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Annual performance of evacuated tubular collector integrated solar still

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ABSTRACT

Evacuated tubular collector (ETC) and solar still (SS) are two solarthermal technologies for heating and purification of water, respectively. ETC stores water at high temperature whereas SS requires heated water for increased evaporation as well as yield. In this paper, an active solar thermal system "evacuated tubular collector integrated solar still (EISS)" (ETC and SS are integrated together) has been analyzed for its annual (January–December 2008) experimental performance for the composite climatic condition of New Delhi, India. The EISS system has been designed to recover the heat loss (which occurs from the ETC's hot water during off-sunshine hours) in the form of distilled water by evaporation–condensation process in SS. Hence, the EISS system provides both hot water as well as potable (distilled) water. The main purpose of the present analysis is to develop a thermal model of EISS, its validation with experimental results, economic analysis, and to compare the performance of EISS with the single slope SS. Results show that EISS system can produce 630 kg/m^2 year of distilled water, compared to the amount of 327 kg/m^2 year yielded from a single slope SS. The maximum overall thermal efficiency of EISS has been found to be 30.1% (16 May 2008) and the annual average, has been found to be 21.3%. An economic analysis of EISS shows the annualized cost of distilled water US $ 0.128 per kg.

Keywords: Solar distillation; Evacuated tubular collector; Thermal efficiency; Distilled water production

1. Introduction

Water is an important necessity for life. It is available in different forms such as seawater, surface water, underground water, and atmospheric water [1]. In spite of large amount of water availability, the man is facing the problem of scarcity of potable water caused due to pollution, ignorance, decreasing level of water table, and increasing use of water in various sectors, etc. [1]. There are various methods available to purify water but most of them use electricity generated from conventional fuel. The recent development in water desalination has been reviewed by Delyannis and Belessiotis [2].

Solar distillation, an analogy to natural hydrological cycle, uses solar energy to purify the saline/brackish water. It is an easy handling, low operating cost, and renewable energy based technology. It uses a device called as "solar still (SS)", to produce distilled (potable) water. Its productivity depends upon various design, operational, and climatic parameters. Researchers have shown that the productivity of single slope SS varies from 1.0 to 1.5 kg/m^2 day in winter to 2.0–2.5 kg/m^2 day in summer at the water depth 0.01 m [1,3,4]. Tiwari and Tiwari [5] have obtained higher annual yield from the single slope SS

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inclined at 30° among different inclinations angles 15°, 30°, and 45°, and recommended latitude angle as the optimum inclination angle of glass cover. Dev et al. [6] have shown that productivity decreases with an increase in water depth for inverted absorber and single slope SS on the basis of experimental and theoretical observations, and their characteristics. The minimum water depth for inverted absorber and single slope SS has been found to be 0.01 m and maximum water depth has been found to be 0.03 m for these SS under the climatic condition of Muscat, Oman [6].

Solar water heating is also an application of solar energy to provide hot water under natural/forced thermo-siphon effect in the presence of solar radiation and gravity. A solar water heater consists of a number of flat plate collectors (FPC) or evacuated tubular collectors (ETCs) and a water storage tank. A FPC has two major drawbacks such as: (i) convection heat loss from collector plate to glass cover due to the presence of air between them and (ii) the absence of sun tracking due to its fixed orientation. On the other hand, an (ETC) overcomes both these drawbacks by the presence of vacuum in annular space between two concentric glass tubes which eliminates the necessity of sun tracking by its tubular design. Dubey and Tiwari [7] have developed a thermal model as a function of design and climatic parameters for a hybrid glass to glass photovoltaic-thermal (PVT) solar water heating system and validated it by using experimental results taken under the climatic condition of New Delhi, India. Farahat et al. [8] have evaluated the energy efficiency of FPC for different parameters such as incident solar radiation, ambient temperature, optical efficiency, wind velocity and fluid inlet temperature, and found optimum values of each parameter. A maximum energy efficiency of FPC has been found to be 3.9% at a collector plate area of 9.14 m^2 and a mass flow rate of 0.0087 kg/s [8]. Dev and Tiwari [9] have developed characteristic curves for the thermal testing of hybrid PVT active SS on an annual basis. It has been shown that time period 10:00–14:00 h is good to obtain characteristic curves for better accuracy because the variation of solar radiation remains close to the average value of solar radiation. Researchers have also studied the performance of ETC at different parameters [10–15]. Tang et al. [10] have studied the uncertainty in measuring the heat loss coefficient for characteristics of ETC and shown that heat loss is strongly sensitive to ambient temperature. A steady state condition for the measurement of heat loss coefficient has been advised [10]. Kim et al. [11] have found a significant increase in the outlet temperature of water and thermal efficiency (about 16.7%) of ETC by using tracking mechanism in comparison to that of stationary ETC. El-Nashar [12] has shown a decrement in the performance of ETC with increase in dust on outer glass tubes in open environment, i.e. the performance drops by 60% when the transmittance of glass tubes decreases from 0.98 (clean glass) to 0.6 (very dusty glass). The use of concentrating PVT systems integrated with multiple effect evaporation for water desalination has been studied by Mittelman [13]. Budihardjo and Morrison [14] found a correlation for thermal efficiency of water-in-glass-type ETC which has been used in the present analysis of EISS. Recently, Sharma and Diaz [15] have studied the mini-channels design of ETC and reported that reducing the heat path from the absorber surface to working fluid increases the operating temperatures. These findings encourage the use of ETC for water heating and also for assisting other solar energy technologies.

An active SS [16] has been used for enhancing evaporation/condensation or both processes, e.g. (i) FPC integrated with single/double slope SS (Esteban et al. [17], Kumar and Tiwari [18], Dwivedi and Tiwari [19]), (ii) SS integrated with auxiliary heating devices (Nassar et al. [20]), etc. An active SS gets additional thermal energy to increase water temperature by using other devices. Zaki et al. [16] have found 33% more distillate by using collector to preheat the SS's water. Esteban et al. [17] have constructed an assisted solar distiller and shown an increment of 70 and 20% in daily productivity over basin-type distiller (BD) and BD coupled with FPC. Kumar and Tiwari [18] have carried out the lifecycle cost and energy payback analysis of "hybrid PVT active solar distillation system" and shown 3.6 and 4.7 years as cost and energy payback time, respectively [19]. Badran and Al-Tahaineh [21] have shown 36% more productivity for "solar still coupled with flat-plate collector (FPC)" in weather conditions of Amman, Jordan. Tanaka and Nakatake [22] have done the parametric study of "vertical multiple effect diffusion solar still coupled with a heat pipe solar collector" and optimized the angle of solar collector by reporting 9% (in summer) and 17% (in winter) more distillate than obtained from the conventional SS. Nassar et al. [20] have developed a new concentrating solar distiller and found yield more than 20 kg/m^2 day. Tiwari et al. [23] have proposed an active solar distillation system consisting of ETC with SS and found 4 kg/m^2 day of distilled water (theoretically). Recently, Kabeel and Agouz [24] have reviewed the development on SSs by describing its passive and active designs.

In this paper, a design of evacuated tubular collector integrated solar still (EISS) has been evaluated for its annual experimental performance for the year 2008. The proposed design is a modified form of earlier design proposed by Tiwari et al. [23]. Here, the proposed design consists of a water storage tank for getting hot water also along with distilled water. The analysis has been carried out for the composite climate of New Delhi, India.

2. Working principle

A SS filled with brackish water up to a certain height receives solar radiation on its inclined glass cover. The glass cover transmits the solar radiation on water surface which further transmits it on to the basin surface. In this process of transmission of solar radiation, the glass cover and water absorb a small fraction of the received solar radiation depending upon their respective absorptivities. The temperature of basin increases due to absorbed solar radiation. The basin transfers a major amount of absorbed heat to the water to heat it up and a small fraction of the amount of absorbed heat is lost by the side walls and the bottom surface to ambient air. The heated water evaporates in vapour form and comes in contact with the inner surface of the glass cover where it losses absorbed heat to the glass cover in condensation process. The glass cover releases heat (absorbed directly from the solar radiation and hot water) to ambient. The condensed water (purified) trickles down to the trough and is collected in a jar placed outside of the SS system. On the other hand, an ETC works on thermo-siphon process. An ETC consists of a number of two concentric glass tubes with vacuum in their annular space. The inner glass tubes are filled with the water and are blacked at its outside surface with a selective coating to absorb maximum solar radiation. Solar radiation incidents on these tubes and is absorbed by these tubes. These tubes transfer the heat to the water filled inside through its contact peripheral surface. The hot water rises up due to low density whereas the cold water takes the place due to gravity and high density. The hot water is collected in the water tank placed above all the tubes. In the present study, these two technologies (SS and ETC) have been connected in series to construct EISS.

EISS can operate under natural/forced mode depending upon the requirement. The placement of the SS above the height of water storage tank of ETC can provide natural circulation of the water. This arrangement can circulate water from SS to ETC's storage tank and hot water from ETC's storage tank back to the SS. Although, it is obvious that the natural mode of operation is a slow process and can be considered only when the requirement is low with ample amount of time. Hence, the other way i.e. forced mode of operation can give better results at large requirement of hot water quickly without any consideration of placement height of SS or ETC as well.

In the present study, EISS operates under forced mode by using an alternating current (AC) water pump during the integration of SS with ETC. Under this effect, water filled in the SS is pumped to the ETC's storage tank from its inlet to put pressure on the water filled in the ETC's storage tank. Because of this pressure, more heated water comes out from the ETC's storage tank through its outlet into the basin of SS. This results in increasing the temperature difference between water and glass cover for SS that further leads to higher evaporation rate of the water.

3. Experimental setup

A photograph of the experimental setup has been shown in Fig. 1. The setup has been installed at Solar Energy Park, Indian Institute of Technology Delhi (IITD), New Delhi, India (latitude 28°35′ N, longitude 77°12′ E, altitude 216 m from mean sea level) in January 2008. The EISS system consists of an ETC, single slope SS, insulated connecting pipes and an AC pump. Various parameters of EISS system have been given in Table 1.

A single slope SS has been made by using glass-reinforced plastic (GRP) in a box-type structure covered with a simple window glass. An ETC (Sonals limited, Model 470-1500/47-24-SSS) has been used for

Fig. 1. A photograph of EISS.

Table 1
Different parameters of EISS

Specification	Dimensions	Specification	Dimensions
A_b	$1 \times 1\,m^2$	M_{ws}	50 kg
A_g	$1.13 \times 1.08\,m^2$	ρ_w	$1000\,kg/m^3$
A_s	$0.2\,m^2$	d_T	0.5 m
l_g	0.004 m	l_T	1.8 m
H_{south}	0.1 m	d_p	1.27 m
k_g	0.78 W/mK	AC pump rating	100 W Measured: $V_{load} = 220\,V$, $I_{load} = 0.5\,A$
β	30°	v	3.0 m/s
l_b	0.005 m	h_{bw}	$50\,W/m^2$
k_b	0.0351 W/mK	$(UA)_T$	80 W
i	24	$\dot{m}$	0.033 kg/s
l_t	1.4 m	η_o	0.536
d_t	0.15 m	a	$0.824\,W/m^2\,°C$
A_r	$1.7 \times 0.5\,m^2$	α'_b, α'_w, and α'_g	0.7, 0.1, and 0.1, respectively
A_t	$0.33\,m^2$	ε_w and ε_g	0.9 and 0.9
φ	40°	M_{wc}	170 kg

water heating. The ETC have concentric borosilicate glass tubes with vacuum in annular space, four reflector plates, and an insulated water tank. The total amount of the water in EISS has been kept 220 kg (i.e. 170 kg in ETC + 50 kg in SS). The inclination of ETC is 40° (which is not the optimized collector angle for the New Delhi, India). The collector has been used as per the availability of this system in the laboratory. An AC pump has been connected between SS and ETC's water storage tank by using insulated galvanized iron (GI) and plastic pipes as shown in Figs. 1 and 2(a). A gate valve between the outlet of the storage tank and the inlet of the SS has been used to regulate the water flow. The outlet of the storage tank has been kept above the inlet as hot water floats above the cold water because of its low density. A schematic diagram of EISS system has been shown in Fig. 2(b).

Calibrated thermocouples (copper-constantan, T-type) connected with digital temperature indicator (resolution of 0.1°C, measuring range −200–350°C and sensitivity of 43 μV/°C) have been used to record various temperatures. These thermocouples have been placed at various places in the SS to measure the temperature viz: (i) basin temperature—thermocouple placed at the centre of the basin liner, (ii) water temperature—one/two thermocouples dipped into the water to measure the highest value according to water depth, (iii) vapor temperature—thermocouple hanged inside the SS, and (iv) temperatures of inner and outer surface of glass cover—thermocouples placed at the centers of the inner and outer surfaces of the glass. These thermocouples have been fixed on the surfaces by using permanent epoxy glue and protected from the direct solar radiation. An ambient temperature has

Fig. 2(a). A photograph of GI, plastic pipes, and thermocouples of EISS with insulation used to protect the heat loss during operation.

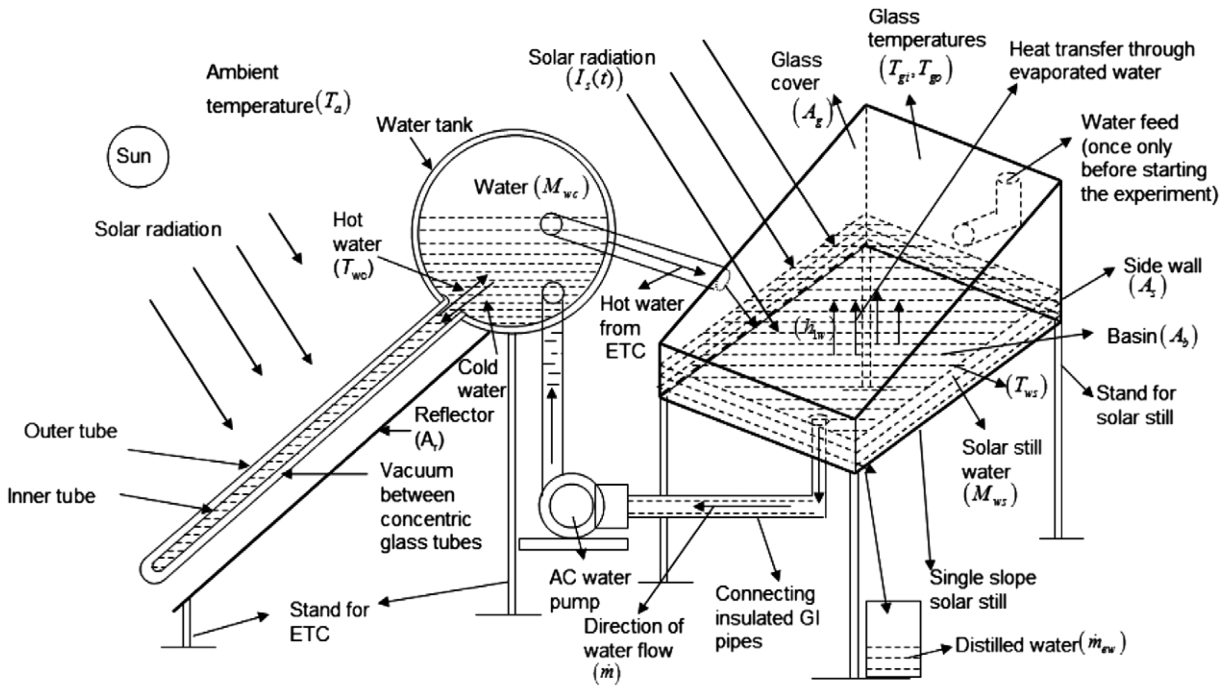

Fig. 2(b). A schematic diagram of EISS.

been recorded by a calibrated mercury thermometer (resolution 1°C and range 0–120°C). The thermometer has been placed under the shade in ambient conditions to measure the ambient temperature without getting affected by direct solar radiation. Solarimeter, Central Electronics Limited (CEL), India from (resolution 20 W/m^2, range 0–1200 W/m^2, model No. 737/8C/243/13) has been used to measure the solar radiation. The distillate output ($\dot{m}_{ew}$) has been measured by a measuring jar (resolution 10 mL and range 0–100 mL). One multimeter has been used for measuring the current and voltage for the AC pump connected between ETC and single slope SS. The least counts of multimeter for measuring the current and voltage are 0.1 A and 0.01 V, respectively. To measure the relative humidity a Lutron-make humidity meter (model HT-3003) of range 0–100 and least count 0.1% have been used.

4. Experimental procedure

A number of experiments have been carried out for a 24 h period starting from 7 am in clear sky condition from January to December 2008. The water depth 0.05 m (i.e. 50 kg of water) has been taken in the SS. The integration of ETC with SS has been made during the time period 11–16 h for the winter season and from 10 to 16 h for the other seasons. This time period has been selected because of various reasons such as: (i) in the winter season, the sun appears in the sky after dispersion of dense fog almost after 9 h, (ii) the time period 9–11 h (i.e. 2 h after the sun's appearance in the sky) has been considered as the heating time of the water filled in ETC under natural thermo-siphon effect and from the point of view of threshold solar radiation in case of winter season [7], (iii) the hot water from the ETC's storage tank can be utilized to increase the temperature of water in SS, (iv) it is the time period of high solar radiation, (v) very low amount of solar radiation after 16 h, (vi) short day length in winter season and, and (vii) to avoid the reverse heat flow i.e. from hot water to ambient through the evacuated tubes after 16 h. But for other months, the "time period of integration" has been advanced by 1 h, i.e. from 10 to 16 h in the absence of fog in the rest of the months excluding winter months for experiments.

For carrying out an experiment, the water has been filled in the ETC and SS. From 7 to 10 h, for summer condition, various temperatures, incident solar radiation, wind velocity, humidity and yield under passive mode of operation of SS have been recorded. From 10 to 16 h, the EISS system works under forced mode. Similar observations have been taken under forced mode. And from 16:00 to 6:00 h, the experimental observations have been recorded under passive mode of operation. Whereas, in winter condition the morning time period of passive mode of operation has been taken from 7:00 to 11:00 h.

5. Thermal model

The energy balance equations for different components of EISS system have been given as follows with assumptions:

(i) the solar distillation unit is vapour leakage proof and is in quasi-steady state,
(ii) the heat capacities of glass, insulation materials, and basin material are negligible,
(iii) temperature-dependant heat transfer coefficients have been considered,
(iv) the ETC has been disconnected from the still during off-sunshine hours,
(v) negligible heat loss from the GI pipe, plastic pipe, and AC pump which have been used to integrate with the ETC with SS,
(vi) the water temperature of ETC is at an average of inlet ($T_{wc\,in}$) and outlet ($T_{wc\,out}$) water temperatures i.e. $T_{wc} = \frac{(T_{wc\,in}+T_{wc\,out})}{2}$.

Following are the energy balance equations for different components:

(a) Inner surface of glass cover:

$$\alpha'_g I_s(t) A_g + h_{1w} A_b (T_{ws} - T_{gi}) = h_{kg} A_g (T_{gi} - T_{go}) \quad (1)$$

(b) Outer surface of glass cover:

$$h_{kg} A_g (T_{gi} - T_{go}) = h_o A_g (T_{go} - T_a) \quad (2)$$

(c) Basin liner:

$$\alpha'_b I_s(t) A_b = h_{bw} A_b (T_b - T_{ws}) + h_{ba} A_b (T_b - T_a) \quad (3)$$

(d) Water mass of the ETC

Heat gain by the water mass of the ETC,

$$\dot{q}_u = \eta_{ic} A_t N I_c(t) = A_t N I_c(t) \left\{ \eta_o - a\frac{(T_{wc} - T_a)}{I_c(t)} \right\} \quad (4)$$

where, efficiency of the ETC: $\eta_{ic} = \eta_o - a\frac{(T_{wc}-T_a)}{I_c(t)}$, obtained from equation given by Budihardjo and Morrison [14] $\{\eta_{ic} = \eta_o - a\frac{(T_{wc}-T_a)}{I_c(t)} - b\frac{(T_{wc}-T_a)^2}{I_c(t)}\}$ after neglecting the term $b\frac{(T_{wc}-T_a)^2}{I_c(t)}$.

Using Eq. (4), the energy balance for water mass of the ETC can be written,

$$A_t N I_c(t)\eta_o - a A_t N (T_{wc} - T_a) = (M_{wc}C_w)\frac{dT_{wc}}{dt} + (UA)_T (T_{wc} - T_a) + (\dot{m}C_w)(T_{wc} - T_{ws}) \quad (5)$$

where, $(M_{wc}C_w)\frac{dT_{wc}}{dt}$ is heat stored in the water mass of ETC.

(e) Water mass of the SS:

$$\alpha'_w I_s(t) A_b + h_{bw} A_b (T_b - T_{ws}) + (\dot{m}C_w)(T_{wc} - T_{ws}) = M_{ws}C_w\frac{dT_{ws}}{dt} + h_{1w} A_b (T_{ws} - T_{gi}) + h_{sw} A_{sw} (T_{ws} - T_a) \quad (6)$$

Solving the above Eqs. (1)–(6), following expressions of various temperature:

$$\text{Outer surface of glass cover}: T_{go} = \frac{h_{kg} T_{gi} + h_o T_a}{h_{kg} + h_o} \quad (7)$$

Inner surface of glass cover :

$$T_{gi} = \frac{\alpha'_g I_s(t) A_g + h_{1w} A_b T_{ws} + h_{go} A_g T_a}{h_{1w} A_b + h_{go} A_g} \quad (8)$$

$$\text{Basin liner}: T_b = \frac{\alpha'_b I_s(t) + h_{bw} T_{ws} + h_{ba} T_a}{h_{bw} + h_{ba}} \quad (9)$$

Eq. (5) can be rewritten for water temperature in ETC by using Eqs. (7)–(9):

$$\frac{dT_{wc}}{dt} + a_1 T_{wc} + b_1 T_{ws} = (g_1(t) \quad (10)$$

Similarly, Eq. (6) can be rewritten for water temperature in SS by using Eqs. (7)–(9):

$$\frac{dT_{ws}}{dt} + a_2 T_{wc} + b_2 T_{ws} = g_2(t) \quad (11)$$

Adding Eqs. (10) and (11)1011 (after multiplying Eq. (11) by β), and solving (after multiplying e^{ct}) further to get

$$\frac{d}{dt}(T_{wc} + \beta T_{ws})e^{ct} = \{g_1(t) + \beta g_2(t)\}e^{ct} \quad (12)$$

where, $(a_1 + \beta a_2) = c$ and $(b_1 + \beta b_2) = \beta c$ and $\beta = \frac{-(a_1-b_2)\pm\sqrt{(a_1-b_2)^2 - 4a_2(-b_1)}}{2a_2}$ (which results two roots of the equation i.e. β^+ and β^- to give two values of c^+ and c^-, respectively).

Further, some assumptions have been made for solving Eq. (12),

(i) small time interval dt(0
(ii) function $f(t)$ is constant, i.e. $f(t) = \overline{f(t)}$ for small interval dt,
(iii) "a" is a constant during the same time interval.

(iv) initial values of water and condensing cover temperatures have been used to determine the value of internal heat transfer coefficients.

From Eq. (12), the following equations can be obtained,

$$T_{wc} + \beta^+ T_{ws} = \left\{ \frac{\overline{g_1(t)} + \beta^+ \overline{g_2(t)}}{c^+} \right\} (1 - e^{-c^+ t}) + (T_{wco} + \beta^+ T_{wso})\, e^{-c^+ t} \quad (13)$$

and

$$T_{wc} + \beta^- T_{ws} = \left\{ \frac{\overline{g_1(t)} + \beta^- \overline{g_2(t)}}{c^-} \right\} (1 - e^{-c^- t}) + (T_{wco} + \beta^- T_{wso}) e^{-c^- t} \quad (14)$$

Multiplying Eq. (13) by β^-,

$$\beta^- T_{wc} + \beta^+ \beta^- T_{ws} = \beta^- \left\{ \frac{\overline{g_1(t)} + \beta^+ \overline{g_2(t)}}{c^+} \right\} (1 - e^{-c^+ t}) + \beta^- \, (T_{wco} + \beta^+ T_{wso})\, e^{-c^+ t} \quad (15)$$

and multiplying Eq. (14) by β^+,

$$\beta^+ T_{wc} + \beta^+ \beta^- T_{ws} = \beta^+ \left\{ \frac{\overline{g_1(t)} + \beta^- \overline{g_2(t)}}{c^-} \right\} (1 - e^{-c^- t}) + \beta^+ (T_{wco} + \beta^- T_{wso})\, e^{-c^- t} \quad (16)$$

Solving Eqs. (15) and (16), the following equations for T_{ws} and T_{wc} have been obtained,

$$T_{ws} = \frac{1}{(\beta^+ - \beta^-)} \left[\overline{g_1(t)} \left\{ \frac{(1 - e^{-c^+ t})}{c^+} - \frac{(1 - e^{-c^- t})}{c^-} \right\} + \overline{g_2(t)} \left\{ \frac{\beta^+ (1 - e^{-c^+ t})}{c^+} - \frac{\beta^- (1 - e^{-c^- t})}{c^-} \right\} + T_{wco} (e^{-c^+ t} - e^{-c^- t}) + T_{wso} (\beta^+ e^{-c^+ t} - \beta^- e^{-c^- t}) \right] \quad (17)$$

and

$$T_{wc} = \frac{1}{(\beta^+ - \beta^-)} \left[\overline{g_1(t)} \left\{ \frac{\beta^+ (1 - e^{-c^- t})}{c^-} - \frac{\beta^- (1 - e^{-c^+ t})}{c^+} \right\} + \beta^+ \beta^- \overline{g_2(t)} \left\{ \frac{(1 - e^{-c^- t})}{c^-} - \frac{(1 - e^{-c^+ t})}{c^+} \right\} + T_{wco} (\beta^+ e^{-c^- t} - \beta^- e^{-c^+ t}) + \beta^+ \beta^- T_{wso} (e^{-c^- t} - e^{-c^+ t}) \right] \quad (18)$$

The intermediate expressions including Dunkle's correlations for the study have been given in Appendix A.

Further, the efficiency of the active SS can be given as,

$$\eta_{is} = \frac{\dot{m}_{ew} L}{\dot{q}_u + I_s(t) A_g} \quad (19)$$

the expression of overall thermal efficiency of EISS system can be given as,

$$\eta_{io} = \eta_{ic}\, \eta_{is} \quad (20)$$

6. Results and discussion

Experimental results for EISS for all months of the year 2008 have been analyzed. Some of the experimental results, for the winter and summer seasons of New Delhi have been given. The hourly measured parameters such as solar intensity, relative humidity, wind speed, various temperatures (ambient, basin, water, inner and outer surface of condensing glass cover) and yields for EISS observed for clear days in winter (January and February) and summer (May and June) months of the year 2008 have been shown in Tables 2–5. Similar observations have also been recorded for other months of the year 2008. The values of current and voltage across the AC pump have been measured to be $I_{load} = 0.5$ A and $V_{load} = 220$ V, respectively.

From Table 2, it has been observed that values of maximum solar radiations incident on SS and collector have been recorded as 820 and 840 W/m^2 at 12:00 h, respectively on 23 January 2008 (Fig. 2(c)). The values of maximum ambient and water temperatures have been found to be 21 and 56.8°C both at 15:00 h respectively. It is obviously due to the emission of long wave radiation from the earth surface to the sky, after absorption of short wave solar radiation in the case of ambient temperature. Whereas, in the case of water and basin temperatures, heat capacities of water and basin are the reasons for time lag in solar radiation and temperatures. The inner surface of glass cover temperature has been found to be maximum at 44.0°C at 12:00 h. And the maximum yield has been obtained 0.275 kg/m^2 h at 16:00 h (Fig. 2(d)). These temperatures decrease at a rapid rate during off-sunshine hours due to the absence of solar radiation. The total yield has been found to be 1.885 kg/m^2 day at a water depth, 0.05 m. It is to be noticed that this yield has been obtained when the EISS system have total quantity of water 220 kg. Observations for other months of the year 2008 have been found similar to the observation

Table 2
Hourly observations of EISS for the winter month of January 2008 at New Delhi, India

23 January 2008	I_g (t)	I_d (t)	I_s (t)	I_c (t)	T_a	T_w	T_b	T_{gi}	T_{go}	ρ (%)	v (m/s)	$\dot{m}_{ew}$ (kg/m^2 h)
Time	(W/m^2)				(°C)							
7:00	0	0	0	0	8.0	6.2	6.2	7.2	6.2	50	0.2	0.000
8:00	0	20	40	20	8.5	7.2	7.2	9.7	8.7	49.0	0.2	0.005
9:00	120	40	140	60	10.0	15.6	17.6	16.4	14.4	46.0	0.4	0.010
10:00	340	80	630	670	13.5	31.8	34.8	33.8	30.8	42.0	0.4	0.030
11:00	440	80	720	770	17.0	52.9	56.4	43.6	40.1	40.0	0.5	0.038
12:00	590	60	820	840	19.0	49.3	52.3	44.0	39.0	42.5	0.9	0.122
13:00	530	60	770	770	20.0	51.3	53.8	43.2	40.7	38.0	1.5	0.160
14:00	500	70	630	630	21.0	54.1	59.1	42.9	37.9	37.1	0.8	0.200
15:00	270	70	420	370	21.0	56.8	61.3	41.1	36.6	37.3	0.8	0.235
16:00	140	40	220	220	19.0	52.3	55.3	39.5	36.5	37.0	0.3	0.275
17:00	100	20	30	0	19.0	46.9	49.9	35.1	32.1	37.2	0.1	0.230
18:00	0	0	0	0	17.0	35.5	37.5	29.8	26.3	37.0	0.1	0.153
19:00	0	0	0	0	15.0	31.3	34.8	26.4	22.9	36.7	0.1	0.097
20:00	0	0	0	0	13.0	27.4	29.4	21.7	19.7	38.0	0.1	0.070
21:00	0	0	0	0	11.0	21.3	22.8	18.1	16.6	40.0	0.1	0.060
22:00	0	0	0	0	10.0	18.7	19.5	15.6	14.8	40.2	0.1	0.038
23:00	0	0	0	0	9.0	15.3	16.3	12.1	11.1	41.5	0.1	0.034
0:00	0	0	0	0	8.4	12.7	13.5	9.9	9.1	43.8	0.1	0.027
1:00	0	0	0	0	8.0	12.0	12.9	9.1	8.2	43.6	0.1	0.024
2:00	0	0	0	0	7.0	9.6	10.5	8.8	7.9	43.2	0.1	0.020
3:00	0	0	0	0	7.0	9.0	10.0	8.6	7.6	42.7	0.1	0.017
4:00	0	0	0	0	6.5	8.2	9.2	8.0	7.0	42.8	0.1	0.015
5:00	0	0	0	0	6.0	7.0	8.0	7.5	6.5	42.2	0.1	0.013
6:00	0	0	0	0	6.0	6.2	5.2	7.0	6.0	42.1	0.1	0.012
Total	3,030	540	4,420	4,350								1.885

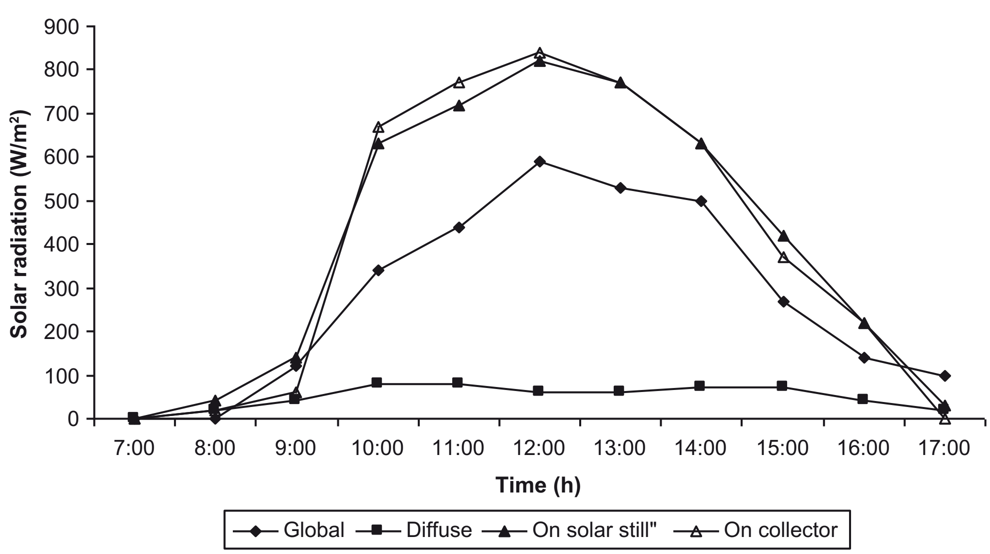

Fig. 2(c). Hourly variation of solar radiation measured on 23 January 2008.

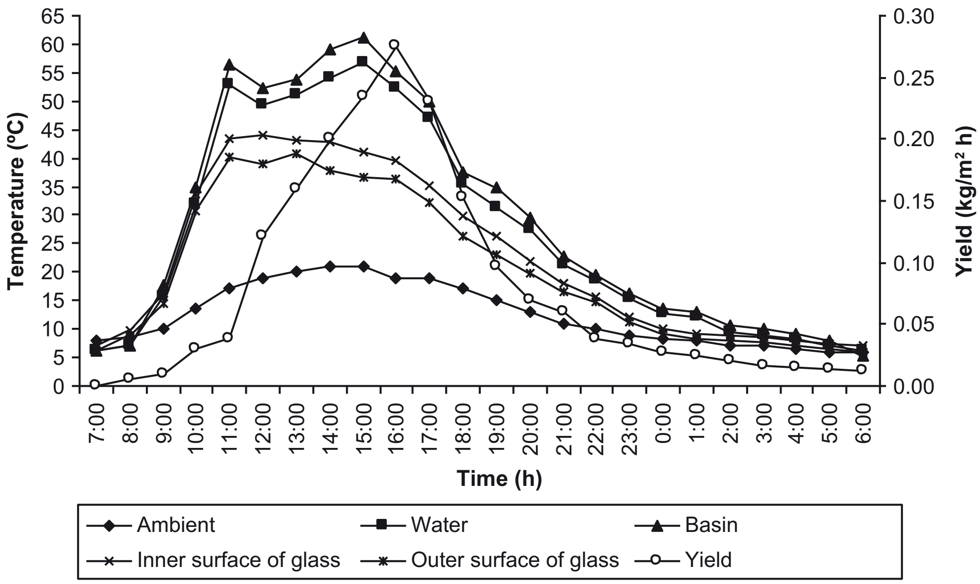

Fig. 2(d). Hourly variation of various temperatures and yield measured on 23 January 2008.

Table 3
Hourly observations of EISS for the winter month of February 2008 at New Delhi, India

27 February 2008	I_g (t)	I_d (t)	I_s (t)	I_c (t)	T_a	T_w	T_b	T_{gi}	T_{go}	ρ (%)	v (m/s)	$\dot{m}_{ew}$ (kg/m^2 h)
Time	(W/m^2)				(°C)							
7:00	0	0	0	0	8.0	8.0	8.0	8.5	7.5	50.0	0.1	0.000
8:00	0	20	40	40	8.5	9.0	9.3	11.0	10.0	49.0	0.2	0.006
9:00	170	70	300	300	14.0	19.1	19.2	23.6	19.9	42.3	0.2	0.015
10:00	400	80	640	640	19.0	32.7	33.1	38.3	35.3	40.8	0.7	0.036
11:00	520	90	740	740	21.0	44.9	46.4	46.4	44.9	35.2	0.5	0.047
12:00	580	140	740	740	23.6	49.2	50.7	50.2	46.2	30.8	0.9	0.150
13:00	620	120	800	800	24.0	50.1	51.6	49.4	45.2	27.1	0.8	0.160
14:00	580	120	690	690	25.0	52.4	56.9	50.7	46.2	28.3	0.7	0.210
15:00	440	100	490	490	24.8	54.6	57.6	47.4	44.4	29.3	0.4	0.253
16:00	280	80	280	280	23.5	59.7	62.2	46.9	44.4	27.5	0.5	0.265
17:00	10	10	50	50	22.0	53.7	55.7	40.9	38.9	27.0	0.4	0.240
18:00	0	0	0	0	21.0	43.0	45.0	35.0	32.7	27.1	0.4	0.155
19:00	0	0	0	0	20.0	36.3	36.9	29.8	27.9	36.7	0.1	0.120
20:00	0	0	0	0	19.5	32.4	32.9	26.9	25.4	38.0	0.1	0.075
21:00	0	0	0	0	19.0	27.5	27.8	22.0	21.0	40.0	0.1	0.070
22:00	0	0	0	0	18.0	25.3	25.6	21.3	20.3	40.2	0.1	0.065
23:00	0	0	0	0	18.0	23.9	23.9	20.7	19.7	41.5	0.1	0.056
0:00	0	0	0	0	17.0	22.0	22.0	19.0	18.3	43.8	0.1	0.046
1:00	0	0	0	0	16.0	20.3	20.3	17.8	17.0	43.6	0.1	0.035
2:00	0	0	0	0	16.0	18.9	18.9	16.3	15.8	43.2	0.0	0.032
3:00	0	0	0	0	15.0	16.3	16.3	15.5	14.5	42.7	0.1	0.028
4:00	0	0	0	0	14.5	16.0	16.0	14.6	13.6	42.8	0.1	0.026
5:00	0	0	0	0	13.0	15.2	15.2	13.1	12.4	42.2	0.0	0.021
6:00	0	0	0	0	12.0	14.1	13.1	11.8	11.3	42.1	0.1	0.018
Total	3,600	830	4,770	4,770								2.129

Table 4
Hourly observations of EISS for the summer month of May 2008 at New Delhi, India

28 May 2008	I_g (t)	I_d (t)	I_s (t)	I_c (t)	T_a	T_w	T_b	T_{gi}	T_{go}	ρ (%)	v (m/s)	$\dot{m}_{ew}$ (kg/m^2 h)
Time	(W/m^2)				(°C)							
7:00	210	100	70	0	26.0	25.0	25.0	24.0	26.0	33.0	0.1	0.000
8:00	280	140	420	400	28.0	40.8	41.2	38.1	36.1	32.0	0.2	0.008
9:00	320	100	340	310	30.0	42.8	43.1	34.8	32.8	32.0	0.2	0.025
10:00	460	150	480	460	33.0	47.5	48.0	45.5	41.5	35.0	0.2	0.030
11:00	610	190	610	560	35.0	65.5	66.0	65.3	59.3	38.0	0.2	0.105
12:00	640	170	600	550	37.0	72.1	72.6	74.9	69.9	42.0	0.4	0.190
13:00	660	180	580	540	37.0	72.7	77.7	78.0	69.6	41.0	0.2	0.300
14:00	620	160	480	420	38.0	88.8	93.6	81.0	76.2	40.0	0.4	0.345
15:00	510	140	360	300	39.0	88.3	92.2	81.2	77.3	40.0	0.3	0.375
16:00	300	120	140	100	38.0	86.5	91.5	78.5	73.5	38.0	0.0	0.410
17:00	140	100	80	30	37.0	69.4	73.4	76.6	72.6	37.0	0.0	0.400
18:00	0	0	0	0	36.0	58.8	61.8	67.9	64.9	36.0	0.0	0.316
19:00	0	0	0	0	36.0	53.0	53.7	60.2	57.4	35.0	0.4	0.186
20:00	0	0	0	0	35.0	49.0	49.7	53.0	50.0	38.0	0.6	0.155
21:00	0	0	0	0	34.0	45.0	47.0	46.1	44.1	41.0	0.8	0.130
22:00	0	0	0	0	31.0	45.3	47.1	46.1	44.3	44.0	1.3	0.090
23:00	0	0	0	0	30.0	40.1	40.4	41.2	39.7	39.0	1.3	0.075
0:00	0	0	0	0	28.0	38.1	38.4	38.7	37.1	40.0	1.6	0.053
1:00	0	0	0	0	27.5	36.9	37.2	37.0	35.5	43.0	1.6	0.032
2:00	0	0	0	0	27.0	35.7	36.0	35.7	34.7	48.0	1.6	0.026
3:00	0	0	0	0	26.0	34.0	34.0	34.7	33.4	47.0	1.6	0.023
4:00	0	0	0	0	25.6	33.0	33.0	33.2	32.3	48.0	1.2	0.021
5:00	0	0	0	0	25.0	32.2	32.2	32.2	31.5	48.0	1.6	0.018
6:00	0	0	0	0	26.0	32.0	32.0	32.0	31.0	48.0	1.0	0.015
Total	4,750	1,550	4,160	3,670								3.328

shown in Figs. 2(c) and 2(d). Some of these observations have been given in Tabular form in Tables 3–5.

Observations for another winter month on 27 February 2008 have been given in Table 3. The values of maximum solar radiations incident on SS and EFC have been found equal, i.e. 800 W/m^2 at 13:00 h. The values of maximum ambient and water temperatures have been found to be 25°C at 14:00 h and 59.7°C at 16:00 h, respectively. The inner surface of glass cover temperature has been found maximum 50.7°C at 14:00 h. The maximum yield has been obtained as 0.265 kg/m^2 h at 16:00 h whereas the total yield has been collected as 2.129 kg/m^2 day.

Table 4 shows the hourly observations measured on 28 May 2008. It has been observed that the maximum solar radiations incident on SS and ETC have found 610 and 560 W/m^2 at 11:00 h, respectively. From the same tables, it has been observed that the maximum basin and water temperatures are 93.6 and 88.8°C at 14:00 h respectively. The inner surface of glass cover temperatures has been found maximum at 81.2°C at 15:00 h. The maximum yield has been found to be 0.410 kg/m^2 h at 16:00 h. And the total yield has been found to be 3.328 kg/m^2 day.

Similarly, Table 5 shows the hourly observations measured for another summer month on 4 June 2008. It has been observed that the maximum solar radiations incident on SS and ETC are found to be 680 and 650 W/m^2 at 12:00 h respectively. It has been observed that the maximum basin and water temperatures are 94.0 and 90.0°C respectively both at 15:00 h. And inner surface of glass cover temperature has been found as 70.3°C at 12:00 h. The maximum yield has been 0.390 kg/m^2 h at 16:00 h (Table 5). Daily yield has been found to be 3.196 kg/m^2 on a day of the month June 2008. From Tables 2–5, it has been observed that the daily yields of different months from EISS are much higher in comparison to yields obtained from conventional single slope SS by various researchers [3,5,6].

Values of total solar radiations observed on the SS and ETC have been observed as 4420 and 4350 W/m^2,

Table 5
Hourly observations of EISS for the summer month of June 2008 at New Delhi, India

4 June 2008	I_g (t)	I_d (t)	I_s (t)	I_c (t)	T_a	T_w	T_b	T_{gi}	T_{go}	ρ (%)	v (m/s)	$\dot{m}_{ew}$ (kg/m^2 h)
Time	(W/m^2)				(°C)							
7:00	140	80	80	0	30.0	30.0	30.0	29.2	31.0	34.0	0.4	0.000
8:00	280	120	290	280	32.0	35.0	35.3	37.4	36.4	32.3	0.8	0.011
9:00	380	140	380	370	33.0	42.0	42.5	47.2	44.9	31.8	1.9	0.030
10:00	560	180	560	540	35.0	64.2	64.9	51.6	48.2	31.5	2.3	0.030
11:00	650	180	650	620	36.0	83.1	83.8	61.1	54.1	29.9	1.8	0.096
12:00	730	200	680	650	38.0	76.1	76.8	66.9	62.2	28.4	1.5	0.170
13:00	660	220	580	540	39.0	71.0	75.5	70.3	57.9	28.1	1.0	0.300
14:00	560	260	460	400	39.0	82.6	87.1	64.7	60.2	30.5	2.5	0.345
15:00	450	220	320	280	40.0	90.8	94.0	63.9	60.7	27.8	1.8	0.360
16:00	180	140	120	100	39.0	86.8	86.3	60.0	53.4	26.4	1.2	0.390
17:00	140	80	80	50	39.0	71.0	70.5	58.6	53.6	26.0	1.8	0.320
18:00	0	0	0	0	38.0	60.3	62.8	49.2	46.3	25.0	2.3	0.290
19:00	0	0	0	0	37.0	50.2	50.9	46.5	43.9	24.0	1.9	0.176
20:00	0	0	0	0	36.0	46.8	47.4	43.5	41.5	23.0	0.2	0.150
21:00	0	0	0	0	34.0	44.2	44.8	41.7	39.6	21.0	0.0	0.135
22:00	0	0	0	0	34.0	41.8	42.5	39.8	38.1	22.0	0.5	0.105
23:00	0	0	0	0	33.0	40.3	41.0	39.0	37.8	24.0	0.1	0.080
0:00	0	0	0	0	33.0	40.0	40.7	39.1	37.7	27.0	0.1	0.059
1:00	0	0	0	0	32.0	39.0	39.6	38.2	36.7	28.0	0.1	0.036
2:00	0	0	0	0	32.0	38.1	39.1	37.0	36.0	29.0	0.2	0.029
3:00	0	0	0	0	31.0	37.0	37.0	36.5	35.5	31.0	0.2	0.025
4:00	0	0	0	0	31.0	36.9	36.9	35.9	35.0	31.0	0.1	0.022
5:00	0	0	0	0	30.0	36.0	36.0	36.4	34.7	32.0	0.1	0.020
6:00	0	0	0	0	30.0	36.2	36.2	34.8	33.6	34.0	0.1	0.017
Total	4,730	1,820	4,200	3,830								3.196

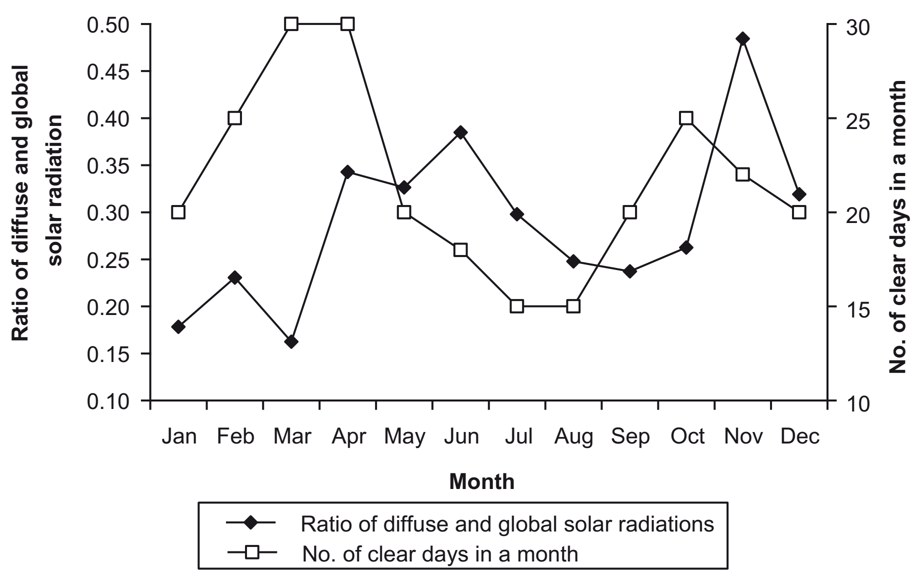

Fig. 3. Monthly variations of ratio of diffuse and global solar radiations, and number of clear days in the respective month for the composite climate of New Delhi, observed in the year 2008.

Table 6
Monthly variation of water temperature in ETC for the year 2008 at New Delhi, India

Months	January	February	March	April	May	June	July	August	September	October	November	December	$\bar{T}_{wc}$
	(°C)												
At 16:00 O'clock	52.3	59.7	79.0	77.6	86.5	86.8	72.3	80.0	82.7	76.8	50.0	48.0	71.0
At 5:00 O'clock (next day morning)	42	45	52	53	64	62	53	54	56	51	42	40	51.2
Maximum temperature during day	56.8 (at 15:00)	59.7 (at 16:00)	79 (at 16:00)	77.6 (at 16.:00)	88.8 (at 14:00)	90.8 (at 15:00)	79 (at 14:00)	80 (at 16:00)	82.7 (at 16:00)	80.4 (at 14:00)	59.9 (at 13:00)	61 (at 14:00)	74.6

respectively in January 2008, whereas in the month of May 2008, these values have been observed to be less as 4160 and 3670 W/m^2. It is due to inclination angles of ETC and SS, and change in declination angle of the sun. The values of total yield have been observed higher in summer months because of low temperature difference between water and ambient, which reduces the heat loss in comparison to winter months (Tables 2–5). In other words, the ambient temperature remains low in winter months due to which heat losses from basin bottom and side walls remain high and result in low yield. But in the case of summer months, both water and ambient temperatures posse high values with their low temperature difference, which reduces the heat losses to ambient.

The variations in values of different temperatures and yield are subjected to the position of sun in the sky and solar intensity (i.e. ratio of diffuse and global solar radiation). As shown in Fig. 3, the minimum and maximum ratios of diffuse and global solar radiations have been found to be 0.18 (23 January 2008) and 0.48 (21 November 2008) respectively, for the year 2008. The number of clear days for respective months (estimated by Kumar [25]) has also been shown in the same figure. It has been observed that foggy and hazy conditions in winter as well as summer months, respectively, lead to higher values of ratios of diffuse and global solar radiations e.g. 0.39 (in June) and 0.48 (in November).

Table 6 shows the monthly variation of water temperature in EISS system at 16:00 h (time of disintegration of ETC with SS) and at 5:00 h of next day. It also shows the maximum water temperature achieved in ETC during the day at different times in each month. It has been observed that the maximum water temperature has been found to be 90.8°C at 15:00 h in the month of June 2008. Similarly, the minimum water temperature has also been found 56.8°C at 15:00 h in the month of January 2008. The average water temperature in ETC over the year has been found as 71.0°C at the time of disintegration. And similarly, it has been found to be 51.2°C at 5:00 h next day morning whereas, the average maximum water temperature achieved by the ETC for the year has been found to be 74.6°C.

Fig. 4 shows the monthly variation of decrement in water temperature of ETC after disintegration time (i.e. 16:00 h) to 5:00 h of the next day. In other words, decrease in water temperature also shows the heat loss occurred from hot water in the ETC to ambient in different months. The heat loss increases with increase in temperature difference between water and ambient especially during night after the disintegration of ETC from SS. The maximum and minimum values of decrement in temperature of water in ETC have been

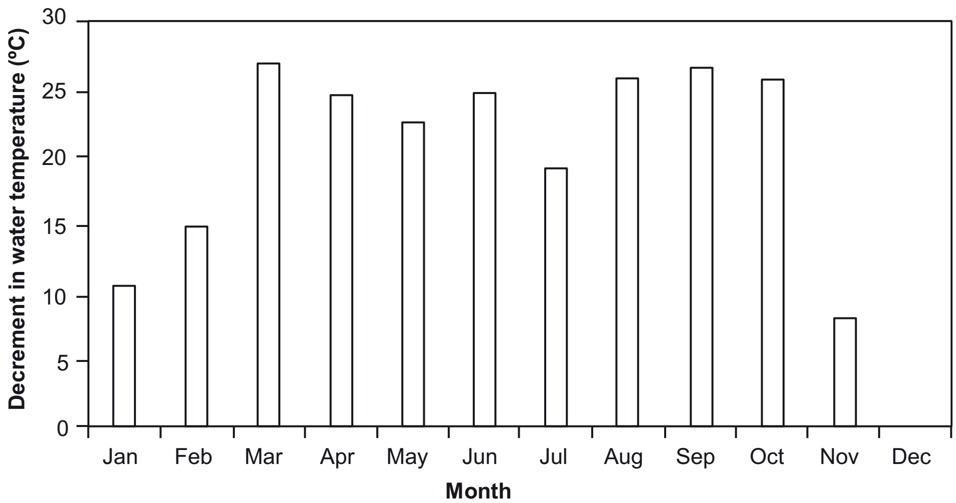

Fig. 4. Monthly variation of decrement in water temperature of ETC in EISS system from 16:00 to 5:00 h observed in the year 2008.

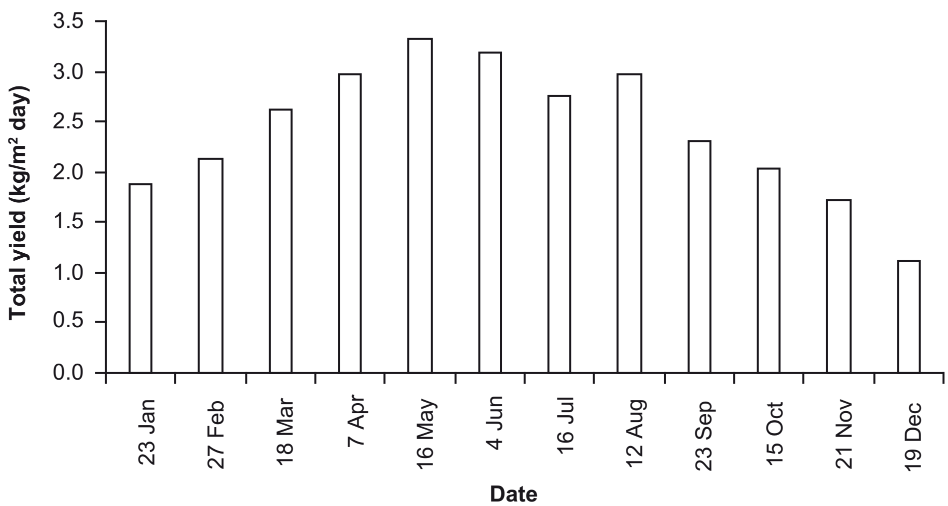

Fig. 5. Monthly variation of total daily yield obtained from EISS for the year 2008.

found to be 27°C in the month of March 2008 and 8°C in the month of December 2008, respectively. Higher water temperatures can be achieved in summer months due to reduced rate of heat loss.

Fig. 5 shows the monthly variation of the total yield obtained from the EISS in 24 h. It has been observed that the maximum and minimum amounts of yields have been obtained as 3.328 kg/m^2 day (16 May 2008) and 1.114 kg/m^2 day (19 December 2008), respectively. The respective dates on which these experiments have been conducted are also shown in the same figure. The average yield per day on annual basis from the EISS can be calculated as 2.42 kg/m^2 day. Hence, net amount of annual yield produced by EISS system can be found approximately to be 630 kg/m^2 year when total number of clear days has been taken as 260.

Similarly, Fig. 6 shows the monthly variation of total amounts of yields obtained from SS only in 24 h at water depth 0.05 m in months from April 2006 to March 2007 [25]. The respective dates of experiments conducted are given in the same figure. This experimental data have been used for a comparative study of EISS and SS. It has been observed that the maximum and minimum amounts of yields are 2.239 (24 April 2006) and 0.597 kg/m^2 day (18 December 2006) respectively. The average yield per day on annual basis from the SS can be calculated

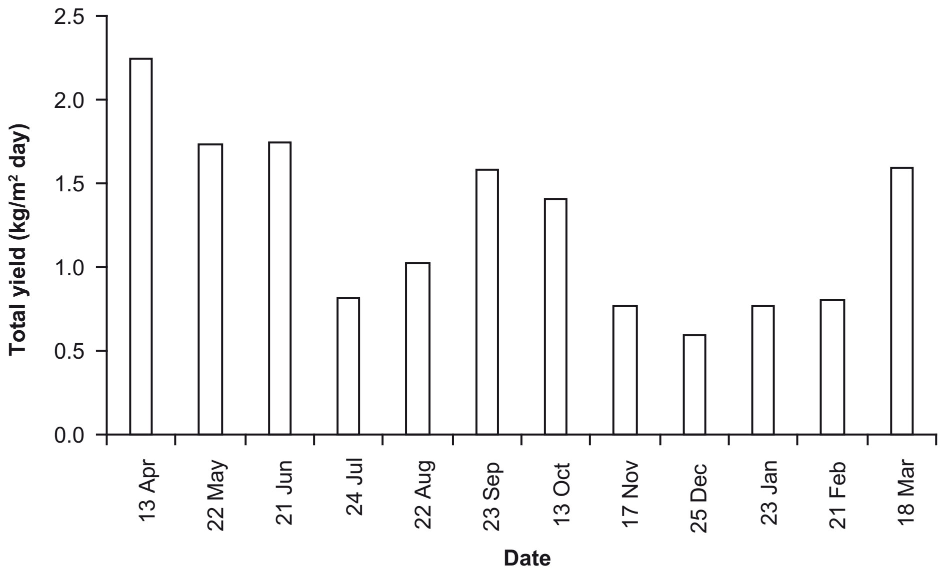

Fig. 6. Monthly variation of amounts of yields obtained from SS for the year April 2006–March 2007 [25].

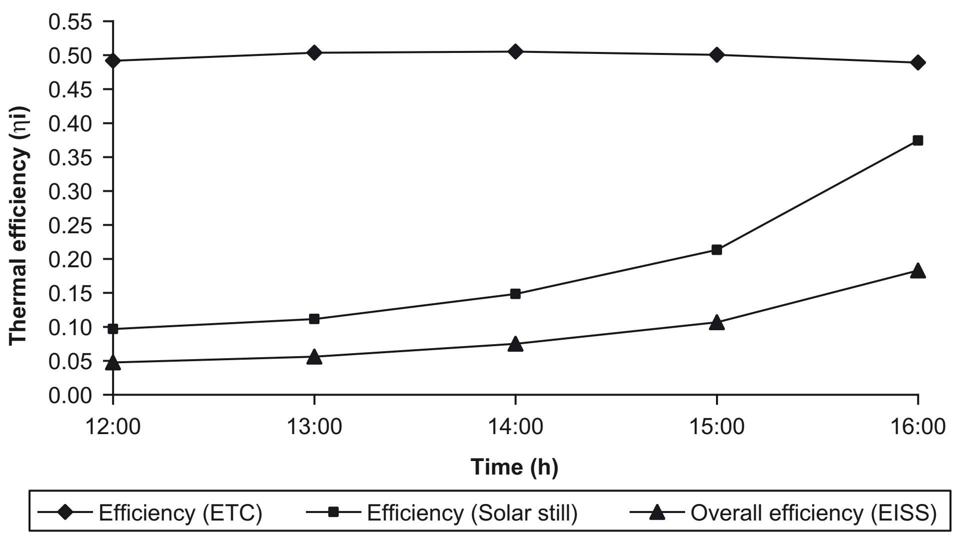

Fig. 7. Hourly variations of thermal efficiencies for a winter month (23 January 2008).

as 1.26 kg/m^2 day. The net amount of annual yield produced by SS system can be around 327 kg/m^2 which is 92.6% lower than that of EISS for annual average yield.

An uncertainty analysis of the measured annual data (January–December, 2008) has also been carried out for various temperatures (Eq. (21)). Mathematical expression for evaluating the internal uncertainty [26] has been given below:

$$\% \text{ Uncertainity} = \frac{U_{\mathrm{I}}}{\bar{X}} \times 100 \tag{21}$$

where, $U_{\mathrm{I}} = \frac{\sqrt{\sum \sigma_i^2}}{N}$ and $\sigma_i = \sqrt{\frac{\sum (X_i - \bar{X})}{N}}$. σ_i is the standard deviation of the ith observation and N is the total number of observations.

The uncertainty for water, inner, and outer surfaces of glass cover and basin temperatures have been found to be 16.1, 16.2, 17.3, and 16.2%, respectively. Similarly, the annual average standard deviation for water, inner and outer surfaces of glass cover and basin temperatures have been found to be 21.6, 19.2, 18.7, and 22.6°C respectively.

Fig. 7 shows the hourly variations of thermal efficiencies for a winter month (only for integration time

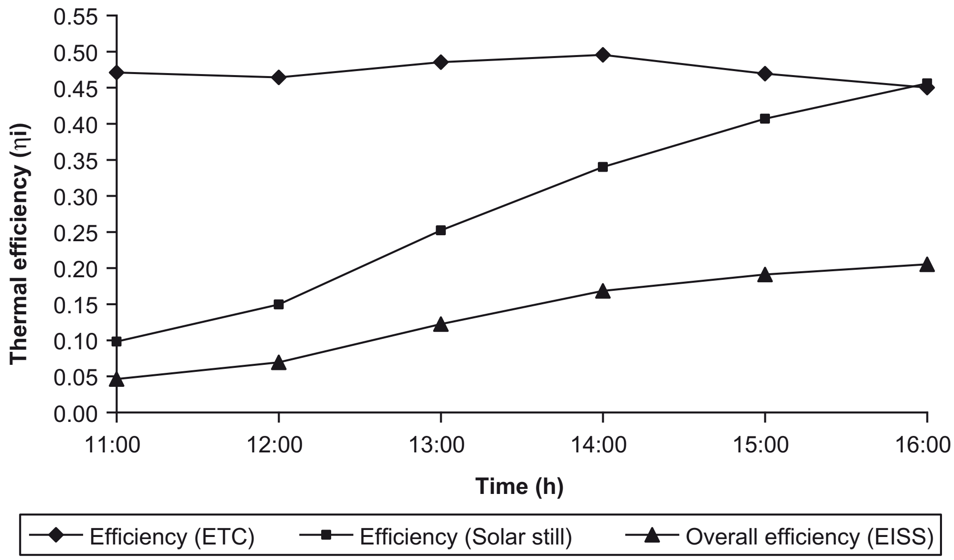

Fig. 8. Hourly variations of thermal efficiencies for a summer month (4 June 2008).

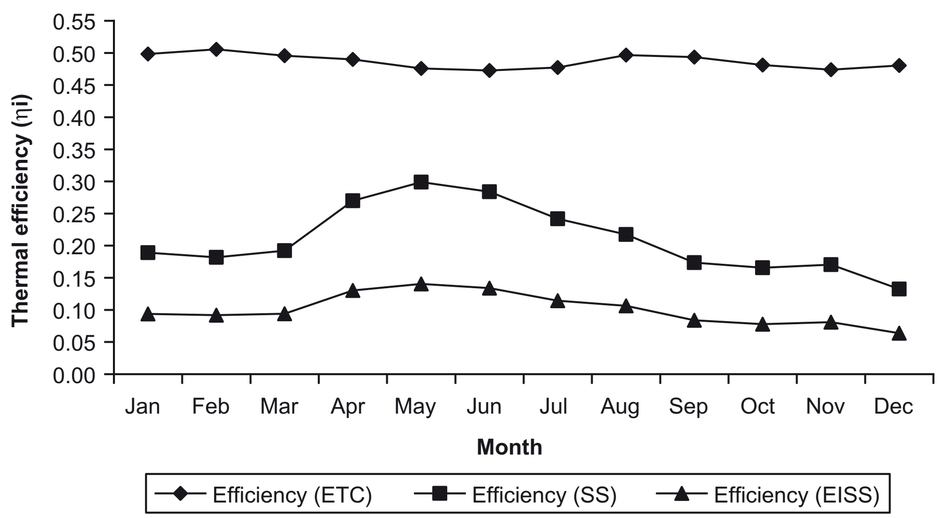

Fig. 9. Monthly variations of daily average thermal efficiencies of ETC, SS, and EISS for the year 2008.

of ETC with SS) such as: efficiency of ETC, efficiency of SS and overall efficiency of the EISS system. These thermal efficiencies have been obtained by using Eqs. (4), (19), and (20). The starting time period has been taken as 12:00 h because at the time of integration, mixing of water (high temperature water from ETC and low temperature water in SS are mixed together) takes place to attain a uniform water temperature. This process takes time for proper mixing of water. The maximum overall thermal efficiency of the system has been found to be 18.3% at 16:00 h. Similar observations have been obtained for other months also as given for 4 June 2008 in Fig. 8. It is to be noted that for other months except from winter months, the integration of ETC with SS has been done at 10:00 h. Hence in Fig. 8, efficiency curves have been plotted starting from 11:00 to 16:00 h. The maximum overall thermal efficiency of EISS has been found to be 20.5% at 16:00 h for a clear day in the month of June (summer month).

The maximum and minimum values of overall efficiencies of EISS have been found to be 30.1% (in a summer month, 4 June 2008, at 16:00 h) and 2.0% (in a winter month, 19 December 2008, at 12:00 h).

Table 7
Total energy consumed by the AC pump and cost incurred during the operation of EISS in the year 2008

V_{load}	I_{load}	Power factor	Energy consumed in an hour	Energy consumed in one day		Energy consumed different months		Total energy consumed in an year	Total energy consumed in an year	Rate of electricity	Total cost of the electricity consumed in a year
(V)	(A)		(Wh)								
				For winter	For other season	For whole winter	For other season	For year 2008	(kWh)		
220	0.5	0.8	88	440	528	53,240	1,29,360	1,82,600	182.6	Rs. 4.65/- or US $ 0.097	Rs. 849.09 ≈ 850/- or US $ 17.68

Fig. 9 shows the monthly variations of daily average thermal efficiencies of ETC, SS, and EISS. The maximum daily average thermal efficiencies of ETC, SS, and EISS have been observed as 50.6%. (27 February 2008), 29.9% (16 May 2008), and 14.0% (16 May 2008) respectively. The annual average thermal efficiencies of ETC, SS, and EISS have been found to be 48.6, 21.3, and 10.1%, respectively.

Table 7 shows the total energy consumed by AC water pump in the year 2008. Electrical energy consumed in a day of winter month i.e. for 5 h of operation and in a day of summer month i.e. for 6 h of operation, have been found to be 440 and 528 Wh respectively. Total electricity consumed in the year 2008 has been found to be 182.6 unit with rate US $ 0.097 per unit (i.e. Rs. 4.65 per unit) for industrial applications. Table 8 shows the economic analysis of the EISS system when the system is only considered for solar distillation purpose. The total initial cost has been found to be US $ 694.53 (i.e. Rs. 33,391/-) for EISS. On the basis of economic analysis, annual cost of distilled water has been found to be US $ 0.128 per kg (i.e. Rs. 6.15/- per kg) when annual average distilled water production from EISS has been taken as 2.5 kg/m^2 at a water depth 0.05 m. It is also to be noted that the minimum life of each component of EISS have been considered as 15 years and the economic analysis has been done only for the minimum life of EISS.

7. Conclusions

On the basis of the above results and discussion, the following conclusions have been made:

(1) The EISS system can be used for both solar water heating and solar distillation.
(2) The integration of ETC with SS increases the water temperatures as well as yield. The maximum and minimum amounts of yield have been 3.328 kg/m^2 day (on 16 May 2008) and 1.114 kg/m^2 day (on 19 December 2008) respectively.
(3) The comparative study of yields obtained from EISS and SS shows that EISS and SS can produce 630 kg/m^2 year and 327 kg/m^2 year respectively.
(4) The maximum overall thermal efficiency of the EISS has been found as 29.9% and annual average of it has been found to be 21.3%.
(5) On the basis of economic analysis, annual cost of distilled water has been found to be US $ 0.128 per kg (i.e. Rs. 6.15 per kg) when annual average distilled water production from EISS has been taken as 2.5 kg/m^2 at water depth 0.05 m.

Table 8
Economic analysis of EISS for the year 2008*

Components	Quantity × cost per item (Rs.)	Total cost of item (Rs.)	Steps for economic analysis (considered 1 Rs. = 0.0208 US $)	
GRP sheet (0.005 m thick)	18.2 kg × 450 per kg	8190	Principle cost (P_{cost})	Rs. 33,391/-
Glass cover (0.004 m thick)	1 × 500 per glass	500	Salvage value (*S*) (taken 15% of principle value)	Rs. 5008.7/-
Iron stand	4 kg × 50 per kg	200	Life of the system (*n*)	15 years
Inlet/outlet nozzle	0.08 kg × 450 per kg	36	Interest rate (*j*)	12%
Iron clamp	1 kg × 50 per kg	50	Capital recovery factor (CRF)	0.15
Black paint	0.4 kg × 150 per kg	60	Sink fund factor (SFF)	0.03
Silicone rubber	5.0 m × 25 per m	125	Annualized first cost	Rs. 5008.7/-
Glass putty	1.5 kg × 20 per kg	30	Annualized salvage value	Rs. 1001.7/-
Evacuated tubular collector (170 L capacity)	1 × 21000 per ETC	21,000	Annual maintenance cost (assuming 15% of annual first cost)	Rs. 751.3/-
AC water pump	1 × 1200 per item	1200		
Fabrication and integration cost		2000	Annualized cost	Rs. 4758.3/-
Electricity consumed to run the AC pump in an year = 182.6 kWh			Annual cost of electricity @ Rs. 4.65 per kWh	Rs. 8,49.1/-
Total cost (Rs.)		33, 391 or US $ 694.53	Total annual cost	Rs. 5607.4/-
			Annual yield of the still (average daily yield × 365) (Assuming average daily yield 2.5 kg/m^2 at water depth 0.05 m)	912.5 kg
			Annual useful energy (annual yield × latent heat of vaporization)	593.1 kWh
			Annualized cost of distilled water per kg	Rs. 6.15/- or US $ 0.128
			Annualized cost of distilled water per kWh	Rs. 9.5 /- or US $ 0.198

*The benefit from the ETC (i.e. heating of the water) has not been considered in economic analysis of EISS. Only the benefit in terms of cost from the point of view of solar distillation has been considered.

Appendix A. Various intermediate expressions for thermal modeling of EISS [27,28]

$h_{kg} = k_g / l_g$

$h_{go} = [\frac{1}{h_{kg}} + \frac{1}{h_o}]^{-1}$

$h_{rw} = \varepsilon_{eff}.\sigma[(T_w + 273)^2 + (T_{gi} + 273)^2][T_w + T_{gi} + 546]$

$h_{cw} = 0.884[(T_w - T_{gi}) + \frac{(P_w - P_{gi})(T_w + 273)}{268.9 \times 10^3 - P_w}]^{1/3}$

$h_{ew} = 0.016273 \times h_{cw} \times \frac{(P_w - P_{gi})}{(T_w - T_{gi})}$

$(T_w - T_{gi}) = \frac{h_{go} A_g T_{ws} - \alpha'_g I_s(t) A_g - h_{go} A_g T_a}{h_{1w} A_b + h_{go} A_g}$

$(T_b - T_{ws}) = \frac{\alpha'_b I_s(t) + h_{ba} T_a - h_{ba} T_{ws}}{h_{bw} + h_{ba}}$

$a_1 = \frac{(UA)_T + U_{L1}}{(M_{wc} C_w)}$

$b_1 = -\frac{\dot{m} C_w}{M_{wc} C_w}$

$g_1(t) = \frac{A_t N I_c(t) \eta_o + U_{L1} T_a}{M_{wc} C_w}$

$U_{L1} = a A_t N + \dot{m} C_w$

$\frac{(a_1 + \beta a_2)}{(b_1 + \beta b_2)} = \frac{c}{\beta c}$

$\alpha_{eff} = \alpha'_b \frac{h_{bw} A_b}{h_{bw} + h_{ba}} + \alpha'_w A_b + \alpha'_g \frac{h_{1w} A_b A_g}{h_{go} A_g + h_{1w} A_b}$

$h_o = 5.7 + 3.8v$

$\varepsilon_{eff} = [\frac{1}{\varepsilon_g} + \frac{1}{\varepsilon_w} - 1]^{-1}$

$P_w = \exp[25.317 - \frac{5144}{T_w + 273.15}]$

$P_{gi} = \exp[25.317 - \frac{5144}{T_{gi} + 273.15}]$

$h_{1w} = h_{cw} + h_{ew} + h_{rw}$

$a_2 = -\frac{\dot{m} C_w}{M_{ws} C_w}$

$b_2 = \frac{\dot{m} C_w + U_{L2}}{(M_{ws} C_w)}$

$g_2(t) = \frac{\alpha_{eff} I_s(t) + U_{L2} T_a}{M_{ws} C_w}$

$U_{L2} = U_t + U_b + U_s$

$U_t = \frac{(h_{1w}.A_b)(h_{go} A_g)}{h_{go} A_g + h_{1w} A_b}$

$U_s = h_{sw} A_{sw}$

$U_b = \frac{h_{bw} h_{ba} A_b}{h_{bw} + h_{ba}}$

$a_2 \beta^2 + (a_1 - b_2)\beta - b_1 = 0$

Symbols

a	—	solar collector efficiency coefficient (W/m^2 °C)
A	—	area of the water tank of ETC (m^2)
A_b	—	area of the basin (m^2)
A_g	—	area of the glass cover (m^2)
A_r	—	area of reflector plate
A_s	—	contact area of water with side wall (m^2)
A_t	—	surface area of one evacuated tube (m^2)
A_T	—	surface area of water tank (m^2)
C_w	—	specific heat of the water (J/kg °C)
d_p	—	diameter of GI pipes used for connection (m)
d_t	—	perimeter of outer tube (m)
d_T	—	diameter of the water tank of ETC (m)
dt	—	small time interval (s)
h_{ba}	—	heat transfer coefficient from basin to ambient (W/m^2 °C)
h_{bw}	—	heat transfer coefficient from basin to water (W/m^2 °C)
h_{kg}	—	heat transfer coefficient of glass cover (W/m^2 °C)
h_{sw}	—	heat transfer coefficient of side wall (W/m^2 °C)
h_{1w}	—	total heat transfer coefficient from water to glass cover including radiative, convective and evaporative heat transfer coefficients (W/m^2 °C)
h_o	—	convective–radiative heat transfer coefficient from outer surface of glass cover to ambient (W/m^2 °C)
h_{go}	—	overall heat transfer coefficient from inner surface of glass cover to ambient (W/m^2 °C)
H_{south}	—	height of south wall of the solar still (m)
I_c (t)	—	solar radiation on ETC (W/m^2)
I_d (t)	—	diffuse solar radiation (W/m^2)
I_g (t)	—	global solar radiation (W/m^2)
I_{load}	—	load current (Amp)
I_s (t)	—	solar radiation on SS (W/m^2)
k_g	—	thermal conductivity of glass cover (W/m^2 °C)
k_b	—	thermal conductivity of glass-reinforced plastic (W/m^2 °C)
l_b	—	thickness of the glass-reinforced plastic (m)
l_g	—	thickness of the glass cover (m)
l_t	—	length of each glass tube (m)
l_T	—	length of the water tank of ETC (m)
$\dot{m}$	—	mass flow rate of the circulating water (kg/h)
$\dot{m}_{ew}$	—	hourly yield through solar still (kg/h)
M_{wc}	—	ETC water tank capacity (kg)
M_{ws}	—	water mass in SS (kg)
N	—	number of evacuated tubes in the ETC

P_{gi} — partial vapour pressure at temperature of inner surface of condensing glass cover (N/m^2)
P_w — partial vapour pressure at temperature of water surface (N/m^2)
$\dot{q}_u$ — heat gain from the ETC tank through flowing water (W)
T_a — ambient temperature (°C)
T_b — basin liner temperature (°C)
T_{gi} — temperature of inner surface of condensing glass cover (°C)
T_{go} — temperature of outer surface of condensing glass cover (°C)
T_{ws} — water temperature in SS (°C)
T_{wc} — water temperature in ETC (°C)
U_b — overall heat transfer coefficient (downward) from water to ambient through basin liner (W/m^2 °C)
U_s — overall heat transfer coefficient from water to ambient through side wall (W/m^2 °C)
U_t — overall heat transfer coefficient (upward) from water to ambient through glass cover (W/m^2 °C)
U_{L2} — total heat transfer coefficient from water to ambient (W/m^2 °C)
$(UA)_T$ — total heat transfer coefficient from ETC water to ambient (W/m^2 °C)
v — wind velocity (m/s)
V_{load} — load voltage (V)
α'_b — effective absorptivity of basin liner (dimensionless)
α'_g — effective absorptivity of glass covers (dimensionless)
α'_w — effective absorptivity of water (dimensionless)
α_{eff} — effective absorptivity of the whole SS assembly (dimensionless)
β — angle of glass cover of from horizontal (°)
ϕ — angle of ETC (°)
ρ — relative humidity (%)
ρ_w — density of the water (kg/m^3)
ε_g — emissivity of glass (dimensionless)
ε_{eff} — effective emissivity of the system (dimensionless)
ε_w — emissivity of water (dimensionless)
η_{ic} — thermal efficiency of ETC (%)
η_{is} — thermal efficiency of active SS (%)
η_{io} — overall thermal efficiency of EISS (%)
η_o — efficiency constant (%)
σ — Stephan-Boltzman constant (W/m^2 K^4)

Subscripts
b — basin
g — glass
r — reflector plate
s — SS
sw — side wall
t — evacuated tube
T — water tank
ba — basin to ambient
bw — basin to water
kg — conductivity of glass
1w — total heat transfer from water to glass
o — outer
go — inner surface of glass to outer
south — south
c — collector
d — diffuse
ew — evaporative water
wc — water in collector
ws — water in still
gi — inner surface of condensing glass cover
u — useful
w — water
eff — effective
i — instantaneous

Abbreviations
AC — alternating current
BD — basin-type distiller
EISS — evacuated tubular collector integrated solar still
ETC — evacuated tubular collector
FPC — flat plate collector
GI — galvanized iron
GRP — glass-reinforced plastic
IIT — Indian Institute of Technology
Rs. — Indian Rupees
SS — single slope solar still

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