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Experimental and theoretical investigations on a double exposure single basin solar still

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ABSTRACT

This paper presents construction and measured performance of a double exposure solar still. Temperatures of water and the condensing surface were measured employing Copper–Constantan thermocouple via data logger. To validate the measured performance, a theoretical analysis was carried out. Explicit expressions were derived for the temperatures of water, absorber and condensing surface of the double exposure solar still. Explicit expression was also derived for the distillate output. Quantitative assessment of the analytical results was made. The water temperature and the condensing surface temperature measured experimentally were compared with the theoretically evaluated values. The correlation coefficient and root mean squire deviation are found to be 0.989 and 0.068, respectively.

Keywords: Solar energy; Solar still; Double exposure; Experimental and theoretical studies

1. Introduction

Solar still is the most popular device to harness solar energy for water purification. The main objective in the design development of the solar still has been to create a greater temperature differential between water and the condensing surface. This helps achieve increased evaporative heat transfer from water surface to the condensing surface yielding enhanced distillate output. The water-to-condensing surface temperature differential can be increased either by reducing the temperature of the condensing surface or by increasing the water temperature. A number of designs of the solar still were developed for this purpose [1–6]. Some of these are referred to as hemispherical solar stills [7,8] roof-type [9], V-covered, multiple effects stills, tilted tray or inclined stepped stills [10,11], tilted wick type, and multiple-wick type [12–16], pyramid solar still [17,18] compound parabolic concentrator solar still [19,20].

One possible way to achieve greater water-to-condensing surface temperature difference is through indirect heating of the basin-water. For this purpose, either solar stills are connected to collectors or waste hot water is fed into the basin of the solar still [21–24]. It is interesting to refer in this context the work of Soliman [25]. Performance studies of solar still coupled to flat-plate solar collector were carried out by Rai and Tiwari [26], and Yadav et al. [27] and more recently by Badran et al. [28]. A periodic theory of the solar still using waste hot water in the basin was given by Sodha et al. [29]. An analysis of a single basin solar still with intermittent flow of waste hot water in the basin was also presented by Madhuri and Tiwari [30], and Yadav and Tiwari [31]. Yadav [32] carried out indoor simulation of a basin-type solar still and tested experimentally the steady state performance by flowing pre-heated water in the basin of the solar still from a constant water temperature bath.

The water temperature can also be increased by allowing the solar radiation to reach the absorber of the solar still from below, through circular reflector, apart from the solar radiation reaching to the absorber from the top. This kind of design of the solar still is developed by integrating basin type solar still on to the exit aperture of the reversed

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flat-plate system, and is termed as a double exposure single basin type solar still. These systems, thus, achieve a greater temperature differential, which is desirable for increased output. In this paper, constructions and performance studies of a double exposure single basin solar still is presented. Further, a transient analysis is carried out to estimate theoretically the water and the condensing surface temperature of the double exposure single basin solar still. The experimentally measured water temperature and the condensing surface temperature were compared with those predicted theoretically.

1.1. Constructions and experiment

A double exposure single basin solar still has a circular reflector section, an absorber of width 0.2 m, a concentration ratio of 1, inclined at 26°10′. The reflector was fabricated using mirror stripes. Aluminum sheet was used as the starting material to construct the single basin solar still. It had a 0.12 m high front wall and a 0.245 m high back wall, resulting in a condensing surface with 20° slope. The single basin solar still sides were enclosed in a plywood enclosure of 0.012 m thickness. The bottom and inner surfaces were coated with blackboard paint. The front wall of the basin has a semi-cylindrical drainage channel across the top side to collect the condensate. On the sides of the top surface of the solar still a rubber gasket was glued using adhesive. A condensing surface was fabricated for the solar still by fastening a glass sheet to the basin with aluminum angle frame and steel screws. Onto the top of the exit aperture of the circular reflector section of the solar still a cavity of 0.03 m height was raised by parallel walls and the basin was mounted. To collect the distillate a rubber tube was used that led the distillate into a plastic bucket covered with aluminum. The aluminum cover of the distillate collecting plastic bucket had a small hole to allow air to exit from the bucket. copper-constantan thermocouple was employed to measure the water temperature and condensing surface temperature through data logger. Fig. 1 shows the photograph of the constructed double exposure single basin solar still put on experiment.

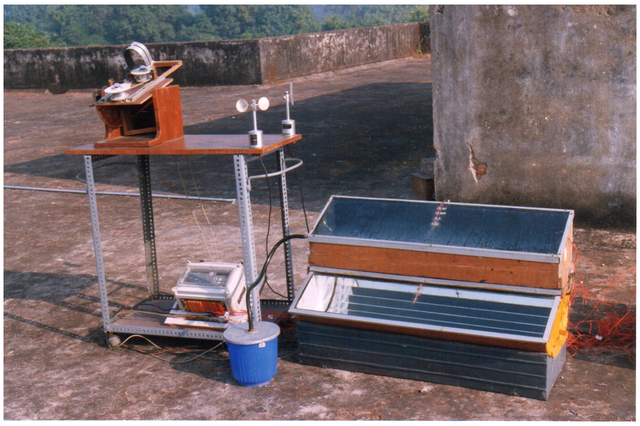

Fig. 1. A double exposure single basin solar still put on experiment.

2. Analytical modelling

The transient analysis is based on the following assumptions:

The amount of solar radiation absorbed by the material of the reflector is negligibly small as compared to that absorbed by the basin-liner of the still. Heat capacity of the material of glass-cover, reflector, aperture cover and the basin-liner is also negligibly small in comparison to that of the water in the basin of the solar still.

The schematic diagram of a double exposure single basin solar still is shown in Fig. 2.

Based on above referred assumptions, the energy balance equations are written for various components of the system as follows.

Energy balance for the double exposure absorber

$$[\rho A_c(1-\alpha_g)]\alpha_p + A_p(1-\alpha_g)H_s\alpha_p = A_p h_{cpw}(T_p - T_w) + A_p h_b(T_p - T_a) \quad (1)$$

Energy balance for the basin-water

$$A_p h_{cpw}(T_p - T_w) = M_w \frac{dT_w}{dt} + h_l A_p (T_w - T_g) \quad (2)$$

Energy balance for the condensing surface

$$h_l A_p (T_w - T_g) = h_2 A_g (T_g - T_a) \quad (3)$$

Substituting the values of T_p and T_g from Eqs. (1) and (3), respectively, in Eq. (2), one can obtain

$$\frac{dT_w}{dt} + \frac{\alpha}{m_w}T_w = \frac{\beta}{m_w}H_s + \frac{\alpha}{m_w}T_a \quad (4)$$

where α and β are constants, and their expressions are given in appendix A.

Eq. (4) subject to the initial condition

$$T_w(t=0) = T_{wo} \quad (5)$$

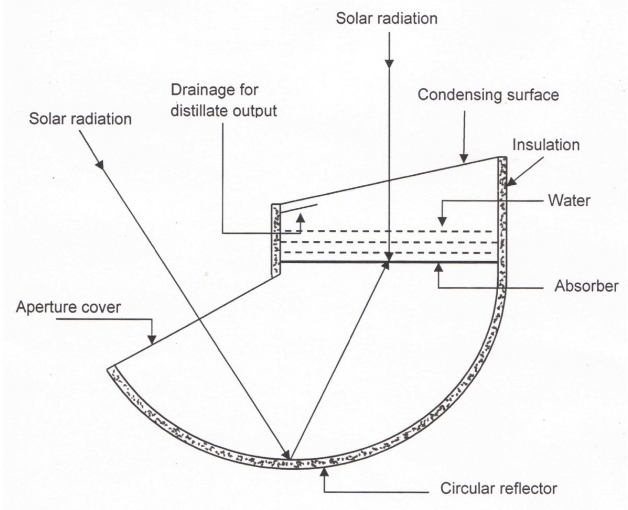

Fig. 2. Schematic diagram of a double exposure basin solar still showing solar radiation reaching the absorber from top and the bottom.

can be solved to obtain expression for the water temperature.

$$T_w = T_{wo}\exp\left(-\frac{\alpha}{m_w}t\right)+\left(\frac{\beta}{\alpha}H_s+T_a\right)\left[1-\exp\left(-\frac{\alpha}{m_w}t\right)\right] \quad (6)$$

Now from Eqs. (3) and (6) expression for the condensing surface temperature can be derived as

$$T_g = b_2T_{wi}\exp\left(-\frac{\alpha}{m_w}t\right)+\frac{b_2\beta}{\alpha}\left\{1-\exp\left(-\frac{\alpha}{m_w}t\right)\right\}H_s + \left[b_2\left\{1-\exp\left(-\frac{\alpha}{m_w}t\right)\right\}+c_2\right]T_a \quad (7)$$

Eqs. (1) and (6) provide following expression for the absorber temperature of the basin-liner

$$T_p = b_1T_{wo}\exp\left(-\frac{\alpha}{m_w}t\right)+\left[a_1+\frac{b_1\beta}{\alpha}\left\{1-\exp\left(-\frac{\alpha}{m_w}t\right)\right\}\right]H_s + \left[b_1\left\{1-\exp\left(-\frac{\alpha}{m_w}t\right)\right\}+C_1\right]T_a \quad (8)$$

The temperature differential between water and the condensing surface is as obtained

$$\Delta T_{wg} = (1-b_2)T_{wo}\exp\left(-\frac{\alpha}{m_w}t\right)+\frac{\beta}{\alpha}(1-b_2)\left\{1-\exp\left(-\frac{\alpha}{m_w}t\right)\right\}H_s + \left[(1-b_2)\left\{1-\exp\left(-\frac{\alpha}{m_w}t\right)\right\}-C_2\right]T_a \quad (9)$$

The distillate output produced per unit time from unit surface area of the double exposure solar still can be written as

$$m_e = \frac{h_{ewg}\Delta T_{wg}}{L} \quad (10)$$

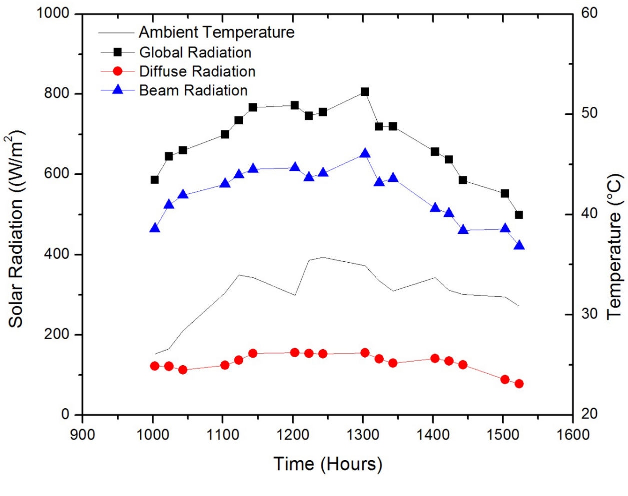

Fig. 3. Solar meteorological parameters as a function of time.

3. Results and discussion

To validate the experimental results of the double exposure single basin solar still quantitative assessment of the analytical results were made employing values of heat transfer coefficients presented by Yadav and Prasad [33]. The solar meteorological parameters measured on the day of experiment, which were used for theoretical evaluation, are shown in Fig. 3.

The solid black squares stand for values of global radiation, the green solid triangles represent the value of beam radiation, the red solid circles represent the values of diffused radiation and the continuous black curve represents the ambient temperature as a function of time.

The values of other relevant parameters taken are: $A_c = 0.2$ m^2; $A_p = 0.2$ m^2; $C_w = 4190$ J kg^{-1} °C^{-1}; $m_w = 3.5$ kg; $\alpha_p = 0.80$; $\alpha_g = 0.05$; $L = 2.297\times10^6$ J kg^{-1}; $\rho = 0.85$

The transient analysis provides explicit expressions for temperature of the basin water, condensing surface and the absorber represented by Eqs. (6)–(8), respectively.

Eq. (9) represents the temperature difference developed between basin water and the condensing surface and is used to estimate theoretically the distillate output produced by the system from Eq. (10). A measure of the agreement between the theoretical prediction based on the above model and the experimental measurement is obtained as Pearson correlation coefficient defined as:

$$r = \frac{N\sum X_EX_T - \sum X_E\sum X_T}{\sqrt{N(\sum X_E^2)-(\sum X_E)^2}\times\sqrt{N(\sum X_T^2)-(\sum X_T)^2}}$$

and root mean square of deviation defined as:

$$\sigma = \sqrt{\frac{\sum(X_T-X_E)^2/X_E^2}{N}}$$

where X_E and X_F are experimental observation and theoretical prediction respectively and N is the total number of observations.

Fig. 4 shows the time variation of water temperature of the system measured experimentally and predicted theoretically. For this case we obtain $r = 0.989$ and $\sigma = 0.068$.

The condensing surface temperature measured experimentally and evaluated theoretically is shown in Fig. 5. In this case, we obtain $r = 0.981$ and $\sigma = 0.089$ implying a good agreement between experimental and theoretical results.

Fig. 5 shows the time variation of the instantaneous distillate output computed using Eq. (10). The black solid squares represent the values computed using the experimentally measured values of temperatures of water and the condensing surface and the red circles those computed from the theoretically predicted ones. The total distillate output during the duration of the experiment predicted by the theoretical model is 0.53 kg. The experimentally obtained total distillate output is 0.7 kg.

4. Conclusions

The analysis presented successfully validates the experimentally measured water temperature and condensing surface temperature of the solar still. The analysis could

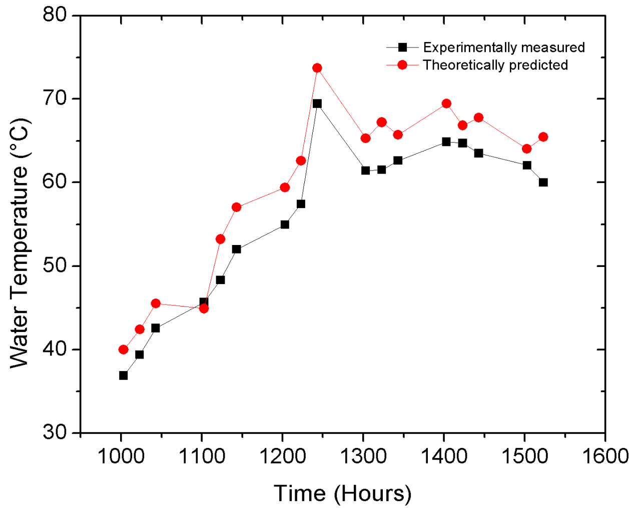

Fig. 4. Experimentally measured (squares) and theoretically predicted (circles) water temperatures of the double exposure single basin solar still.

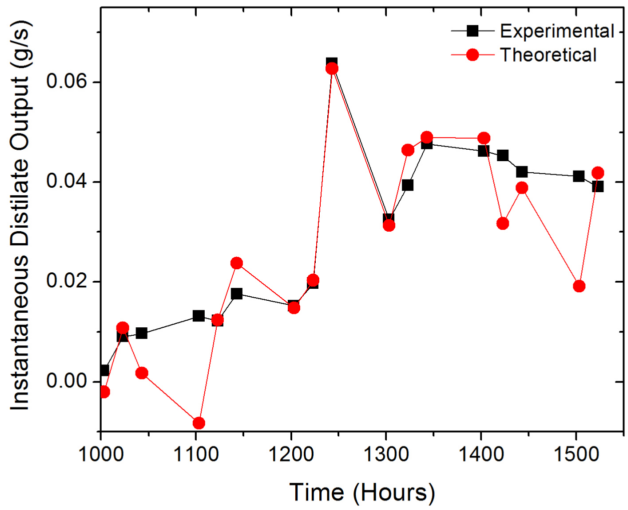

Fig. 6. The experimentally measured (squares) and theoretically predicted (circles) instantaneous distillate output.

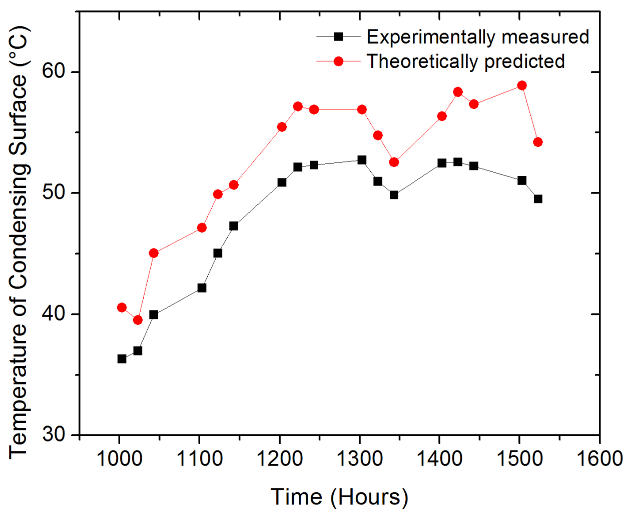

Fig. 5. The experimentally measured (squares) and theoretically predicted (circles) condensing surface temperature of the double exposure single basin solar still.

also be employed to estimate temperatures of remaining component of the system. The prototype system presented in this paper having an absorber surface area (0.2 m^2) yields a distillate output of 0.7 kg over a period of 5 h and 20 min, which can increase if the period of operation is increased further. The circular reflector augments the design of the single basin solar still by allowing solar radiation to reach the absorber from bottom in addition to reaching from top. This increased level of insolation enhances the distillate output. This circular reflector aided design opens the possibility of integration with a compound parabolic linear concentrator (CPC) to further improve the design of conventional single basin solar still.

Acknowledgement

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Appendix

Expressions for constants in terms of various heat transfer coefficients used in analytical expressions

$$\alpha = \frac{1}{C_w}\left[A_p A_{cpw}(1-b_1) + h_1 A_p (1-b_2)\right]$$

$$\beta = \frac{A_p A_{cpw} a_1}{C_w}$$

$$a_1 = \frac{(\rho A_c + A_p)(1-\alpha_g)\alpha_p}{A_p h_{cpw} + A_p h_b}$$

$$b_1 = \frac{A_p h_{cpw}}{A_p h_{cpw} + A_p h_b}$$

$$c_1 = \frac{A_b h_b}{A_p h_{cpw} + A_p h_b}$$

$$b_2 = \frac{A_b h_1}{A_p h_1 + A_g h_2}$$

$$c_2 = \frac{A_b h_2}{A_p h_1 + A_g h_2}$$

Symbols

A_c — Surface area of the aperture cover, m^2.
A_p — Surface area of the basin-liner, m^2.

C_w — Specific heat of water, J kg^{-1} °C^{-1}.
h_1 — Total heat transfer coefficient from the water surface to the condensing surface, W m^{-2} °C^{-1}
h_2 — Total heat transfer coefficient from the condensing surface to outside ambient, W m^{-2} °C^{-1}
h_b — Bottom heat loss coefficient, W m^{-2} °C^{-1}
h_{cga} — Convective heat transfer coefficient from condensing surface to outside ambient, W m^{-2} °C^{-1}
h_{cpw} — Convective heat transfer coefficient from the basin-liner to water mass,W m^{-2} °C^{-1}
h_{cwg} — Convective heat transfer coefficient from the water surface to condensing surface, W m^{-2} °C^{-1}
h_{ewg} — Evaporative heat transfer coefficient from the water surface to condensing surface, W m^{-2} °C^{-1}
H_s — Intensity of the solar radiation, W m^{-2}
t — Time, s
T_a — Ambient temperature, °C
T_g — Condensing surface temperature, °C
T_p — Basin-liner temperature, °C
T_w — Water temperature, °C
ρ — Reflectivity of the reflector
a_g — Fraction of solar radiation absorbed by the condensing surface
γ — Correlation coefficient between experimentally measured and theoretically predicted values
σ — Root mean square of deviation

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