THERMAL EVALUATION OF REGENERATIVE ACTIVE SOLAR DISTILLATION UNDER THERMOSYPHON MODE

A. K. SINGH and G. N. TIWARI†

Centre for Energy Studies, Indian Institute of Technology, Delhi, Hauz Khas, New Delhi-110016, India

(Received 23 March 1992; received for publication 14 October 1992)

Abstract—The thermal performance of a regenerative active solar distillation system working under the thermosyphon mode of operation has been studied for a Delhi climatic condition. The effects of climatic and system design parameters have been incorporated in the basic energy balance equations for each component of the system. The studies have been made in terms of overall thermal efficiency as well as hourly yield from the system. On the basis of the numerical results, it is concluded that (i) there is a significant improvement in overall performance due to water flow over the glass cover and (ii) the hot water available due to the regenerative effect does not enhance the output.

Regenerative solar still Solar distillation Purification of water

NOMENCLATURE

\( A_0 \) = Basin area (m²)
\( A_c \) = Area of collectors (m²)
\( A_s \) = Area of side of basin with water (m²)
\( b \) = Breadth of basin (m)
\( C_w \) = Specific heat of water (J/kg °C)
\( dx \) = Elemental thickness along x (m)
\( H_\text{g} \) = Solar radiation available over glazing of still (W/m²)
\( H_\text{g}' \) = Solar radiation available on inclined surface of collector (W/m²)
\( h_\text{bo} \) = Overall bottom heat loss coefficient from basin liner to ambient through bottom insulation (W/m²°C)
\( h_\text{e} \) = Convective heat transfer coefficient from water surface to glass (W/m²°C)
\( h_\text{ev} \) = Evaporative heat transfer coefficient from water surface to glass cover (W/m²°C)
\( h_\text{r} \) = Radiative heat transfer coefficient from water surface to glass cover (W/m²°C)
\( h_\text{t} \) = Total heat transfer coefficient from water surface to glass cover (W/m²°C)
\( h_\text{t1} \) = Total heat transfer coefficient from lower glass to water flowing over glass cover (W/m²°C)
\( h_\text{t2} \) = Total heat transfer coefficient from flowing water surface to glass cover over it (W/m²°C)
\( h_\text{ct} \) = Convective and radiative heat transfer coefficient from glass cover to ambient (W/m²°C)
\( h_\text{hc} \) = Convective heat transfer coefficient from basin liner to water mass (W/m²°C)
\( K_\text{r} \) = Thermal conductivity of glass (W/m °C)
\( L \) = Length of solar still (m)
\( L_\text{g} \) = Thickness of glass (m)
\( \gamma \) = Latent heat of vaporization of water (J/kg)
\( M \) = Water mass in basin (kg)
\( m_\text{h} \) = Hourly yield from still (kg/m² h)
\( m_\text{w} \) = Water flow rate between glazings (kg/s)
\( P_\text{e} \) = Saturated partial vapour pressure at water temperature at \( t = 0 \)
\( P_\text{p} \) = Saturated partial vapour pressure at glass temperature at \( t = 0 \)
\( Q_\text{r} \) = Useful heat available from panel of collectors (W/m²)
\( R_\text{r} \) = Reflectivity of glass cover
\( R_\text{ct} \) = Reflectivity of water surface
\( T_\text{a} \) = Ambient temperature (°C)
\( T_\text{b} \) = Basin temperature (°C)
\( T_\text{g} \) = Glass temperature at time \( t \) (°C)
\( T_\text{w} \) = Water temperature at time \( t \) (°C)
\( T_\text{wo} \) = Water temperature at \( t = 0 \) (°C)
\( T_\text{w1} \) = Temperature of water flowing between glazings (°C)
\( T_\text{w2} \) = Temperature of water flowing between glazings at \( x = 0 \) (°C)
\( t \) = Time (s)

\( (UA) \) = Overall heat transfer coefficient from absorbing plate of collector to ambient through glass cover and bottom insulation (W/°C)

†To whom all correspondence should be addressed.
(UA)_{hx} = \text{Overall heat transfer coefficient from working fluid in heat exchanger to water in basin (W/°C)}

(UA)_{xt} = \text{Overall heat transfer coefficient from working fluid in connecting pipe to ambient (W/°C)}

v = \text{Wind velocity (m/s)}

(ατ) = \text{Product of absorptivity of collector plate and transmittivity of glass cover}

α_b = \text{Absorptivity of basin liner}

α_c = \text{Absorptivity of glass cover}

α_w = \text{Absorptivity of water mass}

τ_b = \text{Fraction of energy absorbed by basin liner}

τ_c = \text{Fraction of energy absorbed by glass cover}

τ_w = \text{Fraction of energy absorbed by water mass}

μ = \text{Fraction of solar radiation having extinction coefficient η}

η = \text{Extinction coefficient}

η_o = \text{Efficiency of solar still}

**INTRODUCTION**

The basic classifications of a solar still have been given in Table 1. The work on passive solar stills, until 1980, has been reviewed by Malik et al. [1] which includes various designs and their performances, economic viability of conventional solar distillation processes over other methods and applications of conventional solar distillation for enhancement of agricultural products, etc. In order to increase the overall yield l/m² day at higher operating temperature, Rai and Tiwari [2] have studied the performance of a conventional solar still integrated with a collector panel, generally referred to as active solar distillation, under a forced circulation mode of operation. Later on, Lawrence and Tiwari [3] have extended the work on active solar distillation for the natural circulation mode of operation with a heat exchanger. Further, Kudish [4] and Wibulsaw and Suntrirat [5] have suggested the idea of the flow of water over the glass cover and the back wall of the conventional solar distillation system and reutilizing the heated water in the basin, which is called the regenerative solar still system, for further enhancement of output. Recently, Tiwari [6] has reviewed the work of the varieties of passive and active solar distillation systems working under different modes of operation. It also includes the basic internal heat and mass transfer relation in the solar distillation process for all operating temperature ranges. It can be observed that the flow water temperature cannot be higher than the basin water temperature, and hence, there is no need to feed the heated water into the basin. Further, it is important to mention here that the overall performance of the system is increased due to the flow of water over the glass cover as well as over the back wall of the system due to fast utilization of the stored thermal energy in the water.

In this communication, a thermal model of a solar still [Fig. 1(a)] coupled with solar collectors acting under a thermosyphon mode of operation with a flow of water along the length of glazing of the still between two glass covers of the still has been given. The overall thermal efficiency of this proposed system has been studied, which is based on the energy balances of the different components of the system. A comparative study has also been done for passive and active solar stills with and without mass flow over the glazing.

**THEORETICAL STUDY**

The following assumptions have been made in writing the energy balance equations of the system [Fig. 1(a)]:

(i) The heat capacity of the glass cover, insulating material, working fluid in the collector, heat exchanger and collector is very small.

<table>
<thead>
<tr>
<th>Table 1. Basic classification of solar distillation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solar distillation</td>
</tr>
<tr>
<td>Passive solar still</td>
</tr>
<tr>
<td>Active solar still</td>
</tr>
<tr>
<td>Conventional solar still</td>
</tr>
<tr>
<td>Other designs of solar still</td>
</tr>
<tr>
<td>Forced circulation mode</td>
</tr>
<tr>
<td>Natural circulation mode</td>
</tr>
<tr>
<td>Regenerative</td>
</tr>
<tr>
<td>Non-regenerative</td>
</tr>
</tbody>
</table>
The energy balances of the system are as follows:

**Flowing water**

\[
m_{wa} C_w \frac{dT_{wa}}{dx} \; dx = b \; dx \left[ h_1 (T_a - T_{wa}) - h'(T_{wa} - T_a) \right]
\]

**Lower glass cover**

\[
h_1 (T_w - T_a) = h'_1 (T_a - T_{wa})
\]
Basin liner

\((\alpha T)_b H_i = h_3(T_b - T_a) + h_6(T_b - T_s)\)  \((3)\)

Water mass

\((\alpha T)_w H_i + h_{3b}(\alpha T)_b H_i - U_{3b}(T_w - T_s) + Q_\zeta = M_w C_w \frac{dT_w}{dt} + h_1(T_w - T_s) + h_6(T_w - T_s) \frac{A_i}{A_b}\)  \((4)\)

where

\[ h_1 = h_{rw} + h_{cw} + h_{ew} \]
\[ h_{rw} = \frac{[(T_w + 273)^4 - (T_s + 273)^4]}{(T_w - T_s)} \]
\[ h_{cw} = 0.884 \left( \frac{(T_w - T_s)}{(T_s - T_0)} + \frac{(P_\text{a} - P_\text{b})(T_w + 273)}{268.9 \times 10^3 - P_w} \right)^{1/3} \]
\[ h_{ew} = 0.016 \times h_{cw} \times \frac{(P_\text{a} - P_\text{b})}{(T_s - T_0)} \text{ (Tiwari et al. [8])} \]
\[ h_2 = 5.7 + 3.8V \text{ (Duffie and Beckman [7])} \]

\[ h' = \left( \frac{1}{h_1} + \frac{h_2}{h_3} + \frac{1}{h_2} \right)^{-1} \]
\[ h_{11} = \frac{h_1 h_3}{(h_1 h_3)^{1/2}} ; \quad h_{3b} = \frac{h_3}{(h_3 + h_6)} ; \quad U_{3b} = \frac{h_3 h_6}{(h_3 + h_6)} \]

\((\alpha T)_b = \alpha_3 (1 - \alpha_0) \sum \mu_i \exp(-n_i L_1)(1 - R_w)(1 - R_s) (1 - R_3)\)  \((\text{Tiwari et al. [9]}\)\)

\((\alpha T)_w = [1 - \alpha_0 (1 - \alpha_0) \sum \mu_i \exp(-n_i L_1)](1 - R_w)(1 - R_s) (1 - R_3)\)

\[ Q_\zeta = F'[C_1(\alpha T)H_i A_c - C_2(UA)_k(T_w - T_s)]/A_b \text{ (Webster et al. [10])} \]

\[ C_1 = \frac{(UA)_{hx}}{(UA)_{hx} + (UA)_{hp} + F'(UA)_c} \]
\[ C_2 = C_1 + \frac{(UA)_p}{(UA)_{hx} + (UA)_{hp} + F'(UA)_c} \]

After solving equation (2), one gets:

\[ T_w = \frac{h_1 T_w + h'_1 T_{mo}}{h_1 + h'_1} \]  \((5)\)

and using equation (1), one gets:

\[ \frac{dT_w}{dx} + HT_w = f_i(t) \]

where

\[ H = \frac{b(h_{11} + h')}{m_w C_w} \]

\[ f_i(t) = \frac{bh_{11} T_w + bh' T_s}{m_w C_w} \]

or

\[ T_w = \frac{f_i(t)}{H} (1 - e^{-Hx}) + T_{w0} e^{-Hx}. \]  \((6)\)
The average of $T_w$ over the length of the lower glazing is defined with a condition $T_{w1}/T_0 = T_{w0}$ as

$$T_{w0} = \frac{1}{L} \int_0^L T_w \, dx = \left( \frac{h_{11}}{h_{11} + h'} T_w + \frac{h'}{h_{11} + h'} T_s \right) \left( 1 - \frac{1 - e^{-HL}}{HL} \right) + T_{w0} \frac{1 - e^{-HL}}{HL}. \quad (7)$$

Equation (4) can be written as

$$\frac{dT_w}{dt} + a T_w = f(t).$$

The average of $T_w$ over a time $t$ is defined with a condition $T_{w1}/T_0 = T_{w0}$ as

$$\bar{T}_w(t) = \frac{1}{t} \int_0^t T_w \, dt = \frac{f(t)}{a} (1 - e^{-at}) + T_{w0} e^{-at} \quad (8)$$

where

$$f(t) = \frac{1}{M_u C_w} \left( (\alpha T_w H_s + h_{1b}(\alpha T_b)H_s + U_{1b}T_s + h_b T_s) \frac{A_t}{A_b} \right. \left. + \frac{h_{11} h'}{(h_{11} + h')} \left\{ \left( 1 - \exp(-HL) \right) \right\} \left( \frac{A_t}{A_b} \right) \left( C_1(\alpha T_w H_s + C_2(UA)_b T_s) + C_3(\alpha T_b)H_s \right) \right)$$

$$+ \frac{h_{11} h'}{(h_{11} + h')(h_{11} + h')} \left\{ \frac{1 - (1 - e^{-HL})}{HL} \right\} T_s \quad (9)$$

and

$$a = \frac{1}{M_u C_w} \left\{ h_1 + h_b \frac{A_t}{A_b} + U_{1b} - \frac{h_1}{(h_{11} + h')} - \frac{h_{11} h'}{(h_{11} + h')(h_{11} + h')} \left\{ \frac{1 - (1 - e^{-HL})}{HL} \right\} \left( \frac{f^2 C_3(UA)_b}{A_b} \right) \right\}. \quad (10)$$

With the help of equations (8) and (7), $T_{w0}$ can be calculated in terms of $T_w$, and then $T_s$ can be calculated in terms of $T_w$ from equation (5). These values of $T_{w0}$, $T_s$, and $T_w$ are used to calculate $h_1$ for the next set of observations and so on.

The yield during the time interval $(0-t)$ can be evaluated as

$$m = \frac{h_{w0}}{\mathcal{L}} (T_w - T_s) t. \quad (11)$$

During off-sunshine hours:

$H_s$, $H_s'$ and $Q_c$ are taken to be zero and then the basic equations (1)–(4) can be solved similarly to obtain $T_{w0}$, $T_s$ and $T_w$. The overall efficiency of the solar still can be written as follows:

(a) Without collector:

$$\eta_w = \frac{\sum m \cdot \mathcal{L}}{A_b \sum H_s t} \times 100 \quad (12)$$

and

(b) With collector:

$$\eta_w = \frac{\sum m \cdot \mathcal{L}}{A_b \sum H_s t + A_c \sum H_s' t} \times 100. \quad (13)$$

RESULTS AND DISCUSSION

In order to study the performance of regenerative active solar distillation under the thermosyphon mode, the following parameters have been used:

(a) Solar still

$$\alpha = 0.8, \quad \bar{\alpha} = 0.8, \quad R_s = \bar{R} = \bar{\alpha} = 0.05,$$

$$M_w = 100, 80, 60 and 40 \text{ kg}; \quad C_w = 4190 \text{ J/kg °C}; \quad \mathcal{L} = 2.25 \times 10^4 \text{ J/kg};$$
\( A_t = 0.4, \ 0.32, \ 0.24, \ 0.16 \text{ m}^2; \quad A_b = 1 \text{ m}^2; \quad h_2 = 24.7 \text{ W/m}^2 \text{ °C}; \)
\( h_1 = 135 \text{ W/m}^2 \text{ °C}; \quad h_b = 0.8 \text{ W/m}^2 \text{ °C}; \quad L_q = 3.0 \times 10^{-3} \text{ m}; \)
\( K_q = 0.78 \text{ W/m °C}; \quad H_t = 100 \text{ W/m}^2 \text{ °C}; \quad H_i = 100 \text{ W/m}^2 \text{ °C}. \)

During the calculation of the very first value of \( h_1 \), we have assumed \( T_u = T_s + 5.0 \) and \( T_e = T_s + 3.0 \). And at every calculation of \( h_1 \), the value of \( T_{wst} \) has been assumed to be equal to \( T_s \) for the corresponding hour.

(b) Flat-plate collector

\( F^* = 0.8; \quad A_b = 3.47 \text{ m}^2; \quad (\pi \tau) = 0.8; \quad (UA)_c = 12.0 \text{ W/°C}; \)
\( (UA)_p = 12.9 \text{ W/°C}; \quad (UA)_p = 2.62 \text{ W/°C}; \quad (UA)_bs = 11 \text{ W/°C}. \)

The solar intensity incident on both the collector and solar still has been assumed to be the same because the difference between the inclinations to the horizontal of the two receivers is very small. The hourly variations of solar intensity and ambient temperature have been shown in Fig. 2.

In Fig. 3 the hourly variation of the lower basin water temperature \( (T_w) \), lower glass temperature \( (T_g) \) and temperature \( (T_{wst}) \) of the water flowing between the two glasses of the solar still has been shown for a fixed water flow rate \( (m_{wst}) \) and water depth in the lower basin. The value of the temperature \( (T_{wst}) \) is always less than that of \( T_w \) at any time for any flow rate, which is clear from Fig. 3. So, it is not advisable to feed the flowing water (between the glasses of the still) to the lower basin of the still for enhancement of yield as suggested by Kudish [4].

Figure 4 shows that hourly variation of convective \( (h_{eq}) \), radiative \( (h_{eq}) \), evaporative \( (h_{eq}) \) and total heat transfer \( (h_t) \) coefficients from water in the lower basin to the lower glass of the solar still for a fixed water flow rate \( (m_{wst}) \) and water depth in the lower basin. There is no significant variation of the convective and radiative heat transfer coefficients, but the evaporative heat transfer coefficient and, hence, the total heat transfer coefficient vary significantly with hour of the day. The hourly yield has also been shown in Fig. 5. The nature of the curve is similar to that of Fig. 4, as expected.

![Fig. 2. The hourly variation of solar intensity and ambient temperature.](image-url)
Fig. 3. The hourly variation of lower basin, lower glass, flowing water and upper glass temperatures.

Fig. 4. The hourly variation of convective ($h_{cg}$), radiative ($h_{rg}$), evaporative ($h_{ev}$) and total ($h_t$) heat transfer coefficients.
Fig. 5. The hourly yield of the system.

Fig. 6. The variation of overall thermal efficiency with flow rate of water ($m_{\text{in}}$).
The dependence of the overall thermal efficiency on the flow rate of water ($M_{wv}$) between the two glasses of the solar still has been shown in Fig. 6. The overall thermal efficiency increases with increase of the mass flow rate ($M_{wv}$) because the increase in mass flow rate lowers the temperature of the lower glass significantly and, thus, helps in faster condensation of the distillate on the lower surface of the lower glass. The effect of $M_{wv}$ on the temperature of the water ($T_w$) in the lower basin of the solar still is less than that on $T_{wv}$, hence there is a greater difference between the temperatures of the lower basin water and the lower glazing (which is responsible for faster evaporation) than what would have been in the absence of the mass flow between the glasses of the solar still [3].

A comparative study (Fig. 7) between the solar still without collector and mass flow (curve passive conventional still in Fig. 7), the still with collector but without mass flow (curve active conventional still in Fig. 7), the still with mass flow rate but without collector (curve passive regenerative still in Fig. 7) and the still with mass flow rate as well as collector (curve active regenerative still in Fig. 7) has been done.

The overall thermal efficiency (Fig. 7) of the passive and active conventional stills decreases with increase of depth of water mass in the lower basin because of the increase of stored thermal energy in the water mass. After a certain depth in water mass, the overall thermal efficiency of both passive and active conventional stills becomes constant because the fraction of thermal energy available for storage in the water mass has its limit. The overall thermal efficiency of the passive and active regenerative stills decreases with increase of water mass depth in the lower basin, again because of the stored thermal energy in the water mass. In regenerative stills, the efficiency is not becoming constant after a certain depth because, although the fraction of thermal energy available for storage in the water mass has a maximum limit, due to the water flow on the glazing and faster evaporation, the water mass has the storage capacity at large depth also. The overall efficiency of the active stills (conventional and regenerative) is lower than that of the passive stills (conventional and regenerative) at any common depth because the active stills are operating at higher temperatures.
REFERENCES