Thermal modeling of solar stills:  
an experimental validation

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Abstract

Expressions for water and glass temperatures, yield and efficiency of both single and double slope multiwick solar distillation systems in quasi-steady state conditions have been derived. The analysis is based on the basic energy balance for both the systems. A computer model has been developed to predict the performance of the solar stills. Experimental validation of the thermal model has been carried out by using modified heat transfer coefficients. Internal heat transfer coefficients have been evaluated based on both inner and outer glass cover temperatures for typical days namely January 22, and June 19, 2001 in Delhi. A fair agreement has been observed between theoretical and experimental results by using the modified internal heat transfer coefficients based on inner glass cover temperature.

Keywords: Single slope solar distillation; Double slope solar distillation; Multiwick solar stills; Thermal efficiency

1. Introduction

The yield of a solar still mainly depends on the difference between water and glass cover temperatures. Various scientists [3-12] have made attempts to maximize the yield either by passive methods or by active methods.
Nomenclature

$A$  area of solar still (m$^2$)

$C$  constant

$b$  breadth of solar still (m)

$C_w$  specific heat of working fluid (J/kg K)

$g$  acceleration due to gravity (m/s$^2$)

$Gr$  Grashof number

$h_{cw}$  convective heat transfer coefficient from water surface to the glass cover (W/m$^2$ K)

$h_{ca}$  convective heat transfer coefficient from glass cover to the ambient (W/m$^2$ K)

$h_{ew}$  evaporative heat transfer coefficient from water surface to the glass cover (W/m$^2$ K)

$h_{rw}$  radiative heat transfer coefficient from water surface to the glass cover (W/m$^2$ K)

$h_{2g}$  total heat loss coefficient from the glass cover to the ambient (W/m$^2$ K)

$h_{lw}$  total heat loss coefficient from water surface to the glass cover (W/m$^2$ K)

$K$  convective heat transfer coefficient from basin liner to water (W/m$^2$ K)

$h_b$  bottom loss coefficient from basin to ambient (W/m$^2$ K)

$I(t)$  solar radiation incident on the glass cover of the solar still (W/m$^2$)

$K_f$  thermal conductivity of humid air (W/m K)

$K_i$  thermal conductivity of insulation (W/m K)

$h$  thickness of insulation (m)

$m_{ew}$  hourly distillate output (kg/m$^2$/h)

$m_w$  mass flow rate of water over jute cloth (kg/m$^2$/s)

$n$  constant

$Pr$  Prandtl number

$p_w$  partial vapour pressure at water temperature (N/m$^2$)

$p_g$  partial vapour pressure at glass temperature (N/m$^2$)

$q_{ew}$  evaporative heat transfer rate from water to the glass surface (W/m$^2$)

$T$  ambient temperature (8C)

$T_g$  glass temperature (8C)

$T_w$  water temperature (8C)

$t$  time (s)

$u_b$  overall bottom heat loss coefficient (W/m$^2$ K)

$U_L$  overall heat transfer coefficient (W/m$^2$ K)

$u_t$  overall top loss coefficient from water surface to ambient (W/m$^2$ K)

$U_t$  top loss coefficient for solar still (W/m$^2$ K)

$V$  wind velocity

Greek letters

$\mu_f$  viscosity of fluid (N s/m$^2$)

$P'$  coefficient of volumetric thermal expansion (KK$^{-1}$)
Passive methods include:

1. effect of dye [3–4]
2. effect of water mass [10]
3. effect of wind [5,11]
4. effect of insulation [11] and
5. effect of booster mirror [7].

Active methods include:

1. integration of collector with basin [12] and
2. use of waste hot water [6].

It has been reported that the yield is maximum for the least water depth [2]. Based on this concept, a multiwick solar still was developed by Sodha et al. [1]. Yadav and Tiwari [9] modified it and fabricated single and double slope solar stills from fiber reinforced plastic (FRP). The thermal modeling of single and double slope multiwick solar stills has been developed by using the Dunkle's relation for internal heat transfer coefficients [12-14].

Kumar and Tiwari [14] have developed a new model to evaluate convective heat transfer coefficient, $h_{cw}$, without any limitation by using linear regression analysis for the determination of $C$ and $n$. However, they [14] have used the outer glass cover temperature for evaluating $h_{cw}$.

In this paper, an attempt has been made to evaluate $h_{cw}$ for single and double slope multiwick solar stills by considering both the inner and the outer glass cover temperatures. Further experimental validation of model has been also carried out for both the cases. It has been observed that the thermal model validates closely with $h_{cw}$ obtained from the inner glass cover temperature.

2. Experimental setup

2.1. Multiwick single slope solar still

A schematic diagram and a photograph of a single slope multiwick solar still are shown in Fig. 1a and b, respectively. In this type of solar still, one end of a number of wet jute cloth pieces (porous fibers) of different lengths are dipped into a water reservoir while
the other ends are spread over the absorber basin as shown in diagram. The jute cloth pieces are blackened and placed one upon the other, separated by polythene sheets. Here, the wet piece of jute cloth forms the water surface in the still. It could attain a higher temperature due to its negligible heat capacity. This leads to rapid evaporation of water. The still has an effective basin area of 1 m \times 1 m and it is fabricated out of the FRP material. A glass cover with an inclination of 108° is fixed to the vertical wall of the still. To ensure that vapors are not lost to the atmosphere, the glass cover is sealed with a rubber
gasket using an adhesive (M-Seal trademark) and window putty (chalk and linseed oil). To collect the distillate output, a channel was fixed at the end of the lower vertical side of basin. A plastic pipe was connected to the channel to drain the fresh water to an external jar. The thickness of the body of the solar still was kept small at 5 mm to ensure minimum heat loss from the bottom as well as from the sides of the still. An inlet pipe is also fixed at the rear wall of the still for feeding saline water. A separate hole is also drilled in the body of the still to fix thermocouples to sense the temperature of water inside the basin. The whole unit is placed on an angle iron stand at a height of 1 m from ground. The solar still is oriented due south to receive maximum solar radiation throughout the year.

2.2. Multiwick double slope solar still

A schematic diagram and a photograph of double slope multiwick solar still are shown in Fig. 2a and b, respectively. This type of solar still also has a number of wet jute cloth pieces (porous fibers) of different lengths and painted black. It has one end dipped in
Table 1
Experimental observations of January 22, 2001 for single slope multiwick solar still

<table>
<thead>
<tr>
<th>Serial number</th>
<th>Time (h)</th>
<th>Intensity (W/m² 8°C)</th>
<th>Water temperature (8°C)</th>
<th>Inner glass temperature (8°C)</th>
<th>Outer glass temperature (8°C)</th>
<th>Ambient temperature (8°C)</th>
<th>Distillate output (ml)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>10:00</td>
<td>360</td>
<td>23.4</td>
<td>22.0</td>
<td>18.7</td>
<td>11.0</td>
<td>30</td>
</tr>
<tr>
<td>2</td>
<td>11:00</td>
<td>400</td>
<td>32.1</td>
<td>29.8</td>
<td>24.5</td>
<td>11.0</td>
<td>62</td>
</tr>
<tr>
<td>3</td>
<td>12:00</td>
<td>450</td>
<td>34.5</td>
<td>30.1</td>
<td>26.0</td>
<td>12.5</td>
<td>142</td>
</tr>
<tr>
<td>4</td>
<td>13:00</td>
<td>510</td>
<td>38.9</td>
<td>31.0</td>
<td>27.0</td>
<td>13.0</td>
<td>170</td>
</tr>
<tr>
<td>5</td>
<td>14:00</td>
<td>530</td>
<td>45.9</td>
<td>38.7</td>
<td>29.6</td>
<td>13.8</td>
<td>200</td>
</tr>
<tr>
<td>6</td>
<td>15:00</td>
<td>450</td>
<td>44.3</td>
<td>33.2</td>
<td>27.8</td>
<td>12.0</td>
<td>186</td>
</tr>
<tr>
<td>7</td>
<td>16:00</td>
<td>355</td>
<td>42.7</td>
<td>31.9</td>
<td>25.4</td>
<td>11.5</td>
<td>110</td>
</tr>
<tr>
<td>8</td>
<td>17:00</td>
<td>170</td>
<td>35.6</td>
<td>29.8</td>
<td>23.7</td>
<td>10.0</td>
<td>60</td>
</tr>
</tbody>
</table>

the water reservoir while other ends are spread out over the absorber surface (black painted basin of still) on both sides (i.e. east and west) as shown in diagram. This still was oriented along the east-west direction to receive maximum solar radiation. The saline water is fed through inlet while distillate and excess saline water is taken out through the respective outlets. A hole was drilled into side wall of the still for thermocouple entry to measure the temperature of the saline water in the jute cloth pieces. Window glass panes of dimensions 1.1!1.1 m² on each side of still are used as still covers and are fixed on the still with the help of rubber gaskets, adhesive and window putty.

Experiments were performed on both the stills in outdoor environment, during the month of January 2001 and June 2001 for several days but the observations presented in Tables 1–4 are representations of only two typical days, namely, January 22, and June 19, 2001. The solarimeter type SM201, (local trade name 'suryamapi') has been used to measure solar intensity. This instrument is analog type, can measure in the range 1-100 mW/cm² solar intensity with an accuracy of 2 mW/cm². Placing suryamapi on

Table 2
Experimental observations of June 19, 2001 for single slope multiwick solar still

<table>
<thead>
<tr>
<th>Serial number</th>
<th>Time (h)</th>
<th>Intensity (W/m² 8°C)</th>
<th>Water temperature (8°C)</th>
<th>Inner glass temperature (8°C)</th>
<th>Outer glass temperature (8°C)</th>
<th>Ambient temperature (8°C)</th>
<th>Distillate output (ml)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
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<td>430</td>
<td>51.2</td>
<td>45.6</td>
<td>34.2</td>
<td>30.0</td>
<td>130</td>
</tr>
<tr>
<td>2</td>
<td>11:00</td>
<td>630</td>
<td>58.2</td>
<td>52.2</td>
<td>45.2</td>
<td>32.1</td>
<td>185</td>
</tr>
<tr>
<td>3</td>
<td>12:00</td>
<td>780</td>
<td>64.5</td>
<td>56.1</td>
<td>57.3</td>
<td>34.6</td>
<td>188</td>
</tr>
<tr>
<td>4</td>
<td>13:00</td>
<td>720</td>
<td>68.6</td>
<td>61.1</td>
<td>59.2</td>
<td>37.0</td>
<td>223</td>
</tr>
<tr>
<td>5</td>
<td>14:00</td>
<td>670</td>
<td>67.2</td>
<td>60.3</td>
<td>58.2</td>
<td>40.0</td>
<td>300</td>
</tr>
<tr>
<td>6</td>
<td>15:00</td>
<td>600</td>
<td>65.2</td>
<td>60.0</td>
<td>58.0</td>
<td>39.1</td>
<td>260</td>
</tr>
<tr>
<td>7</td>
<td>16:00</td>
<td>470</td>
<td>60.2</td>
<td>56.7</td>
<td>54.0</td>
<td>38.2</td>
<td>241</td>
</tr>
<tr>
<td>8</td>
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<td>310</td>
<td>58.1</td>
<td>52.5</td>
<td>50.3</td>
<td>37.0</td>
<td>205</td>
</tr>
<tr>
<td>9</td>
<td>18:00</td>
<td>250</td>
<td>53.4</td>
<td>47.2</td>
<td>44.9</td>
<td>36.8</td>
<td>194</td>
</tr>
</tbody>
</table>
Table 3
Experimental observations of January 22, 2001 for double slope multiwick solar still (east)

<table>
<thead>
<tr>
<th>Serial number</th>
<th>Time (h)</th>
<th>Intensity (W/m² 8C)</th>
<th>Water temperature (8C)</th>
<th>Inner glass temperature (8C)</th>
<th>Outer glass temperature (8C)</th>
<th>Ambient temperature (8C)</th>
<th>Distillate output (ml)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
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<td>370</td>
<td>29.0</td>
<td>26.0</td>
<td>25.0</td>
<td>11.0</td>
<td>107</td>
</tr>
<tr>
<td>2</td>
<td>11:00</td>
<td>400</td>
<td>32.8</td>
<td>29.0</td>
<td>27.0</td>
<td>11.0</td>
<td>168</td>
</tr>
<tr>
<td>3</td>
<td>12:00</td>
<td>450</td>
<td>37.9</td>
<td>29.8</td>
<td>27.7</td>
<td>12.5</td>
<td>180</td>
</tr>
<tr>
<td>4</td>
<td>13:00</td>
<td>500</td>
<td>40.1</td>
<td>32.0</td>
<td>28.5</td>
<td>13.0</td>
<td>208</td>
</tr>
<tr>
<td>5</td>
<td>14:00</td>
<td>550</td>
<td>42.3</td>
<td>35.2</td>
<td>34.9</td>
<td>13.8</td>
<td>240</td>
</tr>
<tr>
<td>6</td>
<td>15:00</td>
<td>450</td>
<td>40.1</td>
<td>38.1</td>
<td>33.2</td>
<td>12.0</td>
<td>180</td>
</tr>
<tr>
<td>7</td>
<td>16:00</td>
<td>350</td>
<td>39.8</td>
<td>37.8</td>
<td>32.4</td>
<td>11.5</td>
<td>100</td>
</tr>
<tr>
<td>8</td>
<td>17:00</td>
<td>100</td>
<td>37.8</td>
<td>36.1</td>
<td>29.6</td>
<td>10.0</td>
<td>100</td>
</tr>
</tbody>
</table>

the glass surface of solar still, we performed the measurement of solar intensity. Temperature has been measured using copper constantan thermocouples, which was connected to digital temperature indicator. The indicator can be used to measure the temperature in the range of 0-200 8C with an accuracy of 0.1 8C. Wind velocity has been obtained from meteorology station, New Delhi. The sunny period is 1 h more under summer climatic conditions than in winter. Experimental data obtained are used to calculate the internal heat and mass transfer coefficients for both types of solar stills. These are presented in Table 7.

2.3. Experimental uncertainty

The experimental method used is an indirect approach for estimating the convective heat transfer coefficient based on the mass of distillate collected from still. It will therefore have a considerable degree of experimental uncertainty. An estimation of uncertainty [15] has been carried out separately for both the solar stills. Data of a particular measurement for a number of days have been taken and an estimate of individual uncertainties of

Table 4
Experimental observations of June 19, 2001 for double slope multiwick solar still (east)

<table>
<thead>
<tr>
<th>Serial number</th>
<th>Time (h)</th>
<th>Intensity (W/m² 8C)</th>
<th>Water temperature (8C)</th>
<th>Inner glass temperature (8C)</th>
<th>Outer glass temperature (8C)</th>
<th>Ambient temperature (8C)</th>
<th>Distillate output (ml)</th>
</tr>
</thead>
<tbody>
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<td>440</td>
<td>53.8</td>
<td>41.2</td>
<td>32.3</td>
<td>30.0</td>
<td>130</td>
</tr>
<tr>
<td>2</td>
<td>11:00</td>
<td>740</td>
<td>59.3</td>
<td>53.9</td>
<td>50.2</td>
<td>32.1</td>
<td>150</td>
</tr>
<tr>
<td>3</td>
<td>12:00</td>
<td>760</td>
<td>65.6</td>
<td>54.3</td>
<td>53.3</td>
<td>34.6</td>
<td>210</td>
</tr>
<tr>
<td>4</td>
<td>13:00</td>
<td>620</td>
<td>66.7</td>
<td>61.2</td>
<td>57.2</td>
<td>37.0</td>
<td>280</td>
</tr>
<tr>
<td>5</td>
<td>14:00</td>
<td>600</td>
<td>63.6</td>
<td>62.3</td>
<td>61.0</td>
<td>40.0</td>
<td>280</td>
</tr>
<tr>
<td>6</td>
<td>15:00</td>
<td>550</td>
<td>56.6</td>
<td>51.9</td>
<td>47.7</td>
<td>39.1</td>
<td>260</td>
</tr>
<tr>
<td>7</td>
<td>16:00</td>
<td>400</td>
<td>51.7</td>
<td>45.2</td>
<td>42.1</td>
<td>38.2</td>
<td>200</td>
</tr>
<tr>
<td>8</td>
<td>17:00</td>
<td>300</td>
<td>47.6</td>
<td>43.3</td>
<td>39.8</td>
<td>37.0</td>
<td>185</td>
</tr>
<tr>
<td>9</td>
<td>18:00</td>
<td>180</td>
<td>42.6</td>
<td>40.2</td>
<td>36.7</td>
<td>36.8</td>
<td>175</td>
</tr>
</tbody>
</table>
the sample values has been calculated. An estimate of internal uncertainty \((U_i)\) has then been found by

\[
U_i = \sqrt{\frac{\sum s_i^2}{N^2}}
\]

where \(s_i\) is the standard deviation of the \(i\)th sample and \(N\) is the total number of samples.

The total uncertainty for single and double slope multiwick solar stills has been calculated as 20 and 23\%, respectively. The results may be influenced by the thermal storage effect, which has been neglected. The percentage error can be calculated as follows:

\[
\%\text{Error} = \frac{\text{distillate output during off-sunshine hours}}{\text{distillate output during daylight hours}} \times 100
\]

Since thermal storage effect is negligible, hence no evaporation takes place during off-sunshine hours. Therefore, there is no percentage error.

2.4. Mathematical models

Following assumptions have been made to write the energy balance equations for different component of the stills:

(i) The heat capacity of water, glass cover and jute cloth (porous fiber) is negligible.
(ii) The solar still is vapor leakage proof.
(iii) Mass flow rate due to capillary action is in streamline,
(iv) Heat loss from the side of the still is negligible.
(v) Solar radiation, after transmission is completely absorbed by water film due to its small thickness.

Energy balance for the glass cover

\[ h_{lw} \frac{d}{dx} T_w \cdot K T_g \cdot P \cdot Z h_{2g} \frac{d}{dx} T_g \cdot K T_a \cdot P \]

Energy balance for the water mass, considering a small elemental length \(dx\) of constant width \(b\) as shown in Fig. 1c, is given by

\[ (T_w)_{t=0} - h_{lw}(T_w \cdot K T_g \cdot P \cdot K h_{2g} \frac{d}{dx} T_w \cdot K T_J \cdot b) \cdot dx \cdot Z m_{w} C_w \cdot \frac{dT_{tw}}{dt} \cdot \frac{dx}{Z} \]

From Eq. (1), \(T_g\) can be found as

\[ T_g = \frac{h_{lw} C_1 h_{2g} T_a}{h_{lw} C_2 h_{2g}} \]
or rewriting Eq. (1)

\[ h_1 \delta T_w \left( T_{i,p} - Z U_i \delta T_w \right) K T_{a,p} \]

where \( U_i, Z, h_1, h_2, C, h_3, p \)

Substituting Eq. (3b) into Eq. (2)

\[
[T_w/(0 - U_i(T_v - r_a) - h_0(T_w - T_r))]b \ dx = \dot{m}_w C_w \left( \frac{dT_w}{dT} \right) dx
\]

or

\[
[T_w/(0 - U_i \delta T_w K T_{a,p})]b \ dx = \dot{m}_w C_w \left( \frac{dJ}{dx} \right) dx
\]

where \( ULZU_i C h_b \)

Above differential equation can be rewritten as

\[
\frac{dT_w}{T_w IDT P KU_1 \delta T_w K TPZ} = \frac{b}{\dot{m}_w C_w} dx
\]

Solution of Eq. (4) for the initial condition \( T_{w,j} \) is given by

\[
\ln \left[ \frac{b U_1 x}{T_w JX} (T_w - T_a) \right] = \frac{b U_1 x}{\dot{m}_w C_w}
\]

Further

\[
T_w = \left\{ \frac{\tau_w}{U_L} (f(t)) + T_a \right\} \left( 1 - \exp \left( \frac{-U_L h x}{\dot{m}_w C_w} \right) \right) + T_{w,i} \exp \left( \frac{-U_L h x}{\dot{m}_w C_w} \right)
\]

at \( x = L \), \( T_{w,i} Z T_{w,o} \). The water temperature at outlet

\[
T_{w,o} = \sqrt{f(j)} + A_a (x - \exp (j/-)) + T_{w,i} \exp (j/-)
\]

Further average value of water temperature can be found as

\[
\overline{T_w} = \frac{1}{L10} \int_{0}^{L} T_w \ dx = \left\{ \frac{\tau_w}{U_L} (f(t)) + T_a \right\} \left( 1 - \exp \left( \frac{-AU_L h m_w C_w}{AU_L / \dot{m}_w C_w} \right) \right) + T_o \left( 1 - \exp \left( \frac{-AU_L h m_w C_w}{AU_L / \dot{m}_w C_w} \right) \right)
\]
The rate of heat loss due to water flow at exit will be determined as follows:

\[ q_{\text{u}} = \frac{\dot{m}_w C_w}{U_L} \left[ T_w/(0 \cdot \text{KL} \cdot \delta T_w \cdot \text{K} \cdot r_a) \right] \] for small value of \( \dot{m}_w \)

\[ = 0 \] for large value of \( \dot{m}_w \) \( (7) \)

The hourly yield is given by

\[ \dot{m}_{\text{ew}} \approx Z q_{\text{ewl}} \approx Z \frac{1}{3600} \approx T_g \approx Z \frac{\text{T}_{\text{g}}}{3600} \] \( (8) \)

The overall thermal efficiency of the distillate output and excess hot water can be written as

\[ \eta_o = \frac{\sum \dot{m}_{\text{ew}} \cdot \Delta + \sum q_u}{\sum t(\tau)}. \] \( (9) \)

The proposed mathematical model for the multiwick is valid both for the east and the west condensing surfaces for known climatic parameters, namely, solar intensity and ambient temperatures.

2.5. Convective heat transfer coefficients

Computer programmes have been developed in C language to predict the hourly water temperature, glass temperature, distillate output and various heat transfer coefficients for both the solar stills. This model takes the modified values of convective heat transfer coefficients based on both inner and outer glass temperatures, carries out the computations of all performance parameters, and then compares them with the experimental data. It finally brings out the percentage deviation between the experimental and theoretical results. Values of \( C \) and \( n \) for single and double slope multiwick solar stills (Table 7) have been evaluated based on the model by Kumar and Tiwari [14]. It uses the data given in

<table>
<thead>
<tr>
<th>Serial number</th>
<th>Time (h)</th>
<th>Intensity (W/m².°C)</th>
<th>Water temperature (°C)</th>
<th>Inner glass temperature (°C)</th>
<th>Outer glass temperature (°C)</th>
<th>Ambient temperature (°C)</th>
<th>Distillate output (ml)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>10:00</td>
<td>300</td>
<td>26.5</td>
<td>23.0</td>
<td>21.3</td>
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</tr>
<tr>
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<td>28.6</td>
<td>26.0</td>
<td>22.7</td>
<td>11.0</td>
<td>110</td>
</tr>
<tr>
<td>3</td>
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<td>30.0</td>
<td>26.7</td>
<td>12.5</td>
<td>118</td>
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<tr>
<td>4</td>
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<td>550</td>
<td>42.6</td>
<td>35.0</td>
<td>30.5</td>
<td>13.0</td>
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<td>5</td>
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<td>500</td>
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<td>37.8</td>
<td>33.2</td>
<td>12.0</td>
<td>260</td>
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<tr>
<td>7</td>
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<td>400</td>
<td>42.4</td>
<td>36.9</td>
<td>30.4</td>
<td>11.5</td>
<td>190</td>
</tr>
<tr>
<td>8</td>
<td>17:00</td>
<td>250</td>
<td>38.2</td>
<td>33.1</td>
<td>24.6</td>
<td>10.0</td>
<td>180</td>
</tr>
</tbody>
</table>
Table 6
Experimental observations of June 19, 2001 for double slope multiwick solar still (west)

<table>
<thead>
<tr>
<th>Serial number</th>
<th>Time (h)</th>
<th>Intensity (W/m² 8C)</th>
<th>Water temperature (8C)</th>
<th>Inner glass temperature (8C)</th>
<th>Outer glass temperature (8C)</th>
<th>Ambient temperature (8C)</th>
<th>Distillate output (ml)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>10:00</td>
<td>430</td>
<td>48.2</td>
<td>38.7</td>
<td>34.3</td>
<td>30.0</td>
<td>110</td>
</tr>
<tr>
<td>2</td>
<td>11:00</td>
<td>630</td>
<td>55.3</td>
<td>54.9</td>
<td>49.2</td>
<td>32.1</td>
<td>130</td>
</tr>
<tr>
<td>3</td>
<td>12:00</td>
<td>780</td>
<td>61.3</td>
<td>57.3</td>
<td>51.3</td>
<td>34.6</td>
<td>190</td>
</tr>
<tr>
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<td>13:00</td>
<td>730</td>
<td>68.2</td>
<td>62.2</td>
<td>57.2</td>
<td>37.0</td>
<td>340</td>
</tr>
<tr>
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<td>14:00</td>
<td>670</td>
<td>64.1</td>
<td>58.3</td>
<td>61.3</td>
<td>40.0</td>
<td>370</td>
</tr>
<tr>
<td>6</td>
<td>15:00</td>
<td>600</td>
<td>56.2</td>
<td>54.9</td>
<td>53.4</td>
<td>39.1</td>
<td>280</td>
</tr>
<tr>
<td>7</td>
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<td>38.2</td>
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<tr>
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<td>42.3</td>
<td>40.2</td>
<td>37.0</td>
<td>218</td>
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<td>9</td>
<td>18:00</td>
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<td>47.3</td>
<td>40.2</td>
<td>39.1</td>
<td>36.8</td>
<td>190</td>
</tr>
</tbody>
</table>

Tables 1-6 (summer and winter conditions). The results have been shown in Table 7. From Table 7, it can be seen that the value of $C$ and $n$ for single slope solar still is close to the value obtained by Dunkle. However, the value of $C$ and $n$ for east and west slope of multiwick solar still differs significantly (Table 7). Further, it is important to note that the values of $C$ and $n$ based on inner glass cover temperatures also differ significantly from the values of $C$ and $n$ based on outer glass cover temperatures.

Once the value of $C$ and $n$ are known, the convective heat transfer coefficient ($h_{cw}$) can be obtained from the following equation

$$Nu = \frac{h_{cw}d_f}{K_f} = C(Gr \times Pr)^n$$

Dunkle (1961) used the values of $C = 0.075$ and $n = 1/3$, and gave following expression for $h_{cw}$ for normal operating temperature range

$$h_{cw} = 0.884 \left\{ \frac{T_w - T_g}{\frac{\delta P_w K P_f \delta T_w C 273 P_l}{268.9 \times 10^3 K P_w}} \right\}^{1/3}$$

Table 7
$C$ and $n$ values

<table>
<thead>
<tr>
<th>Date</th>
<th>With inner glass temperature</th>
<th></th>
<th>With outer glass temperature</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$C$</td>
<td>$n$</td>
<td>$C$</td>
<td>$n$</td>
</tr>
<tr>
<td><strong>Single slope multiwick solar still</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>January 22, 2001</td>
<td>0.0777</td>
<td>0.378</td>
<td>0.0987</td>
<td>0.463</td>
</tr>
<tr>
<td>June 19, 2001</td>
<td>0.0762</td>
<td>0.336</td>
<td>0.0868</td>
<td>0.445</td>
</tr>
<tr>
<td><strong>Double slope multiwick solar still (east)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>January 22, 2001</td>
<td>0.0656</td>
<td>0.334</td>
<td>0.0686</td>
<td>0.523</td>
</tr>
<tr>
<td>June 19, 2001</td>
<td>0.0742</td>
<td>0.329</td>
<td>0.0887</td>
<td>0.583</td>
</tr>
<tr>
<td><strong>Multiwick solar still (west)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>January 22, 2001</td>
<td>0.0765</td>
<td>0.343</td>
<td>0.0676</td>
<td>0.431</td>
</tr>
<tr>
<td>June 19, 2001</td>
<td>0.0789</td>
<td>0.378</td>
<td>0.0972</td>
<td>0.564</td>
</tr>
</tbody>
</table>
The above equation has been applied to the data of Table 1 in order to evaluate the values of $h_{cw}$ based on Dunkle’s values of $C$ and $n$, for comparison with the proposed model. The variations of $h_{cw}$ for single slope multiwick solar still for a typical day of winter and summer have been shown in Fig. 3a and b, respectively.

It is clear that the values of $h_{cw}$ based on the inner glass cover temperature are greater than the values of $h_{cw}$ based on the outer glass cover temperature. It is due to fact that $(T_w - T_{gi})$ is small but has higher operating temperature. The value of $h_{cw}$ by present model is higher than value of $h_{cw}$ obtained by Dunkle (1961). The hourly variations of convective heat transfer coefficient ($h_{cw}$) obtained for calculated values of $C$ and $n$ corresponding to Table 7 have been shown in Figs. 3-5.

It is clear from Fig. 4, that the values of evaporative heat transfer coefficients for east condensing surface, obtained by using inner glass temperatures are greater than
Fig. 4. Hourly variation of convective, evaporative and radiative heat transfer coefficients for double slope multiwick solar still (east) in (a) January 22, 2001, (b) June 19, 2001.

those obtained by using outer glass temperatures during the same time period. The value of $h_{cw}$ is significantly higher under summer climatic conditions than winter climatic conditions. This is due to fact that the variation in solar intensity is greater in summer than in winter. Similar results have been obtained for west condensing cover as shown in Fig. 5.

For comparison, the hourly variations of $hrw$ and $h_{cw}$ for single and double slope multiwick stills in January and June 2001, respectively, have also been depicted in the same figures. It is clear from these figures that the radiative and convective heat transfer coefficients do not vary significantly for both, the inner as well as the outer glass temperatures, unlike evaporative heat transfer coefficient for single as well as double slope multiwick solar stills.
2.6. Performance studies: experimental validation

Following parameters have been used to compute the hourly water temperature, glass temperature and distillate output for the solar stills using the new calculated values of $C$ and $n$.

2.6.1. Design parameters

(i) For single slope multiwick solar still

\[ T_{wi} = 35 \, ^\circ C, \quad V = 1.0 \, m, \quad b = 1 \, m, \quad A_c = 1.0 \, m^2, \]

\[ h_{2g} = 10.0 \, W/m^2 K, \quad C_w = 4190 \, J/kg K, \quad T_w = 0.6, \quad a_b = 1.0, \quad \text{and} \]

\[ m_w = 1.67 \times 10^5 \, kg/m^2 s, \quad U_l = 6.0 \, W/m^2 K \]
(ii) For double slope multiwick solar still (east and west condensing surfaces)

\[ A = 1.1 \text{m}^2, \quad V = 1.0 \text{ m}=s, \quad T_{wi} = 34.8°C, \quad C_w = 4190 \text{ J/kg K}, \]

\[ U_l = 8 \text{ W/m}^2K, \quad h_{2g} = 10.0 \text{ W/m}^2, \quad a_b = 1.0; \quad \text{and} \]

\[ m_w = 1.94 \times 10^5 \text{ kg/m}^2s. \]

2.6.2. Climatic parameters

The hourly variation of ambient temperature and solar intensities falling on the stills in single and double slope multiwick solar still has been given in Tables 1-6. Eq. (6) has been

![Graph](image_url)
used to evaluate average water temperature for given climatic data of Tables 1-6 and heat transfer coefficients of Figs. 3-5. After knowing $T_w$, the corresponding glass cover temperature has been evaluated from Eq. (3a). Further, the hourly yield can be obtained from Eq. (8). The results for $f_w$ and $T_g$ for single slope multiwick solar still has been shown in Fig. 6.

The inner glass cover temperature for single slope multiwick solar stills is higher than outer glass cover temperature, as expected. It is due to fact that the rate of heat transfer takes place between water and inner surface of glass cover. Further, it is important to mention that the difference between inner and outer glass cover is more prominent in summer in comparison to winter.

The water temperature, calculated by using inner glass temperature gives a closer value to experimental water temperature (Fig. 6). The hourly yield can be calculated from Eq. (8). Further Eq. (9) has been used to compute an overall thermal efficiency of single and double slope multiwick solar stills. It is clear that the overall thermal efficiency of both solar stills in winter month is higher than summer month due to minimum heat loss at lower temperature (Tables 1-6). In winter single slope solar still gives higher efficiency in comparison with double slope solar still. It is due to fact that there is more reflection losses from double slope solar still in winter. The double slope multiwick solar still gives a higher efficiency in summer due to more reflection losses in single slope multiwick solar still.

**Appendix**

The various heat transfer coefficients ($h_s$) are defined as follows:

$$h_{lw} = h_{tw} + h_{cw} + h_{cw}$$

$$h_{tw} = e_{eff} \times \left([T_w + 273] \times \frac{C}{272} \times 2\right) \times \left([C \times \text{r} \times \text{cf} \times 546]\right)$$

$$h_{2g} = h_{cet} + e_{l}[T_e + 273] \times \left(-\left[T_e + 273\right] \times \delta T_e - T_e\right)$$

$$h_{c3} = 2.8 + 3.0 \text{ V}$$

$$r = \frac{c}{h} \text{ h C T_w; h}_{lw} = h_{lw} \text{ C h}$$

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

$$h_{cw} = \frac{K \times \text{Pr} \times \text{Gr} \times \text{Pr} \times \text{Pr} \times \text{Pr}}{d_i}$$

$$Gr = \frac{d_i^3 \times \text{Pr} \times \text{Pr} \times \text{Pr} \times \text{Pr} \times \text{Pr}}{h_i^2}$$
\[ \Delta T' = \left[ (T_w - T_g) + \frac{\delta P_s K P g \delta T_w C 273 F}{P C 268.9 ! 10^{-7} ! P_w} \right] \]

\[ h_{rw} = \frac{P K P}{16.273 ! 10K^{-3} h_{cw} P_w K P g \frac{L_i}{L_i}} \]

\[ K = \left[ \frac{1}{K_i / L_i} + \frac{1}{h_{cw} C h_{cb}} \right] \]

References