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EXPERIMENTAL STUDY OF MERCURY AND NAPHTHALENE THERMOSYPHONS

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ABSTRACT

The technology involving heat pipes and thermosyphons can be applied to several areas, as for example, for heat exchangers, thermal control of space vehicles, refrigeration systems for electronic components and in ovens for the food industry. The appropriate choices of both the working fluid and the pipe material are important considerations for the design of the heat transfer equipment that use the heat pipe and thermosyphon technology. Different working fluids can be employed, such as water, liquefied gases, organic liquids, liquid metals, etc. The present work has as the main objective to investigate the use of naphthalene and mercury as working fluid for high temperature thermosyphons for industrial applications. The experimental apparatus are formed by a vertical themosyphon in an electric furnace. The furnace is connected to a voltage controller and then a control of the heat flux is possible. The thermosyphons were made of stainless steel tube with 1.0 m of length and 25.4 mm of external diameter. Then, the experimental study can supply the temperature distribution on wall surface and the possible rate heat flux that it is designed to transfer. The tests demonstrated that Brazil has developed technology to design equipments which employ naphthalene and mercury, which have great potential as working fluid for high operation temperature industrial equipment.

KEY WORDS: thermosyphons, naphthalene, mercury.

1. INTRODUCTION

The selection of the working fluid and of the tube material is of great importance for the development of heat transfer systems, which employ thermosyphons technology (Mantelli and Milanez, 2004). The heat transfer agents include: water, liquefied gases, organic liquids and liquid metals. Technologies involving thermosyphons differ considerably depending of the temperature operation range.

The working fluid is selected according to the following aspects: operation temperature and pressure, maximum heat flux in the evaporator, thermo physics 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).

The water is considered an excellent working fluid, since it is not toxic and easy to deal with. Also, it presents high latent heat of vaporization. This means that, with a small volume of evaporated water, it is possible the transfer a large amount of heat, compared to other working fluids. Water is highly used as working fluid in relatively low temperature thermosyphons, up to approximately 300 ºC. Literature also cites the use of ammonia (NH_3) and propane (C_3H_8) (Anderson et al, 2004). The high operation pressure at higher temperature levels sets a upper bond to the application of thermosyphons which working fluid is water. The high pressure leads to the use of very thick tubes to stand the working pressure, increasing the equipment thermal resistance to heat transfer and specially its cost (Devarakonda e Olminsky, 2004).

Several applications, such as industrial heat exchangers which fluxes are at higher temperature levels, requires the use of higher temperature level thermosyphons. Literature lists a series of potential working fluid agents for thermosyphons of intermediate temperature (250-450 ºC): naphthalene ($C_{10}H_8$), phenol (C_6H_6O), toluene ($C_6H_5CH_3$), aniline (C_6H_7N) e hydrazine (N_2H_4). For temperatures higher than 450 ºC, liquid metals such as mercury, sodium, lithium and potassium, work well as heat transfer agents (Devarakonda e Anderson, 2005).

Figure 1 shows a comparison between the saturation pressure according to the temperature of water, naphthalene and mercury, which are studied in this work (Perry and Green, 1997).

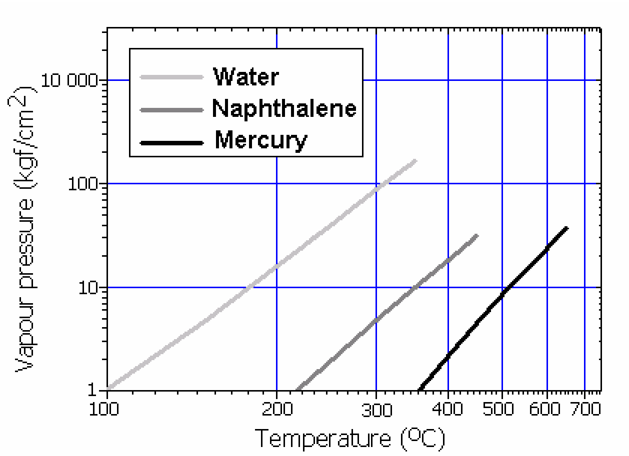


Figure 1. Saturation pressure of these working fluids as a function of the temperature.

One of the limitations of the study of organic compounds as working fluids on thermosyphons is the lack of specific literature about the thermal behavior of these fluids as well as correlations for the calculation of thermosyphon internal resistances.

Therefore, the main objective of this work is to study the thermal behavior of organic compounds and liquid metal thermosyphons. The working fluids studied are naphthalene and mercury. The secondary objective is to obtain data useful for industrial applications where the temperature range is between 300 and 1000 ºC.

2. EXPERIMENTAL METHODOLOGY

2.1 Thermosyphon Using Mercury as Working Fluid

A schematic of the experimental apparatus used in the mercury thrmosyphon tests is shown in Figure 2. This experimental apparatus is formed by an electric furnace, a power input system and a data acquisition system.

The furnace contains three electric resistances, each one with 200 mm of length and 50 mm of diameter. The resistances transfer heat to the evaporation section through radiation. The furnace is isolated with ceramic fiber. Each resistance has a digital controller of temperature that allows the resistance to reach a maximum value of 1200 ºC. The heat flux rate is regulated by a power controller that varies the voltage up to 220 V.

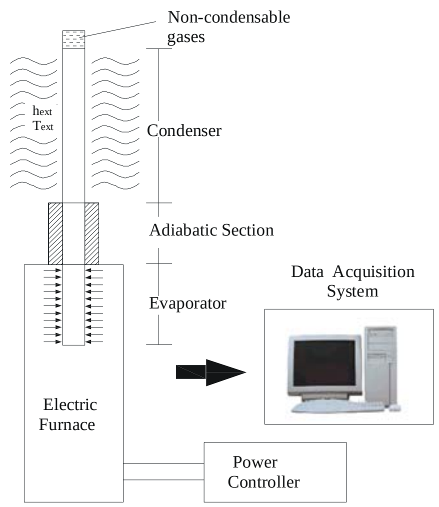


Figure 2. Schematic of diagram of the experimental apparatus.

The mercury thermosyphon tested has the characteristics presented in Table 1. It is made of stainless steel 316L and presents, in the condenser region, thirty-one fins with 50 mm of diameter, 14.6 mm between distant between two fins. The filling ratio, which is the rate between working fluid and evaporator volumes, is approximately 4% or 11.5 mL of mercury.

Table 1. Characteristics of Mercury Thermosyphon

Inner diameter	25.4	mm
Outer diameter	21	mm
Condenser length	524	mm
Evaporator length	200	mm
Adiabatic section length	150	mm
Mass of Mercury	0.148	kg

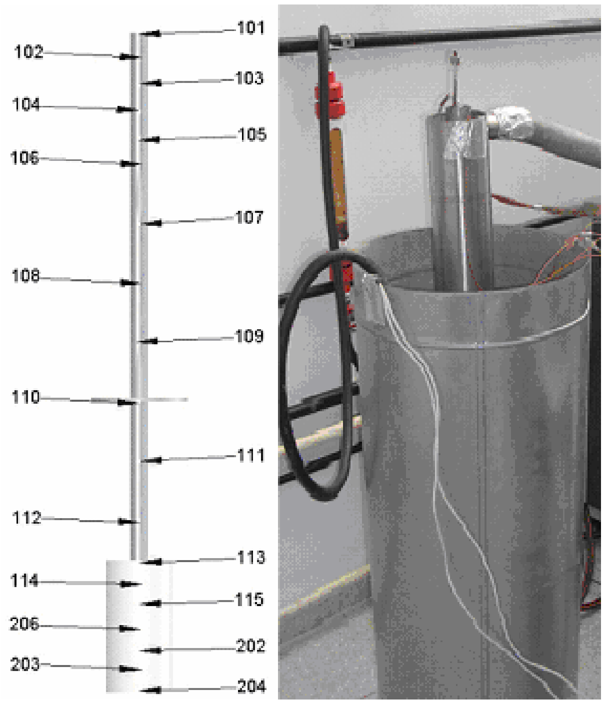
2.2 Thermosyphon Using Naphthalene as Working Fluid

2.2.1 Setting and Instrumentation of Thermosyphon

The naphthalene thermosyphon case is a stainless steel 304 tube of 1000 mm, of length, with 1" of external diameter and wall thickness of 3 mm. The regions of the evaporator, the adiabatic section and the condenser, represent 20, 25 and 55% of the tube length, respectively. The cooling system is composed by a cryostat Lauda LUK thermal bath heat exchanger, where water at a 10 ^{o}C, circulates over the condenser. For all tests, the water flux was fixed in 10 L/min. The cooling water temperature left the exchanger at 11 ºC.

The system was instrumented by means of 19 thermocouples, installed on the external side of the tube, displayed as following: 6 thermocouples in the evaporator region, (119, 118, 117, 116, 115 and 114), 3 thermocouples in the adiabatic section (113, 112 and 111) and 10 thermocouples in the condenser region (110, 109, 108, 107, 106, 105, 104, 103, 102 and 101). The thermocouples 120 and 121 measure the inlet and the outlet temperatures of cooling water. Figure 3 (a) shows a scheme of thermo-couples location and 3(b) the experimental apparatus used in this study.

After the tube sealed, cleaned and evacuated, the working fluid is introduced inside the thermosyphon in the liquid form. In other words, the naphthalene in solid state is melted at around 81 ºC. The filling ratio is 40%, equivalent to 68.6 g of naphthalene. The naphthalene used (Vectec) has level of purity of 98.5%.



(a) (b)

Figure 3. (a) scheme of thermocouples disposition and (b) the experimental apparatus used for the tests.

2.2.2 Methodology of Tests

To evaluate the thermal behavior of the thermosyphon in its working conditions, the power system was switched on to the evaporator section, until steady state conditions were reached. The following power levels were used: 400, 500, 600, 700 and 800 W. An external electric source fed the resistances. 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

3.1 Behavior of Thermosyphon Using Mercury as Working Fluid

Figure 4 shows the outer wall temperature profile throughout the thermosyphon for different heat flux rates. The temperature along the surface of thermosyphon was measure by "K" thermocouples welded in the surface of the pipe and the heat flux rate was estimated by the difference between the power supplied by the electrical resistances and the heat losses to the environment. The thermocouples wires were protected by glass band and its edges by aluminum tapes, to prevent against the radiation effects. The heat losses are due to natural convection through the furnace lateral, surfaces, and they are estimated using correlations from the literature. The power delivered by the resistances ($\dot{Q}_R$) is calculated from the knowledge of the electric tension (V) and the electric resistance *R*..

The temperature profiles, presented in Fig. 4, show that the thermosyphon temperature levels increase as the heat flux increases, as expected. They also show that, for low power level, not all the thermosyphon is working. This fact is observed by the sharp decrease in the temperature level, which tends to the room temperature in the condenser end region, showing that the vapor did not reach the evaporator end. As the heat input increases, the vapor front advances through the thermosyphon. In the higher input power level, the temperature decrease can be found only in the condenser rear position. The temperature decrease observed can be explained by two different reasons. First, non condensable gases eventually formed can block partially the evaporator end. Second, as the temperature level is high, the last condenser thermocouples are under the edge effect influence, i.e., they are cooled down by the environment. From Fig. 4 it is also observed that the difference of mean the temperature level between the evaporator and condenser is 64 ^{o}C, for the heat flux rate of 1432.7 W. This difference is significantly lower when the inside temperature level is considered, since the wall thermal conductivity is low, varying from 16.2 W/m.K (for 100 ^{o}C) to 21.4 W/m.K (for 500 ^{o}C). For the power input of 1432.7 W level, a temperature difference between inner and outer tube surfaces of about 15 ^{o}C is expected for the condenser and about 5 ^{o}C for the evaporator, reducing the temperature difference for 44 ^{o}C.

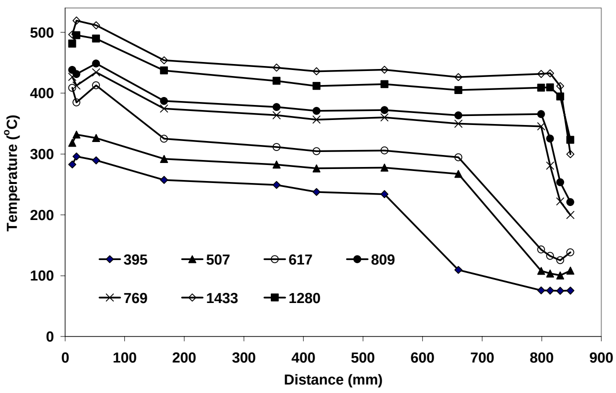


Figure 4. Temperature profile of mercury themosyphon to the different levels of heat flux rate.

The thermal resistance of the thermosyphon can be determined by the following equation:

$$Rt = \Delta\overline{T} \Big/ \dot{Q} \qquad (1)$$

where $\Delta\overline{T}$ is the difference of temperature between the mean temperature of condenser and evaporator.

The values of the thermal resistances for each power step presented in Figure 4 is shown in the Figure 5. It is observed that the thermal resistance decreases as the heat input increases.

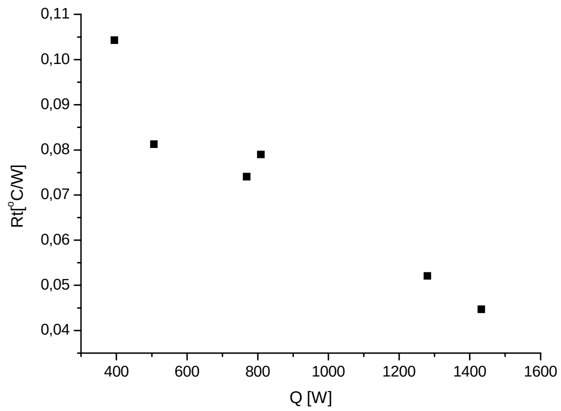


Figure 5. Thermal resistance of mercury thermosyphon.

3.2 Behavior of Thermosyphon Using Naphthalene as Working Fluid

In general, it was observed that the increase of delivered power input to the thermosyphon with naphthalene improved the “start up” condition of the system. According the work of (Mantelli et al., 2006), naphthalene heat pipes shows a slug flow behavior for low power conditions. In this situation, there is a decrease of the amount of working fluid in the evaporator region pool, which in turn decreases the performance of the device. However, the slug flow effect decreases with the increase of power provided to the system.

Figure 6 presents the thermosyphon temperature distribution as a function of different power levels. Each experimental point is obtained as the average of temperatures acquired in 16.7 min time steps. This average is calculated only with steady state condition data.

In all cases, the five thermocouples positioned in the region of the thermosyphon evaporator, displayed temperature levels significantly higher than the other thermocouples. It is believed that, due to the installation procedures, the thermocouples located in the evaporator positions are under the direct influence of the electric heater, and therefore the readings are higher than the actual ones. More efficient insulation would solve such problem. Moreover, the first thermocouple of the evaporator region presents a temperature level below those located closer to the electric resistance, since the thermocouple is positioned in the bottom of the tube, where a larger amount of working fluid can be found. There is a chance that this is the most reliable evaporator temperature, but more conclusive work should be done to allow the confirmation of this statement.

It can be considered that the thermocouples positioned in the adiabatic section and in the condenser presented a uniform behavior. As for the liquid metal thermosyphon, the power input increase cause the temperature level increase. For the 400 W test, there is a sharp decrease of the condenser temperature level, involving the last two thermocouples. This fact indicates that the power input was not enough to generate sufficient vapor to reach the whole thermosyphon. Therefore, as in the liquid metal case, only part of the thermosyphon worked properly.

As the heat power input increases, the temperature level of these thermocouples increases, reaching, for the higher input levels, the same level of the thermocouples.

It is important to stress that the experimental apparatus was able to control the temperatures in the levels of the thermosyphon application, which is around 400 ºC, for the higher input level.

The values of the thermal resistances for each heat flux rate, calculated with Eq. 1, are shown in Figure 7. As already observed for the liquid metal heat pipes, as the heat flux rate increases, the thermal resistance of the thermosyphon decreases.

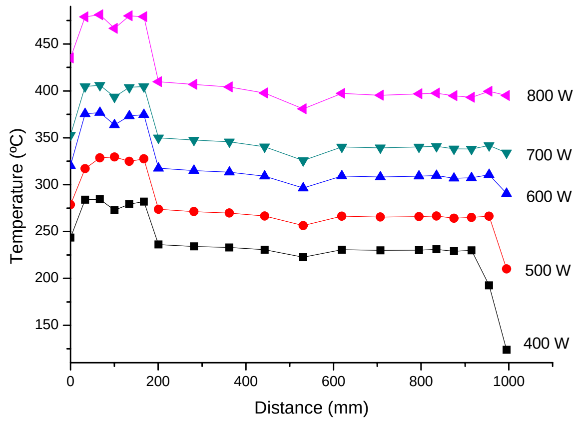


Figure 6. Temperature profile of naphthalene themosyphon for different levels of heat flux rates.

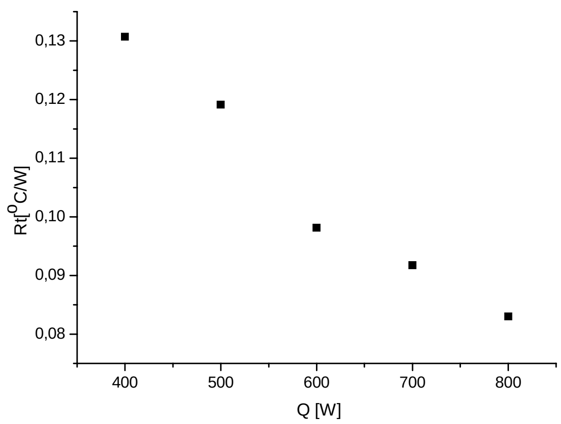


Figure 7. Thermal resistance of naphthalene thermosyphon.

4. CONCLUSIONS

This research showed that it is possible to employ naphthalene and mercury as working fluid in high temperature thermosyphons. Of course mercury can not be considered a suitable working fluid for industrial applications, due to hazard problems. The mercury was employed here for academic study purposes, with the objective of the development and control of high temperature thermosyphon technology by the Heat Pipe Laboratory.

It was verified that the increase of the evaporator power input resulted in an increase of the working temperature of the thermosyphons. Also, the thermosyphosn works better at higher power levels, since the vapor front is able to reach the whole thermosyphon, activating the whole length of the device.

For the maximum power input level, it can be observed that both the naphthalene and mercury thermosyphons reached a working temperature of around 400 ºC, fulfilling the demand for a device that can work in high levels of temperatures. That shows that the naphthalene and mercury are adequate for the use in levels of temperature where it is not recommended the use of water. The mercury thermosyphon could reach even higher temperature levels, but this was not possible in the present work due to the experimental apparatus limitation.

In the near future, the group intends to study problems related to the formation of non condensable gases in thermosyphons and its thermal effect on the thermal behavior of these devices. In such a research it will be necessary long duration tests, in order to allow enough time for the formation of non-condensable gases and for the possible degradation of the working fluids.

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