System Performance of U-Tube and Heat Pipe Solar Water Heaters

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Abstract

System performance of solar water heaters depend upon collector and storage tank design and sizing and weather conditions (solar radiation intensity and ambient temperature). Nocturnal reverse flow and tank insulation dictate the degree of overnight water temperature drop in the storage tank. A tropical country like Malaysia has widely fluctuating and intermittent solar radiation. It is neither practical nor feasible to conduct outdoor tests such as that proposed by International Standards. Indoor collector tests are expensive to conduct and would not provide meaningful information to the domestic or commercial end user. Outdoor system tests would be more informative to consumers who would like to compare the water temperatures that could be achieved in order to choose from the wide range of commercial products available. This paper reports the results of outdoor tests conducted on several evacuated tube solar collectors (U-tube and heat pipe types) under natural and forced convection. Although tested at different times, the long and short term test procedures employed allowed us to compare the performances of the various systems as if they were tested simultaneously side-by-side. It was found that the natural convection heat pipe system performed best among them.

Key Words: Heat Pipe, U-Tube, Solar Water Heater, Natural Convection, Forced Convection

1. Introduction

Solar water heaters (SWHs) have been tested since the early 1970’s. Classical solar collectors were of the tube-in-fin flat plate types. Since then new developments and innovations have resulted in more efficient collectors with the all-glass evacuated tube [1], U-tube [2] and the heat pipe [3] types. Evacuated tubes with selective surfaces minimize convective and emissive heat losses from the solar collectors and result in higher efficient systems.

Natural convection or thermosyphon flow solar water heater (SWH) operates without a circulating pump. The solar collector heats up the water in the tubes of the collector plate which rises up the upriser pipe. Denser cold water in the storage tank flows down the downcomer pipe to take its place. This natural convection recirculating flow of water occurs throughout the day as long as heat is absorbed in the collector plate. The performance of the system depends mainly upon the design and geometric dimensions of the collector, insulation quality of the storage tank, ratio of collector plate area to volume of storage tank, angle of inclination of the collector, connecting pipe sizes and relative height between the storage tank and the collector. Environmental factors such as solar radiation, ambient temperature and wind conditions would determine the storage tank water temperature that could be achieved. Insulation quality of the tank would determine the standing overnight heat losses from the tank and the relative height between the tank and collector would determine reverse flow losses.

It is neither practical nor feasible to conduct outdoor tests according to International test standards [4,5]. Such tests are tedious and expensive to conduct in tropical
countries like Malaysia with highly fluctuating solar radiation intensity. Indoor tests would not provide meaningful information to the end user. Outdoor system tests would be more informative to technically-minded potential owners of systems who are interested to know the water temperatures that could be achieved from the different systems in order make their choice.

2. Objective

This paper reports the results of outdoor tests conducted on several solar hot water heating systems incorporating evacuated tube (U-tube and heat pipe) types of solar collectors under natural and forced convection. The long term and short term procedures was employed to compare the performances of solar heating systems obtained at different times of the year to be compared as if they were placed side-by-side and tested simultaneously. These tests were proposed earlier by Ong [6].

3. Methodology

3.1 Long Term Tests without Water Draw-Off

Performance of a solar system depends upon weather conditions. This series is performed without any water draw-off from the system. Long term here means over a period of at least 7 days in order to be able to obtain results over reasonably widespread weather conditions. This series would enable the maximum temperature that could be achieved over a period of time without draw-off to be obtained. Overnight heat losses result from standing storage tank heat loss and reverse flow loss. Standing heat loss depends upon quality of storage tank insulation. Reverse flow occurs in SWH systems at night when the storage tank water temperature is high and the collectors reject heat to the cold night ambient. Reverse flow depends upon the relative heights between collector and storage tank – the higher the tank is with respect to the collector the less is the reverse flow. The extent of temperature drop is also dependent upon the mean storage tank water temperature during the night. This long term test would enable the overnight water temperature from 5 pm (say) in the evening to 7 am the next morning to be determined.

3.2 Short Term Tests with Daily Water Draw-Off

This series is performed with water draw-off from the system at the end of the day and filling up with fresh water for the next day’s test. This daily test series would enable the average temperature of hot water in the storage tank and the mean system efficiency to be obtained daily. It is important to obtain the mean system efficiency in order to compare equivalent collector area/tank volume ratio for each system.

4. Experimental Investigation

4.1 Experimental Apparatus

Three systems were tested and compared – System A (natural convection U-tube), B (natural convection heat pipe) and C (forced convection heat pipe). The U-tube and heat pipe solar collectors are shown in Figure 1. The U-tube collector consisted of 48 mm O/D \times 33 mm I/D \times 1760 mm long double wall evacuated glass tubes with 10 mm O/D \times 7.5 mm I/D copper U-tubes inside. One end of the evacuated tube was sealed and a selective surface coating applied to the outside wall of the inner glass tube. The heat pipe collector consisted of similar 58 mm O/D \times 47 mm I/D \times 1720 mm long evacuated glass tubes with wickless heat pipes (thermosyphons) inside. The evaporator section of the thermosyphon was 8 mm O/D \times
6 mm I/D × 1700 mm long and the condenser section 25 mm O/D × 23 mm I/D × 90 mm long. A photograph of the three systems located on the roof of Monash University Malaysia is shown in Figure 2. The U-tube system consisted of 16 pipes mounted vertically while the heat pipe systems had 30 pipes each and mounted on steel supporting structures at angles of about 20° to the horizontal. Storage tank capacities for system A was 0.10 m³, system B was 0.27 m³ and system C was 0.20 m³. For system C, a small water pump controlled by two differential temperature sensors installed at the bottom of the tank and the collector array outlet circulated water between the solar collector and the heat exchanger in the tank.

All temperatures were measured using Cu-con (Type T) thermocouples with an accuracy of ± 0.5 °C. In the horizontal tank of system B, nine thermocouples were inserted into the tank via 3 probe tubes as shown in Figure 3. Each probe tube held three thermocouples spaced equally apart to determine the vertical temperature distribution in the tank. For the vertical tanks of systems A and C, 5 probes were located along the axes of each tank. Solar radiation was measured with a Kipp-&-Zonen solarimeter and integrator with an accuracy of ±2%. All temperatures and solarimeter outputs were connected to a data logger and continuously logged over a period of several days.

4.2 Water Temperature Distribution in Storage Tank

A typical water temperature distribution in the horizontal storage tank of system B is shown in Figure 4. Average water temperature at each particular level was calculated by taking the arithmetic mean of the 3 probes at the same tank level. For the vertical tank, mean water temperature was calculated from the arithmetic mean of the 5 probes, Figure 5. As the day progressed, temperature stratification within the tank could be clearly observed. As expected, the highest temperature occurred at the top of the tank. The temperature distribution was very nearly uniform from the middle of the tank to the top in the afternoon. Bulk temperature obtained by integrating the area under the temperature curve and divided by tank height differed from the arithmetic mean by no
4.3 Long Term System Performance Tests

The mean water temperature in the storage tank ($\bar{T}$), ambient temperature ($T_{\text{am}}$) and instantaneous total solar radiation intensity ($H$) were plotted continuously. Accumulated daily total solar radiation ($\Sigma H$) were noted every 24 hours from midnight. Typical results obtained for comparative tests on the natural and force convection heat pipe systems are shown in Figure 6. The weather experienced during the 6 days of testing varied from hot on day 4 when daily total solar radiation recorded was about 5.65 kWh/m$^2$ to cloudy on day 2 with about 2.15 kWh/m$^2$. Ambient temperature varied from about 38 °C during the day to about 24 °C at night. The maximum temperature for the natural convection system was nearly 100 °C. For the force convection system, the maximum temperature was observed to reach 82 °C. Coupled with the heat exchanger in the tank, a penalty had to be paid. Hence the forced circulation system was not able to achieve more than 82 °C. Figure 7 shows the long term results for natural convection U-tube system A obtained at a different time of the year. The maximum temperature for this system was nearly 72 °C.

The overnight temperature drop ($\Delta T_{\text{on}}$) from 5 pm to 7 am the next morning are plotted in Figure 8 for all three systems. The mean water temperature drop ranged from about 4.5–9.0 °C for system A, 2.5–11.5 °C for system B and about 2.5–6.0 °C for system C. Losses are attributed to reverse flow and standing tank heat losses. It should be pointed out here that different insulation materials and thicknesses were provided and the tanks were either horizontal or vertical. The force convection system did not suffer from reverse flow at night because the pump was shut off. As expected, the overnight temperature drop increases with higher initial tank storage temperature. Most of the loss is associated with standing tank heat loss. The U-tube system A had higher overnight heat loss than the other systems.

![Figure 5. Typical water temperature distribution in vertical storage tank, system A.](image)

![Figure 6. Long term performance (no draw-off) of natural convection and forced convection heat pipe SWH.](image)

![Figure 7. Long term performance (no draw-off) of natural convection U-tube SHW facing South.](image)

![Figure 8. Overnight temperature drops of U-tube and heat pipe systems with no water draw-off.](image)
4.4 Daily Performance Tests

For this series of tests, each system was completely drained in the evening around 5 pm local time and left overnight. Water was drawn off after every 24 hours. The temperature of the water in the storage tank ($T$), ambient temperature ($T_{amb}$), instantaneous solar radiation intensity ($H$) were recorded continuously. Accumulated daily total solar radiation ($\Sigma H$) were noted every 24 hours from midnight. Typical daily performances of systems B and C are compared in Figure 9 and for system A in Figure 10. Mean water temperature increases as the day progressed, as expected. The temperature remained steady towards the evening and drops off at night.

The end-of-day temperature rise is calculated from

$$\Delta T = T_{m,5pm} - T_{m,7am}$$  \hspace{1cm} (1)

The mean system efficiency at the end-of-day is defined as:

$$\eta = \frac{\rho V c_p \Delta T}{A \sum_{i=1}^{n} H_i} \times 100 \%$$  \hspace{1cm} (2)

Figure 11 shows the end-of-day mean water temperature rise ($\Delta T$) and mean system efficiency ($\bar{\eta}$) at 5 pm plotted against accumulated total solar radiation. Mean water temperature rise varied from 12–30 °C for system A, 20–30 °C for system B and 13–25 °C for system C. On an average day with about 4.5 kWh/m² of radiation, the expected mean water temperature rise would be 25 °C for system A, 30 °C for system B and 25 °C for system C and the expected mean system efficiency would be 53% for system A, 65% for system B and 41% for system C. However the mean temperature rise depends upon the collector area/storage volume ratio of the system. Large collector areas and low tank volumes would result in higher temperature rise. The mean system efficiency would take this into account. The pro-rated expected mean water temperature rise could be calculated from

$$\Delta T_{m} = \frac{\eta m \sum H}{100 \rho c_p} \left( \frac{A}{V} \right)$$  \hspace{1cm} (3)

Table 1 shows that by pro-rating the results for the area/volume ratio of 11.6 as obtained from system B, the expected water temperature rise at 4.5 kWh/m² for system A and C would be would be 27.0 and 18.5 °C, respectively. Hence it could be concluded that the natural convection heat pipe system performs better than the U-tube and the force convection heat pipe system. The force convection heat pipe system performs worst because of the...
heat exchanger and the stop-start operation of the pump.

5. Conclusion

Short and long term performance tests were conducted on natural and force convection U-tube and heat pipe evacuated tube solar water heaters. The test procedures employed enabled comparative performances of solar water heating systems to be made even when they were tested at different times of the year. The experimental results showed that the natural convection heat pipe system was capable of heating water to 100 °C and performed best among the systems tested.

Nomenclature

\( A \) collector surface area \([m^2]\)
\( c_p \) specific heat of water \([kJ/kg \cdot K]\)
\( FC \) forced convection
\( H \) instantaneous total solar radiation intensity \([kW/m^2]\)
\( NC \) natural convection
\( V \) volume of storage tank \([m^3]\)
\( T \) mean water temperature \([\circ C]\)
\( T_{amb} \) ambient temperature \([\circ C]\)
\( \Sigma H \) accumulated total solar radiation intensity \([kWh/m^2]\)
\( \Delta T \) mean water temperature rise \([\circ C]\)
\( \Delta T_o \) overnight mean water temperature drop \([\circ C]\)
\( \rho \) density of water \([kg/m^3]\)
\( \Theta \) time \((h)\)
\( \bar{\eta} \) mean system efficiency \((\%)\)

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References


Table 1. Details and test results of SWHs

<table>
<thead>
<tr>
<th>System</th>
<th>U-tube (A)</th>
<th>Heat pipe (B)</th>
<th>Heat pipe (C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Storage tank volume ((m^3))</td>
<td>0.10</td>
<td>0.27</td>
<td>0.20</td>
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<tr>
<td>Collector surface area ((m^2))</td>
<td>1.28</td>
<td>3.13</td>
<td>3.13</td>
</tr>
<tr>
<td>Total no of tubes/pipes</td>
<td>16</td>
<td>30</td>
<td>30</td>
</tr>
<tr>
<td>Area/volume ratio ((m^2/m^3))</td>
<td>12.8</td>
<td>11.6</td>
<td>15.7</td>
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<tr>
<td>Max temperature achieved ((\circ C))</td>
<td>72</td>
<td>100</td>
<td>82</td>
</tr>
<tr>
<td>Overnight temperature drop ((\circ C))</td>
<td>4.5-9.0</td>
<td>2.5-11.5</td>
<td>2.5-6.0</td>
</tr>
<tr>
<td>Daily system efficiency at (\Sigma H = 4.5 kW/m^2) (%)</td>
<td>53</td>
<td>65</td>
<td>41</td>
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<tr>
<td>Daily water temperature rise at (\Sigma H = 4.5 kW/m^2) ((\circ C))</td>
<td>25</td>
<td>30</td>
<td>25</td>
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<tr>
<td>Expected daily water temperature rise at (\Sigma H = 4.5 kW/m^2) adjusted for area/volume ratio = 11.6 ((\circ C))</td>
<td>27.0</td>
<td>30.0</td>
<td>18.5</td>
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