Optimization of collector and basin areas for a higher yield for active solar stills

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Abstract

This communication presents a thermal analysis of an active solar still for the optimization of collectors as well as the basin area for a higher yield for a given water depth. Expressions for the temperatures, the water and glass covers and the yield have been derived. In order to have numerical appreciation of the results, meteorological data for a summer day of Delhi climate have been used. It has been observed that the optimization is a strong function of water depth.

Keywords: Solar distillation; Purification of water; Solar energy

1. Introduction

The performance of a solar distillation system is governed by the rate of evaporation from the water surface in the basin. This depends on the water and glass cover temperature difference. The rate of evaporation can be maximized by increasing the temperature difference between the water and glass cover. This is achieved either by passive or active modes. Several researchers [1,2] have reviewed the work on solar distillation systems. There are various active methods:

- Nocturnal production — the feeding of hot water into the basin once in a day in the morning/evening [3–5]
- Pre-heated water application — the feeding of hot water into the basin at a constant flow rate either continuously or intermittently [6,7]
- High temperature distillation — the feeding of hot water into the basin from the collector panel [8–13].

However, no optimization of either collector or basin area was carried out by any one of authors. In this communication an attempt has been made to optimize the collector/basin area for a given climatic condition and other design
parameters. Basic energy balance equations have been used for analytical solutions for water and glass cover temperatures and hourly yield. The overall thermal efficiency of an active system has also been defined. Numerical computations have been carried out for a typical day (15 June 1996) in Delhi. On the basis of numerical results, it is inferred that the optimum number of collectors for maximum yield are 8m² for a 1 m² basin area for 0.15 m water depth in the basin.

2. Energy balances

In order to write the energy balance for different components of this system (Fig. 1), the following assumptions have been made:

1. Inclination of the glass cover is small.
2. The heat capacity of the glass cover and insulating and conductive materials of the solar still and collectors are negligible.
3. The system is perfectly insulated from the side and bottom.

![](image)

Fig. 1. Schematic view of a solar still coupled with a flat plate collector.

4. The solar distiller unit is vapour leakage proof, etc.

The energy balance for different components of number of collectors coupled with solar still are as follows:

- Glass cover:

  \[ \alpha_g I(t) A_s + h_{lw} (T_w - T_g) A_s = h_{lg} (T_g - T) \]  
  \[ (1) \]

- Water mass:

  \[ [\alpha_w I(t) + h_w (T_s - T_w)] A_s \]

  \[ = \left( m_w C_w \right) \frac{dT_w}{dT} + h_{lw} (T_w - T_a) A_s \]  
  \[ (2) \]

- Basin liner:

  \[ \alpha_b I(t) A_s = h_w (T_b - T_w) A_s + h_b (T_a - T_b) A_s \]  
  \[ (3) \]

where

\[ Q_{UN} = A_{CN} F_R \left[ (\alpha \tau)_{ef} I'(t) - U_L (T_w - T_a) \right] \]

\[ m_w = A_s \times d_w \times \rho \]

and the expressions for various heat transfer coefficients are given in the appendix.

After substituting the values for \( T_g \) and \( T_b \) from Eqs. (1) and (3) in Eq. (2) and simplifying, the result may be expressed as follows:

\[ \frac{dT_w}{dT} + a T_w = f(t) \]  

\[ a = \frac{U_L f(t)}{m_w C_w} \]
\[ U_L' = A_{CN} F_{RN} + U_{1b} A_S + U_{1g} \]

\[ U_{1b} = \frac{h_{1w} h_b}{h_w + h_b} \]

\[ U_{1g} = \frac{h_{1w} h_{1g}}{h_{1w} + h_{1g}} \]

\[ f(t) = \]

\[ \frac{\left[A_{CN} F_{RN} (\alpha_g) \gamma'(t) + \left(\alpha_{g'} + \alpha_{h'} + \alpha_{h} \right) \bar{I}(t) A_g\right] + U_L T_a}{m_w C_w} \]

\[ h = \frac{H_{1w}}{h_w + h_b} \]

and

\[ h' = \frac{h_{1w}}{h_{1w} + h_{1g}} \]

The coefficient \( h_{1w} \) can be evaluated at known values of initial water and glass temperature at \( t = 0 \) i.e. \( T_{w_{i-o}} = T_{w_0}, \ T_{g_{i-o}} = T_{g_0} \)

In order to obtain an approximate analytical solution to Eq. (4), the following assumptions have been made:

- the taking interval \( \Delta t = t-0 \) is small
- \( f(t) \) is considered as \( f(t) \) for time interval \( 0-t \)
- \( a \) is constant during \( \Delta t \).

Now the solution to Eq. (4) is

\[ T_w = \frac{\bar{f}(t)}{a} \left[1 - \exp(-at) + T_{w_0} \exp(-at)\right] \quad (5) \]

Now the average water temperature is given by

\[ \bar{T}_w = \frac{1}{t} \int_0^t T_w \, dt \]

\[ \bar{T}_w = \frac{\bar{f}(t)}{a} \left[1 - \frac{1 - \exp(-a\Delta t)}{a\Delta t}\right] \]

\[ + T_{w_0} \left[1 - \frac{1 - \exp(-a\Delta t)}{a\Delta t}\right] \quad (6) \]

After knowing \( T_g \) can be obtained from Eq. (1),

\[ \bar{T}_g = \frac{\alpha_g \bar{I}(t) + h_{1w} \bar{T}_w + h_{1g} \bar{T}_a}{(h_{1w} + h_{1g})} \quad (7) \]

The basic internal heat transfer coefficient can be further evaluated for known \( T_w \) and \( T_g \) for the next set of computations. Eqs. (6) and (7) can be used to evaluate the hourly yield as follows:

\[ \dot{m}_{ew} = \frac{h_{ew} (T_w - T_g) \times 3600}{L} \quad (8) \]

where

\[ L = 2.4935 \times 10^6 \left(1 - 9.4779 \times 10^{-4} T + 1.3132 \times 10^{-7} T^2 - 4.7974 \times 10^{-9} T^3 \right) \]

The overall daily thermal efficiency for active solar still is defined as

\[ \eta = \sum \frac{\dot{m}_{ew} \times L}{\sum I(t) A_s + \sum I'(t) A_C} \times 3600 \quad (9) \]
4. Results and discussion

The following design parameters have been used for numerical computations of Eqs. (6)–(9):

\[ A_c = 2 \text{ m}^2, \quad A_s = 1 \text{ m}^2, \quad N = 1\text{–}5 \]

\[ C_p = C_w = 4190.0 \text{ J/kg}^\circ\text{C} \]

\[ d_w = 0.15 \text{ m}, \quad F' = 0.7, \quad h_{ig} = 20.7 \text{ W/m}^2 \]

\[ U_L = 8 \text{ W/m}^2, \quad v = 4 \text{ m/s}, \quad L = 2.345 \times 10^3 \text{ J/kg} \]

\[ m = 50 \text{ kg/h}, \quad \beta = 45^\circ \]

The hourly variation of solar intensity and ambient temperature are shown in Fig. 2. They have been used to calculate intensity on the collector surface by using the Liu and Jordan formula [14]. Figs. 3–7 show hourly variations of the water and glass cover temperatures, internal heat transfer coefficients and the yield for different basin areas for a given number of collectors and water depths in the basin. It was observed that the temperatures of the water decrease with an increase of basin area due to the large storage capacity of the water mass in the basin. Therefore, there are reductions in the variation of the internal heat transfer coefficients (Figs. 4–6) and the yield (Fig. 7). The effect of the number of collector areas on the hourly yield is shown in Fig. 8. It is clear that the yield increases with increase of number of collectors, as expected, due to more heat transfer from the collector panel into the basin.

Fig. 2. Hourly variation of solar intensity and ambient temperature.

Fig. 3. Hourly variation of water and glass temperatures. \( A_c = 2 \text{ m}^2, \quad N = 5, \quad d_w = 0.15 \text{ m}. \)

Fig. 4. Hourly variation of radiative heat transfer coefficient. \( A_c = 2 \text{ m}^2, \quad N = 5, \quad d_w = 0.15 \text{ m}. \)
Fig. 5. Hourly variation of convective heat transfer coefficient. \(A_s = 2 \text{ m}^2, N = 5, d_w = 0.15 \text{ m.}\)

Fig. 6. Hourly variation of evaporative heat transfer coefficient. \(A_s = 2 \text{ m}^2, N = 5, d_w = 0.15 \text{ m.}\)

Fig. 7. Hourly variation of yield. \(A_s = 2 \text{ m}^2, N = 5, d_w = 0.15 \text{ m.}\)

Fig. 8. Hourly variation of yield. \(A_s = 1 \text{ m}^2, A_r = 2 \text{ m}^2, d_w = 0.15 \text{ m.}\)

The variation of the daily yield with water depth for a given number of collectors is shown in Fig. 9. It shows the decrease of yield with water depth due to large storage capacity. Figs. 10 and 11 show the effect of the number of collector areas and basin area on daily yield, while the overall efficiency curve is shown in Fig. 12. The increase of yield with number of collector further shows the greater transfer of thermal energy from the collector panel (Fig. 10). The optimum number of collectors for maximum yield is 8 m\(^2\) because the increase in gain becomes lower than thermal loss.
Fig. 9. Variation of daily yield vs. water depth. $A_s=1\text{m}^2$, $A_c=2\text{m}^2$, $N=5$.

Fig. 10. Variation of daily yield vs. number of collectors. $A_s=1\text{m}^2$, $A_c=2\text{m}^2$, $d_w=0.15\text{m}$.

Fig. 11. Variation of daily yield vs. still area. $A_s=2\text{m}^2$, $N=5$, $d_w=0.15\text{m}$.

(Fig. 12a). The daily yield and overall thermal efficiency decrease with an increase of basin area due to the large thermal storage capacity for a given depth of water (Figs. 11 and 12b).

5. Symbols

$a_c$ — Area of the solar collector, $\text{m}^2$
$a_s$ — Basin liner area of the solar still, $\text{m}^2$
$a_s'$ — Side area of the solar still, $\text{m}^2$
$c_w$ — Specific heat of water in the solar still, $\text{J/kg.C}$
$c_f$ — Specific heat of fluid through the collector, $\text{J/kg.C}$
$d_w$ — Depth of the water mass, $\text{m}$
$f_{RW}$ — Collector heat removal factor
$f'$ — Collector efficiency factor
$h_b$ — Overall heat transfer coefficient from the basin liner to an ambient air through bottom and side insulation, $\text{W/m}^2\text{C}$
$h_{ig}$ — Convective heat transfer coefficient from the glass cover to an ambient air, $\text{W/m}^2\text{C}$
$h_{iw}$ — Total heat transfer coefficient from the water surface to the glass cover, $\text{W/m}^2\text{C}$
$h_a$ — Convective heat transfer coefficient from the basin liner to the water, $\text{W/m}^2\text{C}$
**Greek**

- $\alpha$ — Absorptivity
- $\alpha_w$ — Fraction of solar flux absorbed by the basin liner
- $\alpha_w'$ — Fraction of solar flux absorbed by the water mass
- $\alpha_g'$ — Fraction solar flux absorbed by the glass cover
- $(\alpha\tau)_{eff}$ — Fraction of energy transferred to the water in the basin
- $\eta$ — Efficiency of still
$\Delta t$ — Temperature difference, °C

$\sigma$ — Stefan-Boltzmann constant, 5.67×10^{-8}, W/m²K

**Subscripts**

$w$ — Water

$g$ — Glass cover

$b$ — Basin liner

$N$ — Number of collectors

**Appendix**

In Eqs. (1), (2) and (3), different heat transfer coefficients are as follows:

$h_{1g} = 5.7 + 3.8 \nu [14]$  

$h_{1w} = h_{ow} + h_{rw} + h_{ew}$

$h_{cw} = 0.884 \left( \frac{(T_w-T_g) + (P_w-P_g)}{(T_w + 273)} \right)$

$h_{rw} = \frac{e_{str} \sigma \left[ (T_w + 273)^4 - (T_g + 273)^4 \right]}{(T_w - T_g)}$

$h_{ow} = 16.273 \times 10^{-3} h_{cw} \times \left( \frac{P_w - P_g}{(T_w - T_g)} \right)$

where the expressions for saturated vapour pressure as a function of temperature (°C) are as follows [13]:

$P_w = \exp \left[ 25.317 - 5144 / (T_w + 273.15) \right]$  

$P_g = \exp \left[ 25.317 - 5144 / (T_g + 273.15) \right]$  

The useful energy of $N$ collectors is:

$$\hat{Q}_{UN} = \dot{m}_{CF} (T_{fon} - T_f)$$

where

$$T_{fon} = \left[ \frac{(\alpha T_f(t))}{U_L} + T_f \right] \left[ 1 - \exp \left( -\frac{NA_c U_L F}{\dot{m}_{CF}} \right) \right]$$

$$+ T_f \exp \left( -\frac{NA_c U_L F}{\dot{m}_{CF}} \right)$$

Then

**References**


\[
\dot{Q}_{UN} = A_{CN} F_{RN} \left[ (\alpha \tau) \Gamma(t) - U_L (T_r - T_o) \right]
\]

where

\[
F_{RN} = F_R \left[ 1 - \frac{1 - K_K}{NK_K} \right]
\]

where

\[
K_K = \frac{A_C F_R U_L}{m_{CF}}
\]

But the \( N \) collector connected in series:

\[
\dot{Q}_{UN} = A_{CN} F_{RN} \left[ (\alpha \tau) \Gamma(t) - U_L (T_w - T_o) \right]
\]

In the above equation, \( T_r = T_w \). Then,