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EXPERIMENTAL ANALYSIS OF A STAINLESS STEEL HEAT PIPE USING WATER AS THE WORKING FLUID

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Abstract. *The paper refers to an experimental analysis of a heat pipe. The heat pipe was produced with a stainless steel tube with an outer diameter of 6 mm, length of 230 mm and capillary structure composed by one round stainless steel screen mesh 100. The working fluid used was deionized water. The heat pipe has an evaporator length of 75 mm and a condenser length of 110 mm. The condenser was cooled by forced convection using a water heat sink set at 20 °C and the evaporator was heated using an electrical resistor in wire geometry. Tests were accomplished for heat loads varying from 5 to 20W for the heat pipe working at following positions: at horizontal, condenser above the evaporator and evaporator above condenser. For all positions the heat pipe worked acceptably.*

Keywords: *Heat Pipe, Experimental Analysis, Water, Stainless Steel Mesh 100*

1. Introduction

Based on estimates of the reduction of energy sources, it is of great importance to develop more efficient processes and / or equipment in terms of energy. The energy efficiency of thermal systems has been one of the main topics of discussion on the preservation of natural resources and the reduction of costs of the processes involved in these systems. A good alternative are heat exchangers assisted for heat pipes that according to Konev *et al.* (1995) have become one of the most efficient and economical devices for the use of residues thermal.

The demand for the use of heat pipes is increasing because they offer advantages over other thermal transfer devices due to their compact and passive method of operation, together with various sizes are commercially available from micro to a richer set more extensive, efficacy in heat recovery, the absence of moving parts, light weight, relative economy, complete separation between hot and cold fluids and security, making the device more appropriate for applications that require a temperature differential.

The transport of large quantities of heat happens in an efficient manner along large distances fundamentally at a temperature invariable without the need for any external power because they operate in a closed cycle two-stage and utilize the latent heat of vaporization for transfer heat to from small temperature differences. Basically consist of a metal tube coated internally by a porous medium drenched with working fluid. Are composed of three distinct regions: evaporator, adiabatic region, condenser.

Yang *et al.* (2003), propose a heat pipe heat exchanger for heating automobile using exhaust gas to waste heat recovery. They developed the calculation method and the feasibility of using heat pipe heat exchangers for heating applying automotive exhaust gas is studied. Was applied the heat pipe heat exchanger for heating HS663, a large bus. They used 50 heat pipes, which each presents 310mm in length, 20 mm in diameter and water as working fluid. They conclude that the design method proposed is really accurate and valuable.

Hagens *et al.* (2007), propose that a heat pipe equipped with air heat exchanger can be a good alternative to those with water-cooled heat exchanger, specifically in long pipes and in warm places. They used a heat pipe with 150cm in length, 16cm in diameter and R134a as working fluid. They applied specifics methods from the literature to measure the performance of the heat pipe and proved this proposition in these conditions.

According to Yau and Ahmadzadehtalatapeh (2010), heat pipe heat exchangers have a great role in different fields including air conditioning systems. The advantage of using a heat pipe over the other methods is that a heat pipe can have an high thermal conductance in steady state operation. Moreover, ability to control and transport high heat rates at various temperature levels are the unique characteristics of heat pipes.

The operating pressure and type of fluid inside heat pipe will depend largely on the operating temperature of the heat pipe. The characteristics which should be considered when selecting the type of working fluid is the property of the surface tension, which must be high in order to increase the capillary effect, and be chemically stable and easily available, cheap and non-toxic. The heat pipes can be easily implemented as heat exchangers in pumps the vapor compression and heat, coolers and other devices for heat transfer. In this work are exposed the experimental results to a heat pipe that utilizes a porous element stainless steel (100 mesh) as the capillary structure. The working fluid is deionized water. Experimental tests were performed to evaluate thermal behavior of the heat pipe to the heat loads from 5 to 20 W in a horizontal position and position in which the condenser was located above the evaporator and where the evaporator was positioned above the condenser. From the results, an analysis is presented of the behavior of the heat pipe in operation.

2. Description of the experimental device

The main characteristic of heat pipes is the low thermal resistance due to the heat transport that occurs by movement of the steam. They can operate in any configuration for positioning the condenser and the evaporator, and operates according to the following principle: in the region of the evaporator, heat is transferred to the heat pipe, vaporizing the fluid contained inside this region. The steam generated is moved due to the pressure difference and the concentration of steam to the cooler regions of the pipe, the condenser, where heat transported is rejected to the vicinity of the tube. In the heat rejection process, the steam condenses, and the condensate is transported back to the evaporator closing the cycle. The adiabatic region, which may have variable dimensions (being absent in some cases) is located between the evaporator and the condenser being isolated from the external environment. The return working fluid from the condenser to the evaporator is through capillary pumping effect resulting from the fluid flow through porous. Therefore, the fluid pumping does not require mechanical pumping, no having thus moving parts. And causing the condenser can be below the evaporator. A sketch of the operating principle of heat pipes is presented in Fig. 1.

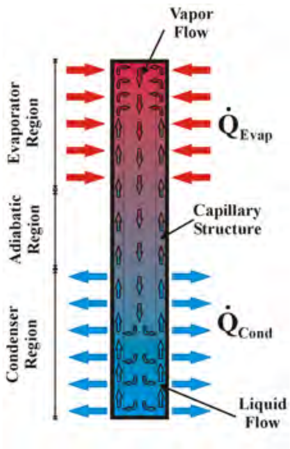

Figure 1. Sketch of the operating principle of heat pipes.

The methodology for manufactoring, tests and analyses of the heat pipe here developed is based on Peterson (1994); Reay and Kew (2006). Thus, a heat pipe was made of a stainless steel tube with outer diameter of 6 mm and 230 mm of length. The heat pipe has an evaporator region with 80 mm in length and a condensation region with 110 mm in length. Fig. 2 shows the heat pipe.

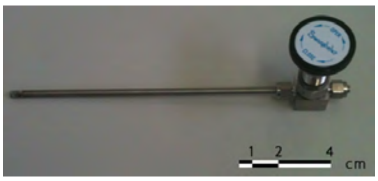

Figure 2. General view of the heat pipe.

A round stainless steel screen Mesh 100 was placed in the pipe to form the capillary structure for the flow of fluid (Fig. 3. Table 1 shows all the features of the heat pipe and working fluid.

Figure 3. Porous structure of stainless steel (mesh 100).

2.1 Filling station

The amount of working fluid inserted in the pipe is very important for capillary pumping system because the heat transfer depends on that amount of fluid. If there is not enough fluid, the pumping system stop to work and the heat pipe

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Table 1. Structural characteristics of the heat pipe.

Characteristic	Heat Pipe
Heat pipe inner diamater	4.0 mm
Heat pipe outer diamater	6.0 mm
Evaporator length	75.0 mm
Adiabatic region length	45.0 mm
Condenser length	110.0 mm
Capillary structure of Stainless steel (Mesh 100)	127μm (pore radius)
Working fluid	Water

collapses. This way there is not heat transferring.

Before the filling of the heat pipe with water, it is necessary to make vaccum inside the tube (Fig. 4). During the vaccum process the pressure inside reached 90 mbar (9 kPa) and the saturation temperature related to this pressure was 43.74 °C.

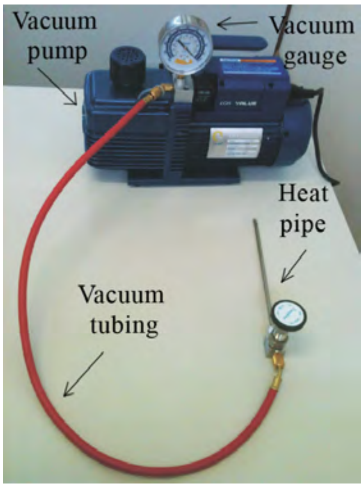

Figure 4. General view of the vacuum pump and the heat pipe.

Fig. 5 shows the filling station of the heat pipe. At the moment of the filling it is necessary to be very careful so that the existing vacuum in the tube is not lost. If it happens, the whole process of realization of the vacuum should be repeated.

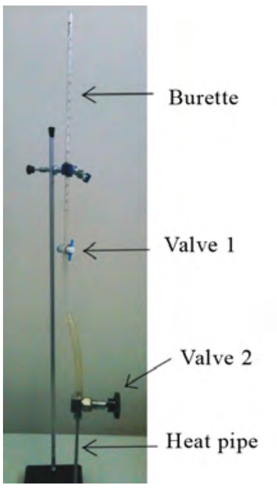

Figure 5. Filling station for the heat pipe.

Initially, the burette is filled with the required volume of working fluid. Then the burette valve is carefully opened to drain the fluid to the polymer hose. After it, this same valve is closed and the pressure valve tube heat is also opened in a careful manner so that there is not any bubble inside the heat pipe. After this step, the pressure valve is closed and the loading of the tube is performed. First, the heat pipe was filled with 0.6 ml. Then the tube was tested and it was detected that was necessary more fluid inside the heat pipe. This way the tube was filled with 0.8 ml and finally with 1.0 ml when

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the heat pipe has operated satisfactorily.

3. Description of test rig

The tube was heated by a power supply which applied a potential difference around the evaporator using a copper wire as an eleitrical resistor, as shown in Fig. 6.

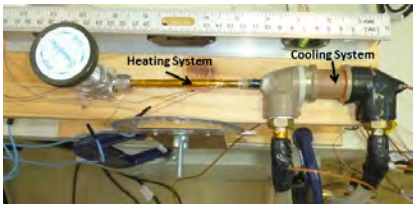

Figure 6. View of the heat pipe, showing the heating and the cooling systems.

The cooling system consists of a thermostatic heat sink with hoses, with controlled temperature, stealing heat from the condenser of the heat pipe, this inserted into a PVC pipe so there are no leaks. The Fig. 6 also shows the cooling system of the heat pipe. The working fluid of the thermostatic bath is deionized, water exiting the thermostatic bath, passes through a meter and a regulator flow, then cools the heat pipe and returned to the thermostatic bath.

The temperatures of the heat pipe are measured by thermocouples and acquired by Agilent data logger, which sends the data to the computer where they are registered. Three thermocouples were attached to the evaporator ($T_{Evaporator,1}$, $T_{Evaporator,2}$, $T_{Evaporator,3}$), two were attached to adiabatic region ($T_{Adiabatic,1}$, $T_{Adiabatic,2}$) and one was attached to condenser ($T_{Condenser,1}$), as it is seen in Fig. 7. Besides, the temperatures were monitored in the water flow in and in the water flow out of the cooling system.

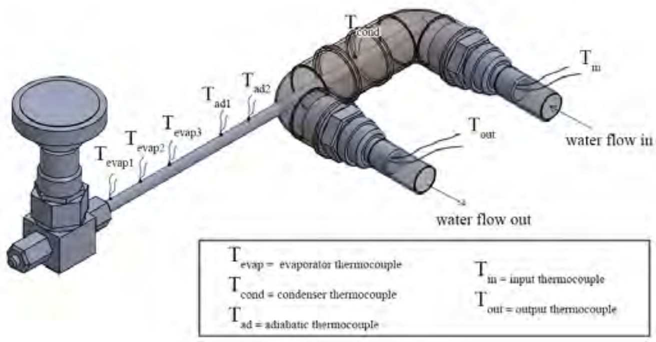

Figure 7. Positions of the thermal sensors along the heat pipe.

Fig. 8 shows the experimental setup used to test the heat pipe. There is a power source that applies heat and there is a thermostatic heat sink which provides cooling water in the condenser region.

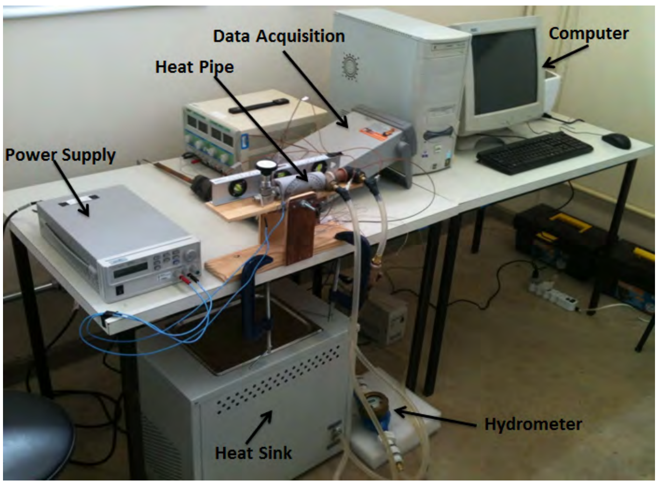

Figure 8. View of the test rig.

It was built a support which allows the rotation of the heat pipe by up to 60° to become possible to determine the

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temperature of the heat pipe in addition to the horizontal position. A protractor and a level meter were installed on the support to aid in positioning.

4. Experimental results

Presents the results of the thermal behavior of the heat pipe using water as the working fluid. Tests were performed for input powers 5 to 20W, taking into account the amount of fluid within the heat pipe and the inclination thereof. An analysis of the results is developed to evaluate the thermal behavior of the heat pipe studied here taking into account the temperatures measured along the outer surface of the heat pipe. The uncertainty of the measurements were estimated for the temperature and power input. Taking into account the accuracy of the temperature sensors (thermocouples type T) and the uncertainties of the data logger (Agilent 34970A with 20 channels), the uncertainty of the temperature measured was estimated at $\pm 1.8\ ^{o}$C. The uncertainty of the electrical power input was estimated at ± 0.28 W including the uncertainty of the power supply unit and the uncertainty of the data logger (Agilent N6700B).

4.1 The Working Fluid Inventory and Startup

This section presents an analysis of the amount of fluid inside the heat pipe taking into account the departure of the same. First, the tube was filled with 0.6 ml of deionized water. Then a power of 5 W was applied to the evaporator. Fig. 9 shows these results mentioned above.

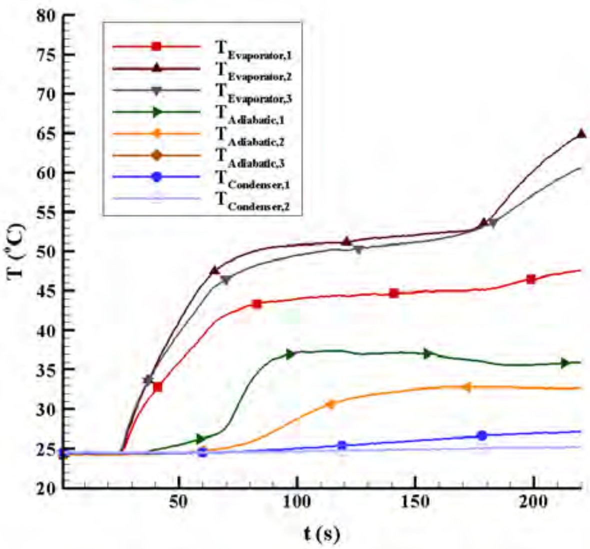

Figure 9. Heat pipe at Horizontal position with liquid volume of 0.6 ml and startup under heat load of 5 W.

Note that the temperatures ($T_{Evaporator,1}$, $T_{Evaporator,2}$ and $T_{Evaporator,3}$) rapidly rise at the moment when power is applied to the evaporator.

After approximately 70 s adiabatic temperature section ($T_{Adiabatic,1}$) rises rapidly, indicating that formation occurred hit the steam and the adiabatic region. From that moment, you realize that the evaporator temperatures tend to stabilize, seeking steady. However, at time equal to 180 s, temperature ($T_{Evaporator,1}$ and $T_{Evaporator,2}$) undergo a sudden rise, showing that the heat pipe failed due to lack of fluid. That is, the amount of fluid has not been sufficient for the thermodynamic cycle was completed.

Then the tube was filled with 0.8 ml of deionized water and was applied to the power of 5 W on the evaporator. Fig. 10 shows the results of this configuration.

As in the previous case, the temperatures ($T_{Evaporator,1}$, $T_{Evaporator,2}$ and $T_{Evaporator,3}$) rise immediately to apply power to the evaporator. After 100 s elapsed, the temperature in the adiabatic region ($T_{Adiabatic,1}$) is increased considerably, showing that in front of evaporation is again in the adiabatic region. Then, the temperature of the evaporator tend to form a permanent regime. However, as in experiment fluid volume 0.6 ml at time 180 s, temperature ($T_{Evaporator,1}$ and $T_{Evaporator,2}$) begin to undergo a sudden rise, but in this case occurs at time equal to 380 sec. This shows that the heat pipe has worked satisfactorily for a longer time, about 200 s to more than the previous one, but there was a lack of fluid to complete the thermodynamic cycle, taking the heat pipe to fail again.

Finally the analysis of the amount of fluid taking into consideration the start of the heat pipe, the pipe was filled with 1.0 ml of deionized water. Again, the heat load applied was 5 W. The results obtained are shown in Fig. 11.

As can be observed, when applying the power of 5 W at evaporator temperatures ($T_{Evaporator,1}$, $T_{Evaporator,2}$ and $T_{Evaporator,3}$) rise slightly. After 50 s, the area steam enters the adiabatic temperature increasing considerably the adia-

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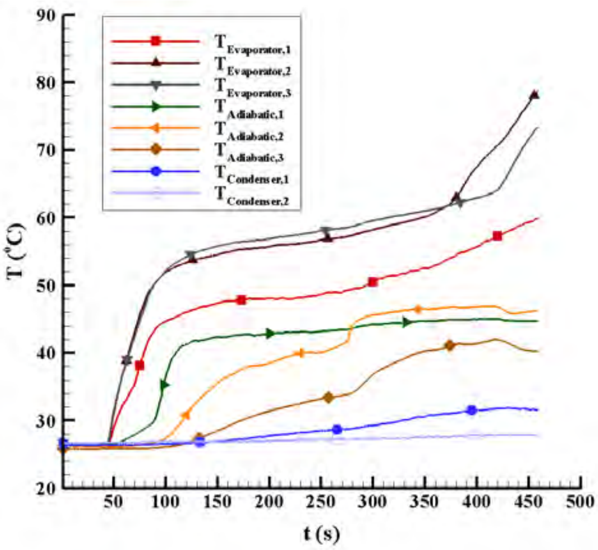

Figure 10. Heat pipe at Horizontal position with liquid volume of 0.8 ml and startup under heat load of 5 W.

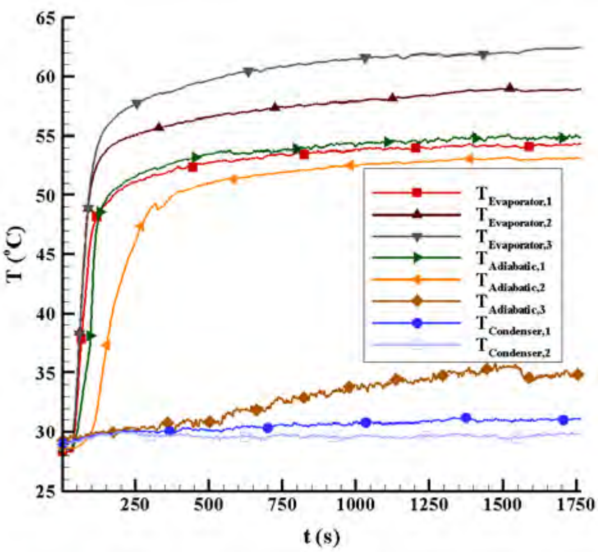

Figure 11. Heat pipe at Horizontal position with liquid volume of 1.0 ml and startup under heat load of 5 W.

batic region ($T_{Adiabatic,1}$). After an time of 200 s, the evaporator temperatures reached a steady state and does not undergo change as occurred in the previous two cases, remained stable until the end of the tests. Thus, the heat pipe has worked satisfactorily, in other words, completed the thermodynamic cycle, reaching its expected performance.

4.2 Temperature of the Heat Pipe as a Function of Heat Load

From the tests above, it could begin to run the tests with the heat pipe with a cooling water at 20 °C. Fig. 12 shows the temperatures of the heat pipe at horizontal position and with the gradual increasing the heat load applied to the evaporator ($T_{Evaporator,1}$, $T_{Evaporator,2}$ and $T_{Evaporator,3}$), in the adiabatic region ($T_{Adiabatic,1}$ and $T_{Adiabatic,2}$) and in the condenser ($T_{Condenser,1}$).

The heat pipe worked satisfactorily for heat loads from 5 to 15 W. It is evident that by increasing the power in the evaporator temperatures soar, with the exception of the condenser temperature ($T_{Condenser,1}$) which remains approximately constant during the test. Under heat load of 5W, the temperatures incrise until 300s, from that time they tend to stabilize. It is noticed that the time to stabilize the temperatures in the heat pipe is about 175 s. This shows that after 300 s, the heat pipe reaches the steady state.

The maximum temperature reached was approximately 110 °C which was achieved under heat load of 20 W, where the power was turned off for safety reasons. The maximum temperature reached in the adiabatic region ($T_{Adiabatic,1}$) was 33 °C. The condenser temperature ($T_{Condenser,1}$) remained approximately at 20 °C.

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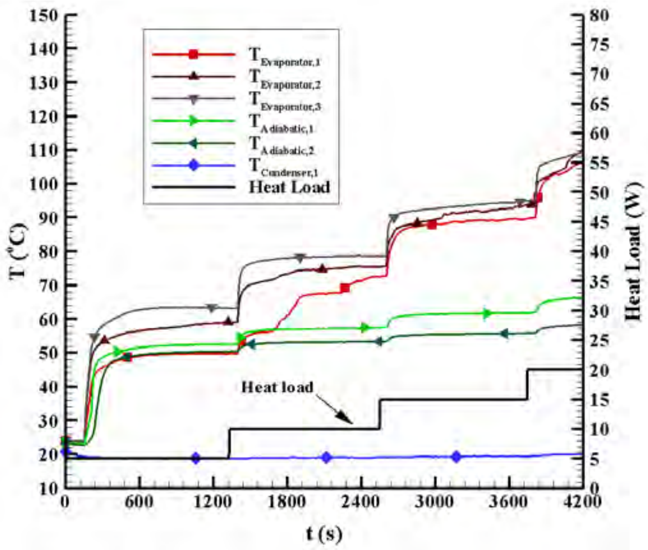

Figure 12. Temperatures of the Heat Pipe for heat loads increasing at horizontal position.

4.3 Inclination of the Heat Pipe

Here it is analyzed the inclination of the heat pipe. Two different scenarios have been analyzed: the condenser positioned above the evaporator in 30° and evaporator positioned above the condenser in 30°, the results obtained are shown in Fig. 13 and Fig. 14, respectively.

The heat pipe functioned satisfactorily in potency 5 and 10 W. All the working characteristics of the obtained horizontal heat pipe were also obtained with the condenser above the evaporator. However, when applying a power of 15 W tube was working satisfactorily when the temperature began to stabilize at approximately 2650 s when there was a rise in temperature of the evaporator ($T_{Evaporator,1}$) and the adiabatic region ($T_{Adiabatic,1}$) suddenly hitting about 115 °C in the evaporator, without signs of stabilizing. For this reason, it was off the power source to avoid compromising the operation of the experiment. This increase probably indicates a problem with the thermocouple because the other evaporator temperatures ($T_{Evaporator,2}$ and $T_{Evaporator,3}$) and the adiabatic region ($T_{Adiabatic,2}$) continued functioning normally.

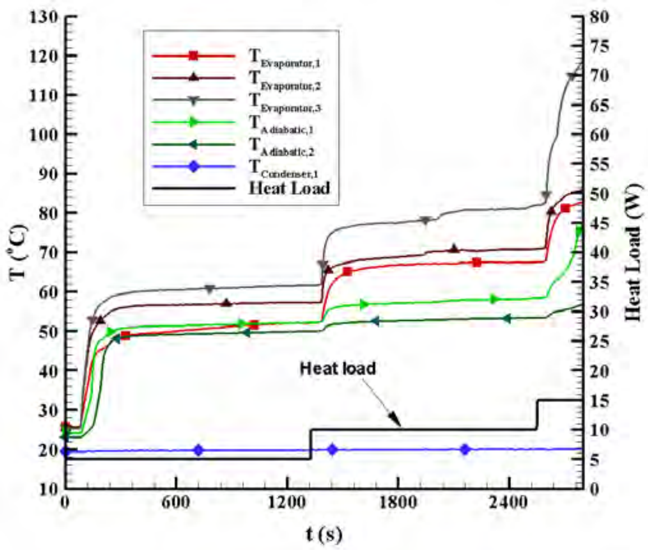

Figure 13. Temperatures of the Heat Pipe for heat loads increasing at position with Condenser above Evaporator.

Now the evaporator above the condenser, the adiabatic region ($T_{Adiabatic,1}$ and $T_{Adiabatic,2}$) of the heat pipe worked satisfactorily to the power of 5 W, stabilizing from the 500 s test. But the temperature of the evaporator ($T_{Evaporator,1}$, $T_{Evaporator,2}$ and $T_{Evaporator,3}$) is not stabilized, featuring not a permanent arrangement. When applied power of 10 W, the temperature of the evaporator $T_{Evaporator,1}$ and $T_{Evaporator,2}$) reached about 114 °C and the heat source turned off, so that no damage to the heat pipe.

The temperature of the condenser ($T_{Condenser,1}$) underwent a slight increase due to the increase in the evaporator

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temperature and the adiabatic region, which consequently increases the amount of heat exchange with the water, working as expected. In general, the heat pipe not worked satisfactorily, this fact is probably due to gravity influence the flow of water, or water that returns from the capillary and the evaporator should remain sitting up to the vapor state flows through the tube heat to the condenser occurs the lack of working fluid in the evaporator and thus the overheating of the region.

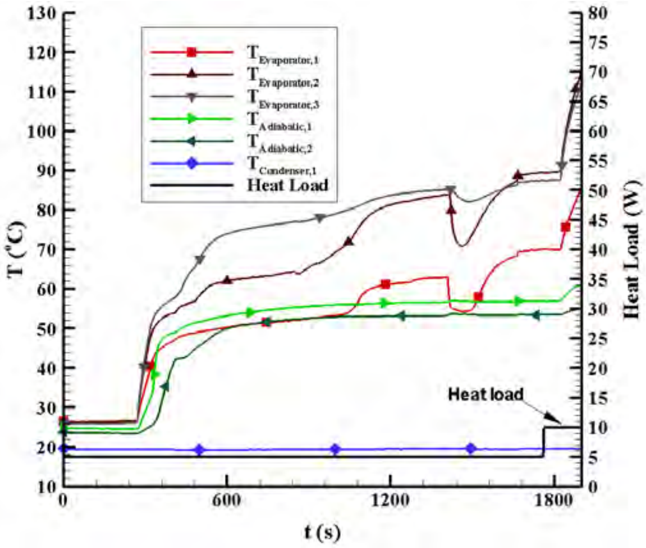

Figure 14. Temperatures of the Heat Pipe for heat loads increasing at position with Evaporator above Condenser.

4.4 Response of the Heat pipe Under Oscillating Heat Loads

Here in this section is analyzed the oscillation of the heat load in order to evaluate the thermal behavior of the heat pipe. First, a heat load of 15 W was applied to the evaporator section. The temperatures of the evaporator ($T_{Evaporator,1}$, $T_{Evaporator,2}$ and $T_{Evaporator,3}$) increased as mentioned before, as well as, the temperatures of adiabatic section ($T_{Adiabatic,1}$ and $T_{Adiabatic,2}$) and the heat pipe trended to reach the steady state condition. Under heat load of 15 W, the maximum temperature reached was approximatly 106 °C ($T_{Evaporator,3}$ and $T_{Evaporator,2}$). This heat load was applied until 1440 s. Next, the heat load was decreased to heat load 5 W and it can be noticed that the temperatures also decreased and the heat pipe reached the steady state condition over again. The maximum temperature was reached at the evaporator ($T_{Evaporator,3}$ = 68 °C) and this heat load was kept until 2700 s. In a sequence, the heat load was increased to 20 W and again the heat pipe reached the steady state condition and the maximum temperature was approximately 108 °C ($T_{Evaporator,3}$. Finally, the heat load was decreased for 10 W and the heat pipe worked satisfactory.

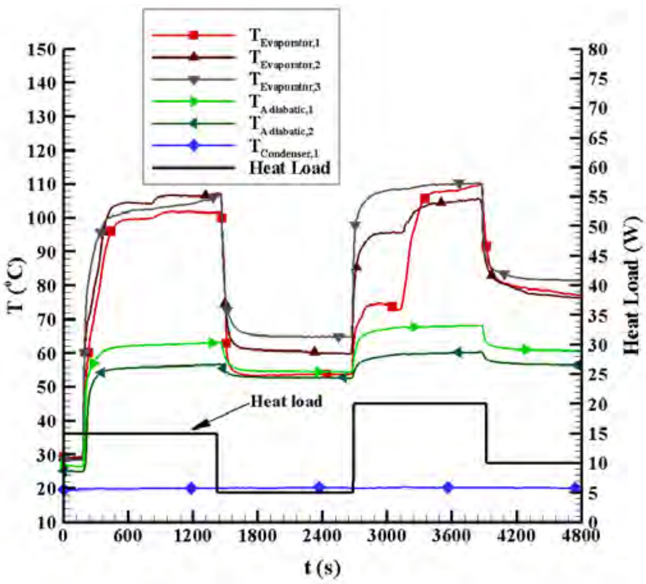

Figure 15. Temperatures of the Heat Pipe under oscillating heat loads.

5. Conclusion

A heat pipe made of stainless steel with a metallic mesh 100 (stainless steel) and water as working fluid was manufactured and tested under several conditions. The heat load was varied from 5 up to 20 W. The amount of working fluid inside the heat pipe was evaluated. The heat pipe was tested at horizontal, at a slope of 30° with the condenser above the evaporator and at a slope of 30° with the evaporator above the condenser. The thermal behavior of the heat pipe was also avaluated under oscillating heat load.

According to the results obtained in the section 4.1, the liquid volume was varied from 0.6 up to 1.0 ml. Only with 1.0 ml the heat pipe reached the steady state. In the section 4.2, the heat pipe worked well for increasing heat load from 5 up to 15 W and the maximum temperature reached was approximately 110 °C. As expected, the heat pipe using metallic mesh did not work satisfactory, although at a slope of 30° with the condenser above the evaporator the heat pipe worked well until 10 W and at a slope of 30° with the evaporator above the condenser (worst condition) the heat pipe worked well until 5 W. This could be improved if the capillary structure was made of a sintered wick.

In section 4.4 the oscillation of the heat load is analized and under heat load 15 W the maximum temperature reached was approximatly 106 °C ($T_{\mathrm{Evaporator},3}$ and $T_{\mathrm{Evaporator},2}$) and under heat load of 20 W the maximum temperature was approximatly 108 °C ($T_{\mathrm{Evaporator},3}$). The thermal response of the heat pipe has shown satisfactory. As a result, it could be conclude that the methodology of manufactoring and test of this kind heat pipe has shown adequate and feasible for developing heat pipes which could be used in heat pipe heat exchangers.

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7. REFERENCES

Hagens, H., Ganzevles, F., van der Geld, C. and Grooten, M., 2007. "Air heat exchangers with long heat pipes: Experiments and predictions". *Applied Thermal Engineering*, Vol. 27, p. 2426?2434.

Konev, S.V., Wang, J.L. and Tu, C.J., 1995. "Characteristics of a heat exchanger based on a collector heat pipe". *Heat Recovery Systems and CHP*, Vol. 15, pp. 493–502.

Peterson, G.P., 1994. *An Introduction to Heat Pipes: Modeling, Testing, and Applications (Thermal Management of Microelectronic and Electronic System Series)*. Wiley-Interscience.

Reay, D. and Kew, P., 2006. *Heat Pipes - Theory, Design and Applications*. Elsevier Science and Technology.

Yang, F., Yuan, X. and Lin, G., 2003. "Waste heat recovery using heat pipe heat exchanger for heating automobile using exhaust gas". *Applied Thermal Engineering*, Vol. 23, p. 367?372.

Yau, Y. and Ahmadzadehtalatapeh, M., 2010. "A review on the application of horizontal heat pipe heat exchangers in air conditioning systems in the tropics". *Applied Thermal Engineering*, Vol. 30, p. 77?84.

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