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ORIGINAL PAPER

Performance Investigation on Variations of Glass Cover Thickness on Solar Still: Experimental and Theoretical Analysis

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Abstract Glass cover is very important component for the efficient design of the solar still. Sunrays are first incident on glass cover and then transfer to the solar still for the purpose of evaporation of water to get potable water. Selection of the proper glass cover is always based on transmittance and it is depends on thickness of the glass cover. Hence, to study effect of transmittance on glass cover thickness, three different thicknesses of glass cover like 4 mm, 5 mm and 6 mm were chosen for the study on three same sized solar stills and tested in composite climate conditions of Mehsana, a city of North Gujarat, India during sunshine hours of January 2011 to June 2011. Theoretical and experimental analysis of three different thicknesses of glass cover is carried out by heat and mass transfer analysis to determine the optimum thickness of glass cover for the effective distillate output from solar still and validation between them. After six months of experiments, it has found that 4 mm and 5 mm glass cover thickness increased average distillate output of 27 % and 12 % compared with 6 mm glass cover thickness. Also theoretical results found good match with experimental results.

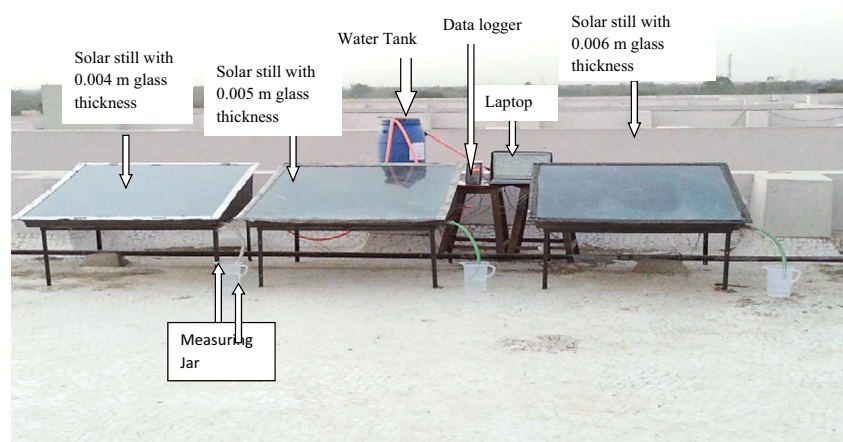**Keywords** Solar still · Glass cover · Distillate output · Solar energy

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Introduction

Depending on the energy available for evaporating the water in the still, the stills are classified into passive and active. In passive stills, the water in the still basin receives heat only by the radiation transmitted through the transparent cover. Hence the performances of this type of stills are improved by optimizing the cover and basin conditions. The cover plate is optimized to receive and transmit maximum radiation into the still. Also, the cover should be capable of condensing maximum mass of water vapour by exhausting heat to the atmosphere. The basin has to receive the maximum radiation transmitted into the still, convert into heat, transfer heat to the water and provide maximum surface area for evaporation. It should also retain excess heat and utilize it when the radiation level falls [8].

The transparent cover receives and transmits radiation into the still. Also, the condensation takes place at its lower surface. Also, it should suppress thermal radiation to the atmosphere. Glass is the best material for cover [7] since it has higher transmittance and less reflectivity. Also glass is opaque for thermal radiation. For higher latitude places, single slope still is preferable and for northern chemosphere the still faces south [1, 5, 17, 19]. The inclination of the cover is optimized to collect the accumulated condensate through drain before it drops down to basin. The condensate mass accumulation depends on solar intensity and condensation rate [19] conducted indoor simulation experiment and found that the production rate is higher for 30° cover inclination. The glass has to withstand its self-weight and thermal stresses. For higher surface area, high thickness glass will be used. But, radiation

transmittance and heat transfer through the glass decrease with thickness. The transmittance loss at cover is less due to film wise condensation at the lower surface. The other transparent materials are not having these characteristics [8]. The glass cover temperature is reduced by continuous flow [2] or intermittent flow [18] of raw cooling water on the cover. The cooling water gains latent heat from condensing water and regenerates it in the basin. Second effect of evaporation and condensation takes place between the covers. [3] result shows increase in production by 20 %. Evacuated tubes played important role for effective utilization of hot water for the increment in distillate output [9–13]. Yousef and Mousa [20] results also show that, the use of the film-cooling increases the still efficiency up to 20 %. Wind velocity is also having its effect on temperature of the glass. At higher wind velocity, due to higher convection heat transfer from the glass to atmosphere the productivity of the still is increasing [4, 15, 16, 20]. Theoretically analyzed the effect of water flowing over the glass cover in a single basin still. The result shows the productivity is increased with flowing water over the glass cover. Also, the yield decrease when the water flow rate increases. CFX has also played crucial role for designing the solar still. [10, 14].

Many researchers have worked on solar still to improve its distillate output and efficiency. But the analysis of glass cover based on transmittance it still unattended by the researchers. Hence, in this present research work, three different sized glass covers transmittance determined by correlation. Theoretical and experimental results of varying glass cover thicknesses were compared and validated by energy balance equations. At last, six months results of different thicknesses glass cover on three same area solar stills compared to find optimum thickness, which is best suited to get enhanced distillate output.

Experimental set up

Figure 1 shows the experimental setup installed at Gujarat Power Engineering & Research Institute, Mehsana, India. The bottom part of each still was painted black to increase the solar energy radiation. In this present experiment all stills used with 1 cm water depth and which is maintained constant by use of solenoid valve attached with each still. Vertical side of the still was at a depth of 0.200 m, whereas the height of the vertical side was kept 0.400 m. The effective basin area of each still is kept as conventional solar still and it is 1 square meter and glass cover angle is kept 23°. It is made of Fiber reinforced plastic (FRP) of 0.050 m insulation thickness. Here, total seven thermocouples are located inside stills. Among, seven thermocouples, six measured water and glass cover temperatures and seventh exposed to atmosphere to measure ambient temperature. The output from the still is collected through a channel fixed at the end of the smaller vertical side of the basin. A storage tank of total capacity of brackish water is 50 kg is put at the top at the front wall of Institute to supply raw water into the solar still. Water level inside the still is maintained constant by use of control valve attachment with each solar still. All temperatures, distillate output from all solar stills were stored by data logger. Table 1 shows errors and accuracies of used measuring instruments and Table 2 shows dimensions of each solar still for the research work.

Theoretical Analysis

Glass cover transmittance

Glass cover is the top component of solar still. It actually has three major objectives: to reduce radiant and convective

Fig. 1 Experimental set up of solar stills with varying glass cover thicknesses

Table 1 Various important instruments with error and range

Sr. No.	Instrument	Accuracy	Range	% error
1	K Type thermocouples	$\pm 0.1\ °C$	$0-100\ °C$	5%
2	Solarimeter	$\pm 1 W/m^2$	0-1400W/m^2	2.5%
3	Measuring Jar	± 10 ml	0-1000 ml	10%
4	Anemometer	± 1 m/s	0-15 m/s	10%

heat loss from the absorber plate, to transmit the incoming sun rays to the absorber plate with minimum heat loss, and to protect the absorber plate from surrounding irregularities. Other important features of glass cover materials are absorption, reflection and transmission. To get maximum efficiency with minimum loss of solar radiations, transmission of sunrays should as high as possible and reflection and absorption should be as low as possible, whilst transmission should be as high as possible [18]. Hence, reasons for attention in choosing the glass cover materials comprises of strength of material, toughness, less degradability when open to the ultraviolet light (UV), and low costs. Usually the common materials used as glass cover materials are glass and plastics

Glass cover is the major material used to glaze solar still. Glass cover material has extremely required property of transmitting 90 % or more than 90 % of the sun incoming short-wavelength radiation, while almost none of the long wavelength incoming sun rays discharged by the absorber plate can escape outwards by transmission. Compared to glass cover, a plastic cover possesses high short- and long-wave Transmissivity and hence high performance. Generally, the main advantages of plastics are resistance to breakage, light weight, and low cost. However, plastics have been reported to have limited life span due to the effect of UV radiation which reduces its transmissivity [20]. Also, plastics are transparent to long-wavelength radiation and are therefore less effective in reducing radiated heat losses from the absorber plate. In addition, plastics cannot withstand high temperature encountered in collector especially when the collector is idle.

Table 2 Dimension of solar still

Parameter	Value
Solar still area including basin	1 m^2
Glass cover tilting angle	23°
Insulation thickness	0.05 m

Generally glass cover is facing south direction to receive solar radiation at different angle and different quantities in enhanced quantity. Hence incoming solar radiations are:

$$Q_i = Q_s \tag{1}$$

Where, $Q_s = A_g I_s$

The utilization of radiation absorbed by the solar still for any given instant is the total solar radiation transmitted through the south-facing glass cover and is given by:

$$Q\tau = Q\tau_s \tag{2}$$

Where $Q\tau_s = \tau_s A_g I_s$

Transmittance of the glass cover is measured by UV-3600 UV-VIS-NIR Spectrophotometer, available at institute. It is found 0.90, 0.84 and 0.79 for 4 mm, 5 mm and 6 mm glass cover thickness. But does not remains constant because it is depends on the incoming solar radiation wavelength i.e. short and long wavelength. Hence, the transmittance of the any glass cover is always depends on three parameters namely solar insolation angle of incidence (θ), coefficient of diffused radiation (K_d) and thickness of glass cover (d). Hence, from above three parameters, [6] have developed a important correlation equation for to determine transmittance of a glass cover and it is used for the study (Fig. 2).

Energy balance equations

In order to write energy balance equations for solar still, following assumptions have been made:

- Condensation of the glass cover is film type.
- There is one dimensional heat flow through back insulation.
- Every hour steady state condition is reached

Inner glass cover energy balance

$$\alpha'_g I(t) + [q_{rg} + q_{cw} + q_{ew}] = q_{cg} \tag{3}$$

or

$$\alpha'_g I(t) + h_1(T_w - T_{ci}) = \frac{K_g}{L_g}(T_{ci} - T_{co}) \tag{4}$$

Outer glass cover energy balance

$$\frac{K_g}{L_g}(T_{ci} - T_{co}) = q_{rg} + q_{cg} \tag{5}$$

$$\frac{K_g}{L_g}(T_{ci} - T_{co}) = h_2(T_{ci} - T_a) \tag{6}$$

Hence, put value of Eq. 6 in Eq. 4

$$\alpha'_g I(t) + h_1(T_w - T_{ci}) = h_2(T_{ci} - T_a) \tag{7}$$

Energy balance for water inside solar still

$$\alpha'_w I(t) + q_b = (MC)_w \frac{dT_w}{dt} + [q_{rw} + q_{cw} + q_{ew}] \tag{8}$$

or

$$\alpha'_w I(t) + h_3(T_b - T_w) = (MC)_w \frac{dT_w}{dt} + h_1(T_w - T_{ci}) \tag{9}$$

Energy balance for basin liner

$$\alpha'_b I(t) = q_w + [q_{bb} + q_{bs}] \tag{10}$$

or

$$\alpha'_b I(t) = h_3(T_b - T_w) + U_b(T_b - T_a) \tag{11}$$

For determining expression for Tci , Eq. 7 can be rearranged as:

$$\alpha'_g I(t) = h_1(T_w - T_{ci}) = h_2(T_{ci} - T_a)$$
$$\alpha'_g I(t) + h_1 T_w - h_1 T_g = h_2 T_g - h_2 T_a$$
$$\alpha'_g I(t) + h_1 T_w + h_2 T_a = (h_1 T_{ci} + h_2 T_{ci})$$
$$\alpha'_g I(t) + h_1 T_w + h_2 T_a = (h_1 + h_2) T_{ci}$$
$$T_{ci} = \frac{\alpha'_g I(t) + h_1 T_w + h_2 T_a}{h_1 + h_2} \tag{12}$$

For determining expression for Tb, Eq. 11 can be written as:

$$\alpha'_b I(t) = h_3(T_b - T_w) + U_b(T_b - T_a)$$
$$\alpha'_b I(t) = h_3 T_b - h_3 T_w + U_b T_b - U_b T_a$$
$$\alpha'_b I(t) + h_3 T_w + U_b T_a = h_3 T_b + U_b T_b$$
$$T_b = \frac{\alpha'_b I(t) + h_3 T_w + U_b T_a}{h_3 + U_b} \tag{13}$$

Now put values of Tci and Tb in Eq. 9

$$\alpha'_w I(t) + h_3(T_b - T_w) = (MC)_w \frac{dT_w}{dt} + h_1(T_w - T_{ci}) \tag{14}$$

Now Divide whole Eq. 14 by (MC)w, then it becomes

$$\frac{\alpha'_w I(t) + h_3(T_b - T_w)}{(MC)_w} = \frac{dT_w}{dt} + \frac{h_1(T_w - T_{ci})}{(MC)_w}$$

$$\frac{\alpha'_w I(t) + \left(h_3\left[\dfrac{\alpha'_b I(t) + h_3 T_w + U_b T_a}{(h_3 + U_b)}\right] - T_w\right)}{(MC)_w} = \frac{dT_w}{dt} + \frac{\dfrac{h_1\left(T_w - \left[\dfrac{\alpha'_g I(t) + h_1 T_w + h_2 T_a}{(h_1 + h_2)}\right]\right)}{}}{(MC)_w} \tag{15}$$

rearranging above (15) as,

$$\frac{\dfrac{\alpha'_b h_w}{h_w + h_3} + \alpha'_w + \alpha'_g \dfrac{h_1}{h_1 + h_2} \times I(t) + \left(\dfrac{h_w h_3}{h_w + h_3} + \dfrac{h_1 h_2}{h_1 + h_2}\right) \times T_a}{(MC)_w} = \frac{dT_w}{dt} + \frac{\left(\dfrac{h_w h_3}{h_w + h_3} + \dfrac{h_1 h_2}{h_1 + h_2}\right)}{(MC)_w} \tag{16}$$

$$\frac{(\alpha\tau)_{eff} I(t) + U_L T_a}{(MC)_w} = \frac{dT_w}{dt} + \frac{U_L}{(MC)_w} T_w$$

Equation 16 can be rearranging as,

$$f(t) = \frac{dT_w}{dt} + aT_w \qquad (17)$$

$$\text{where, } f(t) = \frac{(\alpha\tau)_{eff} \, I(t) + U_L T_a}{(MC)_w}$$

$$\text{where, } (\alpha\tau)_{eff} = \alpha_b \frac{h_w}{h_w + h_3} + \alpha'_w + \alpha'_g \frac{h_1}{h_1 + h_2}$$

$$a = \frac{U_L}{(MC)_w}$$

$$\text{where, } U_L = U_b + U_{t;}$$

$$\text{where, } U_b = \frac{h_w h_3}{h_w + h_3}, U_t = \frac{h_1 h_2}{h_1 + h_2}$$

The rate of evaporative heat loss and the hourly yield of the solar still are given as:

$$q_{ew} = h_{ew}(T_w - T_{ci}) \qquad (18)$$

And

$$m = \frac{h_{ew}(T_w - T_{ci})}{L} \times 3600 \qquad (19)$$

The daily distillate output is given by

$$M_{ew} = \sum_{i=1}^{24} M_{ew} \qquad (20)$$

Efficiency is determined by:

$$\eta = \frac{h_{ew}(T_w - T_{ci})}{I * A} \qquad (21)$$

Result and Discussion

The following design parameters used in Table 2 to determine the theoretical results based on the equations used in the energy balance equations:

α_b	0.36
α_g	0.05
α_w	0.34
F_R	0.831
M_w	30 kg
ε_{eff}	0.82
L_i	0.05 m
K_i	0.57 W/ m K
h_w	250 W/m^2 K
t	3600 s
C_w	4190 J/Kg K
σ	5.67×10^{-8} W/m^{2}K
$(\alpha\tau)_c$	0.8
U_{LC}	2.44 W/m^2 K
h_2	5.7 + 3.8 V, V = 3 m/s
L	2.25×10^5 J/Kg

The alternating climate factors such as solar insolation and ambient temperature have been calculated by standard calibrated instruments and variable parameters used in theoretical calculations.

Experiments have been carried out with varying glass cover thicknesses on different days continuously during January to June 2011 during sunshine days. The solar insolation condition remains equal for all days of the months and observations have been compared for such days only. Among such days having variation in the ambient conditions are same and the days having variation in the ambient conditions are ignored. Figure 3 shows the variation of solar insolation and ambient temperature for the days in which observations made with three different solar stills having different glass cover thicknesses. Solar insolation falling on each solar still would be same. Hence, the single curve is shown and it shows that, solar insolation seems to be maximum between the 12 to 1 pm for all solar stills.

Figure 4 exhibits the variation of total solar insolation fraction including diffused radiation fraction and transmittance of the south facing glass covers having different thicknesses. Correlation proposed by for the transmittance has been used in the present work and it was same for all incident angles of solar radiation on all solar stills. Eventhough the angle of incidence of solar rays is higher during morning as well as evening hours and reverse during noon, hence transmittance will be higher during morning and noon and lower during the noon hours.

Figure 5 exhibits the variations of distillate output production for varying glass cover thicknesses in solar stills throughout the day for 24 hours. Here, 1 cm water depth in each solar still is made constant by use of solenoid valve attachment for the proper comparison of distillate output in each still. From the graph, it is clearly shown that, 4 mm glass cover thickness solar still have obtained higher distillate output throughout the day, when compared with other solar stills having 5 mm and 6 mm glass cover thicknesses. The reason behind getting higher distillate output, is higher transmittance of glass cover for 4 mm glass cover thickness, which allows enhanced solar radiation falling on water inside solar still. Figure 6 shows the total distillate output obtained by each solar still for 24 hours of time interval. It is clear that, total distillate output of 4 mm, 5 mm and 6 mm thickness solar still found 2.51 kg, 2.0 kg and 1.49 kg. Among all solar stills, 4 mm glass cover thickness found 0.342 kg distillate output during off-sunshine hours and remaining 5 mm and 6 mm glass cover thickness found 0.259 and 0.195 kg. Hence, it is proved that, 4 mm glass cover thickness solar still is efficient for producing distillate output not only during sunshine hours but also off-sunshine hours.

Distillate water is a key factor for the efficient design of solar still. But for getting distillate output, water and inner
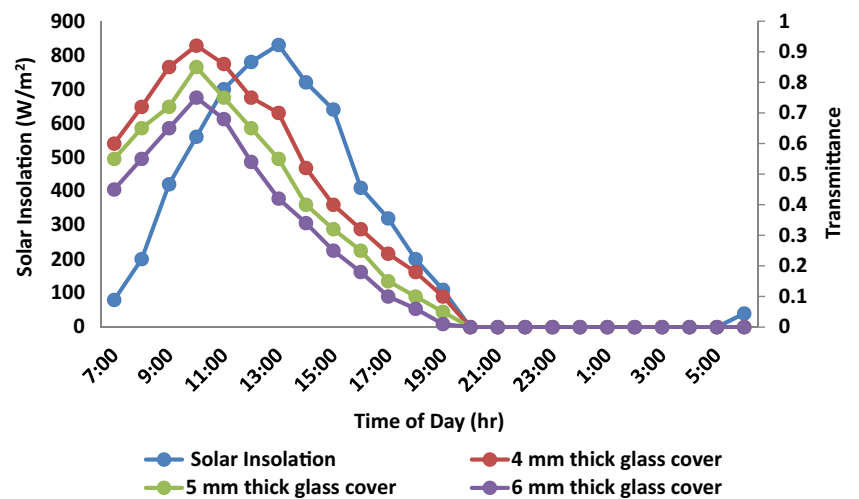
**Fig. 2** Overall Energy-balance equations of sola still
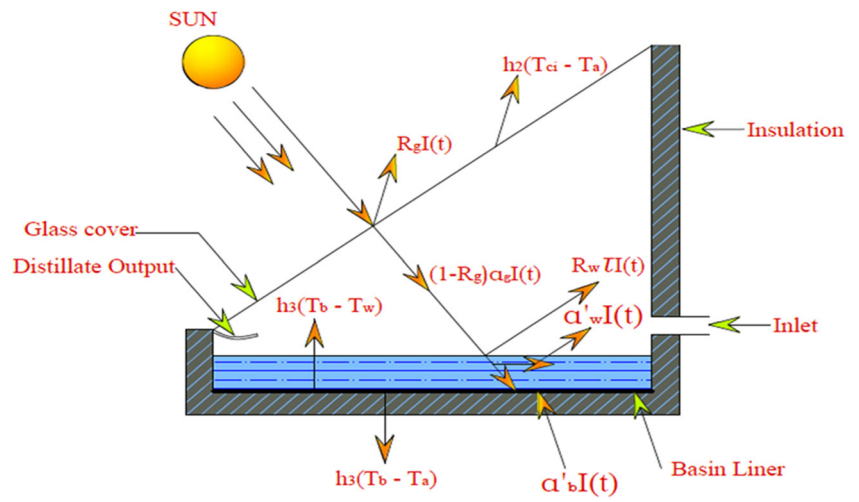
**Fig. 3** Hourly variations of solar insolation solar stills for varying glass cover thicknesses
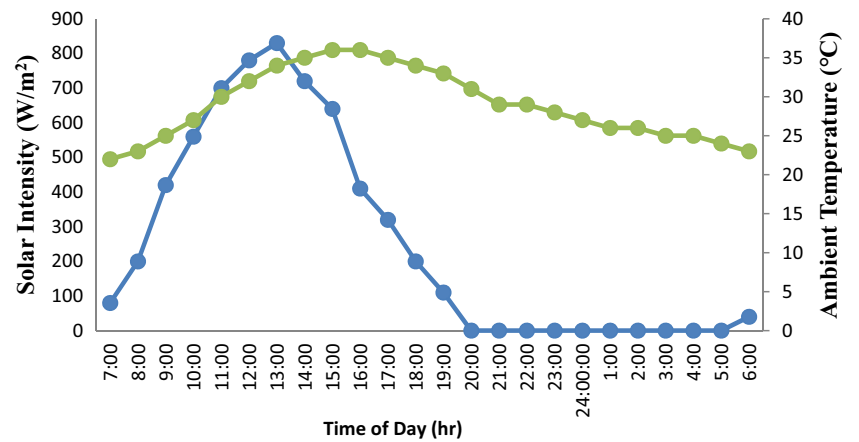
Fig. 4 Hourly Variations of Solar insolation including diffuse radiation fraction and transmittance for solar stills varying glass cover thicknesses
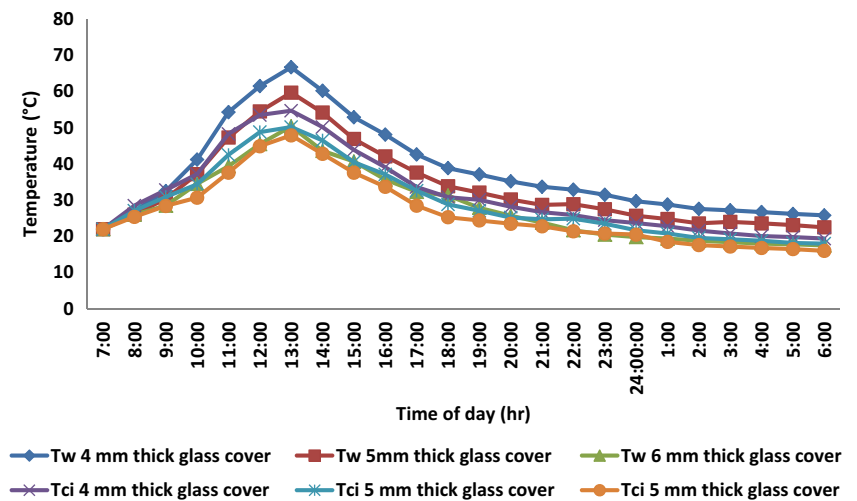
Fig. 5 Variations of hourly distillate output for solar stills having varying glass cover thicknesses
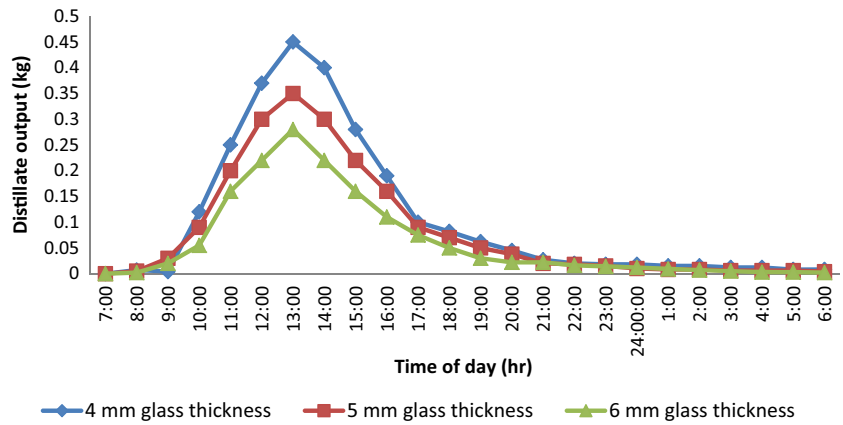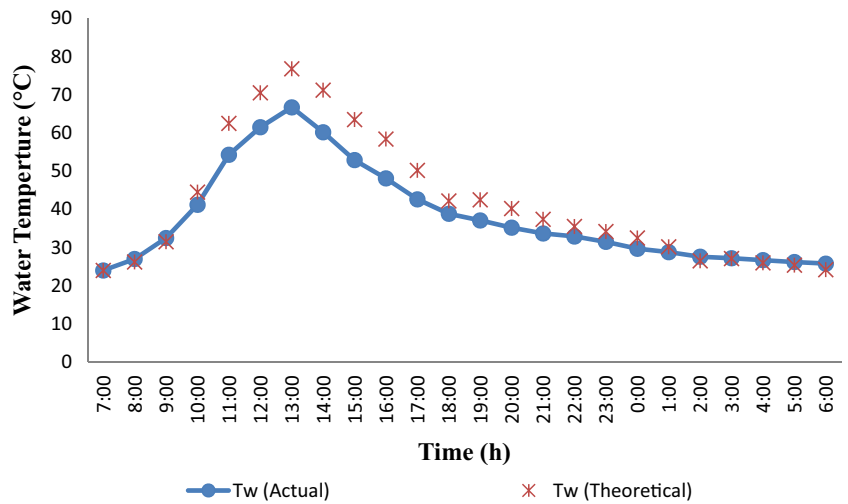

Fig. 6 Variations of total distillate output obtained from solar stills having varying glass cover thicknesses
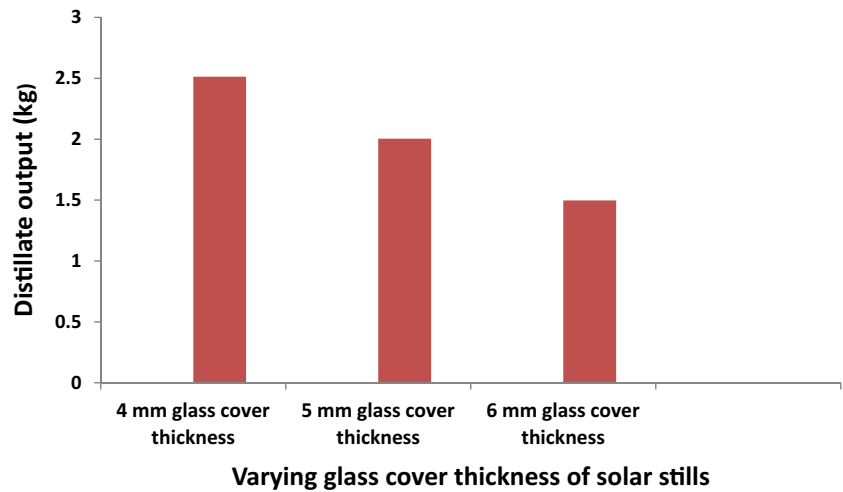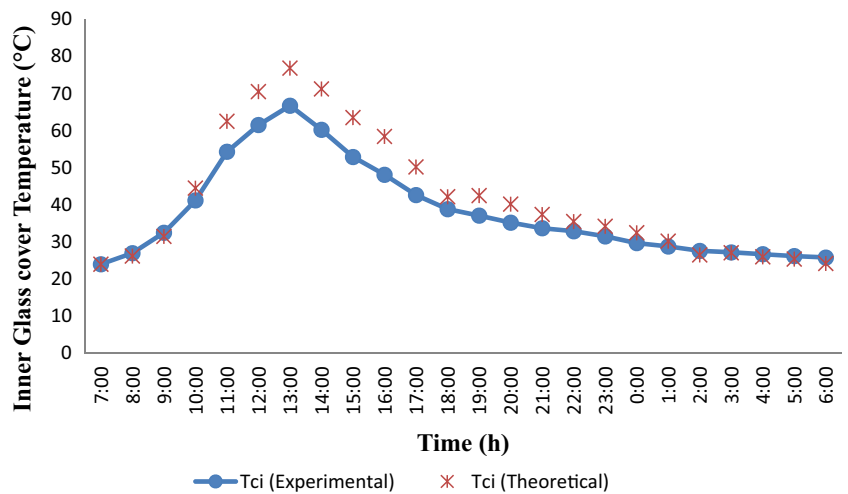

Fig. 7 Hourly variations of water and inner glass cover temperatures

Fig. 8 Hourly variations of theoretical and actual water temperature for solar still having 4 mm glass cover thickness

Fig. 9 Hourly variations of theoretical and actual inner glass cover water temperature for solar still having 4 mm glass cover thickness
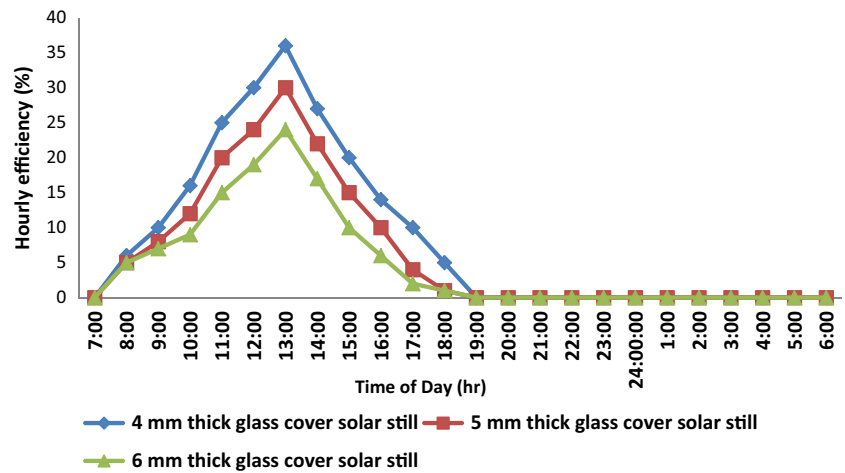

Fig. 10 Hourly variations of theoretical and actual distillate output for solar still having 4 mm glass cover thickness
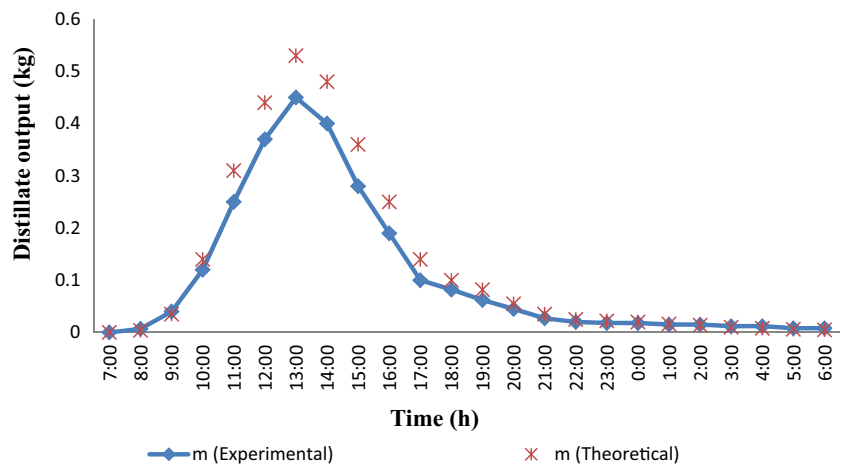
Fig. 11 Hourly variations of efficiency for varying glass cover thicknesses in solar stills

glass cover temperatures are as important as distillate output. Hence, hourly variations of water and inner glass cover temperatures have been measured for each solar stills and shown in Fig. 7. It is clear that, trend of graph for all solar still having varying glass cover. It is also found that, water and inner glass cover temperature found maximum during 1 pm for each still.

A computer program has been written as Microsoft Excel – 2010 for the analytical solutions for the various parameters like water temperature, inner glass cover temperature and distillate output for solar still having 4 mm glass cover thickness is shown in Figs. 8, 9 and 10 respectively. It is clearly shown that, experimental results found good match with theoretical results. At some stages i.e. back and side walls of solar still basin, little deviations found but it is negligible, hence it is not create any disturbance in the comparison.

Efficiency is also one of the most important parameters for performance of any solar still. It shows the percentage of conversion of raw water into potable water hour by hour. Figure 11 exhibits variation of efficiency with respect to time. It is clearly demonstrated that, efficiency is increased

from morning 07:00 am to 13:00 pm and then decrease because of availability of solar insolation. It is also found that, 4 mm, 5 mm and 6 mm glass cover thickness solar stills found 27, 22 and 17 % efficiency during 01:00 pm at noon.

Table 3 shows average daily and monthly distillate output gained by varying the glass cover thickness during the months of January – June 2011. It is clearly demonstrated that, 4 mm glass cover thickness solar still found higher distillate output during all experimental days during January – June 2011 compared with 5 mm and 6 mm thickness solar still. Least and higher distillate output gained during the months of May and January, 2011. The average distillate output of each solar still is calculated by dividing summation of each day distillate output by number of days. Average monthly distillate output is computed by multiplying the average daily distillate output with a number of clear sky days. Hence, the average distillate output gained by 4mm, 5 mm and 6 mm glass cover thickness found 337.94, 299.92 and 265.58 kg distillate output. Hence, percentage increments in distillate output of 4 mm thickness solar still

Table 3 Daily, Monthly Distillate Output obtained Solar Stills with Varying Glass Cover thicknesses during January – June 2011

Month of the year	No. of clear sky days	Average daily yield (Kg)			Average monthly yield		
		4 mm thick	6 mm thick	8 mm thick	4 mm thick	6 mm thick	8 mm thick
January-2011	22	1.4	1.25	1.15	30.8	27.5	25.3
February-2011	24	1.52	1.28	1.22	36.48	30.72	29.28
March-2011	28	2.32	2.1	1.8	64.96	58.8	50.4
April-2011	30	2.54	2.3	2.1	76.2	69	63
May - 2011	30	2.85	2.55	2.3	85.5	76.5	69
June - 2011	22	2	1.7	1.3	44	37.4	28.6
Average		12.63	11.18	9.87	337.94	299.92	265.58

is 12 % compared with 5 mm and 27 % compared with 6 mm thickness

Conclusion

From the present research work, following points are concluded:

- Performance analysis of single basin single slope solar still has been theoretically modeled by consideration of transmittance and solar insolation of south facing glass cover and validated experimentally for typical days of experiments and found good matching of theoretical results with experimental results.
- Solar still having 4 mm glass cover thickness is found among other solar stills having 5 mm and 6 mm glass thickness to increase distillate output by increasing transmittance of solar rays.
- Solar still having 4 mm glass cover thickness is not only increasing distillate output during sunshine hours but also during off-sunshine hours due to getting more heat during sunshine hours.
- Solar still having 4 mm glass cover thickness found 27 % hourly efficiency compared with 22 % of 5 mm thickness solar still and 17 % of 6 mm thickness solar still.
- After 6 months of continuous experiments on solar stills having variations in glass cover thickness, it has been found that, solar still having 4 mm glass cover thickness and 5 mm glass cover thicknesses found 27 % and 12 % increment compared with solar still having 6 mm thickness.

Nomenclatures

Symbol

Notation	Description	Units
α'_g	Absorptivity of glass cover	
α'_w	Absorptivity of water	
α'_b	Absorptivity of basin	
$(MC)_w$	Heat stored by the water	kJ/kg
A_s	Area of Solar still	m^2
h_1	Total heat transfer coefficient	W/ m^{2}°C
h_2	Heat transfer coefficient from glass cover to ambient	W/ m^{2}°C
h_3	Heat transfer coefficient from basin to atmosphere	W/ m^{2}°C
h_{cw}	Convective heat transfer coefficient	W/ m^{2}°C
h_{ew}	Evaporative heat transfer coefficient	W/ m^{2}°C
h_{rw}	Radiative heat transfer coefficient	W/ m^{2}°C
h_{rw}	Radiative heat transfer coefficient	W/ m^{2}°C
h_w	Enthalpy of water	W/ m^2
$I(t)$	Insolation on solar still	W/ m^2
K_g	Thermal Conductivity of glass cover	W/ m K
L	Latent heat of vaporization	kJ/kg
L_g	Thickness of glass cover	M
m	Distillate output gained by passive solar still	kg
M_{ew}	Total distillate output gained by passive solar still at end of each day	kg
M_w	Mass of water stored inside the saline tank	kg
N	Number of observations	
q_b	Rate of heat transfer from basin	W/ m^2
q_{cg}	rate of energy lost from the glass cover by convective	(W/ m^2)
q_{cw}	Rate of energy lost from water by convection	W/ m^2
q_{ew}	Rate of energy lost from water by evaporation	W/ m^2
q_{rg}	Rate of energy lost from glass cover by radiation	W/ m^2
Q_i	Total solar radiations on solar still W/ m^2	W/ m^2
Q_s	Total solar radiation falling on south facing glass cover	W/ m^2
T	Total solar radiation transmitted to solar still	W/ m^2
Q_{Ts}	Total solar radiation transmitted through the solar facing glass cover	W/ m^2
t	Time interval for the experient (3600 s)	Second
T_a	Ambient temperature	°C
T_b	Temperature of basin	°C
T_{co}	Outer glass cover temperature	°C
T_g or T_{ci}	Tempertaure of inner side glass cover	°C
T_w	Temperature of water inside passive solar still	°C
U_b	Heat transfer loss from basin W/ m^2	W/ m^2
U_b	Total Bottom loss from passive solar still	W/ m^2
U_L	Total heat transfer loss from passive solar still	W/ m^2
U_T	Total top loss from passive solar still	W/ m^2

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