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Experimental investigation of single-phase and two-phase closed thermosyphon solar water heater systems

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This study represents an experimental performance comparison between single-phase and two-phase closed thermosyphon solar water heater systems (SWHS). For this aim, two identical small-scale SWHSs were constructed side-by-side. The tests were performed under same environmental and load conditions. In the first one of these systems, water was used as working fluid in the solar collector in the conventional SWHS called single-phase. In the second one of these systems, R-134a was used as working fluid in two-phase SWHS. The performance of these systems under clear-sky conditions were investigated in July under the field conditions of Konya in Turkey. In both of these systems, the temperatures of collector inlets and outlets and water storage tanks were measured. Instantaneous solar radiation data were also taken from Konya Directorate of Meteorology Citation. Cumulative efficiencies of two-phase and single-phase systems by daily were determined. When the two-phase system is compared with the conventional single-phase system, it is derived that the two-phase system is 42.8% more efficient than the other.

Key words: Two-phase solar collector, closed thermosyphon, heat-pipe, refrigerant charged, solar water heater.

INTRODUCTION

Solar energy is one of the best sources of energy for water heating. Conventional natural circulation flat plate SWHS are the most economical and large scale application of solar energy all over the world. However, they suffer from some drawbacks, such as reversed cycle during the night, frost at extreme cold weather, high heat capacity and corrosion. Two phase closed thermosyphons are very promising as a solution to these problems. When the two-phase SWHS is compared with the conventional single-phase SWHS, it has got several advantages. These advantages include thermal diode benefit, small heat capacity and as a result quick response, resistance against corrosion and protection from freeze. The thermal diode benefit and the small heat capacity of two-phase closed thermosyphon flat plate SWHSs result in increased daily efficiency during cloudy days [Hussein, 2003].

A two-phase closed thermosyphon tube is a highly efficient device for heat transfer. It consists of an evacuated closed tube filled with a suitable amount of a working fluid.

Heat is transferred by the processes of evaporation and
condensation of the working fluid at the lower section of the tube (evaporator section) and the upper section of the tube (condenser section), respectively. Therefore, heat is transferred in a latent form (high heat rates) over considerable distances and extremely small temperature drop between the evaporator section (heated region) and the condenser section (cooled region) of the thermostyphon tube with a small degradation of energy [Nada et al., 2004].

Closed two-phase thermosyphon solar collectors consist of heat pipes (or thermosyphon tubes) filled with a refrigerant and used in closed loop SWHSs. Closed loop solar heating systems are suitable for domestic solar water heating, solar swimming pool heating or solar space heating systems. The maximum operating temperature of a heat pipe is the critical temperature of the used heat transfer medium. The low freezing points of the refrigerants and the use of latent heat to transfer energy from one place to another are of special interest in solar applications [Esen and Esen, 2005].

A number of studies have been previously conducted in which various phase change fluids or refrigerants have been evaluated for use in a thermosyphon solar water heater. Akyurt [1984] designed and manufactured numerous heat pipes for SWHSs. Each heat pipe was incorporated into a prototype solar water heater. An extensive testing program lasting for more than a year revealed that the heat pipes performed satisfactorily as heat transfer elements in SWHSs.

Radhwan et al. [1990] investigated experimentally the thermal performances of two R-11 charged integrated solar water heaters for forced and natural circulation water flows. Their results showed that the inclination of the condenser integrated within the collector frame had a remarkable effect for natural circulation water flow, while it had no significant effect for forced circulation flow.

Pluta and Pomiery [1995] studied a two-phase solar thermosyphon for domestic hot water, and indicated that proper construction and choosing suitable phase-change medium play a very important role in assuring proper operating conditions of a phase-change thermosyphon.

Ghaddar and Nasr [1998] fabricated and tested an R-11 charged solar collector with an integrated condenser for secondary-cooling water flow. Forced circulation flow demonstrated instantaneous system efficiency values varying from 60% to 20%, which is in range of conventional water solar collectors.

Joudi and Al-Tabbakh [1999] conducted a theoretical analysis by computer simulation of a two-phase thermosyphon solar domestic hot water. The computer program and calculation procedure were first validated by comparing the results with established results of single-phase systems. Then, calculations were performed for the two-phase thermosyphon system. Their results showed that, in the two-phase system, the collector efficiency did not reveal a serious change with the loading condition. The collector efficiency of the two-phase system was approximately 20% higher than a single-phase collector. Also, the thermal response of the two-phase system was faster than a single-phase system.

Hussein et al. [1999a, 1999b, 2001, 2002, 2003] investigated theoretically and experimentally a thermosyphon flat-plate solar collector. The transient thermal behavior of wickless heat pipe flat plate solar collectors was analyzed with regard to various parameters such as global solar radiation intensity, inlet cooling water temperature, absorber plate material and thickness, ratio of pitch distance to wickless heat pipe diameter and ratio of condenser section length to total wickless heat pipe length. The pitch distance was defined as width of absorber plate. The results revealed that the pitch distance limits the selection of an absorber plate having a high value of thermal conductivity. Also, from the theoretical analysis, it was concluded that the condenser section dimensionless ratio and heat pipe inclination angle had a significant effect on the condensation heat-transfer coefficient inside the inclined wickless heat pipes.

Esen and Esen [2005] constructed and tested a two-phase closed thermosyphon solar collector with heat pipes, and studied experimentally with different refrigerants and compared the performance of systems, simultaneously under same working conditions and showed that R 134a as a working fluid is more efficient than other refrigerants.

In this study, experiments were performed to find out the thermal performance of closed thermosyphon SWHSs with a single-phase and a two-phase solar collector under the same conditions. For this aim, two identical small-scale solar water heating systems were constructed and tested side-by-side under the same conditions.

**EXPERIMENTAL SET-UP AND TEST PROCEDURE**

Experiments were performed to evaluate the thermal performance of both two-phase and single-phase SWHSs under same working conditions such as solar radiation, ambient temperature. Both of these systems were designed and manufactured identically. Both storage tanks and collectors made of same materials and in same dimensions. Schemes of the single-phase and two-phase SWHS were shown in Figures 1 and 2 respectively.

Heat pipes used in two-phase collector and thermosyphon tubes used in single-phase collector were made of 9 column copper tubes which has outer diameter of 12.7 mm with the length of 1380 mm. In both solar collectors, absorber plates have 0.5 mm thickness, 800 mm width and 1380 mm length were made of copper and painted with dull black paint. The absorber plates and associated heat pipes were housed in a collector case of 1500 mm length, 840 mm breadth, and 120 mm thickness. The collector consisted of an aluminum sheet case, an 80 mm thickness insulation of glass wool behind the absorber plates and a 4 mm glass cover with 40 mm air gap between the glass and absorber plates. The tubes were connected to the absorber plates with silver-solder.

Both of these systems have horizontal cylindrical storage tanks have 75 liter. Both of heat exchangers areas have 0.4 m² surface areas into storage tanks. Water was used for single-phase system
and R-134a was used for two-phase system as working fluid. Specifications of the both SWHSs were given Table 1. Fe-Constant thermocouples were used for temperature measurement of collector outlet ($T_{\text{coll}}$) and storage tanks ($T_{\text{tank}}$). The experiments were carried out in the region of Konya (latitude 37.6) in Turkey on 27, 28 and 29 July 2006. Hourly solar radiation values were received from Konya Directorship of Meteorology Citation.

RESULTS AND DISCUSSION

Both of these systems were set-up side by side in 27, 28 and 29 July 2006 and both systems storage tanks were filled with central city water exposed to the solar radiation. The temperatures values of collector outlet and
Table 1. Specifications both of the SWHSs.

<table>
<thead>
<tr>
<th>Properties and dimensions of the both collectors</th>
<th>Single-phase</th>
<th>Two-phase</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length</td>
<td>1.50 m</td>
<td>1.50 m</td>
</tr>
<tr>
<td>Width</td>
<td>0.84 m</td>
<td>0.84 m</td>
</tr>
<tr>
<td>Depth</td>
<td>0.12 m</td>
<td>0.12 m</td>
</tr>
<tr>
<td>Transparent cover</td>
<td>glass</td>
<td>glass</td>
</tr>
<tr>
<td>Thickness</td>
<td>0.004 m</td>
<td>0.004 m</td>
</tr>
<tr>
<td>Air gap</td>
<td>0.05 m</td>
<td>0.05 m</td>
</tr>
<tr>
<td>Collector effective area, $A_{col}$</td>
<td>$1.15 m^2$</td>
<td>$1.15 m^2$</td>
</tr>
<tr>
<td>Absorber plate painted with dull black paint</td>
<td>copper</td>
<td>copper</td>
</tr>
<tr>
<td>Length</td>
<td>1.38 m</td>
<td>1.38 m</td>
</tr>
<tr>
<td>Width</td>
<td>0.80 m</td>
<td>0.80 m</td>
</tr>
<tr>
<td>Thickness</td>
<td>0.0005 m</td>
<td>0.0005 m</td>
</tr>
<tr>
<td>Insulation Material</td>
<td>glass wool</td>
<td>glass wool</td>
</tr>
<tr>
<td>Glass wool back and side thickness</td>
<td>0.05 m, 0.02 m</td>
<td>0.05 m, 0.02 m</td>
</tr>
<tr>
<td>Casing Material</td>
<td>Aluminium profile</td>
<td>Aluminium profile</td>
</tr>
<tr>
<td>Back cover</td>
<td>Galvanized iron sheet</td>
<td>Galvanized iron sheet</td>
</tr>
<tr>
<td>Thermosyphon tubes</td>
<td>copper</td>
<td>copper</td>
</tr>
<tr>
<td>Number of pipes</td>
<td>9</td>
<td>9</td>
</tr>
<tr>
<td>Length</td>
<td>1.38 m</td>
<td>1.38 m</td>
</tr>
<tr>
<td>Outside diameter</td>
<td>0.0127 m</td>
<td>0.0127 m</td>
</tr>
<tr>
<td>Inner diameter</td>
<td>0.0117 m</td>
<td>0.0117 m</td>
</tr>
<tr>
<td>Working fluid</td>
<td>pure water</td>
<td>R134a</td>
</tr>
<tr>
<td>Total weight of the working fluid</td>
<td>18 kg</td>
<td>1.75 kg</td>
</tr>
<tr>
<td>Filling ratio total volume</td>
<td>1.0</td>
<td>0.04</td>
</tr>
<tr>
<td>Filling ratio total height of the collector</td>
<td>1.0</td>
<td>0.36</td>
</tr>
<tr>
<td>Heat exchangers area at the condenser</td>
<td>0.4 m²</td>
<td>0.4 m²</td>
</tr>
<tr>
<td>Hot water storage tank volume</td>
<td>0.075 m³</td>
<td>0.075 m³</td>
</tr>
</tbody>
</table>

storages tanks were measured hourly without input-output of water to-from storages tanks. The temperatures of collectors’ outlet and storages tanks were approximately equal because of the daily solar radiation intensity were approximately equal in three days measurements. So, for only one day (28 July), solar radiation intensity and temperatures hourly values for both systems were given in Table 2.

As it can be seen from Table 2, daily total incident solar radiation is 14506 kJ/m²·day on horizontal plane. When the effective collector area $1.15 m^2$ multiplied to daily total solar radiation, total incident solar radiation on horizontal plane will be 16682 kJ/day. Amounts of heat transferred to the storage tanks can be calculated as follow for both single-phase and two-phase systems respectively.

$$Q_{\text{two-phase}} = mC_p\Delta T = 75kg \times 4.18 \text{ kJ/kg°C} \times (54.0-18.0) \text{ °C} = 11296 \text{ kJ/day}$$

$$Q_{\text{single-phase}} = mC_p\Delta T = 75kg \times 4.18 \text{ kJ/kg°C} \times (43.2-18.0) \text{ °C} = 7907 \text{ kJ/day}$$

Total daily efficiency of both of these systems can be calculated by rating calculated heat energy values to daily total incident solar radiation on horizontal plane as follow;

$$\eta_{\text{two-phase}} = \frac{11296}{16682}, \quad \eta_{\text{two-phase}} = 67.7\%$$

$$\eta_{\text{single-phase}} = \frac{7907}{16682}, \quad \eta_{\text{single-phase}} = 47.4\%$$

The efficiency increasing of two-phase solar system according to single-phase system can be derived as follow;

$$\left(\frac{\eta_{\text{two-phase}} - \eta_{\text{single-phase}}}{\eta_{\text{single-phase}}}\right) / \eta_{\text{single-phase}} = (67.7 - 47.4\%) / 47.4\% = 42.8\%$$

The efficiency increasing of two-phase system was found 42.8 %. This value of the efficiency increasing derived was nearly compatible the study results of ref. [Hussein et al. 1999b, 2001, 2002, 2003]. The temperatures values of collector outlet, storages tanks and ambient and solar radiation intensity hourly for both two-phase and single-phase systems in 28 July 2006 were given in Figure 3 as a graph.
Table 2. The temperatures values of collector outlet, storages tanks and ambient and solar radiation intensity hourly for both two-phase and single-phase systems in 28 July 2006.

<table>
<thead>
<tr>
<th>Hour</th>
<th>Solar radiation I (kJ/hm²)</th>
<th>Temperatures</th>
<th>Two-phase system (R134a)</th>
<th>Single-phase system (water)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>T_ambient (°C)</td>
<td>T_collector (°C)</td>
<td>T_storage tank (°C)</td>
</tr>
<tr>
<td>Initial</td>
<td>9,00</td>
<td>24.5</td>
<td>23.3</td>
<td>18.0</td>
</tr>
<tr>
<td>9.00-10.00</td>
<td>2009</td>
<td>26.5</td>
<td>32.2</td>
<td>25.1</td>
</tr>
<tr>
<td>10.00-11.00</td>
<td>2193</td>
<td>27.0</td>
<td>40.3</td>
<td>32.3</td>
</tr>
<tr>
<td>11.00-12.00</td>
<td>2336</td>
<td>27.0</td>
<td>48.0</td>
<td>39.0</td>
</tr>
<tr>
<td>12.00-13.00</td>
<td>2341</td>
<td>29.0</td>
<td>55.7</td>
<td>45.5</td>
</tr>
<tr>
<td>13.00-14.00</td>
<td>2185</td>
<td>29.5</td>
<td>60.4</td>
<td>50.3</td>
</tr>
<tr>
<td>14.00-15.00</td>
<td>2010</td>
<td>30.0</td>
<td>61.0</td>
<td>53.4</td>
</tr>
<tr>
<td>15.00-16.00</td>
<td>1432</td>
<td>30.0</td>
<td>58.5</td>
<td>54.0</td>
</tr>
<tr>
<td>Total radiation (kJ/m²/day)</td>
<td>14506</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 3. Two-phase and single-phase system’s the temperatures values of collector outlet and storages tanks variation by hourly.

As it can be seen from Figure 3, the temperature differences between storage tanks and collector outlets were below then 10 °C for two-phase system, but these differences were approximately 30 °C for single-phase system. The heat loss of single-phase system is higher than the other because of the temperature differences is high as nearly 30 °C. So, these heat losses decrease the efficiency of the collector and the whole system for single-phase system.

Conclusions

Within the same conditions, in order to compare of the single-phase and two-phase SWHSs, this study was carried out in Konya in 2006, it is concluded that;

1. The efficiency of the two-phase systems is higher (about 42%) than the classical system. It means that instead of using seven collectors with single-phase system, it is sufficient to use approximately five collectors with two-phase.
2. The reasons of much more efficiency of two-phase SWHS than classical system are that; heat is transferred by the process of evaporation and condensation, the coefficient of heat transfer is higher, the heat loss of collector is lower, a small heat capacity and, as a result, a quick response to changes in solar radiation intensity.
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REFERENCES