TRANSIENT ANALYSIS OF
A TRIANGULAR BUILT-IN-STORE SOLAR
WATER HEATER UNDER WINTER CONDITIONS

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(Received 27 March 1993)

Abstract—In this paper, the performance of a triangular built-in-storage solar water heater under winter
conditions has been studied. The triangular cross-section of the system results in higher solar gain and
enhances the natural convection leading to a higher water temperature. The forward finite difference
technique is employed and initial conditions are derived from the assumption that the water temperature
and the temperature at each node are in equilibrium with the ambient temperature. The performance of
the system is analyzed under no flow, constant flow rate and intermittent flow rate conditions. The effect
of the night insulation cover is also analyzed. A comparative study of the triangular water heater with
a rectangular one is also made. The effect of the tilt angle on the water heater is also discussed. The
efficiency of the system under various conditions is also discussed.

NOMENCLATURE

M  mass (kg)
C  specific heat (J kg⁻¹ C⁻¹)
I  solar intensity (W m⁻²)
U  overall heat loss coefficient (W m⁻² K⁻¹)
h  convective heat transfer coefficient (W m⁻² K⁻¹)
Mf  flow rate (kg h⁻¹)
T  temperature (°C)
Qt  transmittance absorptance product
A  area

Subscripts
p  plate
w  water
a  ambient
i  top
b  bottom + edge
s  surface

INTRODUCTION

A solar collection-cum-storage is desirable for efficient and economic utilization of solar energy for
water heating application. A built-in-storage water heater using a rectangular configuration
(Fig. 1(b)) was firstly proposed by Tanishita [1] and theoretically, as well as experimentally, studied
by many researchers [2–6]. The effect of various operating parameters and climatic variables on
the water temperature and collection efficiency have been extensively studied [7–10]. However, this
rectangular design has poor heat transfer and low solar gain, especially in winter in the northern
latitudes above 26° when the solar radiation is dilute and obliquely incident. The rate of heating
during the sunshine hours is faster for a shallow tank than for a deep tank. Ecevit et al. [11]
proposed a triangular built-in-storage solar water heater for improving the performance by natural
convection, leading to better heat transfer between the absorbing surface and the water stored in
the heater.

In this communication, the authors have presented a heat transfer model for a triangular
built-in-storage type solar water heater and predict the thermal performance under various
operating conditions namely, no flow, constant flow and intermittent flow rate for the winter
conditions in Delhi. The effect of the night insulation cover and the comparison with rectangular
solar water heater have been studied and collection efficiency predicted for the given set of conditions. A finite time step marching finite difference technique has been used to predict the transient performance of the system. The results are presented in the form of graphs. It is found that a triangular solar water heater is better than a rectangular built-in-storage water heater under various operating conditions.

**DESIGN OF THE SYSTEM**

As shown in Fig. 1(a), the triangular built-in-storage solar water heater consists of a triangular cross-section steel tank having a volume of 981. The absorbing surface of 1 m² is painted by an ordinary black-board paint to act as a good absorber for solar radiation. All the other sides of the tank are provided with an insulation of 5 cm thick fiber wool and the top is provided with a glazing of 3 mm thick glass sheet, with an air gap of 3 cm above the absorber. Solar radiation after passing through the glass sheet and air gap, is incident on the absorbing surface, thereby heating it. The thermal energy gained by the plate is convectively transferred to water in contact with it, raising its temperature. The performance of the system is studied under various orientations of the system.

**MATHEMATICAL MODELING**

In mathematical modeling, the water heater is divided into two nodes: the absorbing plate and the water. The energy balance equation at the two nodes is written as follows:
Table 1. Values of efficiency for different cases

<table>
<thead>
<tr>
<th>Flow rate (kg h(^{-1}))</th>
<th>Flow duration (h)</th>
<th>Angle of inclination ((^\circ))</th>
<th>Night insulation</th>
<th>Efficiency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0</td>
<td>(0-24)</td>
<td>11.5</td>
<td>OFF</td>
<td>37</td>
</tr>
<tr>
<td>0.0</td>
<td>(0-24)</td>
<td>11.5</td>
<td>ON</td>
<td>54</td>
</tr>
<tr>
<td>9.0</td>
<td>(24-28)</td>
<td>11.5</td>
<td>OFF</td>
<td>56</td>
</tr>
<tr>
<td>18.0</td>
<td>(24-28)</td>
<td>11.5</td>
<td>OFF</td>
<td>65</td>
</tr>
<tr>
<td>27.0</td>
<td>(24-28)</td>
<td>11.5</td>
<td>OFF</td>
<td>71</td>
</tr>
<tr>
<td>36.0</td>
<td>(24-28)</td>
<td>11.5</td>
<td>OFF</td>
<td>74</td>
</tr>
<tr>
<td>45.0</td>
<td>(24-28)</td>
<td>11.5</td>
<td>OFF</td>
<td>47</td>
</tr>
<tr>
<td>54.0</td>
<td>(24-28)</td>
<td>11.5</td>
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<td>54</td>
</tr>
<tr>
<td>63.0</td>
<td>(24-28)</td>
<td>11.5</td>
<td>OFF</td>
<td>59</td>
</tr>
<tr>
<td>72.0</td>
<td>(24-28)</td>
<td>11.5</td>
<td>OFF</td>
<td>43</td>
</tr>
<tr>
<td>81.0</td>
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<td>11.5</td>
<td>OFF</td>
<td>46</td>
</tr>
<tr>
<td>90.0</td>
<td>(24-28)</td>
<td>11.5</td>
<td>OFF</td>
<td>45</td>
</tr>
</tbody>
</table>

\[ M_p C_p \frac{dT_p}{dt} = [(\alpha I) I_s - U_i (T_p - T_a) - h(T_p - T_w)] A \]  

For water:

\[ M_w C_w \frac{dT_w}{dt} = h(T_p - T_w)A - U_{ke}(T_w - T_s)A_{ke} - M_f C_w(T_w - T_s) \]  

The coupled differential equations (1) and (2) are solved using a forward time step marching technique to obtain the instantaneous value of water temperature. In this technique \((dT/dt)\) is replaced by \((T^{i+1} - T^i)/\Delta t\), where \(T^{i+1}\) and \(T^i\) are the values of water temperature just before and after the time interval \(\Delta t\). Initial conditions are that the water temperature at each node is equal to the ambient temperature. The solution of equations (1) and (2) can be written as follows:

\[ T_p^{i+1} = \left\{ 1 - (\Delta t/M_p C_p) \right\} T_p^i + (\Delta t/M_p C_p)[(\alpha I) I_s + U_i T_s^i + hT_w^i] A \]  

\[ T_w^{i+1} = \left\{ 1 - (\Delta t/M_w C_w) \right\} T_w^i + (h/M_w C_w) \left[ (hT_p^i A + U_{ke} A_{ke} + M_f C_w T_s^i) \right] \]  

The average daily efficiency of the heater is defined by

\[ = \left\{ M_w C_w(T_{wf} - T_{wi}) \right\} + \left( \int_0^t M_f C_w(T_w - T_s) \, dt \right) / \left( \int_0^t I \, dt \right) \]  

where the integral in the numerator is over the time interval for which hot water is withdrawn from the heater for use. The instantaneous value of solar radiation on the horizontal surface of any orientation is obtained from the well-known result of Liu and Jorden [12]. The input data of solar radiation on the horizontal surface and the ambient temperature required are measured hourly at I.I.T. Delhi for a typical clear day in the winter season.

![Fig. 2. Hourly variation of solar radiation, ambient air and water temperature with and without night insulation.](image-url)
RESULTS AND DISCUSSION

The performance of water heater under winter conditions is shown in Figs 2–5 and in Table 1. Figure 2 shows the variation in water temperature under no flow condition with and without night insulation. Without night insulation, the next day morning water temperature is 14°C higher than the ambient temperature, whereas with night insulation the next day morning water temperature is nearly 24°C higher than the ambient temperature.

Figure 3 shows the variation in water temperature under constant flow conditions. The flow rate varies between 9 and 36 kg h⁻¹. If the flow rate is 9 kg h⁻¹, the water is available above 25°C for 10 hr from 13 to 23 hr. If the flow rate is doubled, i.e., 18 kg h⁻¹, the water is available above 25°C only for 5 hr from 13 to 19 hr. Even if the flow rate is as high as 36 kg h⁻¹, availability of water above 25°C is only for 4 hr. As the flow rate is increased, the hot water is available for shorter period. As the flow rate is increased from 9 to 36 kg h⁻¹, the maximum water temperature falls from 36 to 26°C.

Figure 4 shows the variation in water temperature under intermittent flow conditions without night insulation. The water is withdrawn from 10–11 h, 14–15 h and 19–21 h at uniform flow rate. Curves are plotted for flow rate 18 kg h⁻¹, 36 kg h⁻¹ and 54 kg h⁻¹. When the flow rate is 18 kg h⁻¹, the temperature of water for the periods 14–15 h and 19–21 h is 30°C and between 25 and 35°C respectively. If the flow rate is 54 kg h⁻¹, the temperature of the outgoing water for 14–15 h and 19–21 h is 26°C and between 23 and 33°C respectively. So, if the flow rate is 18 kg h⁻¹ for the above mentioned periods, 98 l of water is available next morning at a temperature 12°C higher than the ambient temperature. As the flow rate is increased to 54 kg h⁻¹, the next morning water temperature is only 6°C higher than the ambient temperature.
The effect of angle of inclination on water temperature without night insulation is shown in Fig. 5. The angle of inclination is fixed at 11.5°, 30°, 45° and 60° and the effect on water temperature is plotted. It is observed that at 45°, the water temperature is higher for the whole period as compared to the other cases. Even if the angle of inclination is 11.5°, the water temperature is higher as compared to the rectangular solar water heater of similar dimensions. If the angle of inclination is 45°, the maximum water temperature is 45°C and the next day morning temperature is nearly 30°C, therefore 98 l of water is available next morning at 22°C higher than the ambient temperature.

Table 1 shows the efficiency of a triangular built-in-storage solar water heater under various conditions. The efficiency of the water with night insulation is 17% higher than that without night insulation. It is also obvious from the table, that the maximum heat is withdrawn from the heater at constant flow rate. If the flow rate is 36 kg h⁻¹, then 74 per cent of the total heat incident on the heater is transferred to the water. It is also seen that the efficiency of the heater is increased as the intermittent flow rate is increased. The efficiency of the heater is also affected by the angle of inclination, it is maximum when the angle of inclination is 45°.

REFERENCES