WORKING CHARACTERISCS OF A COMPACT SOLAR HOT WATER SYSTEM WITH HEAT PIPES DURING STARTUP AND GEYSER BOILING PERIODS

Samuel L. Abreu, **Jorge A. Skiavine and Sergio Colle**
LABSOLAR - Solar Energy Laboratory – Department of Mechanical Engineering, Federal University of Santa Catarina, Campus Universitario - Trindade, Florianopolis, 88040-900, (SC) Brazil,
Phone + 55 48 2342161, Fax + 55 48 3317615, samuel@emc.ufsc.br

Abstract– Heat pipes are widely used in solar heating systems. Two-phase closed thermosyphon (TPCT) heat pipes are characterized by their constructive simplicity and by gravity pumping of the working fluid inside the pipes. Because solar flat plate collectors are installed on tilted surfaces to maximize the performance along the year, it is possible to use TCPTs in their manufacture. The performance of the TPCTs varies a lot depending on the operation conditions, particularly during startup and geyser boiling periods. The present works shows how some design parameters and operational conditions affect the boiling regime. The effects of the evaporator length, filling ratio, collector slope and cooling temperature are analysed for different heat fluxes.

1. INTRODUCTION

Heat pipes are being used in solar heating systems for several years. The “two-phase closed thermosyphons - TPCTs” are heat pipes characterized by their constructive simplicity, without any kind of internal capillary structure, and by gravity pumping of the working fluid inside the pipes. Because solar flat plate collectors are installed on tilted surfaces to maximize the performance along the year, it is possible to use TCPTs in their manufacture. The main advantages of solar heating systems using TPCTs are: better thermal efficiency, anti-freezing natural protection and thermal diode working characteristics.

The most usual configuration of a domestic solar hot water system with heat pipes is a flat plate welded on the evaporator region of the heat pipes, and a heat exchanger manifold where the cooling water passes through and removes heat from the condenser region of the heat pipes. The water circulates between the heat exchanger and the thermal reservoir, where the heat absorbed in the flat plate collector is stored. The flat plates are mounted inside a glass tube where vacuum is made to minimize the thermal loses. These kind of solar heating systems are more expensive them the traditional systems and therefore they are usually used in cold regions to avoid the freezing problems.

In some locations, like the southern region of Brazil, low temperatures that lead to freezing conditions occurs only few days during the winter, and the vacuum between the flat plate and the glass tube does not decreases the heat loses in the same order than in cold regions. This region is also characterized by lower latitudes than the European and consequently the slope of the flat plate should be lower. The present work shows some characteristics of the performance of a solar heating system with TPCTs that is being developed to work in this kind of weather. This system has a different configuration than the others which will be described in details in the next sessions.

Previous works show studies carried with different types of solar heating systems using heat pipes and deal with the most common tasks in this kind of system. Cucomo and Marinelli (1983) studied the efficiency curve and working limits of a solar flat plate collector using water-charged TPCTs. Oliveti and Arcuri (1996) focuses their work on the utilizability of heat pipe panel during operation and the inertia effects of the system caused by the variation of the solar irradiance are taken into account. Ismail and Abogderah (1992, 1998) used heat pipes with internal capillary structure in the evaporator section and methanol as the working fluid, they also carry their experiment in low latitudes and the condenser of the heat pipes has a slope greater than the evaporator as a tentative to improve the performance. Hussein et al (1999a, 1999b) and Hussein (2002) work on the optimization and transient investigation of solar heating systems using flat plate collectors of TPCTs, their results shows a good agreement between theoretical and experimental data for TPCTs also working in low latitudes. Chun et al (1999) presents an experimental setup, where five individual modules of only one heat pipe coupled with a thermal reservoir were tested. Different working fluids (water, methanol, acetone and ethanol), heat pipes with or without wick, different thermal reservoir volumes and different absorber surface treatment were compared.

In the present work the results were obtained with a compact solar heating system that is being designed to provide solar water heating for low income families in Brazil. First results of this research showed the influence of the heat flux, evaporator size, filling ratio, condenser temperature and slope (Abreu and Colle, 2001) on the overall thermal resistance and efficiency of the TPCTs. In the following work (Abreu et al., 2002) an expression for the instantaneous efficiency was derived, but it was not found good results and the scattering of the fitted curve was high. This scattering occurs because the boiling heat transfer process has different characteristics depending on the experimental settings; therefore it is not possible to find a general expression for the heat transfer coefficients inside the pipe. The present work shows an analysis of the heat transfer during the start-up period and in which conditions the boiling is characterized by the "geyser boiling phenomena".

2. BASIC DESCRIPTION OF THE SOLAR HEATING SYSTEM

In Brazil, most of the families uses water heating only for bathing and the heating load is not so high, then compact solar heating systems has large application in the whole country. In the South and Southeast regions of Brazil there are some days during the year where freezing conditions occur and the use of TPCTs can be an alternative to avoid this problem.

TCPTs are very efficient heat transfer devices that use the latent heat of a fluid in the changing phase as the heat transport media. The heat is absorbed in the low side of the TPCT, called evaporator, where the fluid is changed to vapour phase. The vapour rises to the other side where the heat is rejected, returning the working fluid to the liquid phase. This region is called condenser and the liquid returns from the condenser to the evaporator by gravity. This is the reason that TCPTs are also called "gravity assisted heat pipes". Between the evaporator and the condenser regions there is an insulated region where no heat transfer is desired, called adiabatic region. Figure 1 shows the working mechanism of a TPCT.

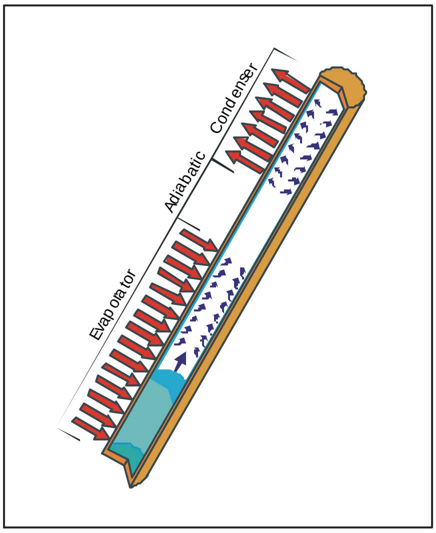

Figure 1. Working mechanism of a TPCT

To achieve a configuration for the proposed solar heating system as compact as possible, it was designed in a way that a heat exchanger is unnecessary. The flat plate absorber is welded to the evaporator section of the TPCTs and the TPCTs were welded to the external wall of the thermal reservoir in the condenser region, avoiding the necessity of a heat exchanger, and consequently, a pumping system between the heat exchanger and the thermal storage. This configuration also makes possible a more compact assembly that minimizes the heat loses of the system. The resulting semicircular geometry of the condenser is not common in solar hot water systems of this type and its heat transfer characteristics were not studied in detail yet. Figure 2 shows the proposed solar heating system.

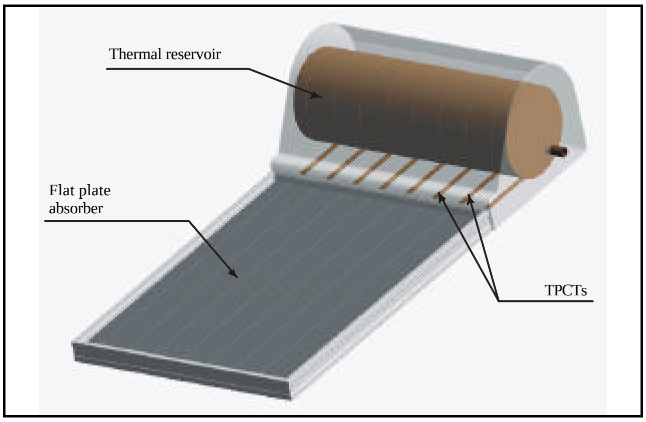

Figure 2. Basic configuration of the proposed system

3. EXPERIMENTAL SETUP

Several works study the heat transfer coefficients and the thermal resistances of inclined TCPTs but usually for a complete straight geometry of the evaporator and condenser sections. The TPCTs used here differs from the others systems by its unusual geometry characterized by a straight evaporator and a semicircular condenser and their heat transfer characteristics were not studied yet. Because of this, individual modules of flat plate plus pipe were constructed and tested in an indoor setup. These modules have the aspect shown in Figure 3.

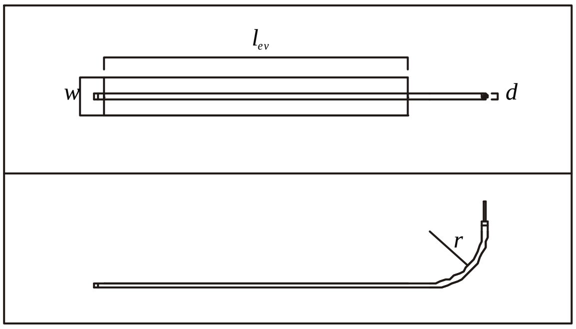

Figure 3. TPCT geometry.

To analyze the performance of the TPCT different levels of the design parameters were tested, as shown in Table 1. These parameters are inclination, cooling temperature, fill ratio and evaporator length. All arrangements among the different levels of the chosen parameters were tested. The heat flux dissipated on the flat plate to simulate the solar radiation was set in the levels of 400, 600, 800, 1000 and 1,200 W/m^2.

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	-
b - Slope [°]	30	45	-
T_c Cooling temperature [°C]	20	40	-

The experimental setup is composed by an insulated box where is the evaporator region of the TPCT. On the flat plate there are some electrical resistances known as "skin heaters" by its sheet shape. The heaters are connected to a DC power supplier that gives the desired heat flux for each test. The condenser region of the TPCT is put inside a cooling jacket that is connected to a thermostatic bath that provides water on a controlled temperature. Along the TPCT there are several T-type (copper-constantan) thermocouples to measure the temperature. A data acquisition system and a microcomputer are used to measure and store the data obtained during the experiments. Figure 4 shows some details of the experimental setup.

Figure 4. Experimental setup

4. RESULTS

Depending on the experimental settings the temperature behaviour of the TPCTs changes according to the boiling regime inside the pipe. Most of the works treat only the periods where nucleate pool and filmwise boiling occurs, otherwise the heat transfer coefficients developed for this condition are not valid during the start up and geyser boiling regime.

4.1 Start-up

Before each test, the entire TPCT was at ambient temperature and in the interface between the liquid pool and the vapour is at saturation condition and the internal pressure can be easily determined using a table of thermodynamic properties. In the pool the water is at compressed liquid state, and its pressure can be calculated integrating the weight of the liquid column over the point where the pressure is desired. Considering that the liquid density of the water in these conditions does not vary a lot, the internal pressure in the bottom of the liquid pool is given by the sum of the saturation pressure plus the weight of the column of liquid.

After the heat flux begins, the internal temperature increases, first maintaining stratification on the temperatures of the liquid pool. As the temperature increases, the saturation condition will be achieved in most of the liquid pool and when the necessary overheating for boiling nucleation is found the TPCT starts your operation as a heat transfer device.

During the start-up most of the heat supplied in the evaporator is used just to increase the liquid temperature until the saturation condition and no latent heat is transferred to the condenser because the evaporation is not occurring yet. Figure 5 shows the behaviour of the temperatures along the TPCT during the start-up period. The evaporator temperature rises continuously until the departure of the first bubble. After this, an instantaneous drop in the temperature occurs caused by the liquid that returns from the condenser. The temperature in the condenser remains the same of the cooling temperature until the first bubble pulls liquid to the condenser side of the TPCT. The same effect is observed in the adiabatic region, but the increase of the external temperature wall before the bubble is caused by the conductive heat transferred through the pipe wall. As the experiment continues the bubble nucleation becomes more frequent and the TPCT come into an operation.

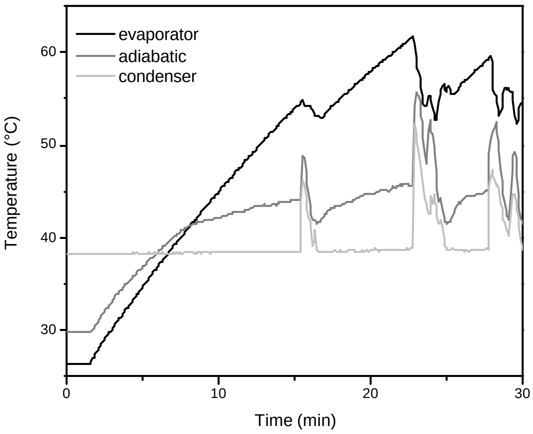

Figure 5. Temperature behaviour during start-up (heat flux = 400 W/m^2; l_{ev} = 1.0 m; *f* = 0.8; T_c = 40°C; *b* = 45°).

4.2 Geyser boiling

After the start-up the boiling heat transfer begins, but depending on the experimental settings for each test the boiling regime can stabilise in different ways. The most common is characterised by small oscillations in the temperature in the evaporator and in the condenser. Two boiling phenomena are occurring in this case: pool and filmwise boiling. Due to its more desirable behaviour for a TPCT it will be called here as "developed boiling".

Sometimes a high overheating in the evaporator followed by an instantaneous heating in the condenser is observed, and in this case the boiling regime is called “geyser boiling”. In general, most of the works about TPCTs are related to the study of the heat transfer in the first manner mentioned above. There is still a third way of the boiling regime, it is characterised by a mixed situation where both regimes occur at the same time. Figure 6 shows the external temperatures of the pipes for the different boiling processes. The present work focuses on the analysis of what conditions lead to the geyser boiling.

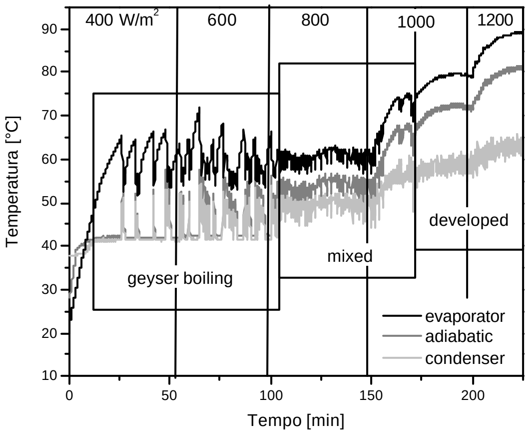

Figure 6. Different boiling regimes in a TPCT (l_{ev} = 1.35 m; f = 0.6; T_c = 40°C; b = 45°).

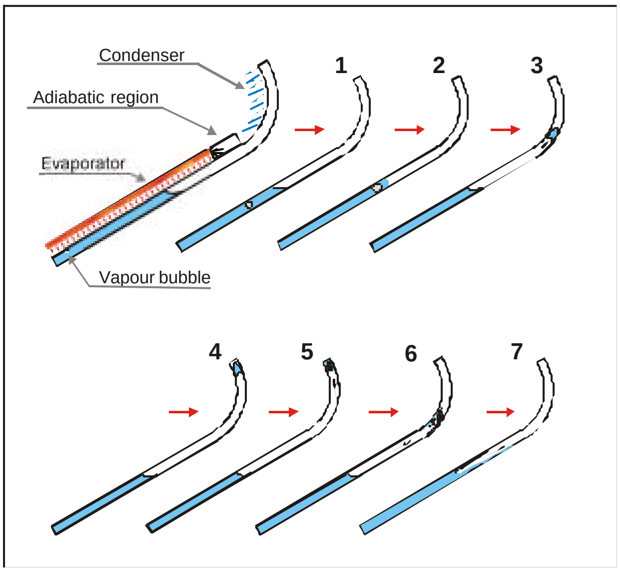

Figure 7. Geyser boiling.

Figure 7 shows how the geyser boiling phenomena occurs. The liquid temperature increases beyond the saturation temperature until the overheating necessary to nucleate ebullition bubbles is found (1). Depending on the internal conditions the bubble will grow quickly, first filling the pipe diameter (2), then expanding, propelling the liquid to the condenser end causing a characteristic sound (3). When the overheated liquid and the vapour bubble reach the condenser, heat is removed by the cooling jacket (4-5) collapsing the bubble and subcooling the liquid (6), consequently the liquid returns to the evaporator by the gravity forces (7) (Fahgri, 1995).

Table 2 shows what boiling regime occurs in each test when the steady state is achieved. The experimental conditions 1 to 4 are respectively: b =30°/T_c=20°C; b =30°/T_c=20°C; b =30°/T_c=20°C and b =30°/T_c=20°C. The boiling regime was symbolized as: G – geyser; M – mixed; and D - developed

Table 2. (A -F) Boiling regimes at steady state for the different TPCTs tested.

A	l_{ev} = 1.0 m; f = 0.8				
	heat flux [W/m^2]				
	400	600	800	1000	1200
exp 1	M	D	D	D	D
exp 2	G	D	D	D	D
exp 3	G	G	M	D	D
exp 4	G	M	D	D	D

B	l_{ev} = 1.0 m; f = 0.6				
	heat flux [W/m^2]				
	400	600	800	1000	1200
exp 1	G	G	G	G	M
exp 2	G	G	G	G	M
exp 3	G	G	G	G	G
exp 4	G	G	G	G	G

C	l_{ev} = 1.35 m; f = 0.8				
	heat flux [W/m^2]				
	400	600	800	1000	1200
exp 1	M	D	D	D	D
exp 2	M	D	D	D	D
exp 3	G	M	D	D	D
exp 4	G	D	G	M	D

D	l_{ev} = 1.35 m; f = 0.6				
	heat flux [W/m^2]				
	400	600	800	1000	1200
exp 1	D	D	D	D	D
exp 2	G	M	D	D	D
exp 3	G	G	G	M	D
exp 4	G	G	M	D	D

E	l_{ev} = 1.5 m; f = 0.8				
	heat flux [W/m^2]				
	400	600	800	1000	1200
exp 1	G	G	G	D	D
exp 2	G	D	D	D	D
exp 3	G	D	G	D	M
exp 4	G	G	D	G	M

Table 2. (Cont.)

F	l_{ev} = 1.5 m; f = 0.6				
	heat flux [W/m^2]				
	400	600	800	1000	1200
exp 1	G	D	D	D	D
exp 2	M	D	D	D	D
exp 3	M	M	D	D	D
exp 4	M	M	M	D	D

Imura et al (1999) also studied experimentally the conditions that led to the geysering and developed boiling and found similar results than that presented here. They used always the same dimensions of the evaporator and condenser regions in a straight TPCT and tested several cooling temperatures and heat flux for different filling ratios and working fluids. They did not study the influence of the slope and the evaporator length.

The geyser boiling occurs in general at low pressures and low heat fluxes. Considering the parameters that were analysed in the present paper it was observed in the Tables 2 that:

- The heat flux is the most important parameter in the determination of the internal boiling regime;
- the decrease in the fill ratio makes it ease the geyser boiling occurrence at higher heat fluxes due to the lower working pressure;
- the increase of the evaporator length causes an increase of the power and the internal pressure, then the geyser boiling reduces the possibility of the geyser boiling;
- the increase of the slope increases the 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, what can be happening during this situation is the fact that the difference between the vapour pressure in the bubble to the vapour in the condenser is higher with the larger slope;
- the influence of the cooling temperature in the range analysed was not conclusive and should be better studied.

As the nature of the boiling phenomena has an unpredictable behaviour, there are some situation where the thermal response of the TPCT can not be easily explained. In the exp. 4 of the Table 2-C, as the heat flux increases, the boiling first passes from geyser to developed regime then returns to geyser, after this it becomes mixed and finally developed again.

The results presented here give the influence of the parameters tested experimentally. For a better prediction of the internal heat transfer coefficients, it is still necessary to find a correlation that can be used to predict what boiling phenomena occurs. Efforts in this direction are being carried and will use the experimental data measured in the same experiment.

5. CONCLUSIONS

The design parameters and operational conditions analyzed in the present work affect the boiling regime of the TPCT. The main effect is caused by the heat flux and the effect of the cooling temperature could not be evaluated with the experimental results obtained.

The next step will be the study of correlations to determine what conditions led to each different boiling regime and in this manner the correct boiling heat transfer correlation can be selected, improving the results obtained by simulation of the complete solar heating system.

ACNOWLEDGEMENTS

The authors of the present work wish to thank Mr. Péricles Chaves for his help with the experimental work, and also to the "Coordination of the Graduate Program of the Ministery of Education of Brazil" (CAPES) for supporting this project.

REFERENCES

Abreu, S. L. and Colle, S. (2001), An experimental study of two-phase closed thermosyphons for compact solar domestic hot-water systems, *Proceedings of ISES- Solar World Congress*, November, Adelaide, Australia

Abreu S. L., Colle, S. and Skiavine, J. A. (2002), Investigation of the performance of a two-phase thermosyphon with an unusual geometry, *Proceedings of 12 IHPC – International Heat Pipe Conference*

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

Cucomo M. and Marinelli V. (1983), Thermal analysis and working limits of heat pipe solar collectors. *Proceedings of European Two Phase Flow Group Meeting*, June, Rome, Italy, paper B5.

Fahgri, A. (1995), *Heat Pipe Science and Technology*, pp 399-400,Taylor & Francis, Washington, EUA

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

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

Hussein, H. M. S. (2002), Transient investigation of a two phase closed thermosyphon flat-plate solar water heater, *Energy Conversion and Management* 43, 2479-2492.

Imura, H., Ishii, K. and Ippohshi, S. (1999), An Experimental Investigation of Geysering in Two-Phase Closed Thermosyphons, *Proceedings of 11th International Heat Pipe Conference*, Vol. A4-3, pp 94-99, Tokyo, Japan

Ismail, K. A. R. and Abogderah, M. M. (1992), Residential solar collector with heat pipes, *Proceedings of 8th International Heat Pipe Conference*, 14-18 September, Beijing, China, paper E-P14.

Ismail, K. A. R. and Abogderah, M. M. (1998), Performance of a heat pipe solar collector, *Journal of Solar Energy Engineering* 120, 51-59.

Oliveti, G. and Arcuri, N. (1996), Solar radiation utilisability method in heat pipe panels, *Solar Energy* 57, 345-360.