Experimental Study of a Wire Mini Heat Pipe for Microgravity Test

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ABSTRACT

This paper present a numerical theoretical and experimental analysis of the diffusion welding wire mini heat pipe, fabricated in Brazil, for testing under four minutes of microgravity conditions aboard an experimental platform to be launched by the VS-V6 Rocket.. An iterative model, based on the Wang and Peterson (2002) and Launay et al. (2003) works, was developed. Two experimental set-ups were mounted for testing: the first using Peltier plate cooling device and the second using a heat exchanger, where the cooling water was supplied by a temperature controlled thermal bath. The mini heat pipe presented an overall resistance 5.4 times larger, when compared with the same device without working fluid. The results for the water heat exchanger in laboratory were better, but the Peltier plate showed to be the convenient cooling device for the microgravity testing, which will happen in October 2004. The model compared reasonable well with the data for both set-up tests.

KEY WORDS: Mini heat pipe, diffusion welding, microgravity

1. INTRODUCTION

Mini heat pipes are currently an active area of research due to its possible applications in several technologically important processes in the electronic industry, in microgravity environments, in spacecraft thermal control, to name a few.

The mini heat pipe used in this study was developed using the diffusion welding procedure as described in Mantelli et al., 2002. The working fluid flows through channels formed by welding parallel cooper wires sandwiched between two thin copper flat plates (Wang, 2002). This manufacturing technique provides channels with very sharp angles in their corners, since there is no deposit of soldering material blocking the corners, as happens in the conventional fabrication procedure (see Mantelli et al, 2002). Due to the surface tension properties, the working fluid flows through these corners, which actually work as porous media, supplying the capillary pumping power necessary for the proper operation of the heat pipe.

In the present work, a mini wire heat pipe, designed to be tested under microgravity conditions, is presented. Constructive and theoretical aspects of this development are exposed as well as experimental results obtained in the laboratory. The device will be tested aboard an experimental platform to be launched in the Cumã Mission of the VS-V6 Rocket, from the Alcântara Rocket Launch Center in Brazil, in October 2004. Around for minutes of microgravity testing time is supplied by the Platform. Actually this launching, planned to happen in April 2004, was postponed due to the damages in Alcântara, resulted from the major accident that happened in August 2003.

2. FABRICATION PROCESS

The mini heat pipes tested in this work were fabricated using the welding diffusion procedures describe in Mantelli et al., 2002. To guarantee a good welding, the wires and the flat plate must be cleaned with 10% sulfuric acid solution to remove any oxidation that could block the copper diffusion, before the thermal cycling. Flowing water was used to rinse the wires and the plate, for about *10 min*. After the welding, acetone was introduced in the mini heat pipe to wash the grooves, which are filled with the working fluid. After the fabrication and cleaning process is concluded, the pipe is leak tested and finally charged.

The charge procedure is the following: the mini heat pipe is linked to the vacuum pump by a small tube (Tygon tube). After the vacuum is established, especial clamp closes the tube and the adequate amount of working fluid (usually very small) is slowly injected into the tygon tube using a micro syringe (Insulin syringe 1 cc). After that, the mini heat pipe is sealed. This process needs to be performed very carefully, because the small hole that the needle produces in the tygon tube can cause leakage if the tube is not closed in the proper position. Vacuum grease is used to avoid this problem in the position where the needle enters in contact with the tube. The vacuum inside the mini heat pipe pull the liquid.

2.1. Working Fluid Volume Determination

One of the main challenges in developing heat pipes is to establish the correct amount of working fluid required for the proper operation of a particular device. During operation, the cross-sectional area of the working fluid liquid phase decreases from the condenser to the evaporator. Also, as the power input increases, the amount of working fluid in the liquid phase spread among the channels decreases (or the amount of vapor increases). Therefore, the total volume of the working fluid depends on the geometry of the channel, on the heat to be transported and on the physical properties of the working fluid.

Actually, the ideal working fluid volume is such that all the corners are completely filled, with no extra working fluid located in the condenser section, which would block the effective condenser length. Launay et al. in 2003, studied theoretically the thermal performance of mini heat pipes with the geometry similar to the one tested in this work. With this information and the theoretical model described next, the optimum charge for this configuration should be 12% of the total volume of the channels.

3. THEORICAL ANALYSIS

The model presented by Wang and Peterson, in 2002, was used to determine the mini heat pipe maximum capillary limit. One dimensional steady state conditions were assumed. The model recently developed by Launay et al. (2003) for a copper plate mini heat pipe was also used. Based on these works, a numerical model to predict the capillary limit was developed. The flow chart of the software especially developed for this analysis can be seen in the Figure 1.

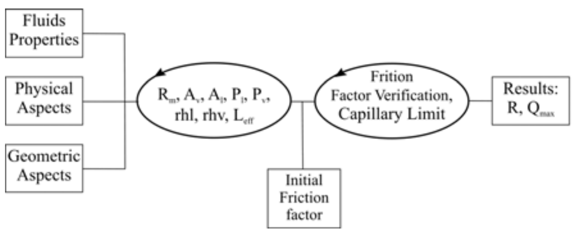

Figure 1. Flowchart used for the numerical analysis.

The flowchart inputs were the geometrical and physical parameters of the mini heat pipe and the thermophysical properties of the working fluid at a pre-determined operating temperature. The vapor flow in then assumed laminar and, according to Peterson (1994) the first guess of the parameter $f_l Re_l$ is 16 (initial friction factor). The correct value of the $f_l Re_l$ parameter is obtained from an interactive procedure. Utilizing the model, the maximum heat transfer capacity can be determined. Details of the mathematical and numerical modeling will not be presented due to the lack of space.

The results obtained for one individual mini heat pipe are shown in Figure 2, in terms of a graph of the maximum heat transfer capacity as a function of the diameter of the wires. This graph shows that, for a specific operational temperature, the wire diameter can dramatically affect the maximum heat transport capacity of the mini heat pipe, i.e., with a little increase in the wire diameter, the maximum heat capacity increases quickly.

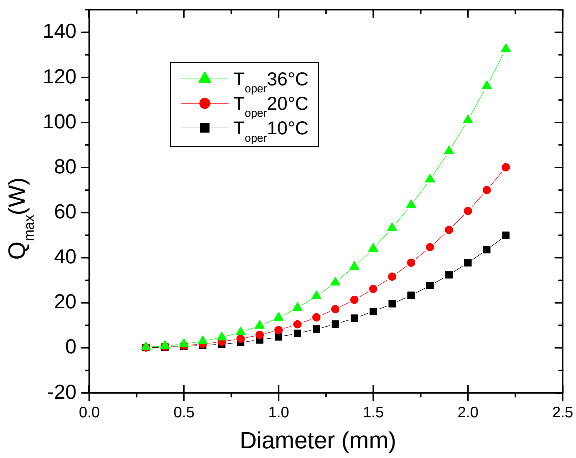

Figure 2. Variation of the heat transport capacity with wire diameters

4. EXPERIMENTAL ANALYSIS

Due the limited space in the rocket, the dimensions of the mini heat pipe proposed is 100 mm of length, 30 mm of width and 2 mm of height. This mini heat pipe has 10 parallel copper wires welded between two thin copper sheets with 0.2 mm of thickness. The distance between two wires is approximately 2 times the wire diameter. The mini heat pipe was charged with 0.520 ml of distilled water, corresponding 12% of total volume. A mini heat pipe sketch can be seen in Figure 3.

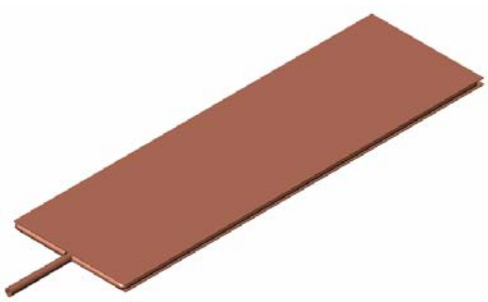

Figure 3. Mini heat pipe sketch

4.1. Peltier Cooling Device

In this section, the experimental set-up developed for testing the mini wire heat pipe is described. A Peltier cooling device is being considered for use in the experiment in space.

When a direct electrical current passes through a cell made of a pair of n- and p-type semiconductor materials, one of the junctions is cooled, while the other is heated. This phenomenon is named Peltier Effect, in honor of Charles Athanase Peltier (1785-1845), who, in 1834, discovered it. A schematic of the device, also denominated as thermoelectric refrigeration system, can be observed in Figure 4. It consists basically of a Peltier element and two heat transfer elements, responsible for transferring the heat generated or absorbed at the two junctions. The efficiencies of the heat transfer at both the cold and the hot junctions are crucial to the operation of the thermo-electric refrigeration system (Riffat, 2002).

In the present work, a Peltier plate is used for removing heat form the mini heat pipe. It is expected the experiment to have a better controlled boundary condition so that the experimental conditions in microgravity could be more reliably reproduced in the laboratory under gravity, and better comparison between the data under gravity and under microgravity, despite the small dimensions of the device.

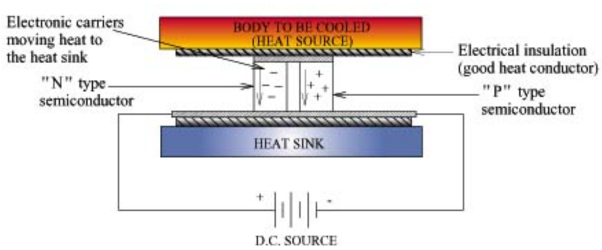

Figure 4. Cross section of the Peltier plate

4.2. Experimental Set-up Description

An aluminum support was built to fasten the entire device in the rocket platform. Polyurethane foam is used to insulate the system from the environment. A data acquisition system was designed especially to monitor the set-up temperatures during the flight, under microgravity conditions.

As usual, the mini heat pipe presents three different regions (see Fig. 5): evaporator, adiabatic section and condenser. Heat is added to the evaporator by means of an electrical skin heater, attached over a length of 20 mm. The adiabatic section, of 50 mm of length, is thermally insulated from the environment (for modeling purposes, it is considered perfectly insulated). Heat is removed from the condenser by the Peltier plate which is installed over a length of 30 mm.

Five thermocouples, as shown in Figure 5, are used for monitoring the temperatures along the tube. They are attached to the mini heat pipe surface by means of Kapton tapes and are directly connected to a HP 34970A Data Acquisition System, controlled by the LabVIEW software, using a personal computer.

The Peltier plate was controlled by a power supply, creating hot and cold regions (upper and lower position, as shown in Fig. 4). The hot region was attached to an aluminum support over which aluminum fins are installed to spread the heat generate by Peltier plate. The cold region was added to the mini heat pipe surface to ensure a constant heat flux removal, which is controlled by means of the current and voltage applied. To improve the thermal contact between all the surfaces (Peltier hot surface and aluminum support; aluminum support an aluminum fins; cold Peltier surface and mini heat pipe surface), a thin layer of high thermal conductivity paste (Omegatherm 201) was used.

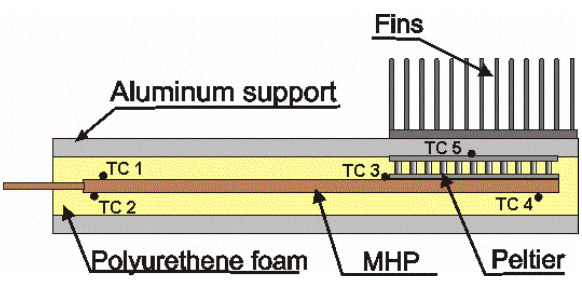

Figure 5. Sketch of experimental apparatus and thermocouples locations

The tests performed using the Peltier plate as heat sink showed that the main problem in using this technology is the difficulty in dissipating the heat generate by the hot side. Due the limitation of space, some aluminum fins were introduced on the hot side. Simulating the same test conditions of microgravity, no fans were used (no forced convection). Fans can not be used in the platform due to the vibrations that happens during the launching, so that devices with mechanical movements are not advised. A test was performed and its results can be seen in Figure 6 in a plot of the temperature as a function of time. When the Peltier was switched on, there was a suddenly temperature drop, which was quickly recovered when the heater was switched on. For a 10 W of power input in the heater, the temperature of the condenser was approximately 36 ^oC. Actually, the 10 W power input was the upper limit possible for this set-up. If more power is applied, the heat released by the Peltier cooling device would reach back the mini heat pipe, spoiling the experimental results. A thick aluminum block, properly designed, can be installed over the hot side of the Peltier plate, to absorb the generated heat, avoiding this undesirable effect. The aluminum block would absorb all the generated heat warming up in transient conditions considering that the time for testing is very short. This procedure will be tested in the near future.

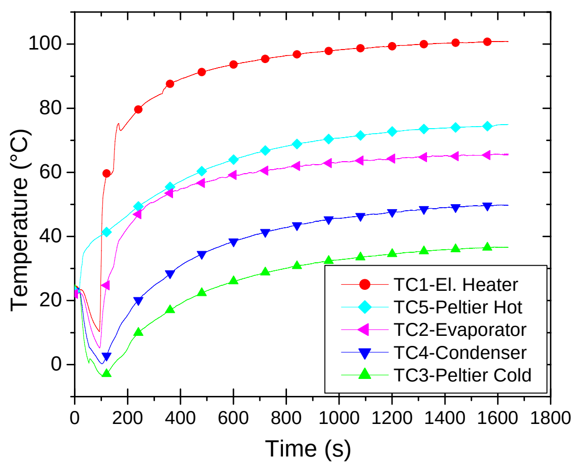

Figure 6. Temperature as a function of time for the set-up tested using the Peltier device, for 10 W of power input.

As already observed, the Peltier plate presents thermal limitations, not suitable for tests with input power higher then 10 W. Therefore, to reach the maximum heat transfer capacity (dry out) of the mini heat pipe, a cooling apparatus was constructed using PCV pipes, as shown in Figure 7. Cooling water, from a controlled thermal bath, flows through the heat exchanger, which ends are closed by caps, removing the heat form the mini heat pipe by forced convection. The cooling bath is set to a required temperature level, which is held constant throughout the test. A rectangular small hole was made in one of the cap to introduce the condenser section of the mini heat pipe. A silicone adhesive and sealant are dump into the empty space between the mini heat pipe surfaces and the wall of the cap, sealing the inside face of the PVC pipe. In this heat exchanger, the condenser is in direct contact with the cooling fluid, during the tests.

Figure 8 shows the thermocouple positions for the water cooling tests. The experimental results for the temperature as a function of power for a mini heat pipe charged with 0.520 ml of distilled water obtained with the use of cooling water, can be observed in Figure 9. The temperature of the end of the evaporator (TC-2) and the temperature of the adiabatic section (TC-3) increased proportionally with the power input. Also, it can be seen that the adiabatic section temperature (TC-3) quickly approaches the evaporator temperature (TC-2). At the condenser section, the temperature increased also but in a different (lower) rate. The dry out can be observed at the point where the temperature start to increase sharply. The dry out corresponds to the point of the maximum transport capacity, for each operating temperature. With this new set-up, it is possible to simulate these maximum heat transport capacity, at various cooling temperatures, simply by changing the temperature of the cooling bath in the condenser section.

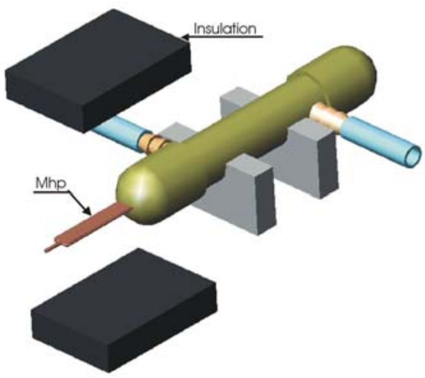

Figure 7. Sketch of the experimental apparatus.

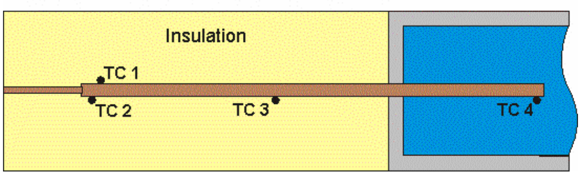

Figure 8. Thermocouple locations for the cooling bath heat transfer set-up.

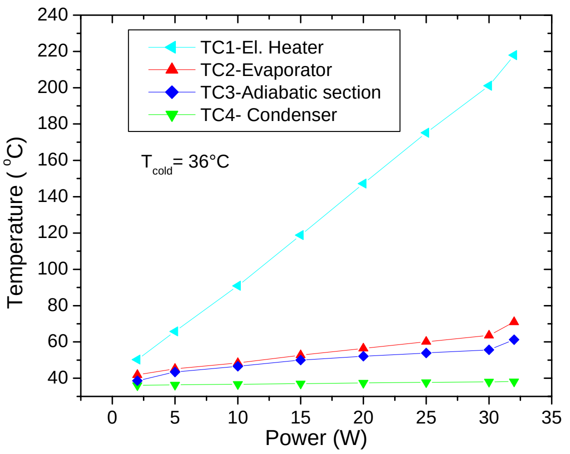

Figure 9. Temperature variation of the mini heat pipe charged with 0,520 ml

The performance of the mini heat pipe can be associated with its capacity to transfer heat power from evaporator to condenser. The overall thermal resistance represents very well this parameter. It is defined as the ratio between the difference of evaporator and condenser temperatures and divided by the power input. Figure 10 shows the thermal resistances obtained for the empty (no working fluid) and the charged mini heat pipe, for the case of the water cooling temperature of 20°C and 36°C. This figure shows that, for the case of 0.520 ml and bath temperature of 36 °C, the overall resistance showed to be 5.4 times that without working fluid at the point where dry out occurred (30W). When the bath temperature is 20°C the dry out occurred at 27 W. One point obtained for the experimental set-up using Peltier plate is also shown. The small difference on the overall thermal resistance obtained from testing the same mini heat pipe with the two different set-ups shows that these apparatus present different experimental uncertainties. The thermal bath cooling water heat exchanger is expected to present more precise results.

The model described in Section 3 was applied to determine the maximum heat transport capacity of the mini heat pipe, when the condenser is at 20 and 36°C. The results are presented in Table, where it can be observed that the model presents, for both cases, higher values than those obtained form the experiments. The comparison is quite good of the 20°C temperature, increasing considerably for 36°C (from around 5 to 28%).

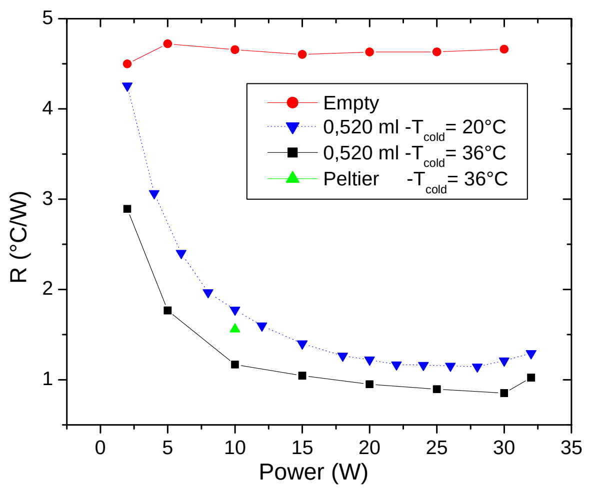

Figure 10. Overall resistance as a function of the power input.

Table 1. Comparison of the model result and the experimental result.

T_{cold} (°C)	Q_{max}(W) Model Results	Q_{max}(W) Experimental Results	Difference %
20	28.5	27	5.26
36	41.4	30	27.53

5. CONCLUSIONS

The heat transfer performance of the mini heat pipe has been investigated both analytical and experimentally. It was found that the maximum heat transfer capacity increases with the increase of the wire diameter, which is in accordance with the paper presented by Wang and Peterson (2002). According to Launay et al, 2003, the correct amount of working fluid was inserted into the mini heat pipe and a better performance was verified.

The Peltier plate was used to test the mini heat pipe only for the 10 W dissipation tests. The comparison of this point with the model result and the data obtained using the water cooling heat transfer device is quite good for this point. Of course the water set-up is much more flexible for laboratory testing. For space conditions, especially for the present experiment which will be tested in microgravity conditions for about only 4 minutes, therefore in transient conditions, the Peltier plate will provide a known heat flux boundary condition, since no steady state temperature are possible to be reached. Beyond this, the 10 W limitation of the experiment using the Peltier plate is not a strong one because the thermal behavior of the mini heat pipe for 10 W and 30 W (dry-out limit) power dissipations is very similar, as one can see in Fig. 10. Therefore, the Peltier plate proved to be suitable for the microgravity test application.

In the current study, for a water mini heat pipe with 10 copper wires of 1.5 mm diameter, the thermal resistance of 0.85 C/W was determined when dry out occurred (30W) at 36°C operating temperature. A reasonable agreement of theoretical and experimental data was observed. To compare the present results with the literature ones, the present model was used to determine the maximum heat flux of a specific brazed mini heat pipe tested by Wang and Peterson. This device is made of 59 aluminum wires of 1.270 mm diameter and used acetone as the working fluid. The theoretical Q_{max} value obtained showed to be 2 times larger by channel. The authors believe that this better performance can be attributed to the diffusion welding fabrication process, which provides a sharp corner angle without blockage, improving the capillary pump capacity of the corners, increasing the performance of the mini heat pipe.

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