Desalination and Water Treatment
www.deswater.com

13 (2010) 400–410
January

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doi: 10.5004/dwt.2010.856

Thermal modeling and carbon credit earned of a double slope passive solar still

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Received 6 January 2009; accepted 3 November 2009

ABSTRACT

In this article an attempt has been made to develop thermal model of double slope passive solar still on the basis of energy balance of east and west condensing covers, water mass and basin liner. Analytical expressions for water temperature, inner and outer condensing covers temperature and distillate yield have been derived as a function of climatic and design parameters. Experimental validations have been carried out by using heat and mass transfer relation given by Dunkle. It is observed that there is a good correlation between theoretical and experimental results with correlation coefficient varies from 0.6958 to 0.9867. The monthly data of yield of double slope passive solar still has been used to evaluate CO_2 emission, mitigation and carbon credit earned for different water depth and life of the system on the basis of energy and exergy.

Keywords: Solar distillation; Thermal modeling; Heat and mass transfer; CO_2 emission

1. Introduction

While the world's population tripled in the 20th century, the use of renewable water resources has grown six-fold. Within the next 50 years, the world population will increase by another 40 to 50%. This population growth—coupled with industrialization and urbanization—will result in an increasing demand for water and will have serious consequences on the environment. In order to meet the requirement of fresh water rigorous research have been carried out by various scientists on design, fabrication and development of solar stills for purification of water.

Relationship for internal heat transfer coefficient for an air–water system in solar stills has been developed in 1961 [1] and is quite popular even today. Digital simulation of experimental solar still data has already been carried out [2]. Many scientists have reviewed the work on passive and active solar distillation systems [3] and [4]. The performance testing and analysis of a double-glazed, air-blown solar still with thermal energy recycling are carried out in 1998 [5]. The life cycle air emission from PV power systems has already been analyzed [6]. Large efforts have been put to develop a highly productive basin type-multiple effects coupled solar still [7]. The validation of a simulation model for water desalination in a green house roof through laboratory experiments have been conducted in 2002 [8]. Dincer reported the linkages between energy and exergy, exergy and the environment, energy and sustainable development, and energy policy making and exergy in detail [9]. A new lumped parameters mathematical model to study the asymmetries that arises in the temperature and distillate yield in double slope solar stills has been reported by Rubio [10].The mathematical model for an inclined solar water distillation system is developed by Aybar [11]. The market for voluntary carbon offsets have been

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explored [12]. The energy and exergy analysis of single and double slope passive solar still has been carried out recently [13].

In this article thermal modeling of double slope passive solar still have been carried out. Water temperature, inner and outer glass cover temperature and hourly yield have been evaluated theoretically with the help of basic energy balance of different components of solar still and results are compared with experimental values. The CO_2 emission, mitigation and carbon credit earned for different water depth and life of the system have also been evaluated on the basis of energy and exergy.

2. Experimental setup and observations

To monitor the performance of double slope passive solar still, experiments were conducted in the campus of Indian Institute of Technology (IIT) Delhi in winter as well as summer months starting from October 2005 to September 2006 for three different water depths namely 0.01 m, 0.02 m and 0.03 m. Experimental observations were taken for each water depth at an interval of 1 h starting at 7 a.m. in the morning and lasted for 24 h. The objective of the experiment was to measure water temperature, inner and outer condensing cover temperature, ambient air temperature, distillate yield and solar intensity on east and west cover of solar still. The schematic diagram and photograph of double slope passive solar still is shown in Fig. 1. The basin area of solar still is kept 2 m^2 and the inclination of condensing covers is 15°. The body of the solar still is made up of glass reinforced plastic (GRP) of thickness 5 mm. The condensing cover of 4 mm thickness is made up of plain glass placed on the basin of solar still. The bottom surface of the still is painted black to have high absorptivity of solar radiation. The yield of solar still is collected into a channel provided at lower side and is taken out through a pipe into a cylinder. For feeding the water in the solar still an inlet pipe is provided to the rear wall. Solar still was placed in east-west direction to receive maximum possible solar radiation. Calibrated thermocouples were used with the help of digital temperature indicator (least count of 0.1 °C) to record the water, inner and outer condensing cover temperatures. The ambient air temperature is recorded with the help of a calibrated mercury thermometer having a least count of 1 °C and a measuring cylinder with a least count of 1.0 mL measures the distillate output. The solar intensity was measured with the help of a solarimeter, having least count of 20 W/m^2.

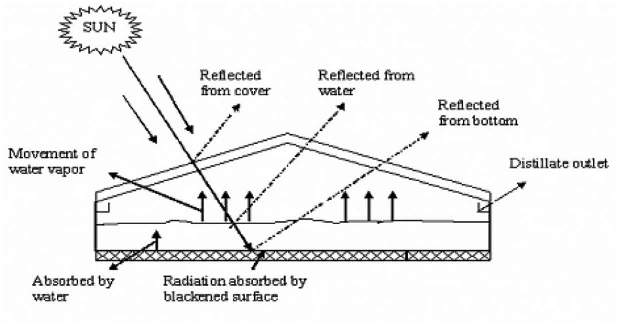

Fig. 1 (a). Schematic diagram of double slope solar still.

Fig. 1 (b). Photograph of double slope passive solar still.

The mass, energy density and embodied energy of different components of solar distillation system (GRP body, GI angle iron and Glass covers) have been given in Table 1. The energy pay back time (EPBT) of double slope solar still has been evaluated and its value is 1.85 years for 0.01 m water depth as also been given in Table 1. The experimental observation of solar intensity and ambient air temperature for the month of December 2005 and June 2006 has been shown in Figs. 2 and 3. The monthly yield have been evaluated

Table 1
Embodied energy and energy pay back time for double slope solar still

Name of component	Mass of component (kg)	Energy density (kWh/kg)	Embodied energy (kWh)
GRP body	24.19	25.64	620.23
GI angle iron	30.00	13.88	416.40
Glass cover	19.36	8.72	168.82

Total embodied energy (E_{in}) = 602.73 kWh
Annual yield/m^2 of basin area = 464.68 kg
Annual energy available from solar still/m^2 of basin area (E_{out}) = 325.50 kWh
Energy pay back time (EPBT) = 1.85 years

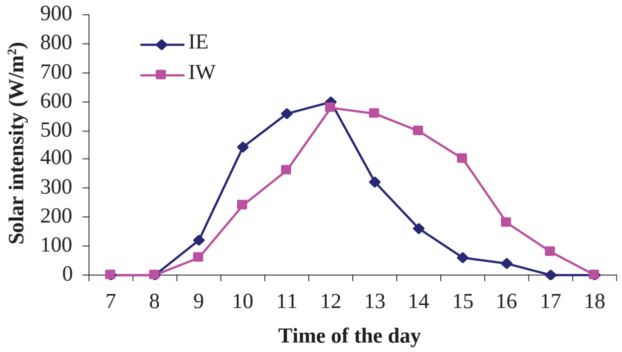

Fig. 2a. Experimental observation of solar intensity on east and west side of condensing covers in the month of December 2005.

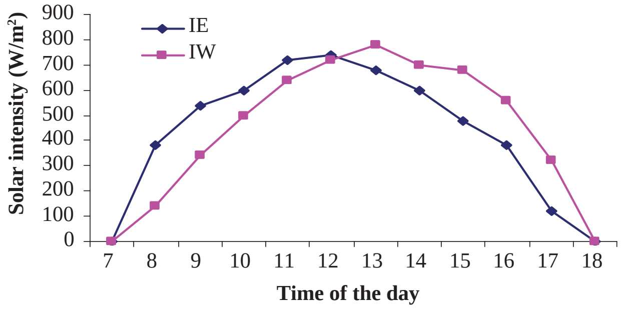

Fig. 2b. Experimental observation of solar intensity on east and west side of condensing covers in the month of June 2006.

by multiplying the daily yield with the number of clear days and results are given in Table 2 for different water depth for double passive slope solar still. The daily yield has been obtained by adding the hourly yield of 24 h. The annual yield is maximum (464.68 kg/m^2) for 0.01 m water depth and it decreases with increase in water depth. The experimental and theoretical observation of inner and outer condensing covers, water temperature and distillate yield have been shown in the Figs. 4–7.

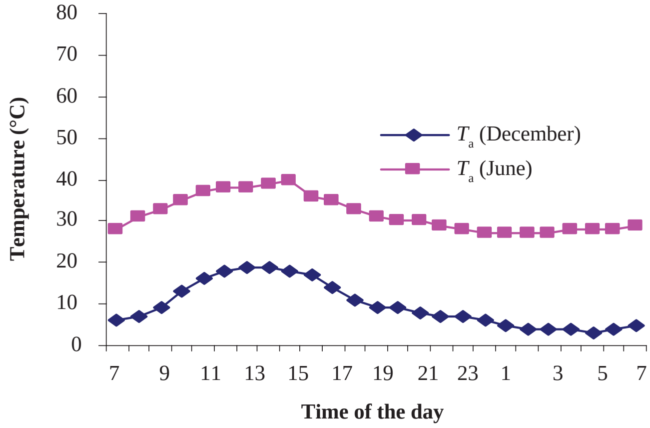

Fig. 3. Experimental observation of ambient air temperature for the month of December 2005 and June 2006.

3. Energy balance equations for modeling double slope passive solar still

The solar intensity falling on the east and west covers of solar still will be different and hence inner and outer glass temperature and hourly yield will also be different for east and west side.

Following assumptions are taken into consideration for writing energy balance equations for different components of a solar still.

1. Thermal capacity of glass covers and insulating material of wall of solar still has been neglected.
2. There is no temperature gradient in the water inside the basin.
3. The system is under quasi-steady state condition.

3.1. Energy balances on East cover

The energy balance for inner and outer surfaces of east condensing cover are as follow

$$\alpha_g' I_E + h_{tE}(T_w - T_{ciE}) - U_{EW}(T_{ciE} - T_{ciW}) = \frac{k_g}{L_g}(T_{ciE} - T_{coE}) \tag{1}$$

and $$\frac{k_g}{L_g}(T_{ciE} - T_{coE}) = h_{aE}(T_{coE-}T_a) \tag{2}$$

where, $h_{tE} = h_{cwE} + h_{ewE} + h_{rwE}$ and

3.2. Energy balances on West cover

The energy balance for inner and outer surfaces of east condensing cover are as follow

$$\alpha_g' I_W + h_{tW}(T_w - T_{ciW}) + U_{EW}(T_{ciE} - T_{ciW}) = \frac{k_g}{L_g}(T_{ciW} - T_{coW}) \tag{3}$$

and $$\frac{k_g}{L_g}(T_{ciW} - T_{coW}) = h_{aW}(T_{coW} - T_a) \tag{4}$$

where, $h_{tW} = h_{cwW} + h_{ewW} + h_{rwW}$

3.3. Energy balance for water mass

The energy balance for water mass is as follows

Table 2
Monthly yield, energy and exergy of a double slope solar still

		Monthly yield = Daily yield × Number of clear days			Monthly energy = Daily energy × No. of clear day			Monthly exergy = Daily exergy × No. of clear days		
		0.01 m	0.02 m	0.03 m	0.01 m	0.02 m	0.03 m	0.01 m	0.02 m	0.03 m
Months	No. of clear days	kg/m^2	kg/m^2	kg/m^2	Wh	Wh	Wh	Wh	Wh	Wh
Oct-05	24	34.5	30.72	29.28	72,558.5	61,589.1	68,273.2	513.0	467.9	416.3
Nov-05	30	34.43	34.2	32.43	73,109.4	80,632.2	80,527.8	396.4	437.9	371.3
Dec-05	22	19.46	19.36	14.3	47,563.1	52,229.3	26,321.3	259.2	227.3	81.0
Jan-06	22	20.57	18.26	23.19	41,614.6	39,688.6	52,789.7	215.8	175.0	265.0
Feb-06	24	32.05	30.48	29.76	72,558.2	55,287.8	57,588.8	475.3	392.0	340.4
Mar-06	28	57.68	56.28	51.16	108,867.7	108,269.5	99,639.2	1,263.9	1,256.2	1,334.4
Apr-06	29	65.93	64.7	58.55	127,947.8	131,822.1	105,114.2	1,519.2	1,573.0	1,375.4
May-06	30	66.08	62.73	49.2	128,911.5	133,937.4	120,692.3	510.8	1,470.3	1,054.3
Jun-06	26	57.29	49.09	48.31	133,822.1	118,075.0	114,942.0	1,484.8	1,173.2	982.7
Jul-06	16	30.45	30.35	26.46	71,743.0	67,966.4	70,973.7	535.2	531.4	471.9
Aug-06	12	20.88	19.02	18.78	51,740.4	50,646.5	58,622.4	348.5	337.2	364.0
Sep-06	16	25.37	23.97	23.71	65,468.1	65,780.6	66643.0	424.5	426.8	468.2
Total	279	464.68	439.16	405.1	995,904.4	965,924.5	922127.6	7946.5	8468.2	7525.0

$$(MC_w)\frac{dT_w}{dt} = (I_E + I_W)\alpha'_w + 2U_{bw}(T_b - T_w) - h_{tE}(T_w - T_{ciE}) - h_{tW}(T_w - T_{ciw}) \qquad (5)$$

3.4. Energy balance for basin liner

The energy balance for basin liner is as follows

$$\alpha'_b(I_E + I_W) = 2U_{bw}(T_b - T_w) + 2U_{ba}(T_b - T_a) \qquad (6)$$

From above Eqs. (1–6), the differential equation obtained is

$$\frac{dT_w}{dt} + aT_w = f(t) \qquad (7a)$$

where, expressions for a, $f(t)$and other constants are given by

$$a = \frac{1}{MC_w}\left[\frac{2U_{bw}U_{ba}}{U_{bw} + U_{ba}} + \frac{(p - A_2)h_{tE}}{p} + \frac{(p - B_2)h_{tW}}{p}\right],$$

$$f(t) = \frac{1}{MC_w}\left[\left(\alpha'_w + \frac{\alpha'_b U_{bw}}{U_{bw} + U_{ba}}\right)(I_E + I_W) + \frac{h_{tE}A_1 + h_{tw}B_1}{p} + \frac{2U_{bw}U_{ba}T_a}{U_{bW} + U_{ba}}\right],$$

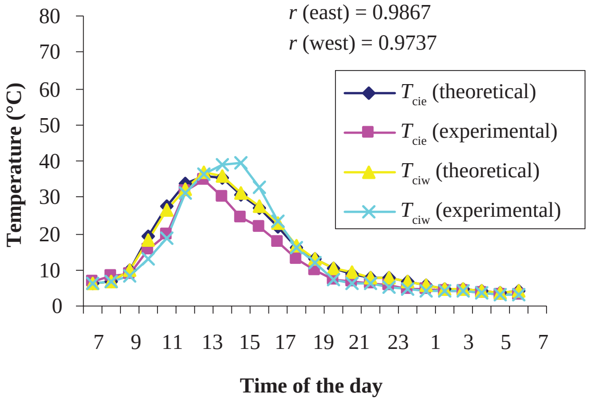

Fig. 4a. Hourly variation of theoretical and experimental inner condensing covers temperature for east and west side of a double slope solar still for the month of December 2005.

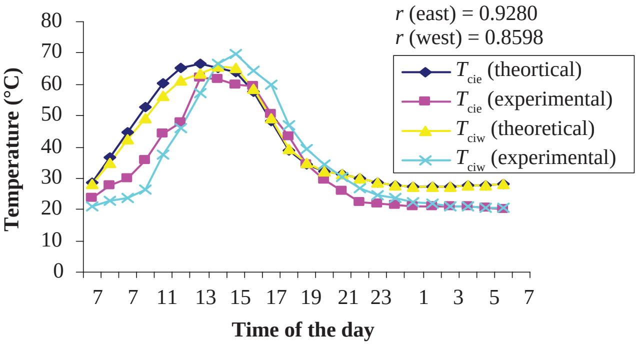

Fig. 4b. Hourly variation of theoretical and experimental inner condensing covers temperature for east and west side of a double slope solar still for the month of June 2006.

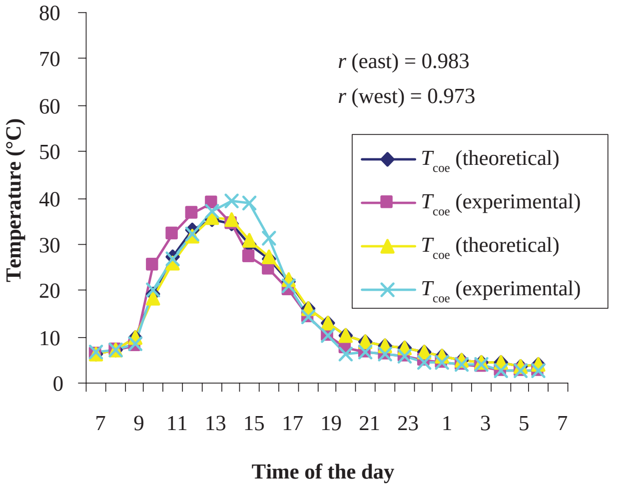

Fig. 5a. Hourly variation of theoretical and experimental outer condensing covers temperature for east and west side of a double slope solar still for the month of December 2005.

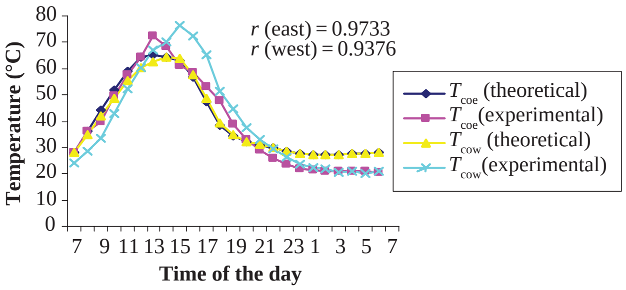

Fig. 5b. Hourly variation of theoretical and experimental outer condensing covers temperature for east and west side of a double slope solar still for the month of June 2006.

$$p = U_1 U_2 - U_{EW}^2$$

$$A_1 = R_1 U_2 + R_2 U_{EW}$$

$$A_2 = h_{tE} U_2 + h_{tW} U_{EW}$$

$$B_1 = R_1 U_{EW} + R_2 U_1$$

$$B_2 = h_{tE} U_{EW} + h_{tW} U_1$$

$$U_1 = U_{aE} + h_{tE} + U_{EW}$$

$$U_2 = U_{aW} + h_{tw} + U_{EW}$$

$$R_1 = \alpha_g' I_E + U_{aE} T_a$$

$$R_2 = \alpha_g' I_W + U_{aW} T_a$$

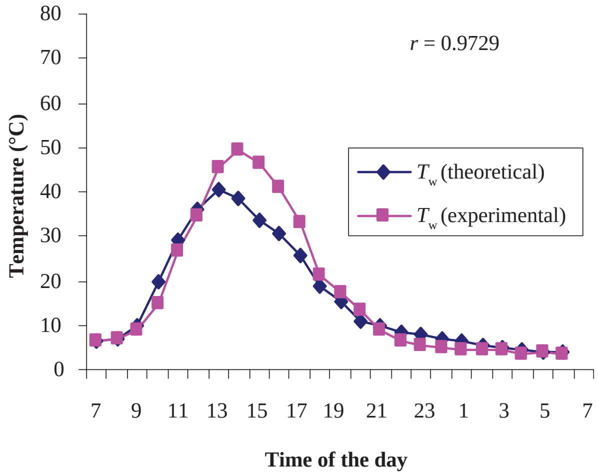

Fig. 6a. Hourly variation of theoretical and experimental water temperature for 0.01 m water depth of a double slope solar still for the month of December 2005.

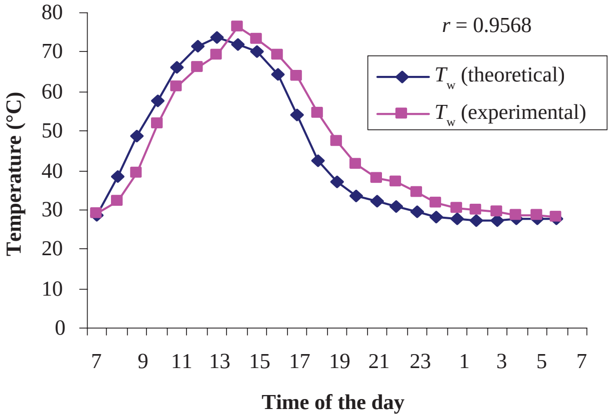

Fig. 6b. Hourly variation of theoretical and experimental water temperature for 0.01 m water depth of a double slope solar still for the month of June 2006.

$$U_{aE} = \frac{k_g h_{aE}}{k_g + h_{aE} L_g} \quad \text{and}$$

$$U_{aW} = \frac{k_g h_{aW}}{k_g + h_{aW} L_g}.$$

In order to solve Eq. (7a), the following assumptions have been made.

(i) The time interval Δt is very small.
(ii) For $0 - t$ time interval, the values of T_a and $I(t)$ have been considered as average value of T_a and $I(t)$ at '0' and 't' time as $\overline{T_a}$and $\overline{I(t)}$, hence $\overline{f(t)}$.
(iii) The internal convective (h_{cw}), evaporative (h_{ew}) and radiative (h_{rw}) heat transfer coefficients for

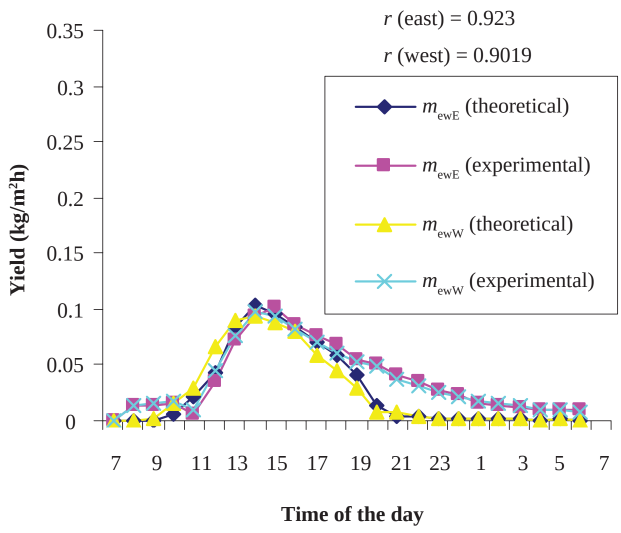

Fig. 7a. Hourly variation of theoretical and experimental yield for 0.01 m water depth of a double slope solar still for the month of December 2005.

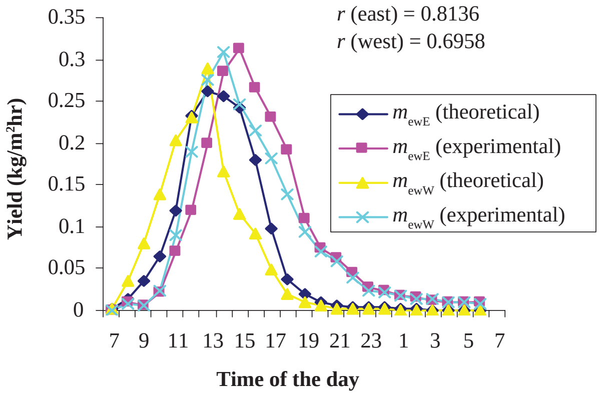

Fig. 7b. Hourly variation of theoretical and experimental yield for 0.01 m water depth of a double slope solar still for the month of June 2006.

east and west condensing cover have been evaluated at initial ($t = 0$) water (T_{w0}) and inner condensing cover (T_{ci0}) temperature and assumed to be constant over $0 - t$ time interval. Hence, h_{tE} and h_{tW} have been considered constant over $0 - t$ time interval.

After making above assumptions, Eq. (7a) becomes one order simple differential equation.

The solution of Eq. (7a) with initial condition, $T_w = T_{w0}$ at $t = 0$, becomes

$$Tw = \frac{\overline{f(t)}}{a}[1 - \exp(-a\Delta t)] + T_{w0}\exp(-a\Delta t) \tag{7b}$$

After knowing water temperature from Eq. (7b), the inner and outer glass cover temperatures can be obtained as

$$T_{ciE} = \frac{A_1 + A_2 T_w}{p} \tag{8a}$$

$$T_{ciW} = \frac{B_1 + B_2 T_w}{p} \tag{8b}$$

$$T_{coE} = \frac{\frac{k_g}{L_g} T_{ciE} + h_{aE} T_a}{\frac{k_g}{L_g} + h_{aE}} \tag{9a}$$

$$T_{coW} = \frac{\frac{k_g}{L_g} T_{ciW} + h_{aW} T_a}{\frac{k_g}{L_g} + h_{aW}} \tag{9b}$$

The obtained values of water and inner condensing cover temperature become initial temperature for next set of calculations. Similarly this procedure has been adopted for other set of time interval.

The evaporative heat transfer rate from east and west side of a double slope solar still is given by

$$\dot{q}_{ewE} = h_{ewE}(T_w - T_{ciE}) \tag{10a}$$

$$\dot{q}_{ewW} = h_{ewW}(T_w - T_{ciW}) \tag{10b}$$

Then, hourly yield can be calculated with the help of following equations

$$\dot{m}_E = \frac{\dot{q}_{ewE} \times 3600}{L} \text{ and,} \tag{11a}$$

$$\dot{m}_W = \frac{\dot{q}_{ewW} \times 3600}{L}, \tag{11b}$$

The hourly yield obtained by Eq. (11) has been shown in the Fig. 7.

The experimental values of daily yield/m^2 can be obtained by adding hourly yield of double slope solar still of basin area 2 m^2 for a period of 24 h as given by equation

$$M_{ew} = \frac{1}{2}\left[\sum_{i=1}^{i=24} \dot{m}_{ewiE} + \sum_{i=1}^{i=24} m_{ewW}\right] \tag{12a}$$

then,

$$\text{Monthly yield} = \text{Daily yield} \times \text{No. of clear day} \tag{12b}$$

The numbers of clear days and monthly yield for different water depth have been given in Table 2.

The daily exergy output from solar still can be written, Petela [14] as:

$$\mathrm{Ex}_{\mathrm{evap}} = \sum (1 - T_a/T_w) \times Q_{ew}/3600 \tag{13a}$$

where,

$$Q_{ew} = Mew \times L$$

$$\text{Monthly exergy output} = \text{Daily exergy} \times \text{No. of clear days} \tag{13b}$$

The monthly exergy outputs have been given in Table 2.

Table 3
Design parameters used in thermal modeling

Design parameters	Value
α_b	0.8
α_g	0.05
α_w	0.6
ϵ_w	0.95
ϵ_g	0.95
$(\alpha\tau)$	0.8
L_b	0.005 m
L_g	0.004 m
K_b	0.035 W/mK
k_g	0.78 0 W/mK
C_W	4188 J/kgK
M	20 kg
σ	5.67×10^{-8} W/m^{2}K^4
V	1.0 m/s

4. CO_2 emission, CO_2 mitigation and carbon credit earned

4.1. CO_2 emission

The average carbon dioxide equivalent intensity for electricity generation from coal is approximately 0.98 kg of CO_2 per kWh at source. If the transmission and distribution losses for Indian condition are taken 40% and domestic appliances losses are around 20%, then figure 0.98 should be taken as 1.58. Therefore,

$$\text{Annual } CO_2 \text{ emission} = (E_{\text{in}} \times 1.58)/t_k \tag{14}$$

where, E_{in} is the embodied energy of solar still and t_k is the life time of solar still.

(Embodied energy (E_{in}) has been calculated by multiplying the mass of each component of solar still with their respective energy densities and are given in Table 1).

Hence,

$$CO_2 \text{ emission over the life time} = E_{\text{in}} \times 1.58 \tag{15}$$

The CO_2 emissions for the lifetime of 20 years have been evaluated by Eq. (15) and are given in Table 4.

3.2 CO_2 mitigation

The CO_2 mitigation (kg of CO_2) per year can be expressed as CO_2 mitigation (kg of CO_2) per year = $E_{\text{out}} \times 1.58$ where, E_{out} is the annual energy output obtained from solar still (The daily energy output is calculated by multiplying the daily yield with latent heat of vaporization whereas monthly energy out has been calculated by multiplying the daily energy output with the number of clear days in the month. Then, annual energy output E_{out} has been found by adding the monthly energy output and are given in Table 2.). and,

$$\begin{aligned} &CO_2 \text{ mitigation (kg of } CO_2\text{) over life time} \\ &\qquad = E_{\text{out}} \times t_k \times 1.58 \end{aligned} \tag{16}$$

Therefore,

$$\begin{aligned} &\text{Net } CO_2 \text{ mitigation (tons of } CO_2\text{) over life time} \\ &\qquad = (E_{\text{out}} \times t_k - E_{\text{in}}) \times 1.58 \times 10^{-3} \end{aligned} \tag{17}$$

The net CO_2 mitigation for the lifetime of 20 years has been evaluated by Eq. (17) and is given in Table 4.

4.3. Carbon credit earned

Presently carbon dioxide has been traded at € 20 per ton of CO_2 mitigation. So, the carbon credit earned by the system in terms of Indian currency (Rs.) can be expressed as

$$\begin{aligned} \text{Carbon credit earned} &= (E_{\text{out}} \times t_k - E_{\text{in}}) \times 1.58 \times 10^{-3} \\ &\quad \times (20 \times 53) \end{aligned} \tag{18}$$

where, € 1 = Rs. 53.

Carbon credit earned by the system for different water depth and life of the system has been evaluated by the Eq. (18) and the results are given in Table 4.

Table 4
CO_2 emission and mitigation for 20 years life time of solar still on the basis of energy

Water depth (m)	0.01 m	0.02 m	0.03 m
Annual yield (kg)	464.68	439.16	405.13
Embodied energy E_{in} (kWh)	602.73	602.73	602.73
Annual energy output from solar still E_{out} (kWh/m^2)	325.28	307.41	283.59
CO_2 emission over the life time (kg)	952.31	952.31	952.31
Net CO_2 mitigation over life time (ton)	9.33	8.76	8.01

Carbon credit earned for different depth and life of solar still on the basis of energy

	Water depth (m)		
	0.01	0.02	0.03
Life of solar still (year)	Carbon credit earned (Rs) [€1 = Rs. 53]		
20	9885.99	9287.62	8489.71
30	15333.72	14436.16	13239.29
40	20781.44	19584.69	17988.88
50	26229.16	24733.23	22738.46

5. Result analysis

The energy balance Eqs. (1–6) are written for different components of solar still such as for east and west side of condensing covers water mass and basin liner. By solving Differential Eq. (7a), water temperatures can be obtained as given by Eq. (7b). Further, inner and outer glass cover temperatures are determined with the help of Eqs. (8) and (9). With the help of evaporative heat transfer coefficients, water and inner glass cover temperatures, distillate output from east and west sides are determined by Eq. (10). A program was developed in MAT LAB 7.0 to find out water temperature, inner and outer glass cover temperature and distillate yield for east and west side of solar still. The design parameters used in the thermal modeling are given in Table 3 whereas the expressions for heat transfer coefficients are given in Appendix. Experimental validations for water, inner and outer glass cover temperatures and distillate yield are carried out for each month of a year but results are shown only for the month of December 2005 and June 2006.

Solar intensity and ambient air temperature data used in the modeling of solar still are given in the Figs. 2 and 3 respectively. The solar intensity falling on the east cover is higher before 12:00 noon whereas it is lower in the after noon in comparison to west cover. The highest value of solar intensity in the month of June at the east cover was found 740 W/m^2 at 12 noon whereas highest value at west cover was 780 W/m^2 and observed at 1:00 p.m. Because of the variation in the solar intensity on the east and west cover there is a variation in the glass cover temperature and distillate yield as shown in Figs. 4, 5 and 6. Since solar intensity on the east cover is higher in the morning hours hence outer and inner glass cover temperatures are also higher and consequently difference in the water and inner glass cover temperatures are lower for east side and higher for the west side. Due to higher temperature difference between water and west glass cover before 12:00 noon distillate yield is higher in the morning hours and lower in the afternoon hours whereas distillate yield for east side is higher in the afternoon hours due to higher temperature difference between water and inner glass cover temperature. Theoretical and experimental observations for inner and outer glass cover temperatures, water temperature and distillate yield for the month of December 2005 and June 2006 have been shown in Figs. 4–7. The highest experimental and predicted value of water temperature in the month of June is 76.3 °C and 73.6 °C respectively. The experimental values of yield for a day in the month of June are higher by 25.14% and 29.67% than predicted values for east and west side respectively. The values of correlation coefficients have been shown in the Figs. 4–7 for inner and outer glass cover temperature, water temperature and distillate yield. The correlation coefficient between experimental and theoretical data for inner and outer glass cover temperatures, water temperature and distillate yield shows closer agreement between experimental and theoretical values. The standard deviation between theoretical and experimental values of water temperature, inner covers (east and west), outer glass cover (east and west) temperature and distillate yield from east and west sides are respectively 14.08, 10.5, 11.85, 11.5, 11.87, 0.03 and 0.032. The monthly yield and corresponding energy output of the system for different month and

Table 5
CO_2 emission and mitigation for 20 year life time of solar still on the basis of exergy

Water depth (m)	0.01 m	0.02 m	0.03 m
Annual yield (kg)	464.68	439.16	405.13
Embodied energy, E_{in} (kWh)	602.73	602.73	602.73
Exergy output from solar still, E_{xout} (kWh)	7.946	8.468	7.524
CO_2 emission over the life time (kg)	952.31	952.31	952.31
Net CO_2 mitigation over life time (ton)	0	0	0

water depth are given in Table 2. The annual output of solar still for water depth of 0.01 m is maximum (464.68 kg/m^2) and it decreases with water depth. The embodied energy per m^2 of basin area of double slope solar still has been given in Table 1. Based on monthly data of yield and embodied energy of the system CO_2 emission, mitigation and carbon credit earned for different water depth and life of the system has also been evaluated. The CO_2 emission and net mitigation from the system on the basis of energy for the life time of 20 years and for different water depth have been evaluated by the Eqs. 21 and 23 respectively and the results are given in Table 4. The net CO_2 mitigation for system life of 20 years is maximum (9.33 ton) for lower water depth of 0.01 m. The carbon credit earned in terms of Indian currency for different water depth and life of the solar still has been calculated by Eq. (24) and results are shown in Table 4. The carbon credits earned is maximum (Rs. 26,229.16) for 0.01 m water depth and 50 years of life of the system. The CO_2 emission and net mitigation from the system have also been analyzed on the basis of exergy. The CO_2 emission and net mitigation on the basis of exergy have been given in Table 5. There is no net CO_2 mitigation on the basis of exergy due to low exergy output from the system and hence no carbon credit will be obtained.

6. Conclusion

Following conclusions can be drawn

(1) On the basis of present studies it is noted that there is a closer agreement between theoretical and experimental values.
(2) The carbon credit earned on the basis of energy in terms of Indian currency for water depth of 0.01 m is Rs. 9,885.9 and Rs. 26,229.16 respectively for 20 and 50 years of lifetime of solar still.
(3) No carbon credit will be obtained on the basis of exergy output of solar still.

Nomenclature

C	specific heat of water (J/kg K)
E_{in}	embodied energy of solar still (kWh/m^2)
E_{out}	annual energy output from solar still (kWh/m^2)
E_{xout}	annual exergy output from solar still (kWh/m^2)
GRP	glass reinforced plastic
GI	galvanized iron
h_{tE}	total internal heat transfer coefficient on east side (W/m^{2}K)
h_{tW}	total internal heat transfer coefficient on west side (W/m^{2}K)
h_{cwE}	internal convective heat transfer coefficient on east side (W/m^{2}K)
h_{cwW}	internal convective heat transfer coefficient on west side (W/m^{2}K)
h_{ewE}	internal evaporative heat transfer coefficient on east side (W/m^{2}K)
h_{ewW}	internal evaporative heat transfer coefficient on west side (W/m^{2}K)
h_{rwE}	internal radiative heat transfer coefficient on east side (W/m^{2}K)
h_{rwW}	internal radiative heat transfer coefficient on west side (W/m^{2}K)
h_{aE}	heat transfer coefficient between outer glass cover of east side and ambient air
h_{aW}	heat transfer coefficient between outer glass cover of east side and ambient air
I_{E}	solar intensity on the east side glass cover (W/m^2)
I_{W}	solar intensity on the west side glass cover (W/m^2)
k_{g}	thermal conductivity of glass cover (W/mK)
k_{b}	thermal conductivity of GRP sheet (W/mK)
L_{g}	thickness of glass cover (m)
L_{b}	thickness of basin of solar still (m)
L	latent heat of vaporization (J/kg)
M	mass of water in the basin of solar still (kg)
$\dot{m}_E$	hourly distillate yield from east side (kg/m^2)
$\dot{m}_W$	hourly distillate yield from west side (kg/m^2)
P_{w}	partial saturated vapor pressure at water temperature (N/m^2)
PV	photovaltaic

P_{ci}	partial saturated vapor pressure at inner glass temperature (N/m^2)
P_{t}	total vapor pressure in the basin (N/m^2)
q_{ewE}	evaporative heat transfer rate from east side (W/m^2)
q_{ewW}	evaporative heat transfer rate from west side (W/m^2)
r	coefficient of correlation
t	time (s)
t_{k}	life time of solar still (year)
T_{w}	water temperature (°C)
T_{ciE}	inner glass covers temperature on east side (°C)
T_{ciW}	inner glass covers temperature on west side (°C)
T_{coE}	outer glass covers temperature on east side (°C)
T_{wo}	water temperature at time $t = 0$ (°C)
T_{coW}	outer glass covers temperature on west side (°C)
T_{a}	ambient air temperature (°C)
T_{b}	basin liner temperature (°C)
U_{EW}	internal radiative heat transfer coefficient between east and west glass cover (W/m^2 °C)
U_{bw}	heat transfer coefficient between basin liner and water (W/m^2 K)
U_{ba}	heat transfer coefficient between basin liner and ambient air (W/m^2 K)
U_{aE}	overall heat transfer coefficient between outer glass cover of east side and ambient air (W/m^2 K)
U_{aW}	overall heat transfer coefficient between outer glass cover of west side and ambient air (W/m^2 K)
V	air velocity (m/s)

Symbols

α'_g	fraction of solar energy absorbed by glass cover
α'_w	fraction of solar energy absorbed by basin water
α'_b	fraction of solar energy absorbed by basin liner
ε_g	emissivity of glass cover
ε_w	emissivity of water
$(\alpha\tau)$	effective absorptance–transmittance product

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Appendix
Relation for heat transfer

External heat transfer

Main mode of heat transfer from glass cover to ambient surface takes place by convection and radiation. The combined convective and radiative heat transfer coefficient (W/m^2 °C) from glass cover to ambient is given by [15]

$$h_{aE} = h_{aW} = 5.7 + 3.8\mathrm{V} \tag{19}$$

The heat transfer from basin to ambient takes place by conduction inside the wall of the still and further by convection and radiation. The overall heat transfer coefficient (W/m^2 °C) from basin to ambient is given by the equation

$$U_{ba} = \frac{1}{\frac{L_b}{k_b} + \frac{1}{h_b}} \tag{20}$$

Internal heat transfer

The heat transfer from water surface to the glass cover takes place by convection, evaporation and radiation. The convective heat transfer coefficient (W/m^2 °C) as given by Dunkle's equation for east and west cover is

$$h_{cwE} = 0.884\left[T_w - T_{ciE} + \frac{(P_w - P_{ciE})T_w}{268.9 \times 10^3 - P_w}\right]^{\frac{1}{3}} \tag{21a}$$

$$h_{cwW} = 0.884\left[T_w - T_{ciW} + \frac{(P_w - P_{ciW})T_w}{268.9 \times 10^3 - P_w}\right]^{\frac{1}{3}} \tag{21b}$$

and evaporative heat transfer coefficient (W/m^2 °C) for east and west side is given by

$$h_{ewE} = 16.276 \times 10^{-3} h_{cwE} \frac{P_w - P_{ciE}}{T_w - T_{ciE}} \tag{22a}$$

$$h_{ewW} = 16.276 \times 10^{-3} h_{cwW} \frac{P_w - P_{ciW}}{T_w - T_{ciW}} \tag{22b}$$

Radiative heat transfer coefficient (W/m^2 °C) for east and west cover is calculated by

$$h_{rwE} = \frac{\sigma(T_w^2 + T_{ciE}^2)(T_w + T_{ciE})}{\frac{1}{\varepsilon_w} + \frac{1}{\varepsilon_g} - 1} \tag{23a}$$

$$h_{rwW} = \frac{\sigma(T_w^2 + T_{ciW}^2)(T_w + T_{ciW})}{\frac{1}{\varepsilon_w} + \frac{1}{\varepsilon_g} - 1} \tag{23b}$$

Radiative heat transfer between east and west surface has also been considered. The radiative heat transfer coefficient between two condensing surfaces is given by

$$U_{EW} = 0.034\sigma\left[(T_{ciE} + 273)^2 + (T_{ciW} + 273)^2\right]\left[T_{ciE} + T_{ciW} + 546\right] \tag{24}$$