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Performance of single-slope single-basin solar still with sensible heat storage materials

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ABSTRACT

A single-slope single-basin solar still with an inner basin size of 1×1 m has been fabricated with a layer of copper sheet in the basin. The still has been provided with a dripping arrangement to pour saline water drop by drop into the basin. The system has been tested with the dripping of saline water and with different sensible heat storage materials like white marble stones, pebbles, black stones, calcium stones, and iron scraps. It has been found that the calcium stones in the basin with dripping of saline water to maintain the least water depth have a significant effect on the production and validated with the experimental results.

Keywords: Basin solar still; Absorbing materials; Sensible heat storage materials

1. Introduction

Solar distillation is the desperate solution for fresh water crisis which results not only from natural factors but also from human actions, widespread pollution of surface and groundwater. With locally available materials, it is possible to construct a simple basin-type still. The rate of production of distillate yield is very less and efforts have been taken by many researchers to increase the rate of production. Inferences have been obtained by the researchers that the decrease in water depth increases the productivity of the still [1–4]. Moreover, the addition of dye in the basin water has increased the absorption of solar radiation and distillate yield [5–7]. Various absorbing materials have been used in addition to saline water by the researchers to provide more distillate yield [8]. Madani and Zaki [9] have used rubber mate for the improvement of the efficiency, and Naim Mona and Abd El Kawi Mervat [10] have used charcoal as the absorbing material in the basin to increase the absorption of solar radiation. Furthermore, Nafey et al. [11] and Abdel-Rehima Zeinab and Lasheen Ashraf [12] have made an attempt to enhance the productivity by using black materials, glass, rubber, and black gravels. Kalidasa Murugavel et al. [13] have used the spreading materials with a thin layer of water to spread the water in the entire area of the basin. Rahim et al. [14] have an approach in a conventional still to store excess energy during daytime that could be used to continue evaporation at night. In this work, the authors divided the basin water into evaporating and heat-storing zone. They found that the heat storage capacity of the water during daytime was about 35% of the total amount of solar energy entering the still. Sakthivel and Shanmugasundram [15] have conducted experiments with black granite gravel of size 6 mm as

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a storage medium kept in the basin of a single-slope solar still with a basin area of 1 × 0.5 m. Arjunan et al. [16] have made provisions to store excess heat energy in solar stills during daytime for the continuation of the process in the evening and during nighttime using a blue metal stone as the energy storage medium. Kalidasa Murugavel et al. [17] have made an attempt to enhance the productivity by using a layer of water and different sensible heat storage materials like quartzite rock, red brick pieces, cement concrete pieces, washed stones, and irons scraps. Recently Kalidasa Murugavel and Sridhar [18] have conducted experiments for the still up to a minimum depth of water and different wick materials like light cotton cloth, sponge sheet, coir mate and waste cotton pieces, and aluminum rectangular fin arranged in different configurations in the basin.

In this paper, a single-slope single-basin solar still with sensible heat storage materials has been tested experimentally and theoretically. The performance of the system has been tested with dripping of saline water drop by drop with different sensible heat storage materials like white marble stones, pebbles, black stones, calcium stones, and iron scraps. Simulation results are presented and discussed in this paper.

2. Design of the system

The photograph and schematic diagram of the experimental single-slope single-basin solar still are shown in Figs. 1a and 1b. The still consists of outer and inner enclosure made of plywood with dimension of 1.3 × 1.3 m and 1.25 × 1.25 m. The gap between the enclosure is filled with glass wool having the thermal conductivity of 0.0038 W/mK. The height of the back wall and the front wall is 0.03 and 0.10 m, respectively. The glass cover of thickness 4 mm is used as the condensing surface, and the slope of the glass cover is fixed as 11° which is equal to the latitude of the location (Coimbatore). The still is made vapor tight with the help of metal putty. The j-shaped drainage channel is fixed near the front wall to collect the distillate yield and the output trickles down to the measuring jar. The basin of the still is made of galvanized iron (GI) sheet and a thin copper sheet is pasted in the basin and is painted black to absorb more solar radiation. A special arrangement has been made to pour saline water drop by drop into the basin to maintain the least water depth. The arrangement is made of heat transfer pipes with drip button fixed at regular intervals of 0.10 m horizontally in the basin. The saline water tank is provided with a gate valve and is connected to the inlet of the drip arrangement. The basin temperature, saline water temperature and condensing cover temperature are measured by fixing copper–constantan thermocouples which are calibrated initially. Solar radiation intensity and ambient temperature are measured with a solar radiation monitor and a digital thermometer.

Experiment was carried out (from 6 am to 6 am) for 24 h with different sensible heat storage materials in the basin during March 2011 at Department of Physics, Karpagam University, Coimbatore 641021 [latitude 11°N, long 77°52′E], Tamilnadu, India. Fig. 2 shows the photograph of the different

Fig. 1a. Photograph of the experimental still.

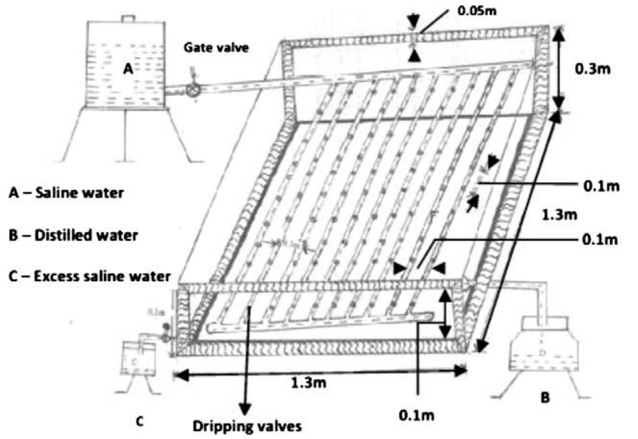

Fig. 1b. Schematic diagram of the experimental still.

Fig. 2. Photograph of the sensible heat storage materials.

sensible heat storage materials used in the experiment.

3. Thermal modeling

3.1. Glass cover transmission

The south-facing condensing glass cover receives the radiation at different angles and quantities. To calculate the energy received by the water mass in the basin, the radiation energy actually received by the glass cover and variation of transmittance of the glass cover with time are to be considered. Researchers have carried out the theoretical evaluation only by considering the radiation energy on the horizontal surface and fixed transmittance of glass cover. For any given instant, the total energy to the still is the total radiation falling on the south-facing glass cover.

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

where $Q_S = A_g I_S$.

The utilization of radiation energy by the still for any given instant is the total solar radiation transmitted through the south-facing covers and it is given by

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

where $Q\tau_S = \tau_S A_g I_S$.

Since the transmittance of the glass cover at anytime is a function of solar radiation incidence angle (θ), diffused radiation fraction (K_d), and thickness of the glass cover (d), Kalidasa Murugavel et al. [19] have developed a correlation equation and it has been used in this study.

3.2. Energy balance equations

The transmitted radiation through the glass cover is absorbed by the saline water in the basin. The saline water temperature increases and heat is transferred from water to glass cover by three modes. Convective, radiative, and evaporative heat transfers occur due to temperature difference between the water surface and lower surface of the glass cover. The evaporative heat transfer is accompanied by the mass transfer due to partial vapor pressure difference between the water surface and the glass cover. The evaporated water vapor condenses at the lower surface of the glass cover and releases its latent heat of vaporization to the glass cover. A small fraction of heat is lost to the surroundings i.e., ambient through the bottom and side walls by conduction and convection. For the shallow basin, the basin temperature and saline water temperature are said to be distinct and are treated as a single element. The saline water is allowed to the basin through a dripping arrangement such that drop by drop flow of water compensates the water mass to take sensible heat to attain equilibrium with basin water.

The following assumptions have been made to write the energy balance equations:

(i) There is no temperature gradient throughout the glass cover surface.
(ii) The system is made vapor tight such that there is no vapor leakage from the still.
(iii) The glass cover and water surface are parallel due to small inclination of the glass cover.

Glass cover

$$I_g \alpha_g A_g + h_1 A_W (T_W - T_g) = h_2 A_g (T_g - T_a) \tag{3}$$

Basin water

$$\begin{aligned}(m_w C_w + m_{em} C_{em}) \frac{dT_W}{dt} &= Q_\tau \alpha_{bw} - h_1 A_w (T_w - T_g) - h_3 A_{bs} (T_w - T_a) \\ &\quad - h_{fw} (T_a - T_w)\end{aligned} \tag{4}$$

Solving Eq. (3), the equation for T_g can be written as

$$T_g = \frac{I_g \alpha_g A_g + h_1 A_w T_w + h_2 A_g T_a}{h_2 A_g + h_1 A_w} \tag{5}$$

where

$$h_1 = h_{\mathrm{cwg}} + h_{\mathrm{rwg}} + h_{\mathrm{ewg}}$$

$$h_2 = h_{\mathrm{rga}} + h_{\mathrm{cga}}$$

$$h_3 = h_{\mathrm{ba}} + h_{\mathrm{sa}}$$

$T_{\mathrm{sky}} = (T_{\mathrm{a}} - 6)$ is the apparent sky temperature

Substituting the equation for T_{g} in Eq. (4) and rearranging, the equation can be written in the form

$$\frac{dT_{\mathrm{w}}}{dt} + PT_{\mathrm{w}} = Q \tag{6}$$

where

$$P = \frac{h_1^2 A_{\mathrm{w}}^2}{(m_{\mathrm{w}}C_{\mathrm{w}} + m_{\mathrm{em}}C_{\mathrm{em}})(h_2 A_{\mathrm{g}} + h_1 A_{\mathrm{w}}}) - \left(\frac{h_1 A_{\mathrm{w}} + h_3 A_{\mathrm{bs}} - h_{\mathrm{fw}}}{m_{\mathrm{w}}C_{\mathrm{w}} + m_{\mathrm{em}}C_{\mathrm{em}}}\right)$$

$$Q = \frac{Q_\tau \alpha_{\mathrm{bw}}}{m_{\mathrm{w}}C_{\mathrm{w}} + m_{\mathrm{em}}C_{\mathrm{em}}} + \frac{h_1 A_{\mathrm{w}} I_{\mathrm{g}} \alpha_{\mathrm{g}} A_{\mathrm{g}} + h_1 h_2 A_{\mathrm{w}} A_{\mathrm{g}} T_{\mathrm{a}}}{(m_{\mathrm{w}}C_{\mathrm{w}} + m_{\mathrm{em}}C_{\mathrm{em}})(h_2 A_{\mathrm{g}} + h_1 A_{\mathrm{w}})} + \frac{(h_3 A_{\mathrm{bs}} - h_{\mathrm{fw}})T_{\mathrm{a}}}{m_{\mathrm{w}}C_{\mathrm{w}} + m_{\mathrm{em}}C_{\mathrm{em}}}$$

The general solution of the Eq. (6) can be written as

$$y \cdot e^{\int p \cdot dt} = \int Q \cdot e^{\int p \cdot dt} \cdot dt + c \tag{7}$$

The equation for T_{w} is

$$T_{\mathrm{w}} = \frac{Q}{p} + c \cdot e^{-pt} \tag{8}$$

Eq. (8) subject to the initial condition when $t = 0$, $T_{\mathrm{w}} = T_{\mathrm{wi}}$

We get

$$c = T_{\mathrm{wi}} - \frac{Q}{p} \tag{9}$$

Substituting the equation for c in Eq. (8), we get

$$T_{\mathrm{w}} = \frac{Q}{p}(1 - e^{-pt}) + T_{\mathrm{wi}} \cdot e^{-pt} \tag{10}$$

Eqs. (5) and (10) are the required explicit expressions for the temperatures of the basin water mass, and glass cover of the still, respectively.

The instantaneous hourly distillate output per unit basin area of the still is calculated by

$$m_{\mathrm{e}} = \left(\frac{h_{\mathrm{ewg}}(T_{\mathrm{w}} - T_{\mathrm{g}}}{L}\right) \times 3600 \tag{11}$$

The efficiency of the still is expressed as

$$\eta\% = \frac{M_{\mathrm{e}} L}{A_{\mathrm{b}} \int I_{\mathrm{s}} \Delta t} \times 100 \tag{12}$$

Where Δt—interval over which the solar radiation is calculated.

4. Results and discussion

The following design parameter was used to evaluate the numerical results based on the analytical solutions obtained by solving the energy balance equations.

$A_{\mathrm{g}} = 1.69\,\mathrm{m}^2$; $A_{\mathrm{w}} = A_{\mathrm{b}} = 1.5625\,\mathrm{m}^2$; $C_{\mathrm{w}} = 4190\,\mathrm{J/kg\,{}^\circ C^{-1}}$; $m_{\mathrm{w}} = 12\,\mathrm{kg}$; $m_{\mathrm{em}} = 30\,\mathrm{kg}$; $A_{\mathrm{bs}} = 0.13\,\mathrm{m}^2$; $\alpha_{\mathrm{bw}} = 0.88$; $\alpha_{\mathrm{g}} = 0.05$; $L = \frac{2372000J}{kg}$; $\sigma = 5.66 \times 10^{-8}\,\mathrm{W/m^2\,k^4}$, $V = 1.4\,\mathrm{m/s}$, $K = 0.038\,\mathrm{W/mk}$.

The intermittent climatic parameters i.e. solar radiation and ambient temperature have been observed and are the variable parameters used in the numerical calculations.

Experiments have been conducted with various sensible heat storage materials on different days continuously during March and April 2011. The radiation condition is same for all the days of the month and observations have been compared for these days. Among these days, atmospheric conditions are same and the days having variation in the atmospheric condition are ignored. Fig. 3 shows the variation of solar radiation and ambient temperature for the days in which observations made with different sensible heat storage materials. The variations have the same trend for all the days and solar radiation intensity seems to be maximum between 12 pm and 2 pm.

Fig. 4 represents the variation of total solar radiation fraction, diffused radiation fraction, and transmittance of the south-facing glass cover. The correlation proposed by Duffie and Beckman [21] for the transmittance has been used in this study and it was observed that the transmittance of the cover is good for all the incident angles of solar radiation. Even though the angle of incidence of solar radiation is

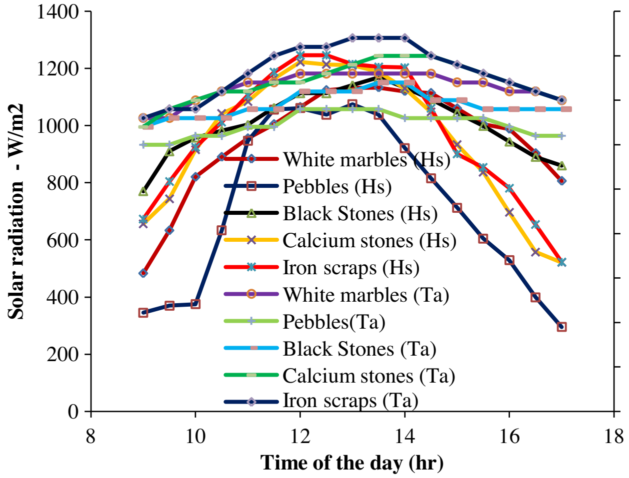

Fig. 3. Variation of solar radiation intensity and ambient temperature.

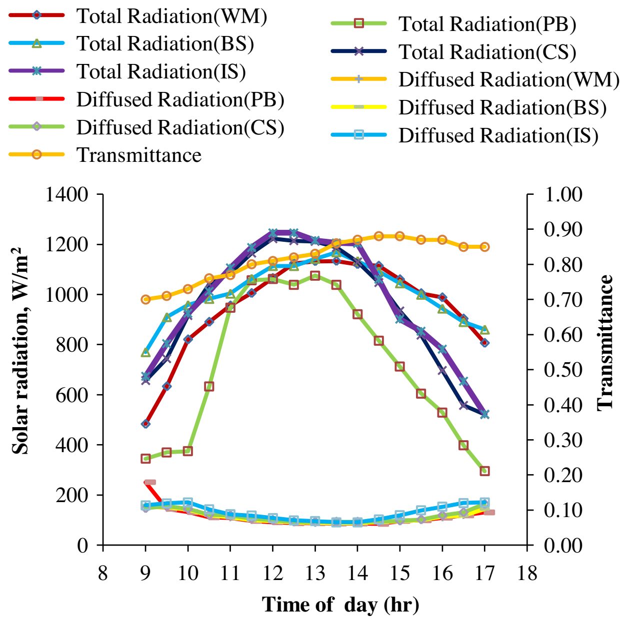

Fig. 4. Variation of total radiation, diffused radiation fraction, and transmittance.

high during morning and evening hours, the transmittance of the glass cover is high. The production rate for the different sensible heat storage materials has been observed and a graph is drawn for the same.

Fig. 5 represents the variation of production rate for different sensible heat storage materials (WM, white marbles; PB, pebbles; BS, black stones; CS, calcium stones; and IS, iron scraps) throughout the day. The observations have been made by dripping the saline water by using the dripping arrangement so that to maintain the least water depth in the basin (1 cm) along with sensible heat storage materials of moderate size. From the graph, it is observed that the sensible heat storage material i.e. calcium stones have given a high production rate throughout the day when compared with the other heat storage materials. Fig. 6 shows the total production rate for the different sensible heat storage materials from 9 am to 5 pm. It is clear from the graph that the total production rate for the calcium stones (4.28 kg/m^2 12 h) in the basin from 9 am to 5 pm is found to be higher than that for the other sensible heat storage materials. On a 24-h cycle, the total distillate yield of the still with calcium stones in the basin is found to be 5.78 kg/m^2. Among the sensible heat storage materials, calcium stones in the

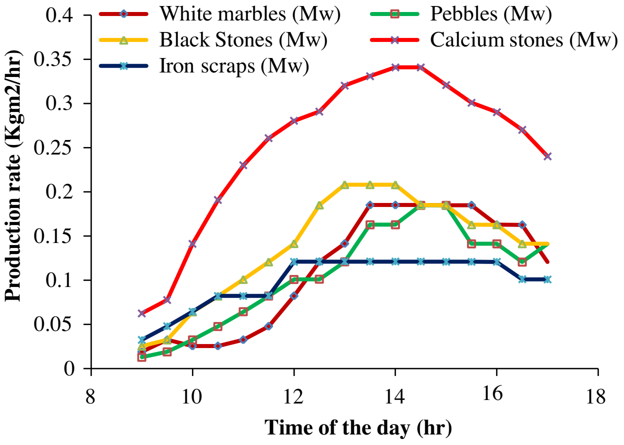

Fig. 5. Variation in production rate for sensible heat storage materials.

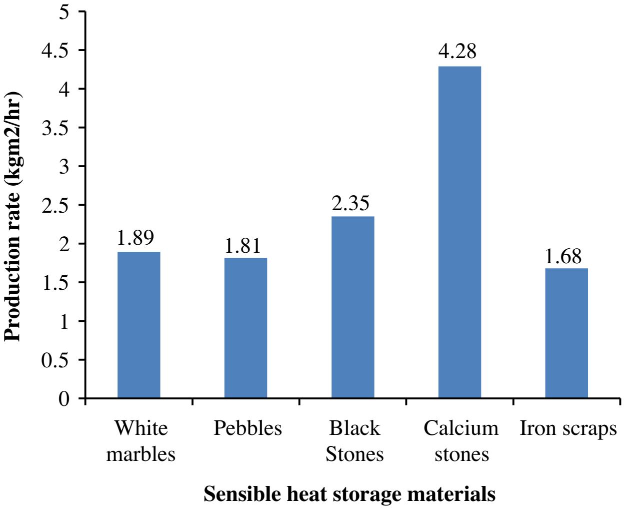

Fig. 6. Variation of total production rate for sensible heat storage materials.

basin have given the nighttime production rate of 1.5 kg/m^2.

Table 1 represents the density, thermal conductivity, and specific heat capacity of the sensible heat storage materials used in this experiment. Among the storage materials, calcium stones have high specific heat capacity than the other. Since the specific heat capacity is high, large amount of solar energy is trapped within the stone and it increases the distillate yield during nighttime. Moreover, the calcium stones have pores to allow the saline water to stay inside; and the energy stored in the water is utilized during low intensity radiation and nighttime for the distillation process.

The variation of water and glass temperature has been observed along with the hourly production rate for the heat storage materials and it is shown in Fig. 7. From the figure, it is clear that the difference in temperature between the evaporating water surface and condensing glass cover surface is maximum during 12 pm to 2.30 pm and after that it decreases gradually for all the sensible heat storage materials in the basin.

It is also observed that for calcium stones in the basin, there exists a remarkable temperature difference between water and the glass cover surface. Due to that, the production rate increases linearly with the increased temperature difference during peak sunny hours. And also during peak sunny hours, the minimum water depth in the basin has been maintained by dripping the saline water in to the basin by the dripping arrangement which enhances the productivity rate due to low thermal capacity of water in the basin. Experiments have also been conducted without the dripping arrangement along with the sensible heat storage materials. It is observed that, for constant maximum water depth in the basin, the productivity decreases when compared to the dripping of saline water slowly into the basin. Throughout the day, 12 L of saline water is introduced to the basin by the dripping arrangement.

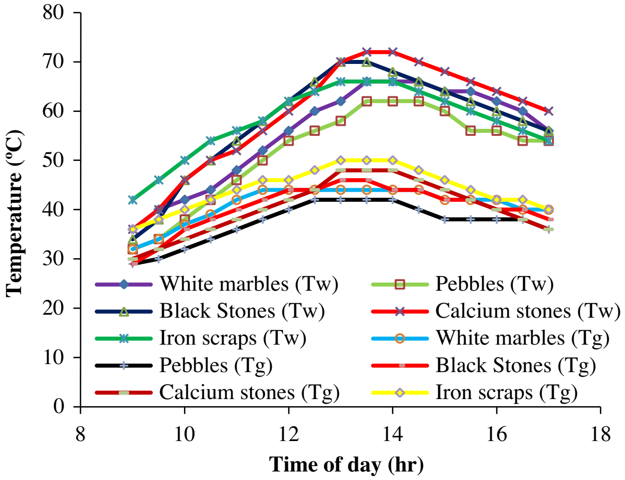

Fig. 7. Variation of water and glass cover temperature.

Fig. 8 shows the variation of various heat transfer coefficients occurring inside and outside of the still during the working hours of the day. It is observed that the external heat transfer coefficients i.e. convective and radiative heat transfer coefficients from the glass cover to ambient are higher than the other internal heat transfer coefficients throughout the day. The heat transfer coefficient of the saline water fed to the still is also higher than the internal heat transfer coefficient. This is because the outer enclosure has direct contact with the surroundings rather than the area inside the still.

A computer program has been written for the analytical solutions for glass cover temperature, water temperature, and production rate for the calcium stones in the basin and is shown in Fig. 9. It is confirmed that the theoretical results are in good agreement with the experimental observations. At some points, there exist some deviations from the experimental observations due to the unaccountable parameters i.e. projection of back and side walls in the basin. This parameter has an influence on the thermal performance of the still and it should be accountable.

Calcium stones having a specific heat capacity of 910 J/kg K are the best sensible heat storage material than the 3/4 in. quartzite rock of specific heat capacity

Table 1

Materials	Density (kg/m^2)	Thermal conductivity (W/mK)	Specific heat capacity (J/kg K)
Calcium stone	2560	1.26–1.33	910
Black stone	3070	2.06–2.90	750
White marbles	2160	2.08–2.94	880
Pebbles stone	3300	2.4–2.6	880
Iron scraps	8000	16	500

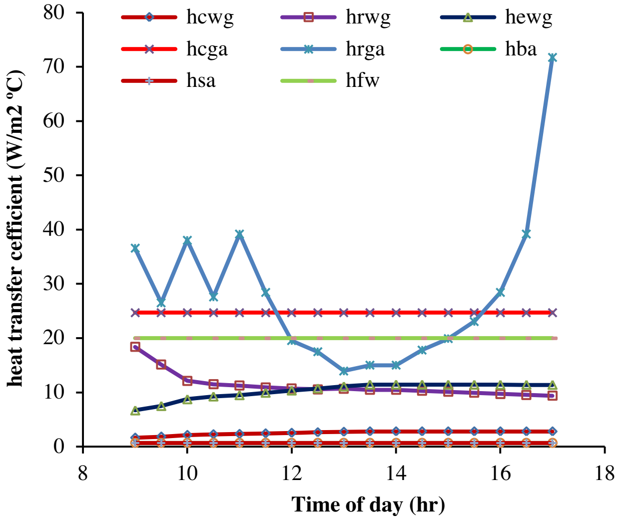

Fig. 8. Variation of average heat transfer coefficient.

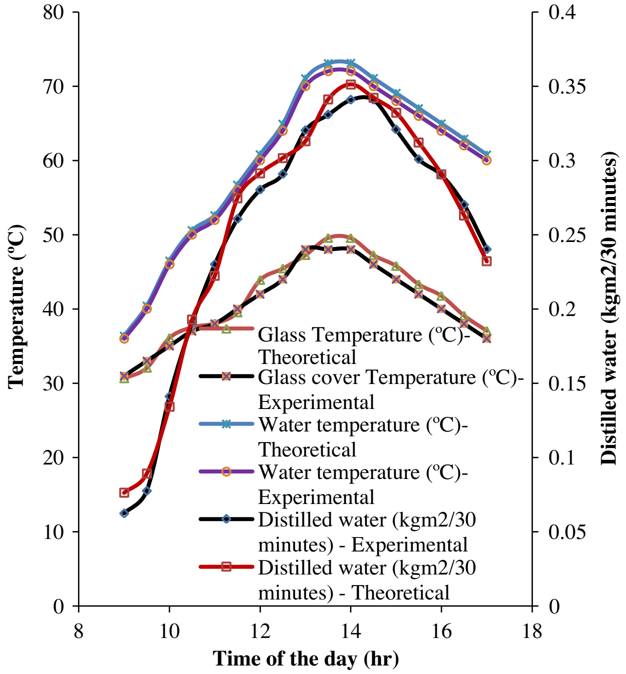

Fig. 9. Variation of distillate yield, glass cover and water temperature.

775 J/kg K [17] and blue metal stones [16] in the basin for effective distillation.

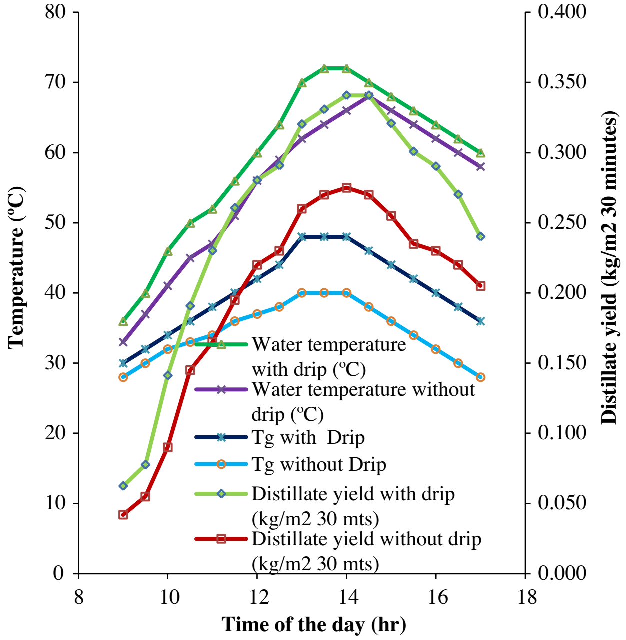

Fig. 10. Variation of production rate, water and glass cover temperature with and without dripping.

The variation of production rate, water and glass cover temperature for calcium stones in the basin by dripping saline water with dripping arrangement to maintain the least water depth has been compared with the same calcium stones without dripping. Experiment without dripping has been carried out with 1.5 cm of saline water along with calcium stones. Fig. 10 shows the variation of production rate, water and glass cover temperature with and without dripping of saline water in the basin. From the graph, it is clear that calcium stones with dripping of saline water in the basin show increased rate of evaporation due to the large temperature difference between water and glass cover temperature. The temperature difference between water and the glass cover without dripping is small due to large thermal capacity and the rate of evaporation is moderate. Moreover, overall distillate output in the 24-h cycle for the system with calcium stone accompanied by dripping is found to be 5.78 kg/m^2 which is 36% higher than the system with saline water in the basin instead of dripping.

Conclusion

The following conclusions are drawn:

(i) The thermal performance of single-basin single-slope solar still has been theoretically modeled including the transmittance and total solar radiation of south-facing condensing cover and it is experimentally validated for the typical days.

(ii) Calcium stones are one of the best sensible heat storage materials to increase the evaporation during nighttime and daytime due to high specific heat capacity.

(iii) Calcium stones in the basin with dripping have significant influence on the thermal performance of the still compared to the production rate without dripping and release the heat energy stored during low intensity of solar radiation.

(iv) In the case of saline water in the basin, the total production decreases due to large thermal capacity. Dripping of saline water increases the temperature difference between the condensing glass cover and water temperature in the basin due to low thermal capacity.

(v) The overall thermal efficiency of the still is found to be 43.67%, and the estimated production rate is in close agreement with the experimental values. Moreover, the production rate depends on water, glass, ambient, and water–glass temperature difference by considering the transmittance on the south-facing condensing cover.

Nomenclature

A_g — area of the glass, m^2
A_w — area of the water surface, m^2
A_{bs} — area of the bottom surface still, m^2
C_w — specific heat capacity of the water, J/kg K
C_{em} — specific heat capacity of the energy storing materials, J/kg K
h_1 — total heat transfer coefficient from water to glass, W/m^2 K
h_2 — total heat transfer coefficient from glass to ambient, W/m^2 K
h_3 — total heat transfer coefficient from bottom and side of the still to ambient, W/m^2 K
h_{ba} — heat transfer coefficient from bottom of the still to the ambient, W/m^2 K
h_{sa} — heat transfer coefficient from the side of the still to the ambient, W/m^2 K
h_{fw} — heat transfer coefficient from ambient to feed water, W/m^2 K
h_{ewg} — evaporative heat loss coefficient from water to glass of the solar still, W/m^2 K
h_{cwg} — convective heat loss coefficient water to glass of the solar still, W/m^2 K
h_{rwg} — radiative heat loss coefficient water to glass of the still, W/m^2 K
h_{rga} — radiative heat loss transfer coefficient from glass to ambient, W/m^2 K
h_{cga} — convective heat loss transfer coefficient from glass to ambient, W/m^2 K
I_g — solar radiations on the glass cover, W/m^2
I_s — solar radiations falling on the south-facing glass cover, W/m^2
L — latent heat of vaporization of water, kJ/kg
m_e — mass of the distillate output, kg/m^2 h
m_{em} — mass of the energy-storing materials, kg/m^2
m_w — mass of the water, kg/m^2
Q_i — total solar radiation to the still, W/m^2
Q_s — total radiation falling on the south-facing glass cover, W/m^2
Q_τ — total radiation transmitted to the still, W/m^2
$Q_{\tau s}$ — total solar radiation transmitted through the south-facing glass cover, W/m^2
T_g — temperature of the glass cover, °C
T_w — temperature of the water, °C
T_a — ambient temperature, °C

Greek symbols

α_g — absorptivity of the glass cover
α_{gw} — absorptivity of basin water
τS — transmittance through the south-facing glass cover
τ — transmittance

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