ABSTRACT

System performance of a solar water heater depends upon collector and storage tank design (dimensions, insulation, pipe connections, etc.) 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 natural and forced convection heat pipe solar hot water heating systems. The natural convection system performed better than the forced convection system and is cheaper. The procedure could be 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.

Keywords: Heat pipe solar water heater, natural convection, forced convection, system performance

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 evacuated tubes [1], U-tubes [2] and the heat pipe [3] system. Evacuated tubes with selective surfaces minimize convective heat losses from the absorber tubes and reduces emissive heat losses. Test standards have also evolved to include indoor performance testing of the solar collectors [4] to outdoor system performance [5]. Huang [6] and Chang [7] suggested modifications to the Taiwanese standard [8].

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. As a result, the water in the insulated storage tank is heated up. 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. The 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 together with the water temperature in the tank. Both these losses contribute to the overnight drop in temperature of the water in the tank.

It is neither practical nor feasible to conduct outdoor tests in a tropical country like Malaysia which is subjected to widely fluctuating and intermittent solar radiation. Indoor tests are expensive to conduct and 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 natural and forced convection heat pipe solar hot water heating systems. The procedure could be 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.
simultaneously.

Two series of tests are proposed, viz., long term without water draw-off and short term with water draw-off in the evening. These tests were proposed earlier.

3. METHODOLOGY

3.1 Long term tests without water draw-off.

This series is performed without any water draw-off from the system. Performance of a solar system depends upon weather conditions. 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 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. Most storage tanks are insulated with 50 mm thick polyurethane foam. 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. There are other factors such as night sky temperature, wind, rain, etc. In this paper, the mean tank temperature at the end-of-day taken at 5 pm is noted as a factor.

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. End-of-day is assumed to occur in the evening at 5 pm. A test day could also commence from midnight or before the sun rises in the morning. Since performance of a solar system depends upon weather conditions, it is recommended that a sufficient number of days of tests be carried out to obtain results over reasonably widespread weather conditions. This daily test series would enable the average temperature of hot water in the storage tank and the mean system efficiency to be obtained. 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

The heat pipe solar collector is shown schematically in Fig. 1. A photograph of the the natural and forced convection SWH systems located on the roof of Monash University Malaysia is shown in Fig. 2. Each array of heat pipe solar collectors consisted of 30 pipes mounted on steel supporting structures and inclined at angles of about 20° to the horizontal. Each pipe consists of a 9 mm copper tube as the evaporator and a 13 mm copper tube as the condenser. Total pipe length was 1.8 m. The evacuated glass tube measured 58 mm O/D x 47 mm I/D. For the natural convection system, the collector was closely coupled to a 0.27 m$^3$ x 1.2 mm thick ss inner tank insulated with 50 mm PU. For the forced convection system, a 0.20 m$^3$ capacity vertical storage tank was located one floor below the roof and is not shown in the photograph. This tank is an indirect system with a heat exchanger in the tank. A small water pump controlled by two differential temperature sensors installed at the bottom of the tank and the collector array outlet circulates water between the solar collector and the heat exchanger in the tank.

For the horizontal tank, nine Cu-con (Type T) thermocouples with an accuracy of ± 0.5°C were inserted into each of the storage tank via 3 probe tubes as shown in Fig. 3. Each probe tube held three thermocouples spaced equally apart to determine the vertical temperature distribution in the tank. For the vertical tank 5 probes were used. Ambient temperature was measured with a Cu-con thermocouple located nearby in the shade. 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. Tank capacities and collector areas are tabulated in Table 1 together with some test results.
A typical water temperature distribution in a horizontal storage tank is shown in Fig. 4. For the horizontal tank, average water temperature at each particular level was calculated by taking the arithmetic mean of the 3 probes at the same tank level. Overall mean water temperature ($\bar{T}$) was calculated by taking the arithmetic mean of all the 9 probes. For the vertical tank, mean water temperature was calculated from the arithmetic mean of the 5 probes. At the start of the experiment, the water in the tank was at a uniform initial temperature. 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 differed from the arithmetic mean by no more than $\pm 0.3^\circ$C at most.

### Table. 1. Details and test results of SWHs.

<table>
<thead>
<tr>
<th>System</th>
<th>Nat conv</th>
<th>Force conv</th>
</tr>
</thead>
<tbody>
<tr>
<td>Storage tank volume (m$^3$)</td>
<td>0.27</td>
<td>0.20</td>
</tr>
<tr>
<td>Collector surface area (m$^2$)</td>
<td>3.13</td>
<td>3.13</td>
</tr>
<tr>
<td>Total no of tubes/pipes</td>
<td>30</td>
<td>30</td>
</tr>
<tr>
<td>Area/volume ratio (m$^3$/m$^2$)</td>
<td>11.6</td>
<td>15.7</td>
</tr>
<tr>
<td>Max temperature achieved (°C)</td>
<td>100</td>
<td>84</td>
</tr>
<tr>
<td>Overnight temperature drop (°C)</td>
<td>2-11</td>
<td>2.5-6.5</td>
</tr>
<tr>
<td>Daily system efficiency at $\Sigma H=4.5$ kW/m$^2$ (%)</td>
<td>65.8</td>
<td>40.8</td>
</tr>
<tr>
<td>Daily water temperature rise at $\Sigma H=4.5$ kW/m$^2$ (°C)</td>
<td>29.9</td>
<td>25.0</td>
</tr>
<tr>
<td>Expected daily water temperature rise at $\Sigma H=4.5$ kW/m$^2$ adjusted for area/volume ratio = 11.0 (°C)</td>
<td>28.4</td>
<td>17.6</td>
</tr>
</tbody>
</table>

### 3.2 Water temperature distribution in storage tank.

### 3.3 Long term system performance tests.

The storage tanks were initially filled with water and then left exposed to be heated up for several days without any water draw-off. The mean water temperature in the storage tank ($\bar{T}$), ambient temperature ($T_{amb}$) and instantaneous total solar radiation intensity ($H$) were plotted hourly. Accumulated daily total solar radiation was noted every 24 hours from midnight. Typical results obtained are shown in Fig. 5. 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. Table 1 compares some performance data. The maximum temperature for the natural convection system was nearly 100°C. For the force convection system, the maximum temperature was observed to reach 84°C. In the forced circulation system, the pump
was set to stop when the temperature at the collector outlet reached 90°C as a safety precaution. Coupled with the heat exchanger in the tank, a penalty had to be paid. Hence the forced circulation system was not able to achieve > 84°C.

The overnight temperature drop (ΔTn) from 5 pm to 7 am the next morning are shown in Fig. 6. As expected, overnight temperature drop increased with higher mean water temperature. The mean water temperature drop ranged from about 2-11°C for the natural convection system and about 2-7°C for the vertical tank. The differences are due to the different insulation materials of the tanks and also that while one is horizontal, the other is vertical. Also, forced convection system did not suffer from reverse flow at night. As expected, the overnight temperature drop is greater the higher the initial storage temperature (T5 pm) in the tank.

3.4 Daily performance tests.

The system was completely drained in the evening around 5 pm local time and left overnight. Water was drawn off every 24 hours later. The temperature of the water in the storage tank (T), ambient temperature (Ta), instantaneous solar radiation intensity (H) were recorded hourly. The cycle of draining and refilling the tank was repeated over a period of several days. Accumulated daily total solar radiation was noted every 24 hours from midnight. A typical daily performance of the SWH systems is shown plotted hourly in Fig. 7. Mean water temperature increases as the day progressed, as expected. The temperature remained steady towards the evening and drops off at night.

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

\[
\eta = \frac{\rho V c_p}{A \sum H} \times 100 \% \quad (1)
\]

where end-of-day temperature rise is calculated from

\[
\Delta T = T_{5 \, pm} - T_{7 \, am} \quad (2)
\]

Figure 8 shows the end-of-day mean water temperature rise (ΔT) and mean system efficiency (η) at 5 pm plotted against accumulated total solar radiation. For the systems tested, mean water temperature rise varied from 15-25°C for the natural convection system and 20-30°C for the forced convection system. On an average day with about 4.5 kWh/m² of radiation, the expected mean water temperature rise would be 30°C and 25°C for the natural convection and forced convection pipe systems, respectively. However the mean temperature rise depends upon the collector area/storage volume ratio of the system. Large collector areas and small 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 Eq. (1), viz.,

\[
\Delta T = \eta \sum H \left( \frac{A}{100 \rho c_p V} \right) \quad (3)
\]

Table 1 shows that by pro-rating the results for an area/volume ratio of 11.03, the expected water temperature rise for the natural convection system at 4.5 kWh/m² would be 30°C and for the forced convection system, 25°C. Hence the natural convection system performs better than the force convection system.

4. CONCLUSIONS

Performance tests were conducted on natural and forced convection heat pipe solar water heaters. The results showed that the natural convection system was capable of heating water to 100°C while the force convection system was less than 84°C. Overnight temperature drop ranged from 6-10°C for tank starting temperatures between 60-100°C and from 2-5°C for starting temperatures between 40-60°C. The natural convection system performed better than the force convection system.

NOMENCLATURE

- A collector surface area [m²]
- cp specific heat of water [kJ/kg K]
- FC forced convection
- H instantaneous total solar radiation intensity [kW/m²]
- NC natural convection
- V volume of storage tank [m³]
- T mean water temperature [°C]
- Tamb ambient temperature [°C]
- \( \sum H \) accumulated total solar radiation intensity [kWh/m²]
- \( \Delta T \) mean water temperature rise [°C]
- \( \Delta T_n \) overnight mean water temperature drop

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\[ \rho \] density of water \([\text{kg/m}^3]\)

\[ \theta \] time (h)

\[ \eta \] mean system efficiency (%)

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REFERENCES


Fig. 5. Long term performance of heat pipe SHWs without draw-off.
Fig. 6. Overnight temperature drops with no water draw-off.

Fig. 7. Typical daily performance of heat pipe SWHs with draw off.

Fig. 8. End-of-day comparative performance with draw off.