Experimental Tests of Wire Mini Heat Pipe under Microgravity Conditions Aboard Suborbital Rockets

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Abstract

Mini heat pipes are devices usually considered for thermal management of electronics for many terrestrial applications, including computers, laptops, etc. In gravity environment, the return of the condensate from the condenser to the evaporator can happen without any kind of capillary structure, or assisted by a wick material, if the device works in the horizontal position. The mini heat pipe under study is made from the welding union of parallel cylindrical copper wires sandwiched between two thin copper plates. The sharp edges formed between the wires and the plates, where the working fluid flows from the condenser to the evaporator, provides the capillary pressure necessary to overcome all the pressure loss through the device length. The objectives of this experimental work were to determine the microgravity effect on the heat transfer of a wire mini heat pipe and to compare the device performance under micro and gravity conditions. Four wire mini heat pipes, charged with distilled water, acetone, methanol and ethanol, were evaluated during six minutes under microgravity conditions aboard a two stage suborbital rocket (VSB-30) launched at Alcantara Base - Brazil. This flight was supported by the Brazilian Space Agency (AEB) in partnership with German Aerospace Center (DRL). The results indicated a good agreement between gravity and microgravity data in the first seconds of the flight. After that, the temperature of the rocket increased affecting the thermal behavior of the mini heat pipes, spoiling the comparison with gravity results. Despite of this fact, small overall thermal resistances were calculated for all devices tested.

Key Words: Mini heat pipe, wire plate heat pipe, microgravity.

1. INTRODUCTION

In recent years, the need of electronic components miniaturization is mainly observed in the computer industry, especially for notebooks thermal management. Nowadays, these devices are used in many different applications, from home utilities to thermal control of electronic devices at the International Space Station. The concentration of heat produced in notebooks have increased quickly along with the development of the processor technology, making heat dissipation control one of the major problems to be solved.

The design of satellites thermal control systems requires an understanding of heat pipe operating characteristics under microgravity environment. These actions could not be properly observed on the Earth environment because gravity tends to act hard in several fluid mechanics phenomenon. Thus, the gravity force can mask some effects, so that when it is decreased or even removed, other forces can assume the control of the fluid mechanics.

According to previous work [1, 2], wire mini heat pipe has shown to be a promising technology for thermal control of electronic equipment. These devices were successfully tested in laboratory and under microgravity aboard the International Space Station (ISS) during Centenario Mission [3]. Due the ISS safe restrictions, only water was tested. If other fluids were used, three barriers would be required to involve the experiment, to guarantee no leak of fluid. Therefore, to continue the microgravity studies started at the ISS, other fluids where tested aboard suborbital rockets in a project financed by the Brazilian Space Agency.

In the present work, four wire mini heat pipes were designed and tested under microgravity conditions. Constructive aspects of this development are exposed as well as the experimental results obtained under microgravity conditions. The device was tested aboard an experimental platform launched in Cumã II Mission of the VSB-30 Rocket, from the Alcântara Rocket Launch Center in Brazil, in July 2007.

2. EXPERIMENTAL ANALYSIS

2-1 Wire mini heat pipes

Many different techniques can be employed in the manufacture of micro or mini heat pipes. One of them consists of brazing aluminum wires between plates, which can block partially the grooves formed between the wire and the plates. In this work, a more sophisticated welding procedure, the diffusion welding, was used in the fabrication of the heat pipes [3, 4, 5, 6]. This technique produces heat pipes that present better thermal performance.

The working fluid is pumped from condenser to the evaporator sections by means of the capillary effect provided by the edges formed between the wires and the flat copper plates. Some studies presented in the literature [2, 5, 7] demonstrate that one of the main challenges in the wire mini heat pipe development is the determination of the accurate volume of working fluid and of the wire diameter to be used. The determination of the space between wires is also challenging. The contact angle between the working fluid and the cooper plate is another parameter that can significantly affect the maximum heat transfer capacity of the device. To evaluate all these parameters and their effects in the thermal performance, an experimental facility was developed at the laboratory. All the mini heat pipes were tested and previous qualified in laboratory before being tested in microgravity in the flight model experiment.

2-2 Experimental facilities at laboratory

To reach the maximum heat transfer capacity, characterized by the mini heat pipe dry out, a cooling apparatus was constructed using PCV pipes, as shown in Figure 1. 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 then held constant throughout the test.

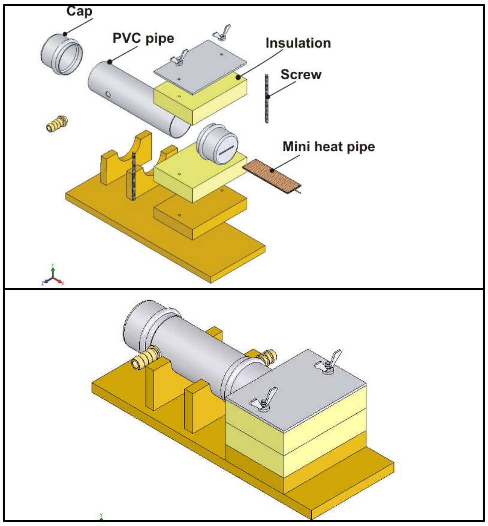

Figure 1: Experimental facility sketch.

A small hole was made in one of the end caps to introduce the condenser section of the mini heat pipe. A silicone sealant adhesive is dump into the empty space between the mini heat pipe surfaces and the cap wall, 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.

As usual, the mini heat pipe presents three different regions: evaporator, adiabatic section and condenser. Heat is added to the evaporator by means of a skin heater attached over a length of 20 mm of the heat pipe. The adiabatic section, of 50 mm of length, is thermally insulated from the environment. Heat is removed from the condenser by a cooling bath, installed over a length of 30 mm. To ensure good contact, thermal grease was introduced between the heater and the evaporator. Figure 2 shows the thermocouple positions for the laboratory tests. Six type T thermocouples (Omega® - TT-T-040) were inserted along the mini heat pipe to monitor the temperature distribution. The thermocouple temperature measurement uncertainty is ± 1ºC

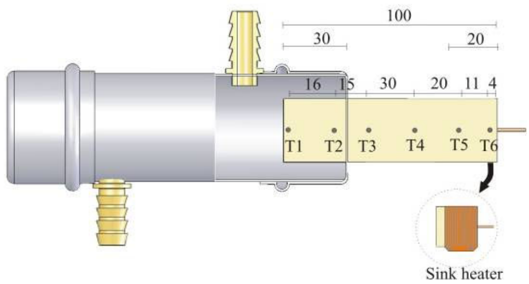

Figure 2: Thermocouples positions.

2-3 Microgravity experiment set-up

Due to the limited space inside the rocket platform, the experimental facilities dimensions were restricted. The experiment was compose by three models identified as PEM-08 A, B and C as described in Table 1.

Table 1: Equipment description.

Name	Description	Dimensions LxWxH (mm)	Mass (kg)
PEM-08A	Ethanol Acetone	174x74x136	2,203
PEM-08B	Water Methanol	200x80x200	3,611
PEM-08C	Acquisition	190x120x200	3,850
		TOTAL	9,664

Both PEM-08 A and B have the same design characteristics and the only differences are the overall dimensions. Figure 3 shows both modules.

Figure 3: PEM-08A and PEM-08B modules.

In these modules, an aluminum support is built to fasten the entire device in the rocket platform. Two insulation plates (polyurethane foam) are used to sandwich the mini heat pipe. This entire assembly is fixed on an aluminum block. Just a small part of the device (condenser) is attached to this heat sink. The aluminum block absorbs the generated heat, warming up in transient conditions, considering that the test time is very short. Fans cannot be used in the platform due to the vibrations during the launching, so that devices with mechanical movements are not suitable.

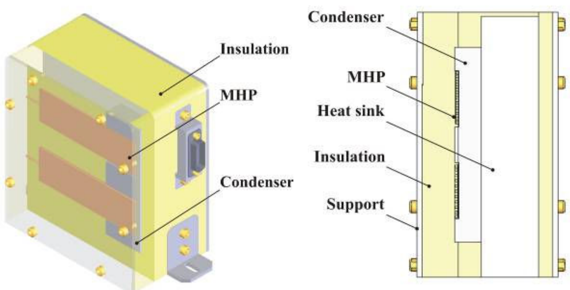

Figure 4: PEM-08A and PEM-08B modules.

Three thermistors of 30 kΩ were placed in each mini heat pipe to measure the temperature distribution and other two were inserted in the opposite side of the aluminum block, to monitor the block temperature profile, as can be seen in Figure 5. The thermistor temperature measurement uncertainty is ± 2ºC.

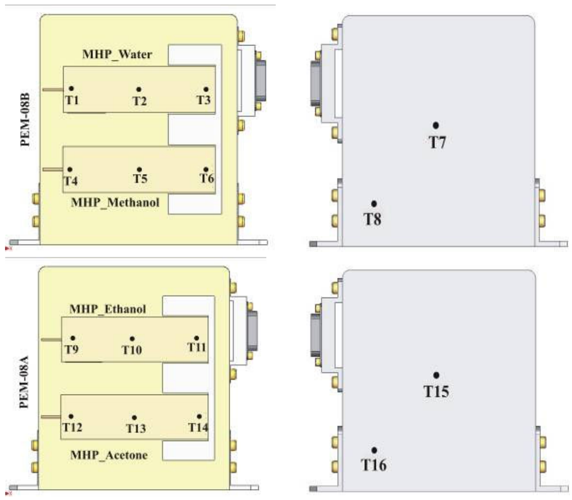

Figure 5: Thermocouples position.

A data acquisition system was designed especially to monitor the set-up temperatures during the flight, under microgravity conditions. An aluminum box with 190x120x200 mm was used to accommodate the data acquisition system (see Figure 6), which is composed of the following equipments: PC/104 board, data acquisition board, DC/DC converter, power control board, batteries and memory card.

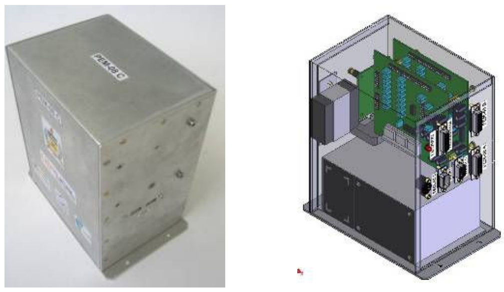

Figure 6: Data acquisition module.

The PC/104 is basically a computer (equivalent to Pentium III, 400MHz). A MSDOS operational system is used to manage the files of the memory card, which is the same as used in digital cameras. The control, read and acquisition programs were developed in C++ language. The software controls great part of the experiment operation. All the data is saved in the memory card and also it is transmitted by telemetry. A lead acid battery of 18V and 4.5Ah is used to provide electricity to the data acquisition system as well as the mini heat pipe skin heaters.

Table 2: Mini heat pipe characteristics

Mini heat pipe	Volume (ml)	Power (W)
Acetone	0.400	5.13
Ethanol	0.400	4.03
Water	0.500	16.82
Methanol	0.300	5.97

Due to the short period of microgravity condition (of approximately 5 minutes), to the battery dimensions and to the power restrictions, only one power step is supplied for each mini heat pipe, by means of electrical heaters. Table 2 describes the power applied to each mini heat pipe.

To control the experiment, a box control is used, as can be observed in Figure 7. With this control, the experiment can be activated, and the lift off and microgravity signs provided, the telemetry data converted and visualized directly in a laptop, and, finally, the battery recharged.

Figure 7: Control box.

2-4 Suborbital rocket

The devices were tested aboard an experimental platform of the VSB-30 Rocket (see Figure 8), from the Alcântara Rocket Launch Center in Brazil, in July 2007. Around five minutes of microgravity testing time was supplied by the platform. This microgravity project is a partnership program with Brazilian Space Agency (AEB) and Dutch Launch Rockets (DLR). VSB-30 is the designation of a Brazilian sounding rocket, developed by Technology Aerospace Center (CTA). The VSB-30 rocket can carry a payload of 407 kg to an altitude of 260 km. It has a liftoff thrust of 102 MN and a total mass of 2,657 kg. The rocket has a diameter of 0.58 m and a length of 12.80 m.

Figure 8: VSB30 rocket and payload.

A special cooling apparatus was placed in an external part of the rocket platform to control the room temperature until the lift off, as shown in Figure 9.

Figure 9: External cooling system.

2-5 Microgravity tests procedure

The experiment was connected to a control box as can be seen in Figure 10. This equipment was placed in the Block House and it was directly connected to the rocket umbilical.

The experiment was started by the control box from the Block House. As soon as it was started, the mini heat pipe temperatures data were sent by RS 485 protocol to a laptop. At the same time, the experiment lift-off and microgravity signs waiting model were activated. Once the rocket was launched and the lift-off sign was turned on, the data acquisition system started to salve data into the flash memory and send it by telemetry.

The power supply for the mini heat pipes took place when the microgravity sign were activated.

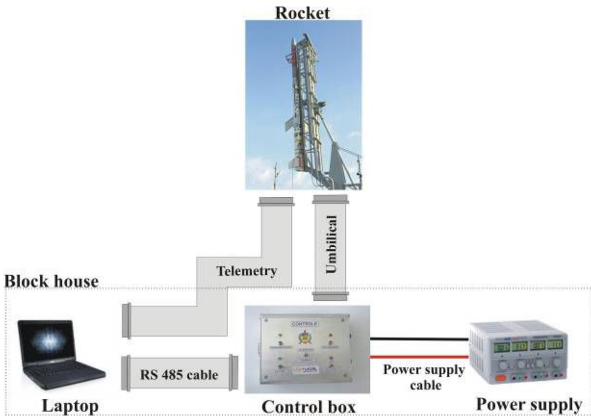

Figure 10: Rocket interface sketch.

3. EXPERIMENTAL RESULTS

3-1 Laboratory results

During the laboratory experimental tests, the heat was added by a DC power supply by means of skin heaters. The power was kept constant until the mini heat pipe reached the steady state conditions. After this condition, the power was increase up to the next power step. The experimental results for the temperature as a function of axial position for mini heat pipes charged with distilled water, acetone and methanol, obtained with the use of cooling water, can be observed in Figure 11, 12 and 13. The temperature of the end of the evaporator (TC-6, Fig.2) and the temperature of the adiabatic section (TC-4) increased proportionally with the power input. Also, it can be seen that the adiabatic section temperature (TC-4) quickly approaches the evaporator temperature (TC-6). At the condenser section, the temperature also increased but in a different (lower) rate. As soon as this temperature starts to increase sharply the liquid starts to evaporate before the end of the pipe. This situation is characterized as the dry out condition, i.e., the point of the maximum transport capacity, for each operating temperature.

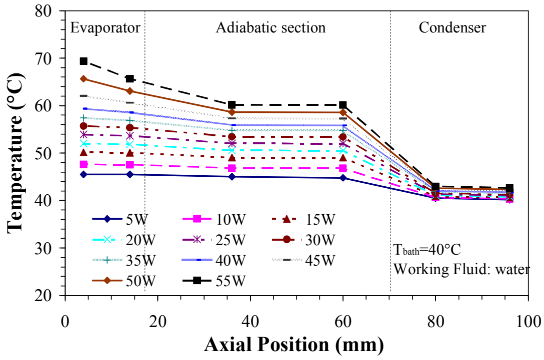

Figure 11: Temperature distribution for mini heat pipe charged with water.

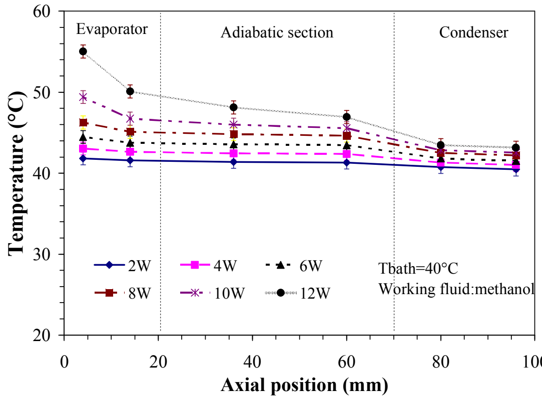

Figure 12: Temperature distribution for mini heat pipe charged with methanol.

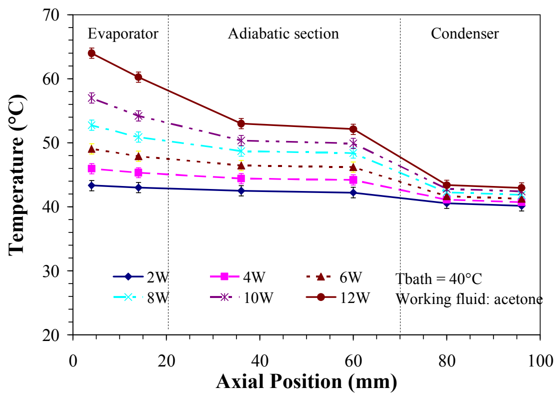

Figure 13: Temperature distribution for mini heat pipe charged with acetone.

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 14, 15 and 16 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, 30°C and 40°C.

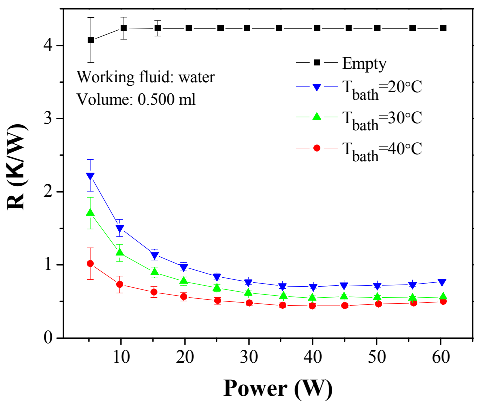

Figure 14: Overall resistance for mini heat pipe charged with water.

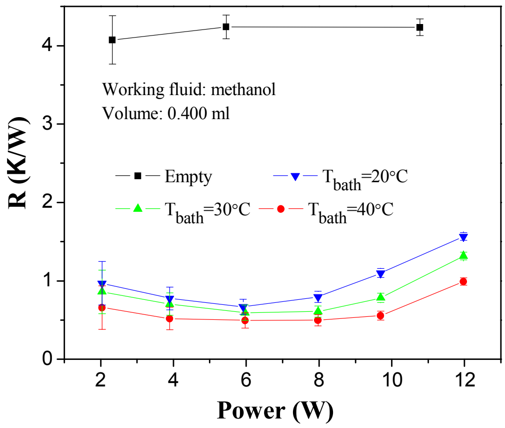

Figure 15: Overall resistance for mini heat pipe charged with methanol.

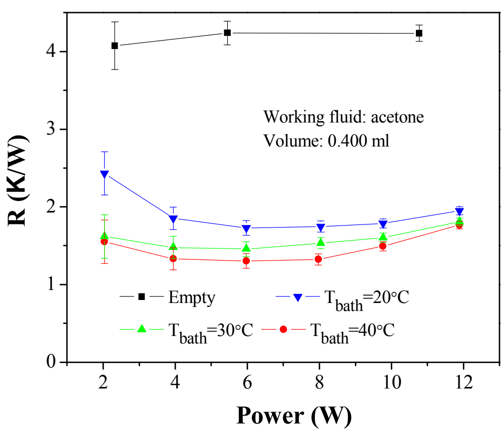

Figure 16: Overall resistance for mini heat pipe charged with acetone.

This figure also shows that, for the case of the cooling water bath at 40°C, the overall resistance showed to be 9 times that without working fluid at the point where dry out occurred (45W). For acetone and methanol these values were 3 and 8.5 times respectively.

3-2 Microgravity results

Figures 17, 18, 19 and 20 present the gravity results using the aluminum block as heat sink, obtained in gravity but inside the rocket platform some days before the flight. The devices did not reach the steady state conditions due to the small capacity of the aluminum heat sink. Even though, the performance of the mini heat pipes were almost the same when their results were compared with the laboratory results, using the cooling bath apparatus.

All the pre-launching activating procedures of the experiment were successfully accomplished. Both signs: lift-off and microgravity were received and executed by the experiment control system. The platform cooling system holds the experiment temperature constant before the launching. According the experiment temperature sensors, the block temperature was at 28°C before launching.
Some problems happened during the flight, affecting the data collection and, therefore, the results analysis. First, the telemetry sign failed during short periods and some data were lost. Other import fact was that the temperature inside the rocket platform increased considerably impeding, in this way, that the mini heat pipe reached the steady state condition or, at least, described similar behavior that was observed under gravity conditions. The data were saved in flash memory, but, unfortunately, the payload was not found.

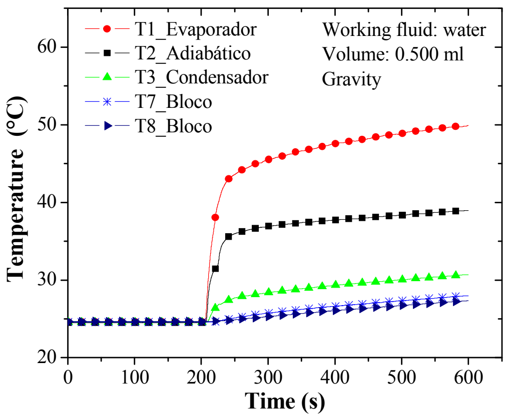

Figure 17: Gravity temperature profile of the mini heat pipe charged with water.

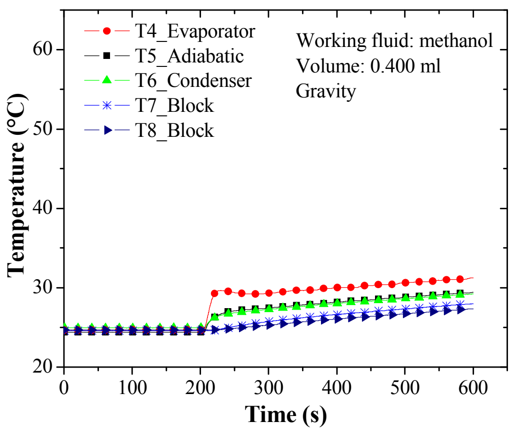

Figure 18: Gravity temperature profile of the mini heat pipe charged with methanol.

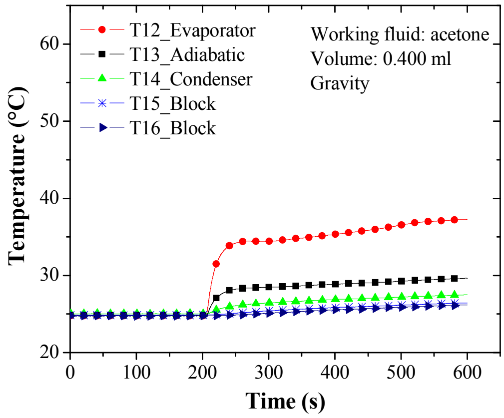

Figure 19: Gravity temperature profile of the mini heat pipe charged with acetone.

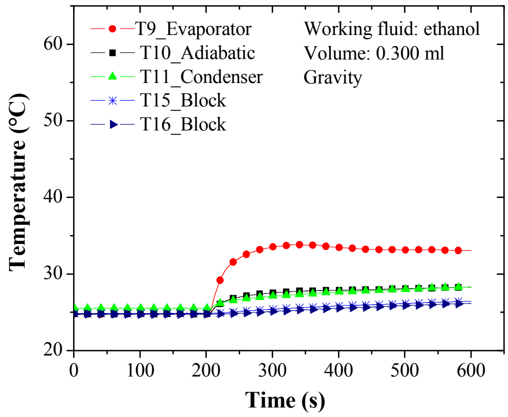

Figure 20: Gravity temperature profile of the mini heat pipe charged with ethanol.

The microgravity results are presented in Figures 21, 22, 23 and 24. As it can be observed, the results indicated a reasonable agreement in the first seconds of the flight, mainly for water, after that, the temperature of the rocket started to increase and the comparison with the gravity results were spoiled. The aluminum heat sink temperature influences very much the heat transfer in the condenser section and, consequently, the mini heat pipe temperature level.

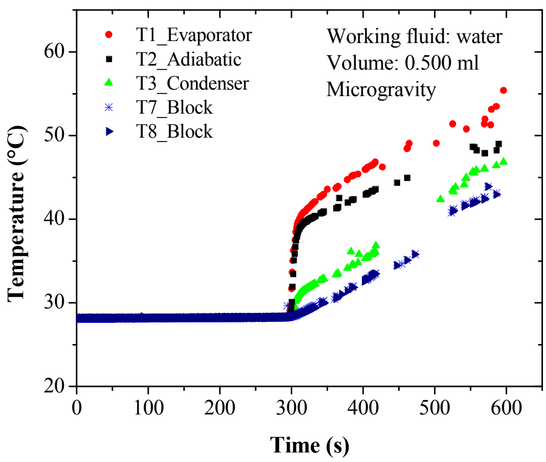

Figure 21: Microgravity temperature profile of the mini heat pipe charged with water.

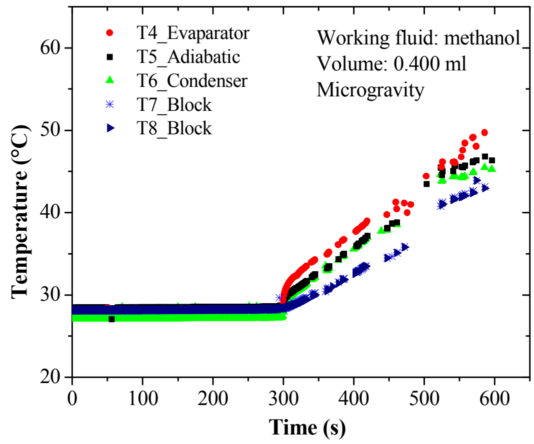

Figure 22: Microgravity temperature profile of the mini heat pipe charged with methanol.

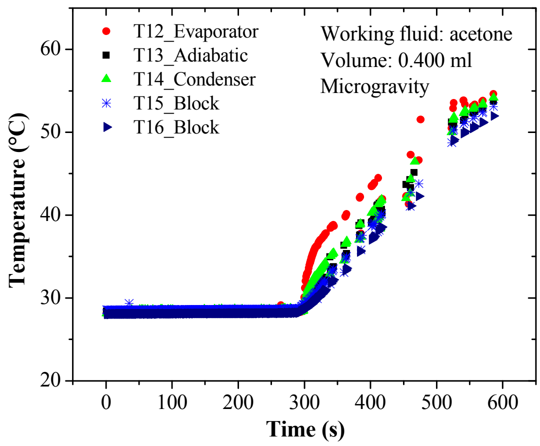

Figure 23: Microgravity temperature profile of the mini heat pipe charged with acetone.

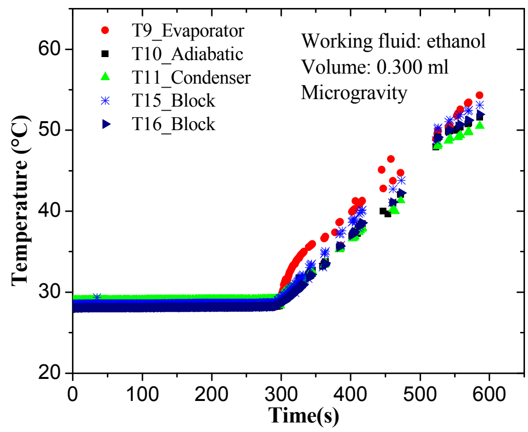

Figure 24: Microgravity temperature profile of the mini heat pipe charged with ethanol.

In the mini heat charged with methanol, acetone and ethanol the temperature profiles – evaporator, adiabatic and condenser section are almost the same as consequence of the high condenser temperature. For the mini heat pipe charged with water, the section temperature profiles are more spaced, because the thermodynamics properties of the water in spite of the block temperature increasing.

4. CONCLUSIONS

The heat transfer performance of the mini heat pipe charged with water, methanol, acetone and ethanol has been investigated experimentally under gravity and microgravity conditions. The data showed the efficiency of the device, mainly due to the small thermal resistances obtained at laboratory.

Although the microgravity results were not so satisfactory, important information about the device temperature profile inside the rocket platform could be obtained. Based on the partial failures of this microgravity experiment, new procedures will be adopted to correct them in the next flight experiments.

The temperature profiles of the microgravity and gravity tests with the same heat pipes are quite different, mainly due to the increasing of the platform temperature during the flight. Despite of this, small thermal resistances were obtained for each wire mini heat pipe tested, showing their efficiency as electronics thermal control devices for gravity and microgravity applications.

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