A LOW COST SOLAR WATER HEATER SUITABLE FOR RURAL, AS WELL AS URBAN, AREAS OF VIETNAM

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Abstract—The built-in-storage type of solar water heater will be suitable for rural as well as urban areas of Vietnam, in general, and the Hanoi region, in particular (mainly for domestic purposes). In this paper, a thermal model for optimisation of the design parameters and estimation of the effect of various parameters on the thermal performance of this solar water heater is presented. The paper also presents the numerical computations with the climatic conditions of the Hanoi region for three cases: (i) using a horizontal collector; (ii) using a sloped collector without reflector; and (iii) using a sloped collector with reflectors. On the basis of the numerical computations, conclusions for the application of this solar water heater in Vietnam have been made.

Key words: Solar water heater  Solar energy  Built-in-storage

NOMENCLATURE

- $A_s$: Absorber area (m$^2$)
- $A_r$: Side area of water heater (m$^2$)
- $A_{ab}$: Reflector area (m$^2$)
- $b$: Breadth of blackened surface (m)
- $d$: Depth of water (m)
- $h$: Total heat loss coefficient from blackened surface to glass cover (W/m$^2$ K)
- $h_{g}$: Total heat loss coefficient from glass cover to ambient (W/m$^2$ K)
- $h_{w}, h_{r}$: Heat loss coefficient from blackened surface to water by natural convection (W/m$^2$ C)
- $h_{b}$: Convective heat transfer coefficient from blackened surface to glass cover (W/m$^2$ C)
- $h_{g}$: Convective heat transfer coefficient from glass cover to ambient (W/m$^2$ C)
- $h_{w}$: Total heat loss coefficient from water to ambient through insulation (W/m$^2$ C)
- $h_{r}$: Radiative heat transfer coefficient from blackened surface to glass cover (W/m$^2$ C)
- $h_{w}$: Radiative heat transfer coefficient from glass cover to ambient (W/m$^2$ C)
- $I_r$: Beam radiation (W/m$^2$)
- $I_d$: Diffuse radiation (W/m$^2$)
- $I_{ho}$: Total radiation on horizontal surface (W/m$^2$)
- $I_{ht}$: Total radiation on tilted surface (W/m$^2$)
- $K_a$: Thermal conductivity of air (W/m C)
- $K_{g}$: Thermal conductivity of glass (W/m C)
- $L$: Thickness of glass cover (m)
- $L_e$: Thickness of insulation (m)
- $L_t$: Length of blackened surface (m)
- $L$: Length of blackened surface (m)
- $M$: Water mass (kg)
- $R$: Ratio of average daily direct radiation on tilted surface to that on horizontal surface
- $T_{a}$: Ambient temperature (°C)
- $T_{b}$: Temperature of blackened surface (°C)
- $T_{w}$: Temperature of glass cover (°C)
- $T_{w}$: Temperature of water (°C)
- $Q$: Overall bottom heat transfer coefficient from water to ambient through insulation (W/m$^2$ C)
- $Q_{w}$: Overall heat transfer coefficient from absorber to ambient through glass cover (W/m$^2$ C)
- $Q_{w}$: Overall heat transfer coefficient from water to ambient through glass cover (W/m$^2$ C)

Greek Symbols

- $\alpha$: Effective transmittance absorptance product of absorber
- $\psi$: Latitude
- $\delta$: Declination

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\( \beta \) = Slope angle between plane surface and horizontal
\( \gamma \) = Surface azimuth angle
\( \theta \) = Angle of incidence
\( \rho \) = Reflectance of surroundings

INTRODUCTION

Being a tropical country, Vietnam is well endowed with solar energy, particularly in the northern part of the territory and in the Hanoi region. Utilisation of solar energy may be an important way of supplementing the energy needs of the Vietnamese people. So, research on a low cost solar water heater, which is suitable for rural as well as urban areas of Vietnam, is necessary and important. The Hanoi region is located at latitude 21° 02' north and longitude 105° 51' east. It has the general climatic conditions of northern Vietnam’s Delta. For research on the solar radiation application, the data which have been recorded at the Hanoi Meteorological Station over 23 years (1955–1978) have been selected [1, 2]. From these data, one can estimate the solar radiation, ambient temperature, wind velocity, moisture and general variation of climatic conditions in the Hanoi region.

Solar water heaters [3] are mostly used for domestic and commercial applications. The main advantages of built-in storage water heaters (Fig. 1) are: simple design, low cost, easy installation and low maintenance requirements when operated in a medium temperature range.

In this communication, a thermal model of a built-in storage water heater with reflectors is presented. For optimisation of design parameters and estimation of the effect of various parameters on the thermal performance of this water heater, numerical computations have been performed with the climatic conditions of the Hanoi region. On the basis of the numerical results, the following conclusions have been drawn:

(i) A 100 l built-in-storage solar water heater with an absorber with \( A_s = 1 \) m\(^2\) facing the equator and two side reflectors facing east and west (Fig. 2) is more proper for domestic purposes in the Hanoi region, in particular, and in Vietnam, in general.

(ii) For the Hanoi region, the collector can be fixed at \( \beta = 35^\circ \) and an optimum slope angle of reflectors equal to 75° can be taken.

(iii) These thermal model and computer programs can be used for research and design purposes not only for the Hanoi region, but also for other regions of Vietnam with a variation of the meteorological conditions.

THERMAL MODEL

In order to write the energy balances, the following assumptions have been made:

(i) the heat capacity of the glass cover, insulation and the absorber is negligible;
(ii) there is no stratification in the water column;
(iii) the unit is in steady-state conditions;

![Fig. 1. Cross-sectional view of built-in storage solar water heater.](image-url)
(iv) the thermal properties of the materials and the water are constant during the operating temperature range etc.

The energy for each component of the system can be written as [3, 4]:

(i) absorber

\[(\pi \tau) I(t) A_s = h_s(T_b - T_s) A_s + U_s(T_b - T_s) A_s.\]  

(1)

(ii) water mass

\[h_s(T_b - T_w) = M_c C_s \frac{dT}{dt} + U_i(T_b - T_s) (A_s + A_i).\]  

(2)

The method of computation of the various heat transfer coefficients and radiation intensity on the inclined surfaces has been given in Appendices A and B, respectively. From equation (1), one gets

\[T_s = \frac{(\pi \tau) I(t) + h_s T_s + U_i T_s}{h_s + U_i}.\]  

(3)
After substituting an expression of $T_b$ in equation (2), one has

$$[h(xT)T_h - U_b(T_v - T_b)]A_h = M_hC_v \frac{dT_w}{dt} + U_b(T_v - T_b)A_b$$

(4)

where

$$h = h_3/(h_1 + u_1), \quad A_h = A_b + A, \quad \text{and} \quad U_b = h_3U_3/(h_3 + U_3) = (1/h_3 + 1/U_3)^{-1}.$$

The solution of equation (4) is given by

$$T_w = \frac{\bar{I}(t)}{a} (1 - e^{-at}) + T_{in} e^{-at}$$

(5)

where

$$\bar{I}(t) = \frac{hA_3(xT)}{(U_bA_b^* + U_3A_3)} \bar{I}(t) + \bar{T}_a$$

$$a = \frac{U_3A_3}{M_hC_v}$$

(6)

$I(t)$ and $T_a$ are average solar intensity and ambient temperature, respectively, during the $0\rightarrow t$ time interval.

After substituting equation (6) into equation (5), one gets:

$$T_w = \left[ \frac{hA_3(xT)}{(U_bA_b^* + U_3A_3)} \bar{I}(t) + \bar{T}_a \right] (1 - e^{-at}) + T_{in} e^{-at}.$$  

(7)

The average water temperature can be obtained as:

$$\bar{T}_w = \frac{1}{t} \int_0^t T_w \, dt \text{ for the } 0\rightarrow t \text{ time interval.}$$

After substituting equation (7) into the above equation, one gets:

$$\bar{T}_w = \left[ \frac{hA_3(xT)}{(U_bA_b^* + U_3A_3)} \bar{I}(t) + \bar{T}_a \right] \left( 1 - \frac{1 - e^{-at}}{at} \right) + T_{in} \frac{1 - e^{-at}}{at}.$$  

(8)

The above equation can be discussed for the following cases:

Case I

If $at \ll 1$ then $(1 - e^{-at})/at \rightarrow 1$. Substituting this value in equation (8), one gets:

$$T_w = T_{in}.$$

The above condition is achieved when

(a) $M_h$ is very large,
(b) $A_b$ and $A_3$ are small.

This condition is not useful for designing a solar water heater because there is no rise in water temperature.

Case II

If $at \gg 1$ then $(1 - e^{-at})/at \rightarrow 0$ and equation (8) becomes

$$\bar{T}_w = \frac{hA_3(xT)}{(U_bA_b^* + U_3A_3)} \bar{I}(t) + \bar{T}_a.$$  

For $at \gg 1$, one should have: (a) $M_h$ should be very small and the built-in-storage water heater should become a flat plate collector.
NUMERICAL RESULTS AND DISCUSSION

To evaluate the hourly variation of the water temperature received in the built-in-storage solar water heater for the three cases: (i) horizontal collector; (ii) fixed slope collector; and (iii) sloped collector with two reflectors, the following parameters have been used for the numerical computation of the above model.

(a) Collector parameters:

\[ A_s = 1 \text{ m}^2, \quad L = 1 \text{ m}, \quad b = 1 \text{ m}, \quad d = 0.1 \text{ m}. \]

\[ L_s = 0.1 \text{ m}, \quad L_{bg} = 0.05 \text{ m}, \quad M_s = 100 \text{ kg}, \quad A_{ref} = 0.5 \text{ m}^2. \]

(b) Climatic parameters:

Hourly ambient temperature and total solar radiation are taken from the data recorded at the Hanoi Meteorological Station for different typical months of four seasons, such as: January is the coldest month of the winter, March is the month of spring, June is the month of summer and October is the month of autumn [2]. The average wind velocity in the Hanoi region is 2 m/s.

The variation of total radiation against time of day for January is shown in Fig. 3. The variation of the ambient temperature, total radiation and water temperature against time of day for January are shown in Fig. 4. Figure 5 shows the variation of the maximum water temperature against the month of the year. Figure 6 shows the effect of the wind velocity, thickness of insulation, effective transmittance-absorptance product of the absorber, depth of the water and heat loss coefficient from the blackened surface to the water against maximum water temperature. The variation of the optimum slope angle of the collector and of the reflector against month of the year are shown in Figs 7 and 8, respectively. The variation of the ratio of the average daily direct radiation on the tilted surface to that on a horizontal surface \( R_t \), against slope angle \( \beta \) for the different months is shown in Fig. 9.

![Figure 3](image-url)

Fig. 3. Hourly variation of total solar radiation for Hanoi region on: (1) horizontal collector; (2) sloped collector with optimum angle \( \beta = 35 \); and (3) sloped collector with two side reflectors.
Fig. 4. Hourly variation for 15th January in Hanoi region of: (1) ambient temperature; (2) total solar radiation on horizontal surface; (3) water temperature using horizontal collector; and (4) water temperature using sloped collector with two side reflectors facing east and west.

On the basis of the numerical computations and figures, the following conclusions may be drawn [5, 6]:

(1) For January, the coldest month in the Hanoi region, the water temperature reached can only be 29.3°C if using a horizontal collector due to the low ambient temperature and low total and direct solar radiation. With the sloped collector, the total radiation is a little more than in comparison to the horizontal one, and the water temperature is also increased. If the sloped collector is used with two side reflectors, one can apparently get more solar radiation which, in turn, increases the water temperature up to 37.2°C in the month of January (Fig. 4). Similar results

Fig. 5. Maximum water temperature received in the built-in-storage solar water heater with $A_s = 1 \text{ m}^2$ for Hanoi region using: (1) horizontal collector; (2) sloped collector; and (3) sloped collector with two side reflectors facing east and west.
Fig. 6. Variation of maximum water temperature for January in Hanoi region depending on: (1) wind velocity; (2) thickness of insulation; (3) effective transmittance-absorptance product of absorber; (4) depth of water; and (5) heat loss coefficient from the blackened surface to the water.

occur for the other months of the year (Fig. 5), except for the month of June where the water temperature reached up to 65°C.

(2) A built-in-storage solar water heater with an absorber is more proper for domestic purposes. The thickness of insulation \( L_i = 0.05-0.1 \) m has been taken. A cost analysis showed that these low cost solar water heaters are suitable not only for the Hanoi region, but also for other regions of

Fig. 7. Variation of the optimum slope angle of collector for Hanoi region vs month of the year.
Vietnam, especially for southern Vietnam where the availability of sunshine hours is good and the cost of electrical energy and other fuels is high.

(3) The thermal performance of the built-in storage solar water heater is good only when the effective transmittance-absorptance product of the absorber is taken on the higher side (Fig. 6). Hence, the glass cover is to be cleaned for good transmissivity, and repainting of the blackened surface becomes necessary due to dust deposition and fading of colour as a result of weathering.

(4) For application in rural as well as in urban areas of the Hanoi region, the collector can be fixed at a slope of 35°, as this is the optimum angle for January, the coldest month of the year, and also, $R_s$ does not change much against the slope angle for the other months (Fig. 9).

(5) The numerical computations show that, with the same optimum slope angle, the side reflectors facing east and west (Fig. 2) provide higher total solar radiation than the top and bottom reflectors facing north and south. Hence, two side reflectors, facing east and west, are chosen for design and application purposes. An optimum slope angle of 75° for the reflectors has been taken (Fig. 8).

(6) These thermal models and computer programs could be used for research and design purposes.
not only in the Hanoi region, but their use can be extended for other regions of Vietnam with different meteorological conditions.

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APPENDIX A

Calculation of heat transfer coefficients

The calculation of heat transfer coefficients is as follows:

\[ h = h_n + h_u \]  \hspace{1cm} (A1)

For natural convection, \( Nu = C(Gr \cdot Pr)^{\frac{1}{3}} \), and for hot plates facing in the upward direction, \( C = 0.54 \) and \( n = 1/4 \), so \( h_n \) can be calculated as

\[ h_n = \frac{k}{L_n} \cdot 0.54(Gr \cdot Pr)^{\frac{1}{3}} \]  \hspace{1cm} (A2)

and

\[ h_u = \frac{\alpha \cdot (T_u + 273)^{\frac{1}{3}} - (T_a + 273)^{\frac{1}{3}}}{(T_u - T_a)} \]  \hspace{1cm} (A3)

\[ h = h_n + h_u \]  \hspace{1cm} (A4)

Preferred for calculation of \( h \):[1]:

\[ h = 5.7 + 3.8 \nu \]

\[ U = \left[ \frac{1}{h_n + L_n} + \frac{1}{h} \right] \]  \hspace{1cm} (A5)

\[ U_u = \left[ \frac{1}{h_u + L_u + \frac{1}{h_u}} \right] \]  \hspace{1cm} (A6)

Calculation of \( h \) is given below:

\[ Nu = \frac{hL}{K_n} = 0.27(Gr \cdot Pr)^{\frac{1}{4}} \], thus,

\[ h_n = 0.27K_n(Gr \cdot Pr)^{\frac{1}{4}} \]

APPENDIX B

Solar radiation on inclined surfaces

In order to determine the solar intensity on tilted surfaces, as in this case for the sloped collector and reflectors shown in Fig. 2, a model is used as given below. The declination \( \delta \) can be calculated using the following expression[1]:

\[ \delta = 23.43 \sin \left( \frac{360 \cdot \frac{284 - n}{365}}{2} \right) \]  \hspace{1cm} (B1)

where \( n \) is the day of the year.

The equation relating the angle of incidence of beam, radiation \( \theta \) and the other angles is:

\[ \cos \theta = \sin \delta \sin \phi \cos \beta - \cos \gamma \cos \phi \sin \beta \]

\[ + \cos \phi \cos \beta \sin \phi \sin \beta \cos \gamma \cos \delta \cos \omega \]

\[ + \cos \delta \sin \omega \sin \beta \sin \gamma \]  \hspace{1cm} (B2)
For a horizontal surface, $\beta = 0^\circ$, and the angle of incidence is the zenith angle of the sun $\theta_z$. Now the equation becomes:

$$\cos \theta_z = \cos \delta \cos \phi \cos \omega + \sin \delta \sin \phi.$$  \hspace{1cm} (B3)

The geometric factor, $R_b$, the ratio of beam radiation on the tilted surface to that on the horizontal surface at any time, can be calculated as:

$$R_b = \frac{G_b}{G_h} = \frac{G_b \cos \theta_z}{G_h \cos \theta} = \frac{\cos \theta}{\cos \theta_z},$$  \hspace{1cm} (B4)

where $\cos \theta$ and $\cos \theta_z$ are determined from equations (B2) and (B3).

To use horizontal total radiation data to estimate radiation on the tilted plane of a collector of fixed orientation, it is necessary to know $R$, the ratio of the total radiation on a tilted surface to that on a horizontal surface:

$$R = \frac{I_t}{I_h} = \frac{I_t}{\frac{1}{2} I_h + \frac{1}{2} I_d}.$$  \hspace{1cm} (B5)

An improvement has been derived by Liu and Jordan (in [1]) by considering the radiation on the tilted surface to be made of three components: beam radiation, diffuse radiation and solar radiation reflected from the ground. The total solar radiation on the tilted surface for an hour is, then, the sum of three terms:

$$I_t = I_b R_b + I_d \left[ \frac{1 + \cos \beta}{2} \right] + (I_b + I_d) \left[ \frac{1 - \cos \beta}{2} \right],$$  \hspace{1cm} (B6)

and by definition

$$R = \frac{I_t}{I_h} = \frac{I_t}{\frac{1}{2} I_h + \frac{1}{2} (1 + \cos \beta) + \frac{1}{2} (1 - \cos \beta) \phi}.$$  \hspace{1cm} (B7)