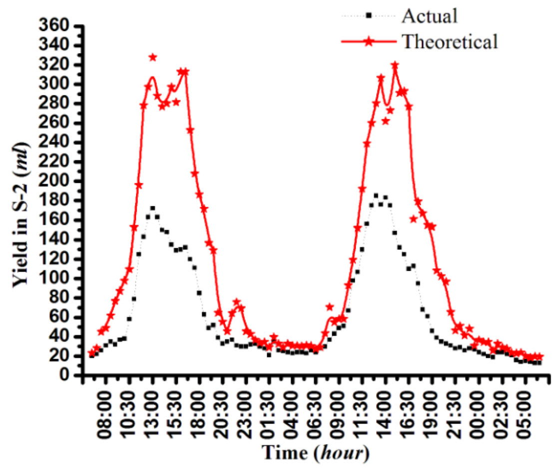

Figure 12 Hourly variations of the actual and theoretical distillate output i.e yield from solar stills S-2

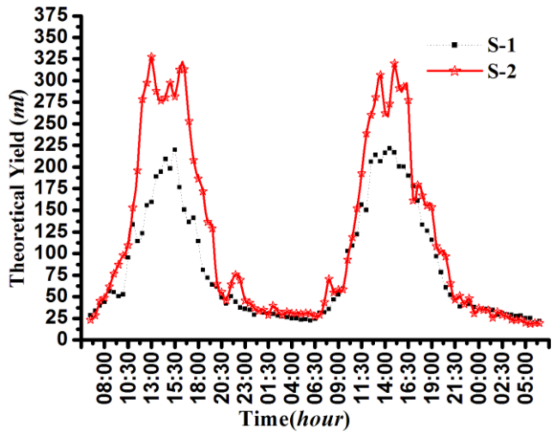

Figure 13 Hourly variations of theoretical distillate output i.e yield from both solar stills S-1 and S-2.

The theoretically predicted and actually found hourly output from both the solar stills have been compared and shown in **Figure 13** and **14** respectively. In both graphs the yield for both solar stills S-1 and S-2 slowly increases as the sun moves up and start decreasing just after the noon. The yield reaches to its minimum by the dawn of next day and the cycle repeats

However the half hourly actual and theoretical yield from both solar stills S-1 and S-2 with respect to the duration for 48 years has been shown in **Figure 13** and **14** respectively. The solar still S-1 lags behind solar still S-2 always from starting for the yield the reason is higher heat capacity of nearby ground earth mass of solar still S-2 because of black polythene used with charcoal powder.

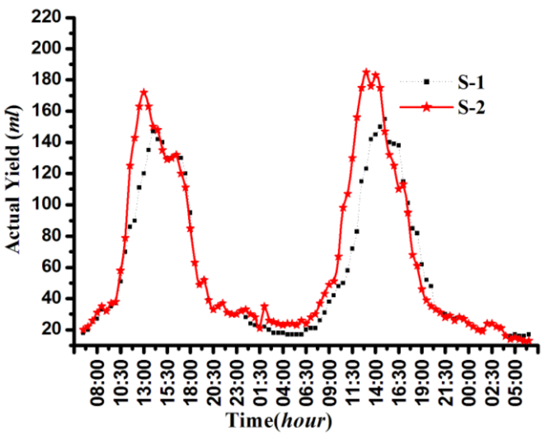

Figure 14 Hourly variations of the actual distillate output i.e yield from both solar stills S-1 and S-2.

It is explicitly clear in **Figure 13** and **14** that the solar still S-2 has shown its superiority over the solar still S-1 throughout the duration of experiment. To be precise to actual yield obtained the solar still S-2 delivers 7.55% more yield for the period 6:30 to 10:30 but the difference increases by 26.85% during 10:30 to 14:30 latter on slowly this difference reduces to 16.91% in mid night and the cycle repeats. The actual yield from solar still S-1 and S-2 has been found 5.530 and 6.205 liters in two days respectively. However the actual total yield on 1st day from solar still S-1 and S-2 has been found 2.768 and 3.081 liters respectively whereas the same on 2nd day was found 2.762 and 3.124 liters respectively. On average basis it can be concluded that the yield from solar still S-1 and S-2 is 2.765 and 3.102 liters per day respectively. Thus solar still S-2 gives 12.81 % more yield per day than solar still S-1. This superiority of solar still S-2 over the S-1 is because of the black polythene spread over the ground surrounding the still that actually increases the heat storing capacity of earth mass near the still area. Thus annual yield from solar still S-2 will be more with comparison to the solar still S-1.

CONCLUSION

In this present work two arrangements of solar still naming S-1 and S-2 has been compared for its output of distillate in liters per day. A mathematical model proposed and yield has been predicted as theoretical yield that is found almost same as the experimental yield obtained. Thus proposed mathematical model is validated. Not only the yield but also other various related things like water temperature, glass temperature has been observed. The other parameters like internal heat transfer coefficient, evaporative heat transfer coefficient, and theoretical yield for both solar stills have been predicted and have been validated with experimental data. The wet sand top surface temperature that resembles the water temperature of solar still of both arrangements increases slowly as the sun rises up and reaches to its maximum at ***1:30 pm of 1st as well as 2nd day*** by rise of ***231 % and 125 %*** more with comparison to morning temperature respectively for solar still S-1. The same water temperature for solar still S-2 also reaches to its maximum at same time ***1:30 pm of 1st as well as 2nd day*** by rise of ***234 % and 139 %*** respectively.

It has been observed that the second solar still S-2 remains always ahead as for as yield is concerned. Finally in two days of observation the second still gives ***12.20% more yield (6.205 litres in comparison to5.530 litres) per m^2 area in 48 hours*** of the basin in comparison to the first solar still S-1 under consideration. This yield can be increased significantly by increasing the area of the basin. One more interesting conclusion is the fact that in still wet sand nearly behaves as a free water surface.

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