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EXPERIMENTAL INVESTIGATION OF THE THERMAL PERFORMANCE OF TWO-PHASE CLOSED THERMOSYPHONS WITH ADDITION OF A LIQUID RETENTION HELICOIDAL STRUCTURE IN THE EVAPORATOR REGION

Samuel Luna Abreu, Sergio Colle, João Felipe Almeida Destri
LABSOLAR/UFSC – Solar Energy Laboratory, Federal University of Santa Catarina
Campus Universitário – Trindade – 88040-900 – Florianópolis - SC
Phone: 55 48 2342161, Fax: 55 48 3317615, E-mail: samuel@emc.ufsc.br

ABSTRACT

Two-Phase Closed Thermosyphons – TPCTs can be applied in solar flat-plate collectors. In this case, the slope of the TPCT decreases with location's latitude and the dry-out limitation may easily occur. The filling ratio can be increased to avoid this problem; however, this would not be desirable since the thermal resistance increases. On the other hand, during startup and operation at low heat fluxes, the geyser boiling phenomenon may occur. The main condition that leads to geyser boiling effect is the high overheating necessary to nucleate bubbles at low heat fluxes inside a smooth pipe. The present work reports the experimental investigation of the thermal behavior of two TPCTs that are especially proposed for solar flat-plate collector applications. One TPCT is made with a copper smooth pipe and the other TPCT has the same envelope, except that a liquid retention structure made with a helicoidal of copper wire is inserted in the TPCT's evaporator region. The proposed modification is intended to increase the wetted region without increasing the filling ratio. The additional effect is to promote bubble nucleation sites along the evaporator region, thus avoiding geyser boiling. The thermal performance of the two TPCTs is compared for different heat fluxes. Experimental results for both TPCTs are presented, in order to demonstrate the improvement of the thermal performance of the modified TPCT.

KEYWORDS: Two-phase closed thermosyphon, solar flat-plate collectors

1. INTRODUCTION

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 Two-Phase Closed Thermosyphons – 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 on the storage tank wall.

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). As found in the case previously studied, "dry-out" limitation easily occurs for low latitude locations. Additional working fluid can avoid this problem. However it is not desirable because it increases the overall thermal resistance. On the other hand, 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). These circumstances should be avoided in benefit of the thermal performance of the TPCT.

The present work reports the experimental investigation of the effects of a liquid retention structure on the thermal behavior of TPCTs. One TPCT is made with a copper smooth pipe while the other is made with the same envelope, except that a liquid retention helicoidal of copper wire is inserted in the evaporator region. The purpose of the liquid retention structure is twofold, to increase the wetted region by the working fluid without increasing the filling ratio, and to promote bubble nucleation sites along the evaporator region.

The thermal performance of the two TPCTs is compared, for different heat fluxes and filling ratios. Experimental results are presented to demonstrate the effect of the capillary structure on the performance of the modified TPCT.

2. BACKGROUND

Several works focusing the thermal performance of heat pipes and TPCTs can be found in the literature. In the present work, special attention is addressed to those which have focused the application and operational conditions of the TPCT investigated in this work.

Ismail and Abogderah (1992, 1998) designed a solar flat-plate collector with heat pipes for low latitude locations. In order to improve the performance, the heat pipes had a capillary structure in the evaporator and the condenser was smooth and tilted with a higher angle than the evaporator.

Chun et al. (1999) tested five different configurations of heat pipes for solar flat-plate collectors. The parameters modified in the tests are: capillary structure (wrapped screen wick and TPCT), working fluid (water, methanol, acetone and ethanol), storage tank capacity (15 and 11 liters), collector area (0.17, 0.16 and 0.15 m^2) and absorber surface treatment (selective spray and black-chrome). The number of analyzed parameters is large and the test of all combinations among them would be practically unfeasible. Due to this, a complete study taken into account the combination of all possible cases was not carried out. A conclusion drawn from this work, is that at low heat fluxes the heat pipes with capillary structure had a better thermal behavior than the TPCTs.

Hussein et al. (1999a) developed a theoretical model and carried out a parametric analysis of TPCTs for a solar flat-plate collector in terms of cooling temperature, material and thickness of the flat-plate absorber, pipe diameter, solar irradiation and condenser length. Later, a comparison with experimental data was carried out and the efficiency curve was determined (Hussein et al., 1999b). An interesting remark of this work was the low filling ratio used (0.2), in spite of recommendations for filling ratios from 0.6 to 0.8 for inclined TPCTs to avoid the dry-out limitation found in the literature (Groll, 1991).

Abreu and Colle (2004) tested several TPCT configurations and detected oscillations typical from the geyser boiling phenomenon. The geyser boiling phenomenon occurs at low heat fluxes and large filling ratio as seen in Fahgri (1995) which are operating conditions commonly found in solar flat-plate collectors. Abreu et al. (2003) and Abreu (2003) studied the thermal behavior of TPCTs for solar flat-plate collectors varying filling ratio, evaporator length, cooling temperature, and tilt angle. Several conclusion are drawn from this work:
- the heat flux is the most important parameter in the determination of the internal boiling regime;
- decreasing the filling ratio gives rise to the geyser boiling effect, due to the lower working pressure;
- increasing the evaporator length causes an increase of the power and the internal pressure leading to a reduction of the geyser boiling conditions;
- increasing the slope increases geyser boiling. This effect was unexpected because the internal pressure is higher with the larger slope due too the larger height of the liquid pool. A possible explanation to this is that the difference between the vapor pressure in the bubble and the vapor pressure in the condenser is higher in the case of larger slope;
- the influence of the cooling temperature was not sufficiently studied and therefore it should be better investigated.

The efficiency curve obtained by Hussein et al. (1999b) is higher then that obtained by Abreu (2003). The main difference between the TPCTs was the lower filling ratio used by the first authors. 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

Four TPCTs were constructed as individual modules of flat-plate plus pipe and tested in an indoor setup. Technical characteristics of each TPCT are shown in Table 1. The filling ratio is defined as the liquid volume divided by the total volume of the evaporator region and two values are tested in the present work. The TPCTs differ by the helicoidal wire structure and by the filling ratio. The structure is made of a copper wire winded up in a helicoidal form with constant pitch. The heat flux applied on the flat plate, in order to simulate the absorbed solar irradiation was set to levels of 200, 400, 600, 800, 1,000 and 1,200 W/m^2 , which are equivalent to powers of 33.75, 67.5, 101.25, 135, 168.5 and 202.5 W, respectively.

Table 1. TPCT design characteristics

TPCT	A	B	C	D
evaporator	1.30 m			
condenser	0.14 m			
adiabatic region	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			
filling ratio	0.6	0.4	0.6	0.4
capillary structure	no	no	yes	yes
helicoidal wire diameter	-		0.66 mm	
helicoidal pitch	-		4.2 mm	

The experimental setup consists of an insulated box where the evaporator region of the TPCT is located. On the flat plate are mounted skin heaters that are connected to a DC power supply, which delivers the heat power for each test. The condenser region of the TPCT is put inside a cooling manifold connected to a thermostatic bath that provides a controlled water temperature. Along the TPCT, T-type thermocouples (copper-constantan) were installed to measure the temperature. Inside one of the TPCTs, three thermocouples were mounted to measure the temperatures of the liquid pool, of the vapor in the adiabatic region, and of the vapor in the condenser. A data acquisition system and is used to acquire and to store the data collected during the experiments. Figure 1 shows details of the experimental setup. The list of equipments used is given in Table 2. Figure 2 shows a picture of the heating and cooling sections connected to the thermostatic bath.

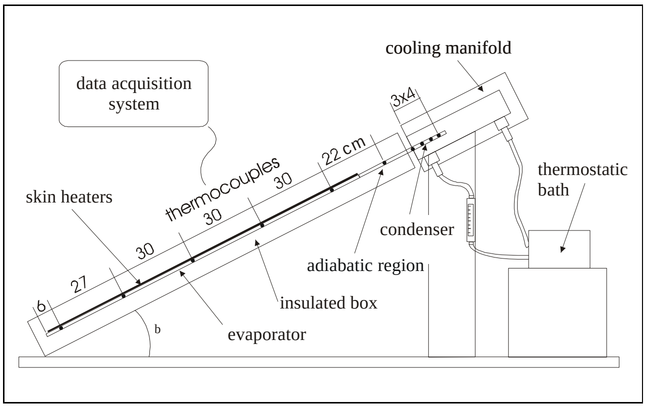

Figure 1. Experimental setup

Table 2. Measuring equipment

Equipment	Manufacturer	Model
data acquisition system	Hewlett Packard	34970A
DC power supply	Hewlett Packard	6030A
flow meter	Conaut	Duran060
thermostatic bath	Lauda	RK 8 KP

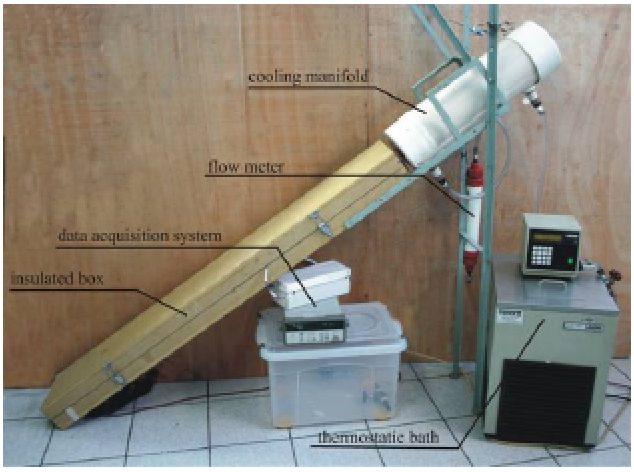

Figure 2. Picture of the heating and cooling sections of the TPCT.

4. DISCUSSION OF THE RESULTS

The results reported in this paper are limited to the TPCTs with filling ratio equal to 0.6. Figure 3 shows a comparison of the start-up of TPCTs with and without the helicoidal structure in the evaporator, in terms of the measured temperatures.

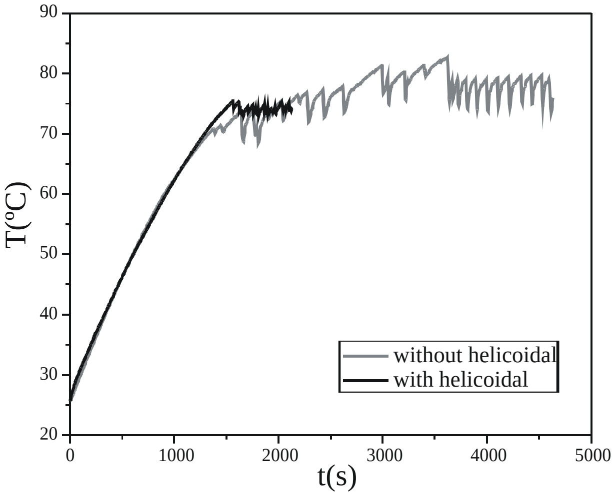

Figure 3. Start-up evaporator temperatures of the TPCTs with filling ratio equal to 0.6 and heat flux equal to 400 W/m^2 (67.5 W).

It can be observed that during the free convection period the temperature behavior of both TPCTs is almost the same. The boiling process starts up at the same time, but it becomes rapidly stable for the TPCT provided with the helicoidal structure, while it takes a long period to stabilize in the case without the helicoidal structure. This fact is in favor of solar flat-plate collectors, for a fast start up is desirable in order to increase its thermal response to solar radiation inputs.

The steady state overall thermal resistance of the TPCTs is used to compare the performance of the two TPCTs, as given by:

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

where T_{co} is the average condenser temperature, T_{ev} is the average evaporator 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, by taken into account the heat losses.

The boiling process is characterized by temperature oscillations, even in the case of steady state. Thus, an average of the measured values corresponding to the steady state (the last temperature values) is performed, in order to find the temperature that better represents the steady state. The number of temperature values used is chosen by calculating the average and standard deviation of different sample sizes. The value with lower standard deviation is chosen. Figure 4 shows the typical results found.

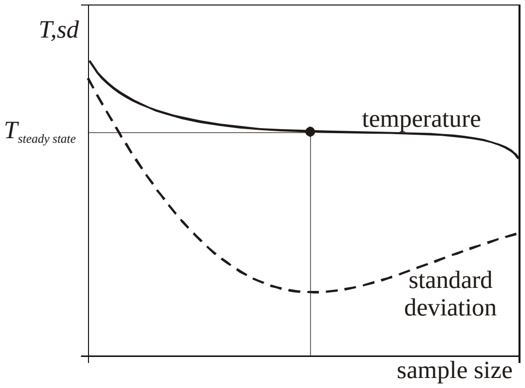

Figure 4. Steady state temperature and standard deviation of the temperatures, as a function of the sample size.

Figure 5 shows the overall thermal resistance as a function of the applied heat flux. It can be seen that the thermal resistance is always lower for the case with the helicoidal structure. The overall thermal resistance decreases with the increase of the heat flux in the case with the helicoidal structure, but the same did not happen with the smooth pipe. A substantial increase of the thermal resistance of the smooth pipe is detected for heat fluxes around 1,000 W/m^2, which indicates that the boiling regime changed to nucleate boiling. In order to verify that the nucleate boiling regime is really reached, the test run was repeated and a pretty similar result was obtained. The high thermal resistance of the smooth pipe may be explained by the fact that the vapor bubbles in contact with the portion of the pipe that is brazed to the flat-plate, contributes to increase the local thermal resistance. The same is not verified with the enhanced pipe, which is supposed to have a larger wetted perimeter due to the helicoidal wire.

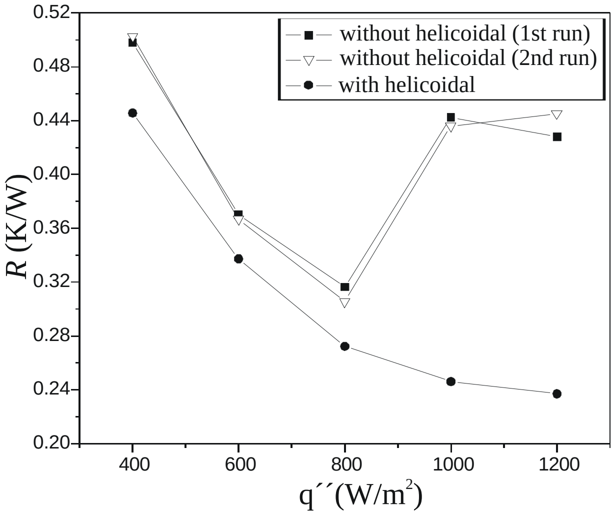

Figure 5. Overall thermal resistance as a function of the heat flux

3. CONCLUSIONS

The present results enables one to conclude that it is possible to improve the performance of TPCTs by the addition of a copper wire helicoidal inserted in the evaporator section. It is a rather cheap solution in comparison to wicks or grooved pipes, which are in general more expensive. The results presented here are far from being conclusive. In order to define design criteria for applications of this type of TPCT to flat-plate collectors, further tests should be carried out, considering lower filling ratios, lower heat fluxes, different pitch values of the helicoidal, different wire diameter, as well as lower tilt angles. A good solar collector should have low critical utilizability level. In other words, it is desirable that a solar flat-plate collector should start up at low irradiation levels and low working fluid temperatures. Therefore, additional experimental work is necessary in order to determine the critical working limits.

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