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Effect of cover materials on heat and mass transfer coefficients in a plastic solar still

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ABSTRACT

The intention of this work was to study the effect of cover materials on heat and mass transfer coefficient and hence productivity of the still. Two plastic stills having similar geometrical features were constructed to maintain the comparison under the same weather conditions. The condensing surface of one still was an acrylic (plastic) cover (3 mm thick) while of the other still it was a glass cover (3 mm thick), both fixed in an aluminum frame. It was found that for water depth of 10 cm the plastic solar still with the glass cover produced 30–35% more output than the plastic solar still with Plexiglas cover. The evaporative heat transfer coefficient for the glass cover still was 57% more than that for the still with the plastic cover which resulted in a higher output. Plastic can be used as the structural material for solar stills but increased costs do not always increase the distillate output.

Keywords: Plastic solar still; Cover materials; Heat transfer coefficients; Solar energy; Productivity

1. Introduction

There is a growing understanding that there is a need for a long-term solution to shortage of potable water involving water management, purification, and conservation. A key feature to this approach is the development of an environmentally friendly and sustainable water purification technique [1,2]. While the most common desalination methods are based on fossil-fueled thermal processes, alternative techniques, such as solar desalination, are also being considered. Solar methods are well suited for the arid and sunny regions of the world as in North Africa and the Arabian Peninsula. A variety of solar desalination devices have been developed. It has become apparent that a key feature in improving overall efficiency is the need to gain a better understanding of the thermodynamics of the processes and how the designs can be made more efficient, materials of construction, plant size and location, and operating costs must all be taken into account. Therefore, both efficiency and economics need to be considered when choosing a solar desalination system. In many countries which face shortage of water, such as countries of the Middle East and North Africa, over 80% of all fresh water consumed is used for agriculture [3]. As fresh water resources are limited, there is an inexorable pressure to reduce agricultural use of water to meet the growing demand for domestic and industrial use. Because of simple technology, non-requirement of skilled labor and low energy consumption, solar distillation is a very good alternative.

A conventional still is simply an airtight basin that contains salt water and a top cover of any transparent material such as glass or Plexiglas. When the still is exposed to the sun, the solar energy is trapped which heats the water and evaporates. The air inside of the solar still gets saturated and water condenses on the inside sur-

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face of the transparent cover. The condensed water glides downward in the drainage and is collected in bottles out of the still [4].

The choice of appropriate materials is one of the most important issues in the development of a solar still. The structural materials used in a solar still are wood, galvanized iron, aluminum, asbestos cement, masonry bricks and concrete. It has been observed that the use of galvanized iron for basin or distillate channel is not good choice since it corrodes when in contact with saline water. Aluminum can also be used but it also corrodes at high temperature. Wood can be used in a small still but with time it gets damaged. The materials like asbestos cement, masonry bricks and concrete can also be used for a solar still, but their main problem is weight, particularly when these are to be transported to remote areas. Similarly the choice for the transparent cover can be either glass or acrylic sheet/plastic film [5].

The intention of this work was to study the effect of cover materials on heat and mass transfer coefficient and hence productivity of the still. Using the glass and plastic (Plexiglas) as cover material for two stills, experiments were conducted under the same operating conditions.

2. Theoretical study

Using the measured values of solar intensity, wind velocity and ambient temperature as input data, the daily productivity of the solar still was calculated. The mathematical model was developed according to the relation of heat transfer coefficients. A schematic diagram of a single sloped conventional solar still is shown in Fig. 1.

The basic heat flux components at various points are shown in the same figure. The energy balance equations of the solar still can be written as follows with the following assumption [6].

- Temperature gradient across the thickness of the cover is insignificant.
- Heat transfer coefficient is considered to be constant at the selected time interval.
- Heat capacity of the basin liner and insulation are neglected.
- The variation in the absorptivity and transmittivity of the Plexiglas, glass and water surfaces with the variation in angle of the incoming radiation is neglected.

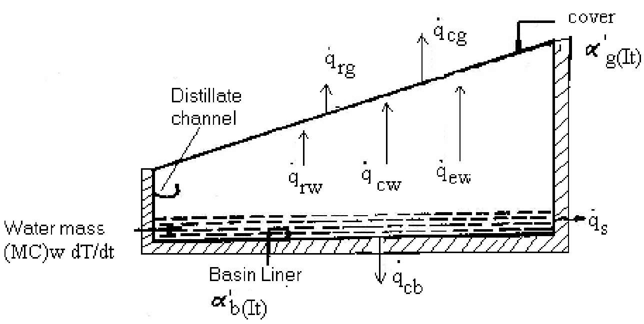

Fig. 1. Schematic diagram of heat transfer in a solar still.

Energy balance for cover:

$$\alpha'_g I(t) + [q_{rw} + q_{cw} + q_{ew}] = q_{rg} + q_{cg} \tag{1}$$

Energy balance for basin water:

$$\alpha'_w I(t) + q_w = (MC)_w \; dT_w / dt + q_{rw} + q_{cw} + q_{ew} \tag{2}$$

Energy balance for basin:

$$\alpha'_b I(t) = q_w + \left[q_{cb} + q_s\left(A_{ss} / A_s\right)\right] \tag{3}$$

Heat transfer coefficients.

$$hl_g = 5.7 + 3.8\,V \quad [7] \tag{4}$$

$$q_g = q_{rg} + q_{cg} \tag{5}$$

$$q_g = hl_g\left(T_w - T_a\right) \tag{6}$$

$$hl_w = h_{rw} + h_{cw} + h_{ew} \tag{7}$$

$$U_t = \left[1/hl_g + 1/hl_w\right]^{-1} \tag{8}$$

$$U_L = U_t + U_b \tag{9}$$

$$q_{loss} = U_L\left(T_w - T_a\right) \tag{10}$$

$$q_{rw} = h_{rw}\left(T_w - T_a\right) \tag{11}$$

$$h_{rw} = \epsilon_{eff}\ \sigma\left[\left(T_w + 273\right)^2 + \left(T_g + 273\right)^2\right] \left[T_w + T_g + 546\right] \quad [8,9] \tag{12}$$

$$\sigma = 5.669 \times 10^{-8}\ \text{W/m}^2.K^4 \tag{13}$$

$$\epsilon_{eff} = \left[1/\epsilon_g + 1/\epsilon_w - 1\right]^{-1} \tag{14}$$

$$\epsilon_g = \epsilon_w = 0.9$$

$$h_{cw} = 0.884\left[T_w - T_g + \left(P_w - P_g\right)\left(T_w + 273\right) / \left(268.9 \times 10^3 - P_w\right)\right]^{1/3} \quad [10] \tag{15}$$

$$q_{cw} = h_{cw}\left(T_w - T_g\right) \tag{16}$$

$$h_{ew} = 16.273 \times 10^{-3} h_{cw}\left(P_w - P_g\right) / \left(T_w - T_g\right) \quad [11] \tag{17}$$

$$q_{ew} = h_{ew}\left(T_w - T_g\right) \tag{18}$$

Convection and radiation from the bottom or side surface of the basin transfer heat from the basin water to the ambient through the insulation. The bottom loss coefficient is given by [12]

$$U_b = \left[1/h_w + 1/\left(K_i / L_i\right) + 1/\left(h_{cb} + h_{rb}\right)\right]^{-1} \tag{19}$$

$$h_w = 135\,\text{W/m}^2\ ^\circ\text{C} \qquad [13] \tag{20}$$

Side heat loss coefficient can be written as

$$U_e = U_b\left(A_{ss} / A_s\right) \tag{21}$$

For small water depth, U_e can be neglected.

The rate of heat loss per m^2 from basin liner to ambient is given by

$$q_b = h_b\left(T_b - T_a\right) \tag{22}$$

$$h_b = \left[L_i / K_i + 1/\left(h_{cb} + h_{rb}\right)\right]^{-1} \tag{23}$$

The values of (h_{cb} + h_{rb}) are obtained from the equation:

$$hl_g = 5.7 + 3.8\,V \tag{24}$$

by substituting V = 0, since there is no wind velocity at the bottom of the insulation.

$$hl_g = h_{cb} + h_{rb} \tag{25}$$

The hourly yield is calculated as

$$M_{ew} = \left(q_{ew} / L\right) \times 3600 = \left[h_{ew}\left(T_w - T_g\right) / L\right] \times 3600 \tag{26}$$

3. Methodology

In this work effect of cover materials on heat and mass transfer coefficients in plastic solar stills was studied experimentally. Two plastic stills having similar geometrical features were constructed to maintain the comparison under the same weather conditions of Malegaon (Baramati, India).

Each unit consisted of an acrylic box having five sides. These sides were made of acrylic sheets of 3.0 mm thick. The base and two of these sides were of rectangular shape, while the other sides were trapezoidal. Two holes in each units were made, one of which was in the back side for drainage and for feeding and the other hole was in the front side for distilled water output. The base and sides of each box were painted black from inside to increase the solar absorptivity. The base and all sides of each unit were insulated with glass wool.

(Thermal conductivity = 0.044 W/m k) of 25 mm thickness. The insulation was applied on the wall by adhesive. A collection track was used for each still box to collect the distillate. This track was fixed to the all sides of the box. The condensing surface of one still was an acrylic (Plexiglas) cover while of the other still it was glass cover, both were fixed in an aluminum frame with three middle supports as shown in Fig. 2.

To support properly the plastic stills were kept in wooden boxes. The cover of each still was adjusted on the edge of the sides with an angle of 20° and oriented with its face to the south. Silicon rubber sealant was used to prevent leakage from any gap between the acrylic cover and the still box [14]. Plastic beakers of two-liter capacity were used to measure the hourly yield. Rubber tubes were used to discharge distilled water from each unit to the bottles.

4. Results and discussion

The experiments were conducted under the same operating conditions on the above developed plastic so-

Fig. 2. Acrylic and glass cover solar stills.

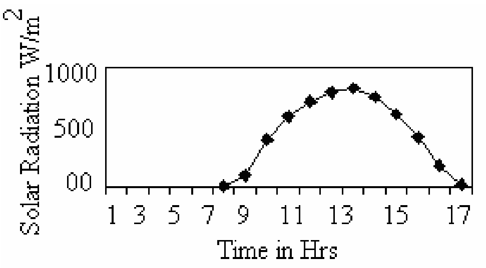

Fig. 3. Hourly variation of solar radiation.

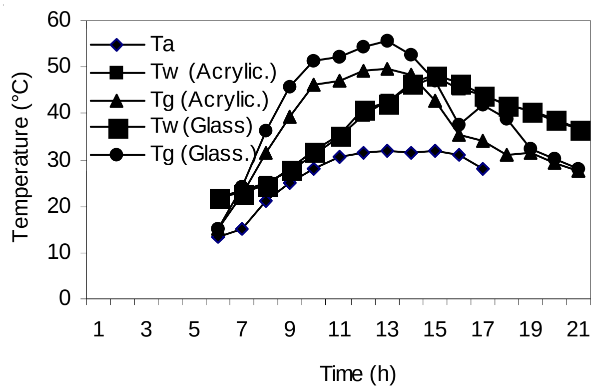

Fig. 4. Hourly variation of cover and basin water temperature.

lar stills. Fig. 3 shows hourly variation of solar radiation for a typical day. A sample experimental data for basin water temperature and cover temperature is as shown in Table 1.

The experimental results of the two cases are presented in Figs. 4–8 for the same basin water depth (10 cm). The hourly variation of cover temperatures and basin water temperatures is shown in Fig. 4. It is clear from Table 1 that the rise in basin water temperature of the still with the glass cover is 2–4°C more than the other still with the acrylic cover which increases the internal heat transfer coefficients and hence the productivity of that still. The glass cover temperature was 5–6°C more than the plastic cover. Also the glass cover cools faster than the plastic cover and the difference between basin water temperature and cover temperature increases, which is the driving force for more distillate output. The basin water depth has a significant effect on productivity of the still. Investigations show that the water depth is inversely proportional to the productivity of the still [15]. Experiments with deep basin revealed that the productivity of the still decreases with an increase in the depth of water during daylight and the reverse is the case for overnight production.

The evaporative heat transfer coefficient and mass transfer coefficient are shown in Fig. 5 and Fig. 6. The evaporative heat transfer coefficient for the glass cover still was 57% more than that for the plastic cover still. The higher is the evaporative heat transfer coefficient, the higher is the output. That is why more output was obtained in the case of the glass cover still. Mass transfer coefficient is also more by 28% in the case of the still with the glass cover.

Fig. 7 explains the variation of internal heat transfer coefficients with time for both stills under consideration. The radiative heat transfer coefficients are higher than convective heat transfer coefficients and evaporative heat transfer coefficients are highest in both cases. There is little variation in radiative and convective heat transfer coefficients throughout the experimental period. Rapid increase in evaporative heat transfer coefficient was observed as the solar intensity increased in both cases; but there was more rise in the case of the still with the glass

Table 1
Hourly temperature measurements for different cover materials

No.	Time (h)	Solar intensity (W/m²)	Basin water temperature (°C)		Cover (inner) temperature (°C)		Ambient temperature (°C)
			For plastic still with acrylic cover	For plastic still with glass cover	For plastic still with acrylic cover	For plastic still with glass cover	
1	7.00 a.m.	9	22	22	15	15	19
2	8.00 a.m.	101	23	23	22	24	21
3	9.00 a.m.	399	25	26	31	36	24
4	10.00 a.m.	591	28	30	39	46	27
5	11.00 a.m.	716	31	34	46	51	29
6	12.00 a.m.	792	35	38	47	52	33
7	13.00 p.m.	828	40	44	49	54	33
8	14.00 p.m.	756	43	46	50	56	35
9	15.00 p.m.	610	41	43	49	53	37
10	16.00 p.m.	419	40	41	43	47	38
11	17.00 p.m.	182	45	47	35	37	36

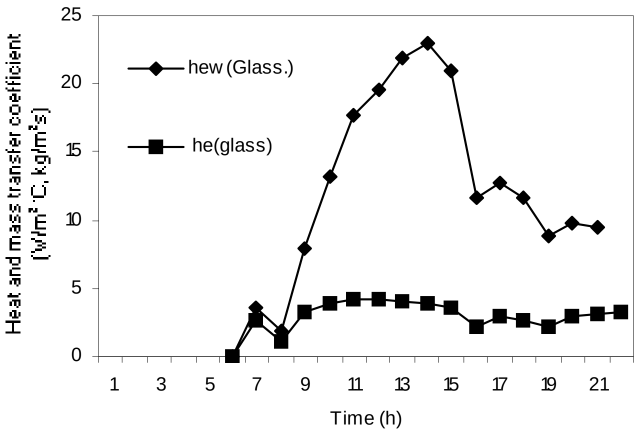

Fig. 5. Hourly variation of evaporative heat transfer coefficient and mass transfer coefficient for the glass cover.

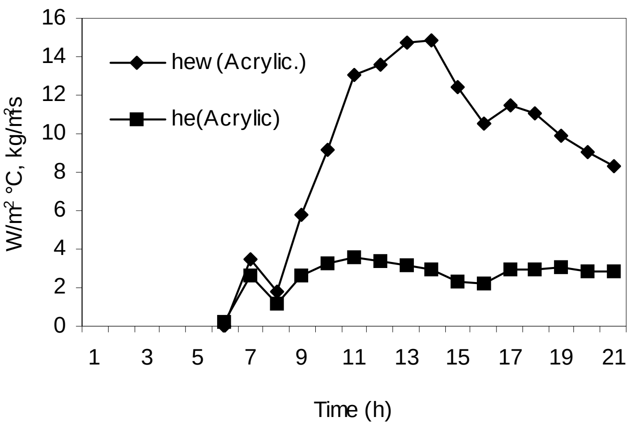

Fig. 6. Hourly variation of evaporative heat transfer coefficient and mass transfer coefficient for the acrylic cover.

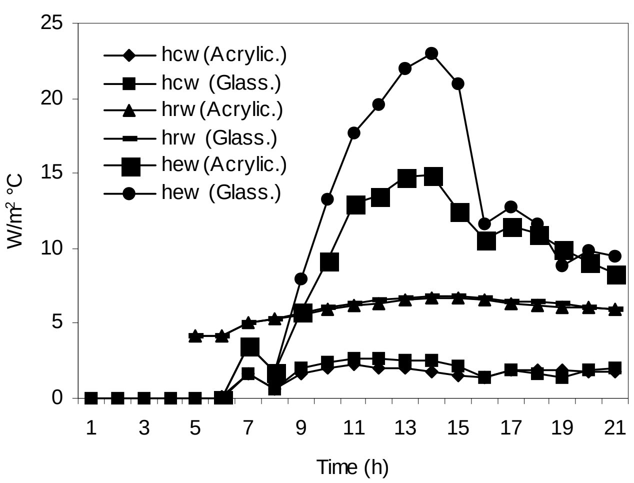

Fig. 7. Hourly variation of internal heat transfer coefficients.

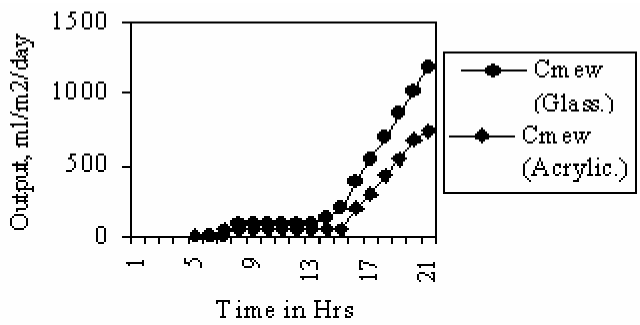

Fig. 8. Comparison of distillate output from both stills.

cover. This may be due to high transmittivity of glass cover.

The variation of cumulative productivity (C_{mew}) with time is shown in Fig. 8 for both stills. The plastic solar still with the glass cover is superior. The distillate output for the glass cover plastic solar still was 30–35% more than that of the plastic solar still with acrylic cover. The reason for this more output is that the evaporative heat transfer coefficient for the still with the glass cover is higher than that of the other still under consideration. Also the difference between the basin water temperature and cover temperature is higher for the plastic solar still with the glass cover.

Cappelletti [16] reported that the greatest quantity of fresh water obtained by a plastic solar still was 1.7–1.8 L/m^2/d. The quantity of fresh water obtained from the tested still in this research work was 1.8–2.1 L/m^2/d which is about 60% more than in the previous work. Polyester can be used as cover material since it shows good mechanical strength and great transparency to solar radiation [17]. The output of the still also depends on the type of glass used for the cover. Khoukhi et al. [18] reported that the instantaneous efficiency of the solar collector with a low iron glass cover is higher than the efficiency of the system with the clear glass cover. For plastic surfaces, such as Plexiglas, drop type condensation and fogging are produced. Considerable solar energy is reflected or scattered by small droplets, diminishing the transmitted solar energy.

5. Conclusions

It was found that for water depth of 10 cm the plastic solar still with the glass cover produced 30–35% more water than the plastic solar still with the Plexiglas cover. The evaporative heat transfer coefficient for the glass cover still was 57% more than that for the still with the plastic cover. Mass transfer coefficient was also more by 28% in the case of the still with the glass cover. The system is more sensitive to ambient temperature. Plastic can be used as the structural material for solar stills but increased costs do not always increase the distillate output.

Symbols

A_c — Area of cover, m^2
A_s — Area of basin liner, m^2
A_{ss} — Area of solar still sides, m^2
C_{mew} — Cumulative productivity of still, ml/m^2/d
h_{cw} — Convective heat transfer coefficient from water to cover, W/m^2 °C
h_e — Mass transfer coefficient from water to cover, W/m^2°C
h_w — Convective heat transfer coefficient from basin liner to water, W/m^2 °C
h_{cb} — Convective heat transfer coefficient from bottom insulation to ambient, W/m^2°C
h_{rb} — Radiative heat transfer coefficient from bottom insulation to ambient, W/m^2°C
h_{rw} — Radiative heat transfer coefficient from water to cover, W/m^2 °C
h_{ew} — Evaporative heat transfer coefficient from water to cover, W/m^2 °C
h_{1w} — Total heat transfer coefficient from water to cover, W/m^2 °C
h_{1g} — Total heat transfer coefficient from cover to atmosphere, W/m^2 °C
$I(t)$ — Total solar radiation, W/m^2
K_i — Thermal conductivity of insulating material, W/m^2 °C
L — Latent heat of vaporization, J/kg
L_i — Thickness of insulation, m
$(MC)_w$ — Heat capacity of water mass in basin, J/m^2 °C
M_{ew} — Distillate output from still, kg/m^2/d
P_w — Partial pressure at basin water temperature, N/m^2
P_g — Partial pressure at cover temperature, N/m^2
q_{cw} — Convective heat transfer from water to cover, W/m^2
q_{rw} — Radiative heat transfer from water to cover, W/m^2
q_{ew} — Evaporative heat transfer from water to cover, W/m^2
q_{loss} — Overall heat loss from water surface to ambient through top and bottom, W/m^2
q_{cb} — Heat transfer from base to ambient by conduction, W/m^2
q_s — Side heat loss to ambient by conduction, W/m^2
q_{cg} — Convective heat loss from cover to ambient, W/m^2
q_{rg} — Radiative heat loss from cover to ambient, W/m^2
T_a — Ambient temperature °C
T_g — Cover temperature, °C
T_w — Basin water temperature, °C
U_b — Overall bottom loss coefficient, W/m^2 °C
U_e — Overall side heat loss coefficient, W/m^2 °C
U_L — Overall heat transfer coefficient W/m^2 °C
U_t — Overall top loss coefficient, W/m^2 °C
V — Wind speed, m/s

Greek

α'_g — Solar flux absorbed by cover
α'_w — Solar flux absorbed by basin water
α'_b — Solar flux absorbed by basin
$\in_{eff}$ — Effective emissivity
$\in_g$ — Emissivity of cover
$\in_w$ — Emissivity of water
σ — Stefan Boltzmann constant

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