EXPERIMENTAL STUDY OF MERCURY THERMOSYPHONS

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Abstract. *This article presents and discusses the experimental results obtained from mercury thermosyphons developed at LABTUCAL-UFSC (Heat Pipe Laboratory of the Federal University of Santa Catarina). Also, details of the experimental apparatus will be shown. This study is the first of this kind undertaken in Brazil with high temperature thermosyphons.The thermal resistances is calculated and decrease when the heat transfer rate is increased, as expected. It is also observed that the difference of mean temperature between the condenser and evaporator is significant in the mercury thermosyphon, because of the temperature drop at the vapor-liquid interface in the liquid film.*

Keywords*: Thermosyphon, High Temperature, Liquid Metal, Mercury, Heat Pipe*

1. INTRODUCTION

Thermosyphons are devices with high thermal conductivity that can transfer high quantities of heat. In its most simple form, a thermosyphon is a hollow evacuated metal pipe, charged with a pre-determined amount of an appropriate working fluid. It can be divided into three main sections: evaporator, where the heat is delivered to the device, an adiabatic section (which can or can not exist) and a condenser, where the heat is released. The heat causes the evaporation of the working fluid resulting the vapor that goes towards the condenser region by means of pressure gradients, where it condenses, returning to the evaporator by gravity.

The selection of the working fluid is of great importance for the development of thermosyphons technology (Mantelli and Milanez, 2004) with the following aspects: operating temperature and pressure, maximum heat flux in the evaporator, thermophysics properties of the fluids (boiling point, melting point, critical parameters, latent heat of vaporization, steam density, etc), toxicity, ignition and explosion risk in conditions of equipment operation during its lifetime. (Anderson et al, 2004).

For temperatures above of 400, that it is the case of high temperature thermosyphons, liquid metal is used such as mercury, sodium, potassium and so on. High temperature thermosyphons can be applied in regenerative heat exchangers of petroleum plants, where high temperature streams (above 400 °C) are released to atmosphere from furnaces. The use of this energy to preheat air in industrial furnaces, represents a good example of recoverable thermal energy. The development of new thermosyphon technology will enable the increase of the energetic efficiency of industrial processes.

Although the mercury has some troublesome factors such as toxicity that prevent the mercury thermosyphons from being put to practical use, this work presents experimental results obtained from experimental study of mercury thermosyphon developed at LABTUCAL (Heat Pipe Laboratory of Federal University of Santa Catarina). The objective is starting the study of high temperature thermosyphons using mercury and after this leaving for other fluids as sodium and potassium.

The usable range of mercury thermosyphons is between 250 ^{o}C and 650 ^{o}C, but mercury thermosyphons show good performance in the temperature range of 400 ^{o}C to 500 ^{o}C. Yamamoto et al. present a study to collect basic data required for the development of mercury heat pipe (thermosyphon with screen mesh wick) operating in the temperature range of 350 ^{o}C e 600 ^{o}C.

2. EXPERIMENTAL APPARATUS AND METHOD

A schematic of the experimental apparatus used in the mercury thermosyphon tests is shown in Fig. 1. This experimental apparatus is formed by an electric furnace, a power controller and a data acquisition system. The furnace contains three lined electric resistances, each one with 200 mm of length and 50 mm of diameter. The resistances transfer heat to the evaporator section through radiation. This furnace is isolated by ceramic fiber. Each resistance has a digital controller of temperature that allows the resistance to reach a maximum value of 1200 ^{o}C. The heat flux rate, which is dissipated by the resistances, is regulated by a power controller that varies the voltage up to 220 V.

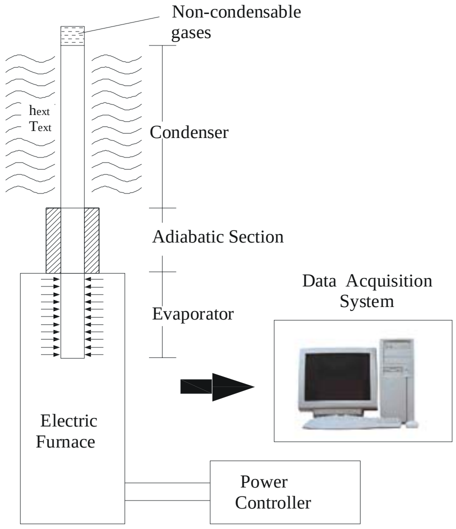

Figure 1. Schematic diagram of the experimental apparatus.

Two kinds of thermosyphons were designed for experiment (Thermosyphon *A* and Thermosyphon *B*) as show in Tab. 1. These thermosyphons are made of stainless steel 316L with 25.4 mm of outer diameter and 21 mm of inner diameter and are fixed in the furnace through adjustable connecting rods. The superior region of the condenser, approximately 500 mm, presents thirty-one fins with 50 mm of diameter, which one14.6 mm distant between two fins.

The amount of the mercury used is different for each thermosyphon, as show in Tab. 1. The filling ratio, which is the rate between working fluid and evaporator volumes, is approximately 4% to the thermosyphon *A* and 45% to the thermosyphon *B*.

Table 1. Specifications of Mercury Thermosyphon

Description	***Thermosyphon A***	***Thermosyphon B***
Condenser length	524 mm	710 mm
Evaporator length	200 mm	200 mm
Adiabatic section length	150 mm	90 mm
volume of mercury	11.5 ml	30.5 ml

The thermosyphons were instrumented with of K-type thermocouples manufactured for OMEGA. These thermocouples were spot-welded on the external wall of tube to guarantee a good contact with the wall and, consequently, a good measure of the temperature. The thermocouples are protected against of the radiation and convection through aluminum ribbon and glass ribbon.

A Data Acquisition System HP Bench-link Data Logger 34970 was used to acquire data in regular time intervals of 10 s.

3. RESULTS AND DISCUSSION

The tests were recorded after some hours of operation when the steady state of thermosyphon is reached. The heat transfer rate transferred for the thermosyphon ($\dot{Q}_T$) is estimated by the power dissipated by the electric resistances ($\dot{Q}_R$) and the heat loss by the furnace walls ($\dot{Q}_W$) by means of the following equation:

$$\dot{Q}_T = \dot{Q}_R - \dot{Q}_W \tag{1}$$

The heat losses are calculated by the natural convection correlations for the vertical walls available in the literature, such as the heat transfer correlation of Churchill e Chu (Incropera 2002), given by:

$$\overline{h}_L = \left(\frac{k_{air}}{L}\right)\left\{0,825+\frac{0,387Ra_L^{1/6}}{\left[1+(0,492/\Pr)^{9/16}\right]^{8/27}}\right\}^2 \tag{2}$$

where Ra_L is the Rayleigh number, Pr is the Prandtl number, L the length of furnace wall and k_{air} is the thermal conductivity of air. For this purpose, thermocouples had been instrumented in the furnace walls.

To evaluate the temperature profile of the thermosyphon, the power system was switched on to the evaporator section, until steady state conditions were reached. Figure 2 shows the outer wall temperature profile of thermosyphon A for several heat transfer input rates: 994.8 W, 506.5 W, 617 W, 768.7 W, 809 W, 1280 W and 1432.7 W. It can be observed that when the heat transfer rate is increased, the operation temperature and the effective length of thermosyphon are increased too. The effective length is the region of thermosyphon where there is significant heat transfer, that is, the thermosyphon wall temperature is significantly higher than ambient. For example, the effective length is about 550 mm for the 394.8 W test .

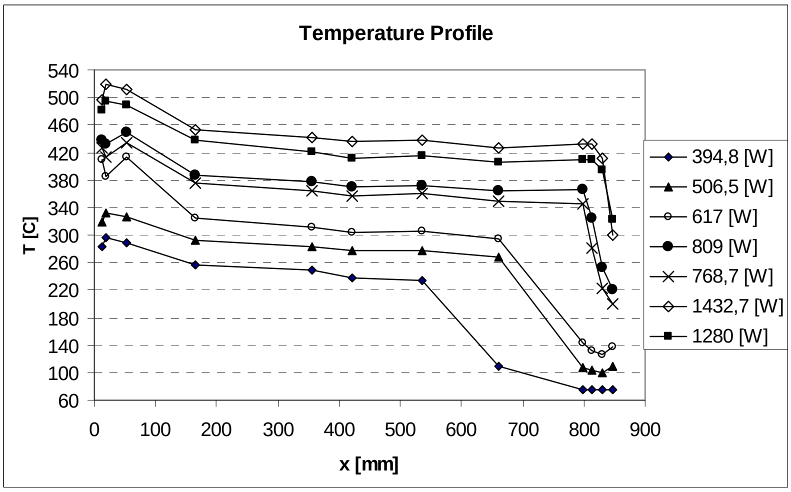

Figure 2. Outer wall temperature profile of Thermosyphon *A* for some heat transfer rate.

Figures 3 and 4 show the outer wall temperature profile of thermosyphon *B* with heat transfer rate of 486 W and 1985 W, respectively. Comparing the temperature profiles of thermosyphon *B* of Fig. 3 with thermosyphon *A* of Fig. 2, which are at almost the same heat transfer rate level (approximately 500 W), it can be observed that the mean temperature of condenser in the thermosyphon *A* is higher than thermosyphon *B*, whereas in the evaporator is the inverse, that is, the mean temperature is higher in thermosyphon *B* than thermosyphon *A* (The mean temperatures of condenser and evaporator are given in the Tab. 1).

Then it can be concluded that the thermosyphon *B* is more efficient than thermosyphon *A.* That is because thermosyphon *B* have a higher working fluid filling ratio in the evaporator. It is still necessary to test filling ratios larger than 50% in order to know whether this fact is also valid for larger filling ratios.

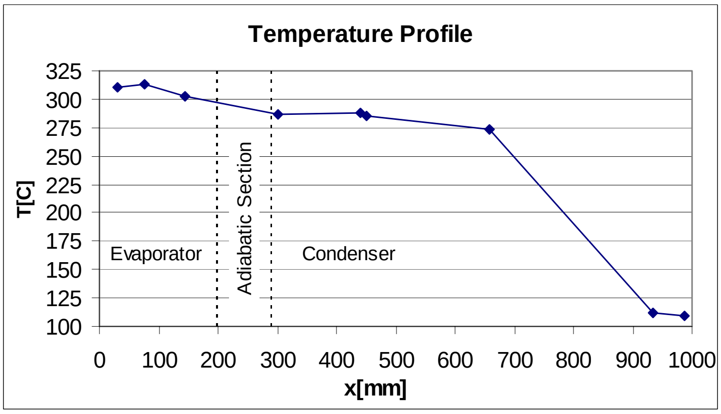

Figure 3. Outer wall temperature profile of Thermosyphon *B* for 486 W.

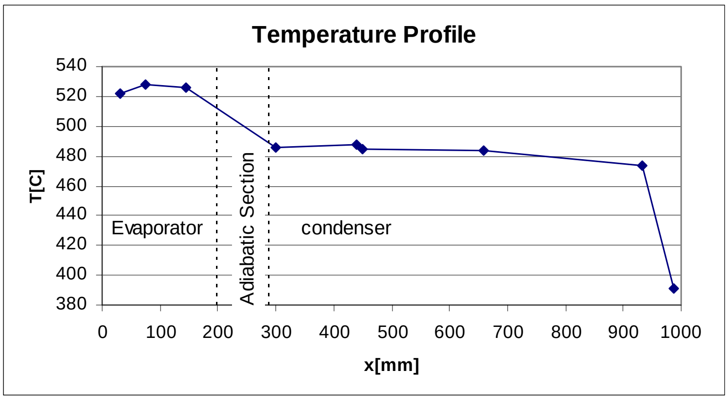

Figure 4. Outer wall temperature profile of Thermosyphon *B* for 1985 W.

Table 2 shows the mean temperatures of the condenser and of the evaporator, the heat transfer rate and the thermal resistance for each test of thermosyphons. The thermal resistance (R_t) is an important characteristic of the thermosyphon, which establishes the heat transfer rate ($\dot{Q}_T$) when a temperature difference (ΔT_T) is applied. It is given by the relation:

$$R_t = \frac{\Delta T_T}{\dot{Q}_T} \tag{3}$$

Table 2. The mean temperature, the heat transfer rate and the thermal resistance of thermosyphon A and B

	Mean Temperature [^oC]			
Tests	*Condenser*	*Evaporator*	$\dot{Q}_T$ *[W]*	R_t *[C/W]*
Thermosyphon *A*	240.27	281.40	394.8	0.1042
	276.03	317.20	506.5	0.0813
	304.1	382.80	617.0	0.1276
	362.46	426.35	809.0	0.0789
	355.12	412.05	768.7	0.0740
	431.25	495.30	1432.7	0.0447
	409.10	475.76	1280.0	0.0520
Thermosyphon *B*	283.18	308.46	486.0	0.0520
	482.94	525.26	1985.1	0.0213

The graph of thermal resistance versus heat transfer rate is shows in Fig. 5. It can be noticed that thermal resistance decreases when the heat transfer rate is increased for both thermosyphons. The thermal resistance of thermosyphon B is smaller than the thermosyphon A. Consequently, it is more efficient than thermosyphon A, as already concluded previously.

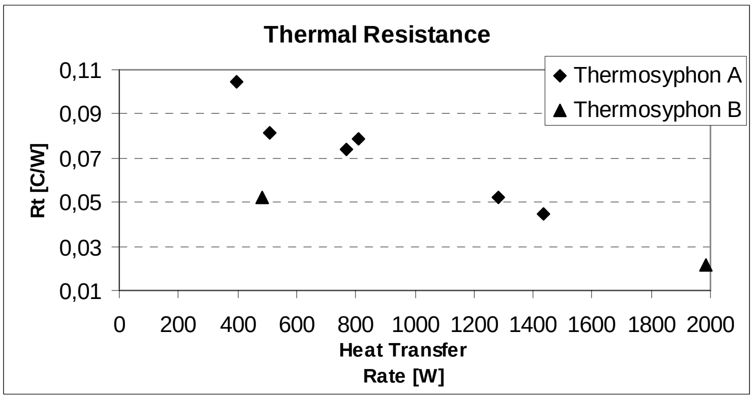

Figure 5. The thermal resistance of thermosyphons *A* and *B* versus the heat transfer rate.

The difference of mean temperature between the condenser and evaporator is significant in the mercury thermosyphon, as show in the Tab. 1. Some investigators have suggested that the excess temperature drop occurs at the vapor-liquid interface in the liquid film as result of net transfer of matter from vapor to the liquid phase (Necmi and Rose, 1976; Stephan, 1992). For the conversion of the vapor into the liquid phase, a temperature drop directly at the interface between the vapor and liquid is necessary.

An analysis of the uncertainty of the temperature and the heat transfer rate was carried through. It was calculated that for the temperature measurements, the accuracy is around ± 8 ^{o}C, whereas for the heat transfer rate, the accuracy is ± 2% for each test.

4. CONCLUSION

This paper presents an experimental study on a mercury thermosyphon. The outer wall temperature profile and the thermal resistance were showed for two distinct thermosyphons (A and B). Thermosyphon *B* is more efficient than thermosyphon *A* due to the fact that thermosyphon B have a higher filling ratio in the evaporator. However, it is still the necessary to perform further tests with even larger filling ratios than 50%

In mercury thermosyphons the difference of mean temperature between the condenser and evaporator is significant. This fact occurs due the temperature drop at the vapor-liquid interface in the liquid film as result of net transfer of matter from vapor to the liquid phase.

5. ACKNOWLEDGEMENTS

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