EXPERIMENTAL INVESTIGATION OF TWO-PHASE CLOSED THERMOSYPHONS WITH A LIQUID RETENTION STRUCTURE FOR SDHWS

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ABSTRACT

The heat pipe technology is used in solar flat-plate collectors worldwide mainly when cold weather conditions are found. The main scope of this research is to develop a compact solar heating system using heat pipe technology with costs similar to conventional systems. Heat pipes of the two-phase closed thermosyphon – TPCT type were chosen, so that simple smooth pipes could be used. In the present work, some improvements are added to the TPCTs to reduce their thermal resistance. A liquid retention structure, made with a helicoidal of copper wire, is inserted in the evaporator, providing boiling nucleation sites and increasing the wetted region of the evaporator. Different configurations were tested. Four different filling ratios (0.2, 0.4, 0.6 and 0.8), the insertion or not of the liquid retention structure and the use of ethanol or water as working fluid are combined, resulting in sixteen different configurations.

1. INTRODUCTION

The two-phase closed thermosyphon is a high thermal conductance device used in several fields in engineering, being an evacuated tube filled with an amount of working fluid. The heat exchange occurs by phase change, in the evaporator and in the condenser. The evaporator is positioned lower than the condenser, in order to allow the condensed fluid return to the evaporator region through gravity.

Solar flat-plate collectors are tilted with the horizontal with an angle around the latitude plus 10 degrees in order to maximize useful energy during the year, due to this, they can be constructed with TPCTs. The evaporator of the TPCT is brazed to the flat-plate absorber and the condenser can either be immersed in a cooling manifold or fixed to the storage tank wall.

For solar flat-plate collectors, the TPCT has a series of advantages in comparison with the traditional single phase thermosyphon installation; some of them are:
- it works as a heat diode, so the heat stored in the tank is not lost through reversible flow;
- the collector is resistant to freezing;
- the heat transfer coefficients are much higher for the phase changes (boiling and condensation) than for the case of free convection in single phase thermosyphon solar collectors;

The present work reports the experimental investigation of the effects of a liquid retention structure on the thermal behavior of TPCTs. The liquid retention structure has two purposes, to increase the region wetted by the working fluid without increasing the filling ratio, and to promote bubble nucleation sites along the evaporator region. Water and ethanol were used as working fluids, and different filling ratios were also evaluated. Experimental results are presented to demonstrate the effect of the liquid retention structure and other variables on the performance of the modified TPCT.

2. BACKGROUND

In previous works, the current authors detected some operational problems using TPCTs in a specific design for compact solar heating systems (Abreu and Colle, 2004; Abreu et al., 2003; Abreu, 2003).

It was found that the “dry-out” limitation easily occurs for low latitude sites. Additional working fluid could avoid this problem; however it is not desirable because it increases the overall thermal resistance.

Furthermore, during the startup and operation at low heat fluxes, the heat transfer inside the evaporator of a TPCT is followed by the "geyser boiling" phenomenon (Fahgri, 1995). The geyser boiling phenomenon occurs at low heat fluxes and large filling ratio, which are typical operating conditions for solar flat-plate collectors. These circumstances should be avoided in benefit of the thermal performance of the TPCT.

Abreu et al. (2003) and Abreu (2003) investigated the thermal behavior of TPCTs for solar flat-plate collectors, studying the effects of varying filling ratio, evaporator length, cooling temperature, and tilt angle. Several conclusions were drawn from this work:

- heat flux is the primary parameter in determination of internal boiling regime;
- heat flux is also the most significant variable over the thermal resistance of the heat pipe – the higher is the heat flux, the lower is the thermal resistance; with exceptions related to the internal boiling regime;
- increasing the evaporator length causes a rise in the internal pressure leading to a reduction of geyser boiling conditions;
- increasing the slope intensifies geyser boiling;
- variations in the evaporator length and in the slope had little effect over the thermal resistance in the studied ranges;
- the influence of the cooling temperature was not sufficiently studied and therefore should be better investigated.

Hussein et al. (1999) obtained a better efficiency curve then that achieved by Abreu (2003). The main difference between the TPCTs was the lower filling ratio used by the first authors, thus the reduction of the filling ratio improves the TPCT performance.

In the present work, the modifications added to the TPCTs configuration aim to reduce the filling ratio, while avoiding the dry-out limitation and providing nucleation sites in order to reduce the geyser boiling at low heat fluxes.

3. EXPERIMENTAL SETUP

Sixteen TPCTs were constructed and tested in an indoor setup. The heat pipes are brazed to the flat-plate on the evaporator region, and the solar irradiation absorbed is simulated using electrical skin heaters placed on the flat plate. The heaters are connected to a DC power supply, which delivers the power for each test. This assembly is located inside an insulated box. The heat is removed in the condenser side through a cooling manifold connected to a thermostatic bath with temperature-controlled circulating water. The temperatures are measured with T-type thermocouples (copper-constantan) and their values are recorded using a data acquisition system.

Figure 1 shows details of the experimental setup. The list of equipments used is given in Table 1. Figure 2 shows a picture of the experimental apparatus.

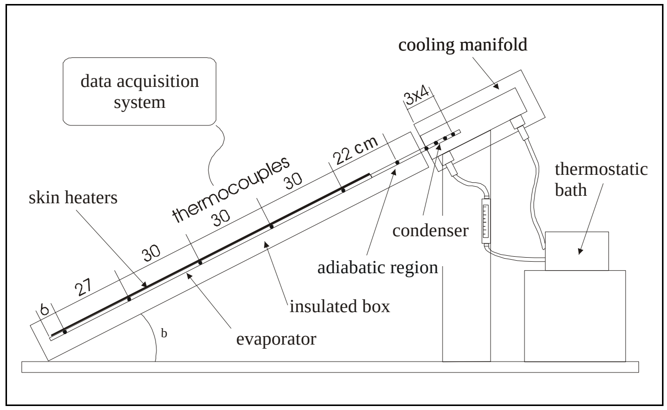

Figure 1. Experimental setup

TABLE 1. MEASURING EQUIPMENT

Equipment	Manufacturer	Model
data acquisition system	Hewlett Packard	34970A
DC power supply	Heinzinger	PTN 125-10
flow meter	Conaut	Duran060
thermostatic bath	Lauda	RK 8 KP

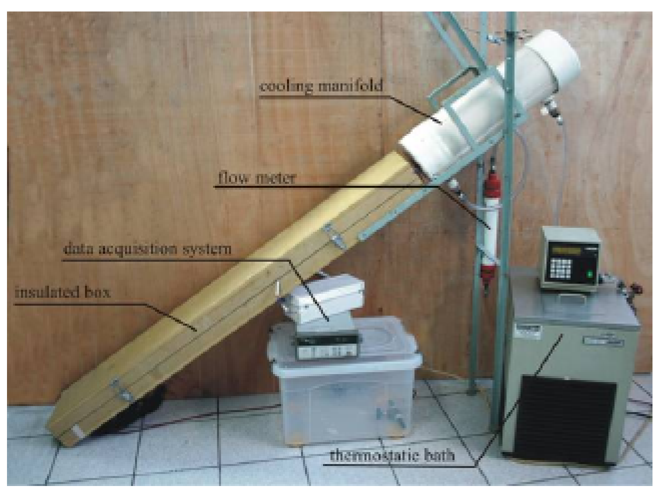

Figure 2. Picture of the heating and cooling sections of the TPCT.

Technical characteristics of each TPCT are shown in Table 2. The TPCTs differ by the use of the helicoidal wire structure, the filling ratio and the working fluid (water or ethanol). The filling ratio is defined as the liquid volume divided by the total volume of the evaporator region and four values are tested in the present work. The structure is made of a copper wire and is inserted in the evaporator region in a helicoidal form with constant pitch. On the flat plate of each TPCT was applied heat fluxes at 200, 400, 600, 800, 1,000 and 1,200 W/m^2, in order to simulate the absorbed solar irradiation, which are equivalent to powers of 33.75, 67.5, 101.25, 135, 168.5 and 202.5 W, respectively.

TABLE 2. TPCT DESIGN CHARACTERISTICS

evaporator length	1.30 m
condenser lenght	0.14 m
adiabatic region lenght	0.25 m
outer diameter	12.7 mm
inner diameter	11.7 mm
flat-plate width	0.125 m
flat-plate thickness	0.3 mm
cooling temperature	40 °C
helicoidal wire diameter (if any)	0.66 mm
helicoidal pitch (if any)	4.2 mm

TPCT number	TPCT code	filling ratio	working fluid	presence of helicoidal wire
1.	02WH	0.2	water	yes
2.	04WH	0.4	water	yes
3.	06WH	0.6	water	yes
4.	08WH	0.8	water	yes
5.	02W	0.2	water	no
6.	04W	0.4	water	no
7.	06W	0.6	water	no
8.	08W	0.8	water	no
9.	02EH	0.2	ethanol	yes
10.	04EH	0.4	ethanol	yes
11.	06EH	0.6	ethanol	yes
12.	08EH	0.8	ethanol	yes
13.	02E	0.2	ethanol	no
14.	04E	0.4	ethanol	no
15.	06E	0.6	ethanol	no
16.	08E	0.8	ethanol	no

4. DISCUSSION OF THE RESULTS

The steady state overall thermal resistance is used to evaluate the performance of the TPCTs, and is calculated from experimental data as follows:

$$R = (T_{co} - T_{ev})/Q \qquad (1)$$

where T_{co} is the condenser average temperature, T_{ev} is the evaporator average temperature, and Q is the power transported by the TPCT. The value of Q can be calculated either by the heat removed in the cooling manifold or by the power dissipated on the flat-plate, taken into account the heat losses.

Figure 3 shows a comparison of the start-up of TPCTs with and without the helicoidal structure, in terms of the measured temperatures in the evaporator. While the prevailing internal regime is free convection, the temperature behavior of both TPCTs is similar. The boiling process starts up at the same time, but it becomes rapidly steady for the TPCT provided with the helicoidal structure, while it takes a long period to become stable for the case without the helicoidal structure. This behavior is attractive for solar flat-plate collectors, since a fast start up is desirable in order to improve their thermal response to solar radiation inputs.

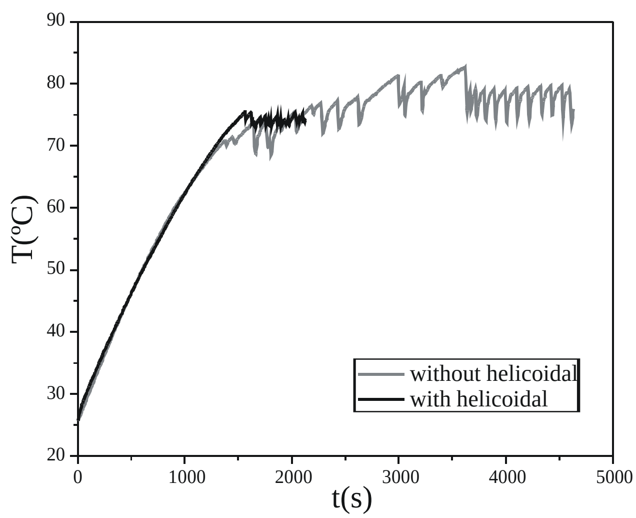

Figure 3. Start-up evaporator temperatures of TPCTs with filling ratio equal to 0.6, water as working fluid and heat flux equal to 400 W/m^2 (67.5 W).

The presence of the helicoidal structure was also successful in minimizing the thermal resistance of the device. Figure 4 shows the overall thermal resistance as a function of the applied heat flux, for several heat pipe tests. It is clear that the thermal resistance is always lower for the heat pipes with the helicoidal structure, when considering the same filling ratio and the same working fluid. That may be explained by the larger area wetted with liquid film due to the retention of condensed fluid that falls from the condenser region.

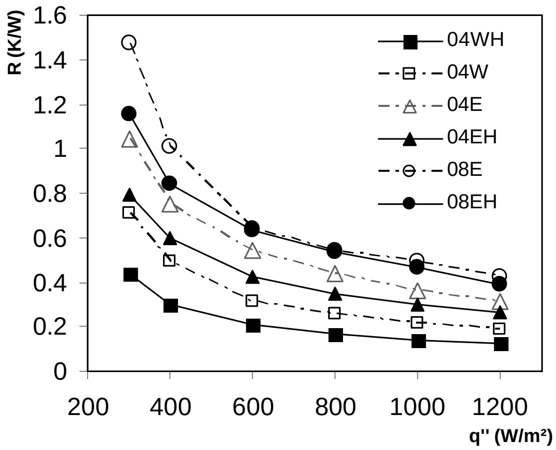

Figure 4. Overall thermal resistance of TPCTs as a function of the heat flux showing lower thermal resistances when the helicoidal wire is present.

The overall thermal resistance decreases with the increase of the heat flux for most cases, but the same did not happen with the water charged smooth pipe for the filling ratios of 0.4 and 0.6 (Figure 5). A substantial increase of the thermal resistance of the smooth pipe can be noticed at heat fluxes around 800 W/m^2; looking at the transient data it can be concluded that it occurs during the transition from the geyser to nucleate boiling regime.

In order to verify that the nucleate boiling regime is really reached, each run was replicated and a pretty similar result was obtained. The high thermal resistance of the smooth pipe may be explained by the fact that the necessary overheating for the vapor bubble nucleation is higher for this case. The same is not verified with the enhanced pipe, which is supposed to have more nucleation sites.

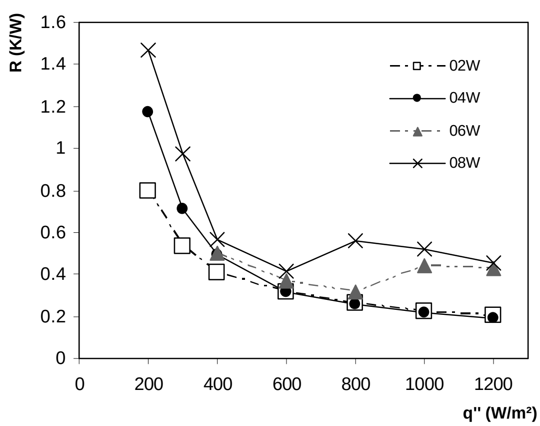

Figure 5. Overall thermal resistance of TPCTs as a function of the heat flux for water as working fluid and no helicoidal wire.

Effect of filling ratio

It was observed that in a general way, with only one exception (see 04WH in Figure 6), decreasing the initial filling ratio reduces the overall thermal resistance of the TPCTs. This can be explained by the fact that liquid film boiling conductance is much higher than nucleate pool boiling conductance, as can be proved by means of the Nusselt Theory. Hence, the higher the liquid pool height, the higher is the mean thermal resistance of the evaporator.

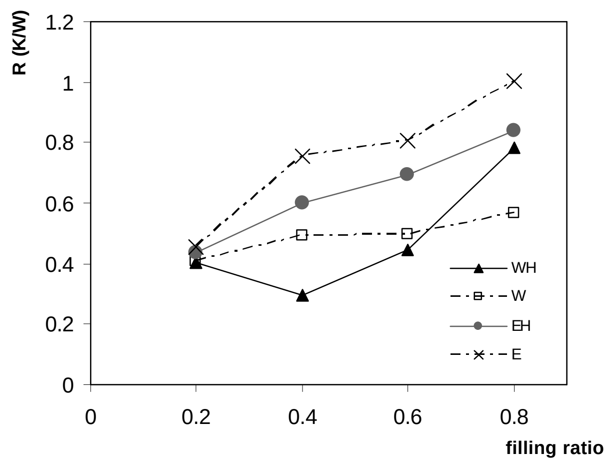

Figure 6. Overall thermal resistance of TPCTs as a function of the filling ratio for all TPCTs, with heat flux equal to 400 W/m^2 (67.5 W).

Effect of the working fluid

Water and ethanol were used as working fluid because they are appropriate for the temperature range of the studied cases, as seen in Faghri, 1995 and Groll, 1991. It was observed that for the same filling ratio, using water as working fluid resulted in lower thermal resistances in comparison with ethanol, for most conditions. Empirical correlations predict the Nusselt number for ethanol being higher than for water in the studied cases, but the higher conductivity of water made the liquid film boiling conductance of water higher than that of ethanol, in particular for the best case scenarios, with the minimum thermal resistances (Figure 7). However ethanol presented a more stable and predictable behavior, without changes in the internal boiling regime, which resulted in lower thermal resistances compared to water for some cases, considering the same filling ratio (Figure 8). That is also an advantage for the development of a trustworthy model to predict the thermal behavior of this TPCT using ethanol in the future.

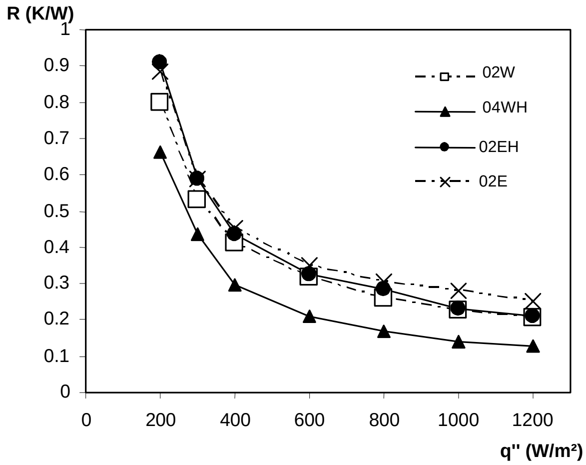

Figure 7. Overall thermal resistance of TPCTs as a function of the heat flux for the best case scenarios for either water or ethanol as working fluid and with or without the helicoidal wire.

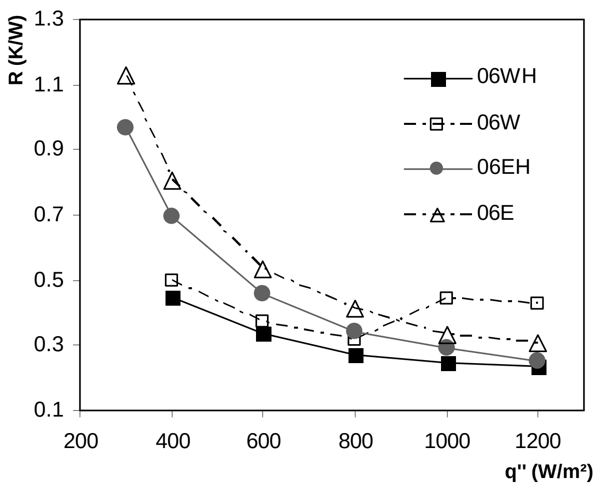

Figure 8. Overall thermal resistance of TPCTs as a function of the heat flux with filling ratio equal to 0.6.

5. CONCLUSIONS

The results show improvements in the thermal performance with the addition of the liquid retention structure, both in terms of overall thermal resistance and start up. Reducing the filling ratio decreases the overall thermal resistance and the dry-out limitation was not detected even for the lowest filling ratio (0.2). Changes in the boiling process inside the TPCTs were also verified. The geyser boiling phenomenon, which can lessen the lifecycle of the TPCTs, was not detected for the cases with the liquid retention structure. In a further research, a correlation may be developed with the test results and compared with those present in the literature.

6. ACKNOWLEDGMENTS

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