Available online at www.sciencedirect.com
SCIENCE DIRECT®
Solar Energy 76 (2004) 141–145
SOLAR ENERGY
www.elsevier.com/locate/solener

An experimental study of two-phase closed thermosyphons for compact solar domestic hot-water systems

Samuel Luna Abreu *, Sergio Colle

LABSOLAR—Department of Mechanical Engineering, Federal University of Santa Catarina, CP 476 Trindade, 88040-900 Florianópolis, SC, Brazil

Received 17 January 2003; accepted 14 February 2003

Abstract

This paper focuses on the experimental analysis of the thermal behavior of two-phase closed thermosyphons with an unusual geometry characterized by a semicircular condenser and a straight evaporator. All the tests were done in an experimental indoor setup that uses electrical skin heaters to simulate the solar radiation. Different evaporator length, fill ratio of working fluid, cooling temperature and slope of the evaporator were tested for different heat fluxes, and the effects of these parameters on the overall thermal resistance were verified. An analysis of the transient results and the steady state performance was conducted in order to provide information for the design of a compact solar domestic hot-water system.

1. Introduction

Heat pipes are high efficiency thermal control and heat transport devices, widely used in different engineering applications, from aerospace to microelectronic applications (Groll and Rösler, 1992). The "two-phase closed thermosyphon" (TPCT), also called gravity heat pipe, is the most simple kind of heat pipe and has several applications in industrial heat recovery. It is also an attractive alternative in flat plate solar collectors due to its relative simplicity and to the gravity pumping which is effective in tilted surfaces.

A new configuration is being developed to design a compact "solar domestic hot-water system" (SDHWS) made with a group of TPCT modules assembled in parallel. Each individual module has a TPCT coupled with a flat plate absorber in the evaporator and with the thermal reservoir in the condenser. The TPCT has an inclined evaporator and the condenser has a semicircular profile due to individual characteristics of the proposal design. Copper pipes charged with water were chosen according to the final application and the operational conditions. Fig. 1 shows the proposed configuration for the compact SDHWS.

Previous works present studies of heat pipes in SDHWS using different configurations than the proposed in this paper. The works of Oliveti and Arcuri (1996), Ismail and Abogderah (1992, 1998) and Hussein et al. (1999a,b) present the results obtained with heat pipe flat plate solar collectors where the condensers of the pipes were immersed in a cooling manifold. Oliveti and Arcuri and Hussein et al. made use of TPCTs with water as the working fluid, while Ismail and Abogderah made use of heat pipes with internal capillary structure in the evaporator section and methanol as the working fluid. Another work, from Chun et al. (1999), presents a similar configuration of the proposed here, where five individual modules of only one pipe coupled with a thermal reservoir were tested. Different working fluids (water, methanol, acetone and ethanol), pipes with or without wick, different thermal reservoir volumes and different absorber surface treatment were compared.

The present configuration differs from the configurations above due to its unusual geometry of the condenser section. While the other authors make use of

* Corresponding author. Tel.: +55-48-2342161; fax: +55-48-3317615.
E-mail address: samuel@emc.ufsc.br (S.L. Abreu).

0038-092X/$ - see front matter © 2003 Elsevier Ltd. All rights reserved.
doi:10.1016/j.solener.2003.02.001

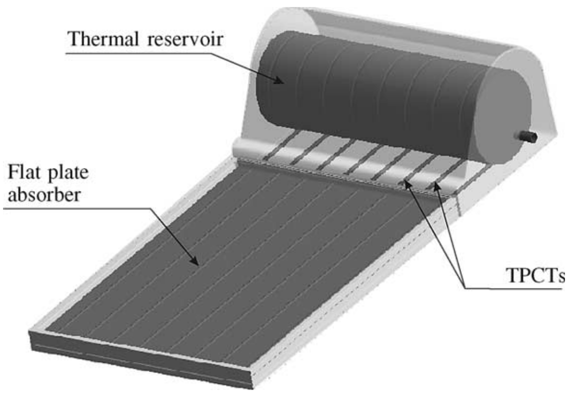

Fig. 1. Proposed configuration of the compact SDHWS.

straight pipes, here the condenser was curved to allow an external coupling between the pipes and the thermal reservoir. This solution enables a more compact assembly and in the case of low latitude locations, where collector's slope is small, it also assures the performance of the TPCT.

An experimental setup was constructed to investigate the effect of the basic design parameters on the performance of the thermosyphons. This can help in the determination of the optimum dimensions of the compact SDHWS prototype. This device allows accomplishing the performance of each individual TPCT module. Different evaporator lengths, evaporator inclination and filling ratio, are tested for any desired heat flux in the absorber plate. The condenser section is immersed in a cooling manifold in the experimental setup. This experiment is carried out entirely indoor, hence standardized weather conditions are not needed in order to run the tests.

2. Experimental setup

Fig. 2 shows the experimental setup used in the present work. The TPCTs are put inside an insulated box of wood and polyurethane foam. Over the flat plate absorber, which corresponds to the evaporator, a group of skin heaters electrical resistances are placed with a high thermally conductive paste. These resistances are connected with a DC power supply; by this way it is possible to simulate different solar radiation levels. The condenser is placed inside a PVC cooling manifold and a compact thermostat provides water in a controlled temperature to the jacket. Along the entire pipe there are several thermocouples T-type (copper-constantan),

Fig. 2. Experimental setup.

Table 1
Levels of analysis of the chosen parameters

Level	1	2	3
l_{ev}—Evaporator length [m]	1	1.35	1.5
f—Fill ratio [dimensionless]	0.6	0.8	–
β—Slope [°]	30	45	–
T_c—Cooling temperature [°C]	20	40	–

Table 2
Fixed experimental parameters

d—Pipe diameter [mm]	15
γ—Pipe thickness [mm]	0.7
r—Condenser curvature radius [mm]	180
w—Flat plate width [mm]	125
δ—Flat plate thickness [mm]	0.3
ϕ—Contact angle [°]	60

Table 3
Value of the variable parameters in each experiment

N	l_{ev} [m]	f	β [°]	T_c [°C]
1	1.00	0.8	30	20
2	1.00	0.8	30	40
3	1.00	0.8	45	20
4	1.00	0.8	45	40
5	1.00	0.6	30	20
6	1.00	0.6	30	40
7	1.00	0.6	45	20
8	1.00	0.6	45	40
9	1.35	0.8	30	20
10	1.35	0.8	30	40
11	1.35	0.8	45	20
12	1.35	0.8	45	40
13	1.35	0.6	30	20
14	1.35	0.6	30	40
15	1.35	0.6	45	20
16	1.35	0.6	45	40
17	1.50	0.8	30	20
18	1.50	0.8	30	40
19	1.50	0.8	45	20
20	1.50	0.8	45	40
21	1.50	0.6	30	20
22	1.50	0.6	30	40
23	1.50	0.6	45	20
24	1.50	0.6	45	40

whose signals are read by a data acquisition system and stored in a microcomputer.

Some design parameters were chosen to determine their influence in the performance of the TPCTs. The following parameters were analyzed: length of the evaporator, fill ratio of the working fluid, slope of the evaporator and cooling temperature. All the arrangements were tested in five different heat fluxes from 400 to 1200 W/m^2. It was necessary to construct six TPCTs to test all possible arrangements between the

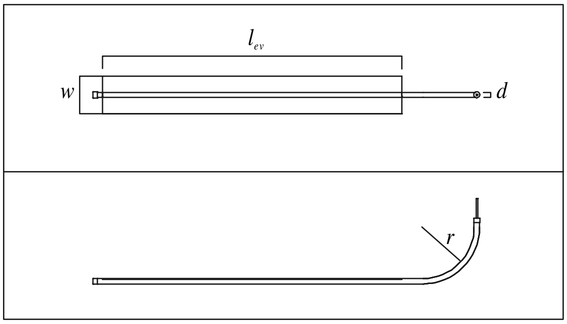

Fig. 3. TPCT geometry.

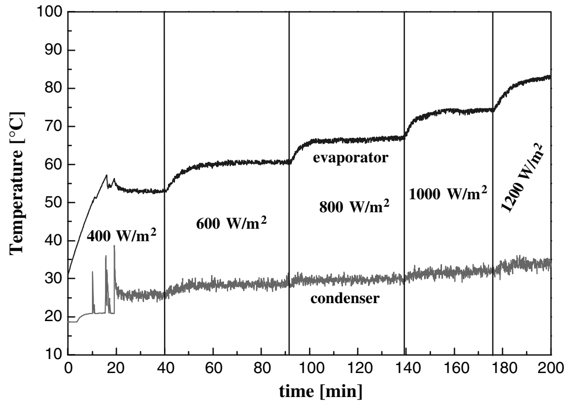

Fig. 4. Transient temperatures for the TPCT with $l_{ev} = 1$ m, $f = 0.8$, $T_c = 20$ °C, $\beta = 30°$.

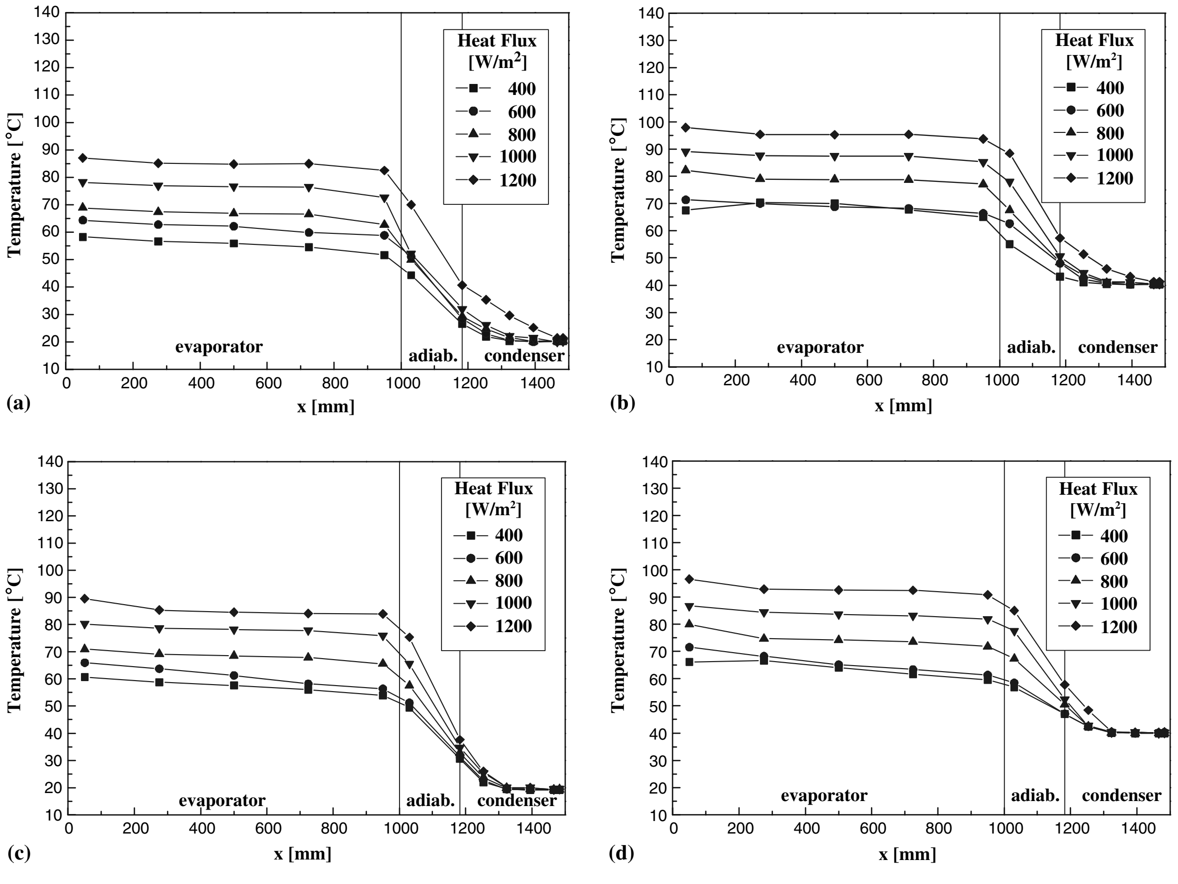

Fig. 5. Steady state temperatures for the TPCT with $l_{ev} = 1$ m and $f = 0.8$, (a) $T_c = 20$ °C, $\beta = 30°$, (b) $T_c = 40$ °C, $\beta = 30°$, (c) $T_c = 20$ °C, $\beta = 45°$, (d) $T_c = 40$ °C, $\beta = 45°$.

different parameters to be analyzed; other arrangements were achieved by changing the workbench. Table 1 shows the values of the design parameters chosen to perform the present analysis, as well as the combinations of these parameters were tested, resulting in 24 (twenty four) different experimental cases. The configurations tested are shown in Table 3.

The design parameters shown in the Table 2 are fixed for all experimental cases considered. Fig. 3 shows the geometry of the TPCTs investigated.

The experimental procedure was to set a heat flux and then to wait for the stabilization of the temperatures, which took about 50 min. Even in the steady state there are oscillations in the temperatures, in such cases the average of the last measured values was taken. After the stabilization, the heat flux was increased in steps of 200 W/m^2 and the process was repeated until the heat flux reached 1200 W/m^2. The time interval chosen was 10 s between measurements.

3. Results and discussion

First, some results of the transient behavior of one of the TPCTs will be presented. Fig. 4 shows the temperatures in the middle of the evaporator and in the beginning of the condenser, respectively. It can be observed that in the evaporator it is easy to see the transitions between the different levels of heat fluxes, while in the condenser the transitions are not very clear. The startup is characterized by an initial heating, where only natural convection occurs inside the pipe. After this the boiling process starts causing initially an overheating that denotes a geyser boiling as described in Fahgri (1995). As the temperature increases, the overheating decreases and the boiling process becomes more stable, denoting a pool nucleate boiling where small oscillations continue to occur.

The steady state results lead to some interesting conclusions about the behavior of the TPCTs. In Fig. 5, results obtained with the TPCT that has $l_{ev} = 1$ m and $f = 0.8$ can be seen. The x-axis represents the linear distance from the beginning of the evaporator for different cooling temperatures and inclinations. The behavior of the temperatures along the TPCT is almost the same, with a small decrease of the temperature in the evaporator and a large decrease from the end of the evaporator until the condenser. However some differences can be observed, the most relevant is the fact that when the cooling temperature held to 40 °C (B and D), for the lowest heat flux, the temperature along the pipe first increases and then decreases in the direction of the top of the liquid pool. As the heat flux increases, the temperature distribution becomes everywhere decreasing toward the top of the pool. This occurs due to the transition from the geyser boiling to the nucleate boiling, where the necessary overheating to nucleate bubbles is lower. The difference in the temperature between the evaporator and the condenser is lower when the cooling temperature is higher; and this denotes a decrease of the overall thermal resistance of the TPCTs with an increase in the cooling temperature. Comparing the cases a and b with c and d, where the slope of the TPCTs was changed from 30° to 45°, it can be seen that for the larger slope the vapor front advances more than for the smaller slope, thus more energy is transferred to the cooling flow.

The effect of the fill ratio is shown in Fig. 6, where TPCTs with $l_{ev} = 1.5$ m are tested for fill ratios of 0.6 and 0.8. It can be seen that the evaporator temperature is higher in the case of $f = 0.8$, which denotes the higher thermal resistance of this TPCT.

In Fig. 7 the TPCTs with different evaporator lengths are shown, the x-axis was normalized by the evaporator length (l_{ev}) to compare the evaporator temperatures. Comparing the temperatures of the condenser it can be seen that they are almost the same despite the fact that the dissipated power on the flat plate increases with the

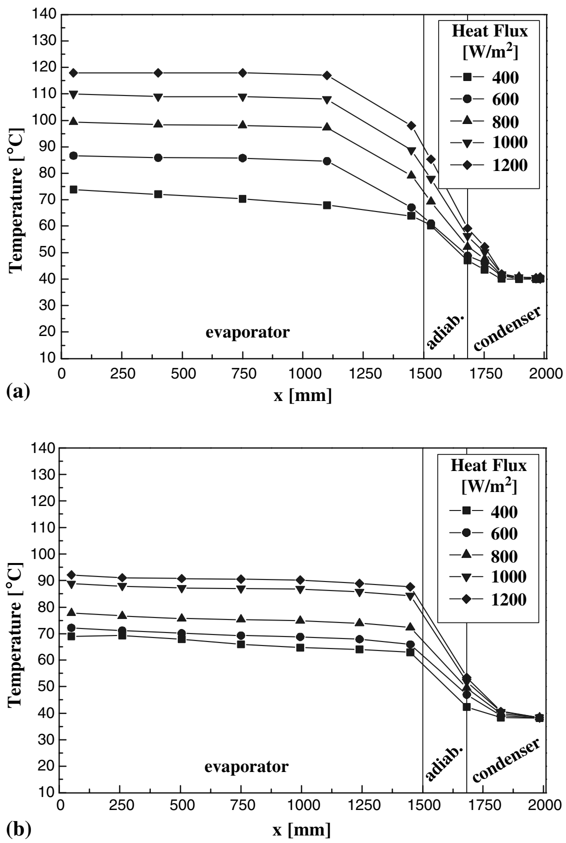

Fig. 6. Steady state temperatures for the TPCT with $l_{ev} = 1.5$ m, $T_c = 40$ °C and $\beta = 30°$, (a) $f = 0.8$, (b) $f = 0.6$.

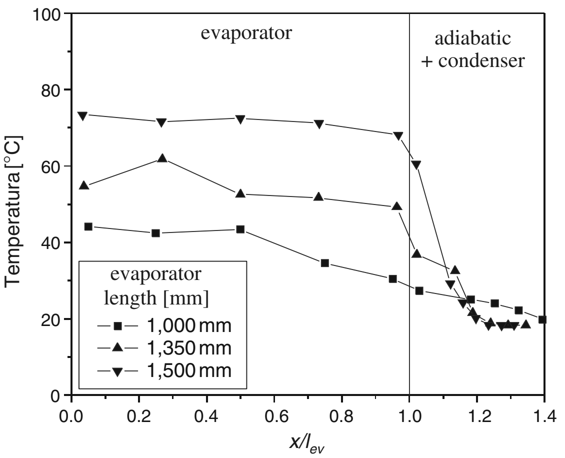

Fig. 7. Steady state temperatures for the TPCT for three different evaporator lengths with $f = 0.6$, $T_c = 20$ °C and $\beta = 30°$, heat flux = 800 W/m^2.

evaporator length for the same heat flux and it also happens with the overall thermal resistance. As the evaporator temperatures and area increase with the evaporator length, the heat losses are also increased.

4. Conclusions

A transient analysis was carried out. It was shown that during the startup geyser boiling occurs and in the steady state some oscillations occur in the temperature. The effects of cooling temperature, slope, fill ratio, and evaporator length were determined for different heat fluxes. An increase in the cooling temperature decreases the overall thermal resistance. For the smallest slope, better results were achieved; however a dry-out limitation can occur, although it was not observed during the experiments. The thermal resistance decreases for the lowest fill ratio, but it is necessary to take care about the dry-out limitation too. Changing the evaporator length will also change the power input, but the lowest thermal resistances were achieved for the shortest TPCT evaporator.

The results shown in the present work will be used in the design and construction of a prototype of the compact SDHWS. With the prototype it will be possible to obtain results of the performance of the whole system.

References

Chun, W., Kang, Y.H., Kwak, H.Y., Lee, Y.S., 1999. An experimental study of the utilization of heat pipes for solar water heaters. Applied Thermal Engineering 19, 807–817.

Fahgri, A., 1995. Heat Pipe Science and Technology. Taylor & Francis, Washington.

Groll, M., Rösler, S., 1992. Operation principles and performance of heat pipes and closed two-phase thermosyphons. Journal of Non-Equilibrium Thermodynamics 17, 91–151.

Hussein, H.M.S., Mohamad, M.A., El-Asfouri, A.S., 1999a. Transient investigation of a thermosyphon flat-plate solar collector. Applied Thermal Engineering 19, 789–800.

Hussein, H.M.S., Mohamad, M.A., El-Asfouri, A.S., 1999b. Optimization of a wicklees heat pipe flat plate collector. Energy Conversion and Management 40, 1949–1961.

Ismail, K.A.R., Abogderah, M.M., 1992. Residential solar collector with heat pipes. In: Proceedings 8th International Heat Pipe Conference, Beijing, China.

Ismail, K.A.R., Abogderah, M.M., 1998. Performance of a heat pipe solar collector. Journal of Solar Energy Engineering 120, 51–59.

Oliveti, G., Arcuri, N., 1996. Solar radiation utilisability method in heat pipe panels. Solar Energy 57, 345–360.