# EVALUATING THE BEHAVIOR OF CAPILLARY EVAPORATORS DURING LOOP HEAT PIPES OPERATION

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***Abstract.*** *Loop heat pipes (LHPs) are versatile heat transfer devices, which have recently gained increasing acceptance for spacecraft thermal control, presenting reliable operation and require no moving parts. In space applications, LHPs are mainly developed as thermal control devices for electronics, batteries, structures and sensors and present reliable operation in the severe space conditions. For the present study, two LHPs were designed and built to promote the thermal management on power cycles of up to 80 W, where each LHP presents different configuration of their capillary evaporator, as one presents the primary wick structure with axial grooves while the other present circumferential grooves, machined on outer diameter. Laboratory life tests have shown reliable operation during the power cycles where the heat source temperatures were properly controlled and the potential in using acetone as an alternative working fluid in LHPs have been demonstrated. Better thermal performances were achieved when using the LHP that present the capillary evaporator with circumferential grooves as lower heat sources temperatures were observed. The comparisons between the two LHPs are important to evaluate the influence the configuration geometry in the evaporator design and its influence on the LHP overall performance.*

***Keywords***: *loop heat pipe, thermal control, capillary evaporator, and grooves geometry*

## 1. INTRODUCTION

Loop Heat Pipes (LHPs) have been investigated during the last decade for space applications for the thermal control of satellites spacecrafts, electronics and components. It is considered a reliable passive thermal control device as it can dissipate large amounts of heat while keeping a control of the heat source temperature. Several applications of LHPs have showed reliable operation (Ku, 1999; Ku and Birur 2001; Dutra and Riehl, 2003; Maydanik, 2005). The components of LHP are a capillary evaporator, condenser (or two-phase reservoir), liquid and vapor lines and compensation chamber. It operates by means of capillary forces generated in an evaporator, which is responsible by evaporation and generating the capillary forces that will drive the working fluid, and then the vapor flows in the vapor line towards the condenser, where it is condensed and flows back to the evaporator by the liquid line. The compensation chamber is responsible for establishing the loop's operation pressure and temperature. Depending on the power applied to the capillary evaporator, the working fluid flow rate may increase or decrease, which will determine the amount of working fluid that must be supplied or removed by the compensation chamber. A special issue regarding the operation of LHPs is always related to the working fluid used, especially when ammonia is used in several applications. It is always desired to find new potential working fluids that represent less hazard and lower costs for purification and charging. The search to substitute the so used ammonia is related to reduce the hazard during the working fluid manipulation, as well as a reliable thermal management for low power LHPs (Riehl, 2004; Riehl and Dutra, 2005). The selection of acetone also relies on its low freezing temperature (-93.15 °C), which is below the –78 °C for ammonia (Faghri, 1995) and indication that it is compatible with stainless steel (Peterson, 1994). Such a construction gives the LHP many advantages, including self-start without pre-conditioning, and robust operation. Diverse other works have been made for Ku et al. (2002) focusing at to improve the project, operation and application of LHP.

Focusing the development of this technology is designed to perform the thermal management of up to 80 W on power cycles using acetone as the working fluid. This paper presents the results of the investigation of two LHPs, which were designed, built and tested using acetone as the working fluid, where each LHP presents different configuration of their capillary evaporator. The capillary evaporators basically differ from each other on the geometry of the grooves on the primary wick structure as one present axial grooves while the other present circumferential, machined on the primary wick outer diameter. The comparisons between the two LHPs are important to evaluate the influence the configuration geometry in the evaporator design and its influence on the LHP overall performance, in order to required information to refine the project and qualify them for future applications.

## 2. LOOP HEAT PIPES DESIGN AND DEVELOPMENT

The LHP development program presented in this paper is part of a chronogram focused on qualifying this device for future applications. This program is related to extensive life tests in laboratory conditions to evaluate the lifetime of LHPs, materials interaction, wick structure design and production and fabrication processes. So far, the current technology development has resulted in several LHPs built and under constant operation for different purposes, where the important consideration should be given for the certification of this device to operate in space conditions for up to 5 years without any maintenance requirement.

For purpose of this research, two LHPs were built and tested in laboratory conditions at horizontal orientation. Tests using acetone as working fluid are necessary to better relate to the use of this fluid, specially related to the non-condensable gases (NCGs) influence. In each LHP, the liquid inventory of 25 grams was used, with 50% of the compensation chamber filled with liquid in the cold mode. Following the project requirements, the entire experimental setup was built in 316L ASTM stainless steel tubing and aluminum (alloy 6061) on the capillary evaporators saddles (70 x 45 mm) and condensation plates (300mm x 300mm x 4mm thick) with the geometric characteristics described in Table 1. The devices, treated as Thermal Control Devices (TCD), were named as TCD- LHP2 and TCD- LHP3.

Table 1. Geometric characteristics of both LHPs

| **Capillary Evaporator** | | **Liquid of Line** | |
|---|---|---|---|
| Total Length (mm) | 100 | Diameter ID (mm) | 2.85 |
| Active Length (mm) | 67 | Length (mm) | 8.50 |
| Diameter OD/ID (mm) | 19.0/16.5 | Material | Stainless steel grade 316L(ASTM) |
| Material | Stainless steel grade 316L(ASTM) | | |
| **UHMW Polyethylene Wick** | | **Condenser** | |
| Pore Radius (μm) | 6 | Diameter ID (mm) | 2.85 |
| Permeability ($m^2$) | $10^{-13}$ | Length (mm) | 1000 |
| Porosity (%) | 50 | Material | Stainless steel grade 316L(ASTM) |
| Number of Axial Grooves | 14 (TCD- LHP2) | | |
| Number of Circumferential Grooves | 23+1 Axial (TCD-LHP3) | | |
| **Compensation Chamber** | | **Vapor of Line** | |
| Volume ($cm^3$) | 20 | Diameter ID (mm) | 2.85 |
| Diameter OD/ID(mm) | 19.0/17.0 | Length (mm) | 5.50 |
| Length (mm) | 95 | Material | Stainless steel grade 316L(ASTM) |
| Material | Stainless steel grade 316L(ASTM) | | |

Twenty type-T thermocouples (deviation of ± 0.3 °C at 100 °C) were installed throughout the loop as is presented by Fig.1a. Special techniques for machining the porous wick have been developed to be able to produce the grooves (Fig. 1b), while keeping the proper porosity. Arteries can be obtained by special folding techniques of the secondary structure made of stainless steel screen mesh #200 (Fig. 1c). A data acquisition system was responsible for reading and recording the temperatures, which was used to monitor the loop's behavior during the tests. The condensation plate was the cover plate of a heat exchanger with embedded channels, circulating a mixture of 50% water and 50% ethylene glycol at a rate of 9 L/min. The condensation temperatures used to test both LHPs varied from –20 °C to + 5 °C for all tests, which were intended to verify the LHPs behavior in different condenser operation as found in many satellites applications. In order to improve the capillary evaporator thermal behavior, its housing was also machined with micro threads on its inner diameter.

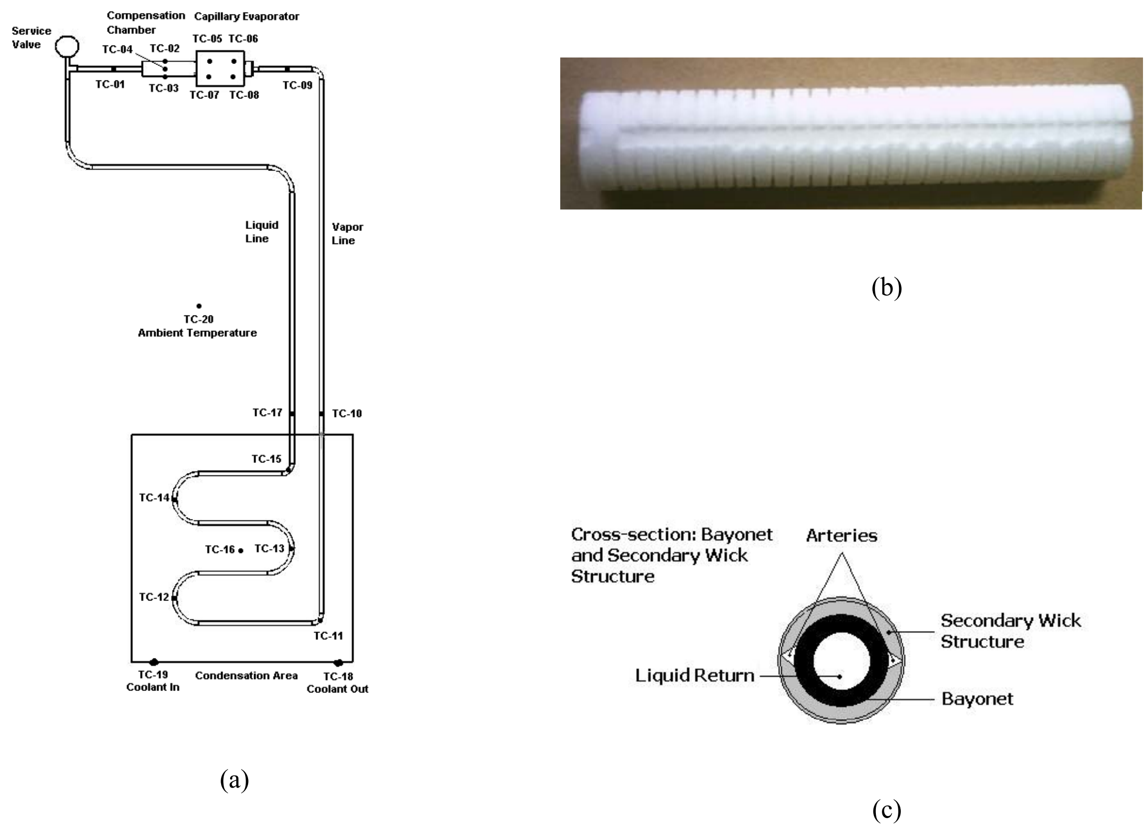



Figure 1. Loop heat pipe setup: (a) instruments locations; (b) circumferential grooves on primary wick; (c) arteries on secondary wick.

Heat was applied to the capillary evaporator through an aluminum saddle where a kapton skin heater was attached (15mm x 25 mm, 14.5 Ohms). The configuration for the LHP design presented above was established to perform the thermal control of up to 100 W, even though this specific application would carry up to 80 W. The connections of the LHP capillary evaporator and compensation chamber were welded, as the rest of the loop, using an orbital automatic system in order to be in agreement with the requirements for space qualification procedures. Figure 2a presents the set capillary evaporator/compensation chamber assembly, Fig 2b presents the cross section for the primary wick structure with axial and Fig. 2c with circumferential grooves.

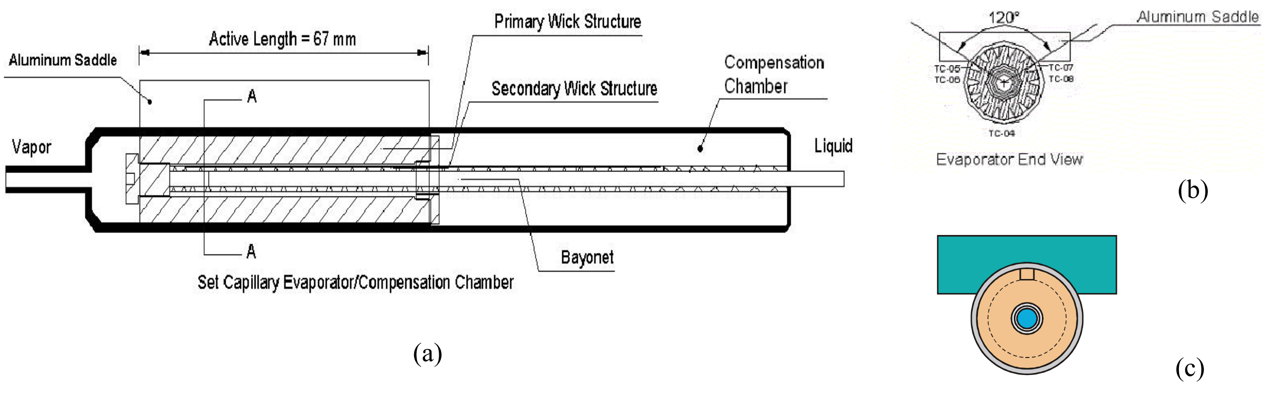



Figure 2. (a) set capillary evaporator/compensation chamber; (b) cross section with axial grooves; (c) cross-section with circumferential grooves.

All tests were performed without pre-conditioning procedures prior the startups and without temperature control of the compensation chamber. The LHPs were tested with a room temperature controlled between 18 and 20 °C, on power cycle test profiles as presented by Table 2. Each profile test sequence was tested with each LHP at a time and after finishing the tests, the other LHP was then tested. Tests have been carried out to check the LHPs performance along time, in order to certify them as thermal control devices for space applications for regular satellites (low orbit) as well as geo-stationeries (high orbit), with attention to the possible effect of NCG influence on their operation along time.

Table 2. Power cycles applied to test the LHPs.

| Profile | Power Cycles (W) | Startup Power (W) |
|---|---|---|
| 1 | 20-2-30-2-40-60 | 20 |
| 2 | 40-10-60-5-20-80 | 40 |
| 3 | 2-5-1-2-1-5 | 2 |
| 4 | 60-5-80-2-40-10 | 60 |

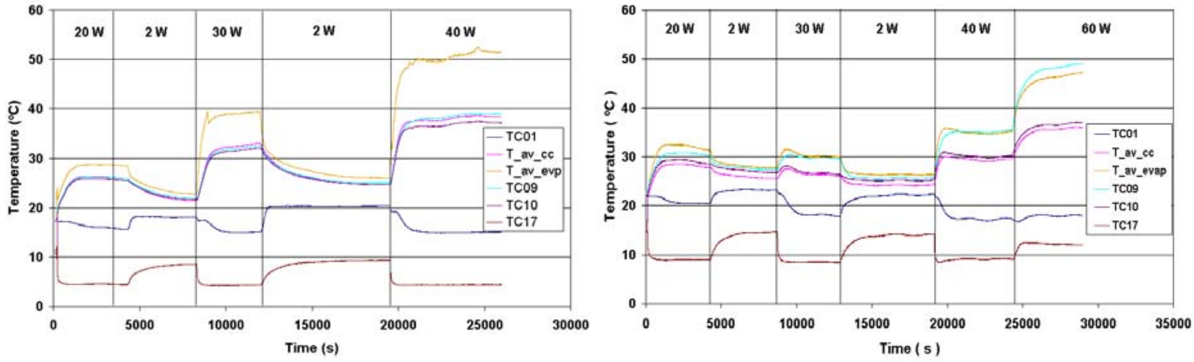
This way, each LHP could operate individually which was important for the proper data analysis. For the startup tests, the objective was to investigate the LHP capability on initiating its operation, where the required superheating and time to start and reach the steady state regime was analyzed. It was also intended to investigate how the LHP operation conditions would interact in order to reach the operation temperature for a given heat load and condensation temperature. The power cycle tests were selected according to potential LHPs operation modes. In this test sequence, an important attention is given to profile 3 were reduced heat loads are applied to the capillary evaporator of each LHP in order to evaluate their capability in promoting the heat transport in the sleeping mode. This entire test sequence, performed with both LHPs, it is important to analyze the devices operation along the life tests, promote potential design improvements and better evaluate the use of the working fluid. During their operation, the thermal performance was also investigated specially when two different evaporator designs have been used.

## 3. RESULTS AND DISCUSSIONS

Experimental tests were carried out without temperature control of the compensation chamber and pre-conditioning procedures (common in capillary pumped loops-CPLs) for both startups and load profile tests. The startup tests for the designed LHP presented to be very reliable and some interesting characteristics were observed at all values of the heat applied to the evaporator. The objective on such tests was to verify the LHP capability on initiating its operation without the need of pre-conditioning procedures frequently used in CPL systems.

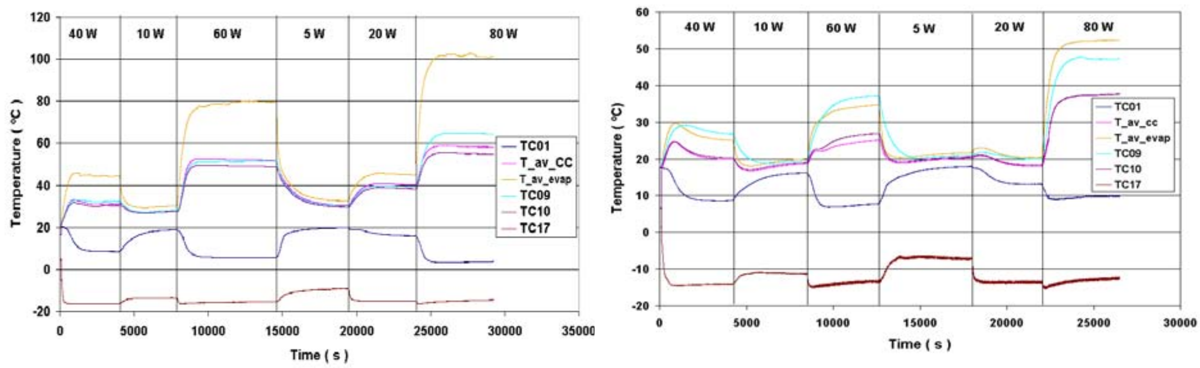
Tests with TCD-LHP2 showed the reliable thermal management capability but the evaporator and operation temperatures were higher then those verified with TCD-LHP3 (Fig. 3). This increase on the evaporator temperature is directly related to the increase of the compensation chamber temperature, which is due to increase of the heat leak (heat transfer from the evaporator to the compensation chamber). Basically, due to the specific TCD-LHP2 design, higher heat leaks are found during this device operation contributing to increase the heat source temperature. In the case of the TCD-LHP3, the geometric characteristics of the primary wick and the more efficient fluid exchange with the compensation chamber given by the secondary wick arteries, resulted in lower heat leaks, directly contributing to reduce the heat source temperatures. With lower heat source temperature, the TCD-LHP3 could operate with more reliability as it could reach higher heat loads than it was designed for (Riehl and Santos, 2006). Even though higher temperatures are verified for all heat loads applied to the evaporator, the TCD-LHP2 always presented reliable operation and no indication of temperature overshoot as showed by Figs 3 e 4. However, better thermal performance related to the maximum heat source temperatures could be obtained by the TCD-LHP3, mainly due to the improved designed of its set capillary evaporator/compensation chamber.

At low power levels, the TCD-LHP2 presented continuous operation and constant heat transport when the LHP had to operate in sleeping mode (profile 3) as showed by Figs 5 and 6. Few oscillations were observed, which are mainly due to the reduced flow rates especially at 1 W. This special operation mode is important to be evaluated as the LHP might not be under full operation at all times and in order to potentially reduce the risks of system failure, specially during the startup, it is kept under operation at a very reduced heat load.



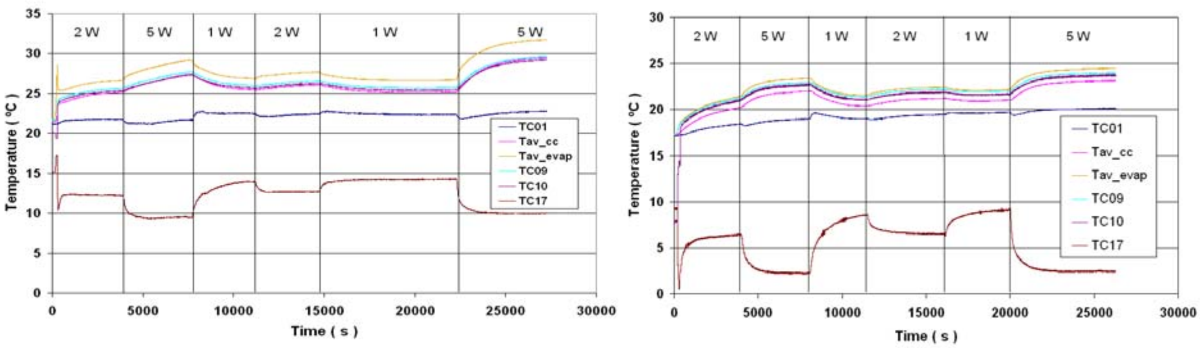

(a) (b)

Figure 3. Comparison Test: Profile 1 - sink at 5°C: (a) TCD-LHP2 and (b) TCD-LH




(a) (b)

Figure 4. Comparison Test: Profile 2 - sink at – 20°C: (a) TCD-LHP2 and (b) TCD-LHP3

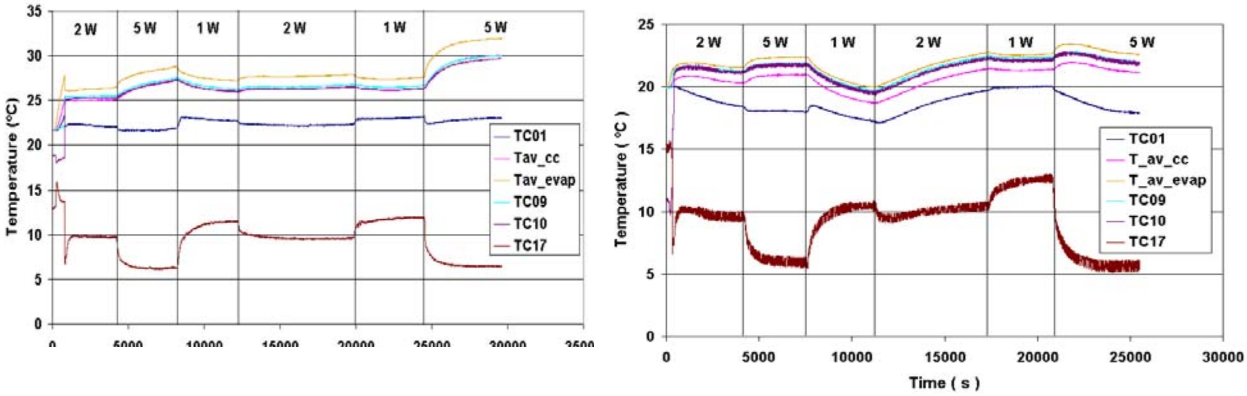



(a) (b)

Figure 5. Sleeping mode operation –Profile 3 - sink at 5°C: (a) TCD-LHP2 and (b) TCD-LHP3

With the design improvement obtained used the TCD-LHP3 conception, it has been possible to perform all the tests required for certifying the LHP while observing reduced heat source temperatures. This is a direct result of the increase on the contact area between the evaporator inner surface and the wick structure, which resulted in an increase of 20% on the contact area while keeping the same active length. This modification on the project of the capillary evaporator resulted in a remarkable operation that could observe through the experimental results.

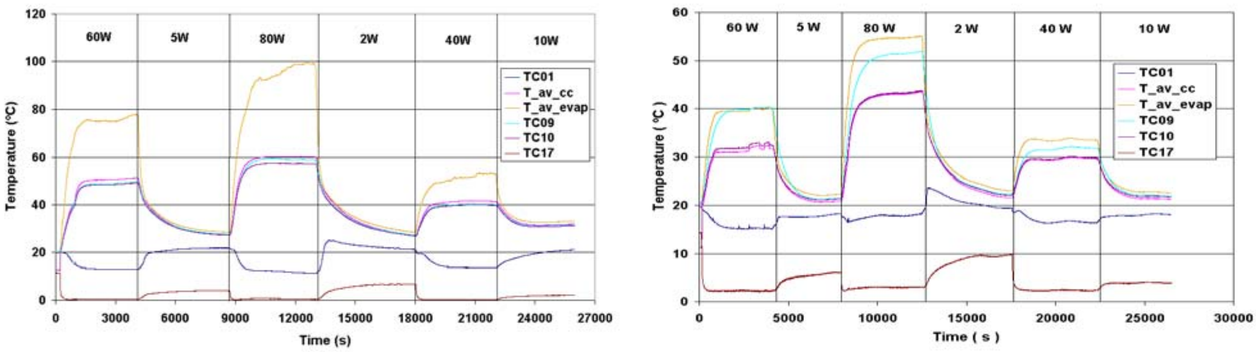
The TCD-LHP3 also showed reliable operation at both low and high heat loads, especially when its operation at the sleeping mode is evaluated. Continuous heat transport was observed when the TCD-LHP3 was operating at profile 3 for both temperatures of the sink, as presented by Fig. 6. It is possible to verify that the project presented to be robust and efficient when operating in low heat loads.




(a) (b)

Figure 6. Sleeping mode operation – Profile 3- sink at 0°C: (a) TCD-LHP2 and (b) TCD-LHP3

During the tests, a substantial reduction of the temperature of the evaporator during high heat loads could be observed when compared with the results verified with the TCD-LHP2. The TCD-LHP3 passed for all the tests of the program with acceptable results, without presenting any indication of influence of the NGCs during its operation. Figure 7 it presents the behavior of the temperature of the evaporator (heat source) in regard to the heat load. It can be verified that the temperatures present high values while testing the TCD-LHP2 and substantial decrease on the evaporator temperature while testing the TCD-LHP3. This represents a gain in the capability to control the temperature carried out by the TCD-LHP3.




(a) (b)

Figure 7. Comparison Test: Profile 4 - sink at 0°C: (a) TCD-LHP2 and (b) TCD-LHP3

When evaluating the behavior of the temperature of the evaporator (heat source) in regard to the managed heat loads, it can be observed that the temperatures of the evaporator are as higher as 50% with the TCD-LHP2 when compared to the same operation conditions with the TCD-LHP3. This is an important comparison specially when considering that the sets capillary evaporator/compensation chamber in these devices present the same configurations, only differing in primary wick design and the grooves on the secondary wick. This proves that the circumferential grooves promote a substantial reduction in the temperature of the evaporator, being an important factor to the overall operation of the LHP. Lower temperatures of operation at the same heat loads could be reached, resulting in the TCD-LHP3 operation below the limit established for the project.

The tests in the laboratory have shown reliability during the operation for all heat loads where the heat source temperatures had been efficiently controlled and the potentiality in the use of acetone as a working fluid. It becomes important to mention that this specific working fluid has passed by all the required tests to be used in future space applications as a substitute for the ammonia.

## 4. CONCLUSION

This paper presented the experimental results of an investigation with two loop heat pipes, designed to accomplish several project requirements towards its use in space missions as a passive thermal control device. Both LHPs presented reliable operation during all tests, with acceptable temperature control of the heat source for the highest heat load of 80 W as required by the project. The better thermal performances were achieved using the TCD-LHP3, which present the capillary evaporator with circumferential grooves as lower heat sources temperatures were observed. The comparisons between the two LHPs are important to evaluate the influence the configuration geometry in the evaporator design and its influence on the LHP overall performance. The investigation presented in this paper has shown the great potential in using alternative working fluids such as acetone for a certain operation temperature, as well as the configurations of the porous structure with reliable results.

## 5. ACKNOWLEDGMENTS

This work has been supported by Fundação de Amparo a Pesquisa no Estado de São Paulo (FAPESP/Brazil), grants 03/08365-6, 03/11477-0 and 04/15578-9.

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