NOVEL LOOP HEAT PIPES DEVELOPMENT FOR GROUND AND SPACE APPLICATIONS

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Abstract. *Current efforts have focused the development of loop heat pipes (LHPs) for space applications with possibility of using them in several ground applications, such as water heating systems, etc. However, some issues related to the use of LHPs rely on their design and development depending on the required use. Thus, a novel LHP technology has been developed for future space applications and new configurations have been designed and tested focusing on ground applications as well. This paper presents the results of what has been developed regarding the novel LHP technology, which includes devices for electronics cooling operating in its classical design (one evaporator and one condenser), reversible and ramified (multiple evaporators and condensers) LHPs. The experimental results obtained have shown the great potential in using LHPs as passive thermal control devices as they present reliable operation and continuous heat transport from the heat source to the sink using an alternative working fluid. Continuous tests have shown that the novel LHPs can control the heat source temperature within the required limits without failure of the systems tested. The proper development of this technology can be used for space applications (satellites), avionics thermal control, turbines and wings anti-icing systems, water heating systems, etc.*

Keywords*: loop heat pipe, thermal control, capillary evaporator, two-phase flow*

1. Introduction

Loop heat pipes (LHPs) are devices that operate passively by means of capillary forces generated in a porous structure, which are able to transport heat from a source to a sink over long distances without moving parts or power consumption. The capillary forces are generated using a porous structure and a volatile working fluid that is in its pure state in the loop. LHPs usually present in their classical configuration the following parts: a capillary evaporator with an integral compensation chamber (or reservoir), liquid and vapor transport lines and a condenser. The capillary evaporator is in thermal contact to the heat source which dissipates heat (for example, electronics chips). Heat is transferred by conduction through the evaporator case and evaporates the working fluid that is in the porous wick. As vapor is generated and LHPs are characterized as thermal diodes, vapor flows towards the condenser where the working fluid is condensed back to the liquid phase and returns to the capillary evaporator to complete the cycle. The compensation chamber establishes the correct fluid volume in the loop depending on the power applied to the capillary evaporator and self regulates the operation temperature. LHPs are able to promote the thermal control with high accuracy ranging from cryogenics temperatures to liquid metal applications (i.e. nuclear reactors). Ku (1999) presents the operation characteristics of LHPs and issues that must be considered during their design and tests.

During the last decade, LHPs have been extensively investigated in order to be applied as passive thermal control devices in spacecrafts and satellites (Swanson and Birur, 2002; Birur et al, 2002; Goncharov e Kolesnikov, 2002). Such an effort to design and qualify LHPs for space applications rely on the fact that so far, passive thermal control devices such as capillary pumped loops (CPLs) and LHPs still require extensive development to achieve reliability during their operation in space conditions. The choice in concentrating efforts to develop reliable LHPs instead of CPLs rely on the better operation performance verified by LHPs and their total passive operation when compared to CPLs that require active temperature control of their reservoirs.

Several applications for LHPs are possible not only for space but also for ground use. In space applications, LHPs are mainly developed as thermal control devices of electronics, batteries, structures and sensors and an extensive program for qualifying these devices for flight is highly required. Such a qualification procedure involves launching forces simulation of up to 12-g, thermal cycling and proper thermal management during the device's designed life. For ground applications, LHPs can be applied in several areas such as: refrigeration and air conditioning systems, avionics thermal control, anti-icing systems of aircraft turbines and wings, computer cooling, water heating systems, etc (Delil et al, 2003). However, each application must have its own LHP development according to its requirements for proper operation. An important parameter that must be carefully considered is the presence of people where a LHP must operate as usually has ammonia as the working fluid. In this case, an alternative working fluid must be applied but before this can be done, extensive tests must be performed to proper consider a given substance as a potential working fluid. This is necessary because few working fluids have been applied to LHPs so far (like ammonia and propylene) thus informations regarding long term operation of these devices are rare. Also, when using LHPs as passive thermal control devices, several considerations regarding their long term operation and reliability must be evaluated as their failure could cause serious damage to the components. Such considerations are related to materials used, potential chemical incompatibility between all parts, range of heat loads applied to the capillary evaporator, etc.

Focusing on the broad application for LHPs, this paper presents an investigation related to a novel development of these devices that can find many applications. Devices that have been developed for space applications are presented, showing the results of performance life tests in laboratory conditions towards their flight qualification as well as other options of LHPs for both space and ground applications.

2. Loop Heat Pipe Development Program

The LHP technology that has been under development in this institute is part of a long term project to qualify this device for future space applications such as the thermal control of electronic and structures in satellites. The entire program is based on the development of the design, manufacturing, construction, tests and qualification procedures for this purpose with a strong intention to apply this technology in commercial type equipments.

As part of the program, alternative working fluids have been considered and used in order to substitute the so-used anhydrous ammonia. This is an important contribution to the development of this field as ammonia represents high risks during manipulation and hazard to people. This is one of the reasons why systems that use ammonia cannot be placed in the International Space Station (ISS) where people are present. On the same way, using high purity ammonia (i.e. with 99.9995 % minimum of purity in laboratory applications) requires special chemical plants to achieve such purity levels, contributing to the increase of costs. When using alternative working fluids such as acetone and methanol, several issues are well addressed such as: less hazard to people, less costs involved with purification, out-gassing and fluid transfer to the loop and lower operation pressures. The LHP program has to be developed to manage up to 80 W of heat applied to the capillary evaporator. For this level of heat, the operation temperature is below 85 °C which for acetone for example, represents an operation pressure of 1.6 bar while for ammonia is equivalent to 39 bar. Another important factor that must be considered is the freezing point of acetone (-93.15 °C) when compared to ammonia (-78 °C) (Faghri, 1996). When using ammonia in LHPs for space applications for example, their condenser/radiator must be designed to face the freezing conditions when positioned to the cold space. In the case of acetone, this parameter is not a major issue as the temperatures on the radiator, in common applications, usually do not drop below -85 °C. Thus, applying acetone as an alternative working fluid is an important contribution to the development of the entire program, which results in several advantages for the entire program for the required range of power applied to the capillary evaporator.

2.1. Single Evaporator and Condenser LHP

Developing LHPs for future space applications require several important considerations, which are specially related to the maximum heat load that must be managed by the system, range of operating temperature, materials involved and life time. Currently, the heat load management that must be faced by a LHP is up to 150 W for heat sources temperatures below 100 °C. Looking at the potential in using the developed LHPs for ground applications for commercial purposes, it is also important to check the operationability of a LHP when gravity force plays an important role in its thermal performance.

There are currently two LHPs being developed for space applications but their potential application in ground have also being evaluated. Both LHPs were built in 316L stainless steel and all parts were welded together using orbital mechanical welding system, so they can be in agreement to space qualification standards. Figure 1 presents the representation of both LHPs that have been under development and Table 1 shows their geometric characteristics. Both LHPs have being undergoing performance life tests under laboratory conditions using high grade acetone as working fluid. Each LHP has been charged with a liquid inventory of 36 grams, keeping the compensation chamber with 50% of void fraction in the cold mode. The entire life test program has resulted in over 24 months of performance tests recorded, where the LHPs have to face power cycles ranging from 1 to 80 W, with sink temperatures from 5 to -20 °C.

Performance life tests are important to evaluate the continuous operation of the LHPs under several operation conditions, related to the heat loads applied to the capillary evaporator, condensation (sink) temperatures and gravity force effect on their performance. Tests are repeated continuously as a requirement for qualification of this device to check their operationability along time and the potential influence of non-condensable gases (NCGs). In the event of generating NCGs due to chemical incompatibility between the working fluid and materials that are formed along time and exposure to high temperatures, these gases will eventually block the liquid flow to the capillary evaporator core resulting in its failure. Thus the performance life tests are extremely important to evaluate the LHP capability over time.

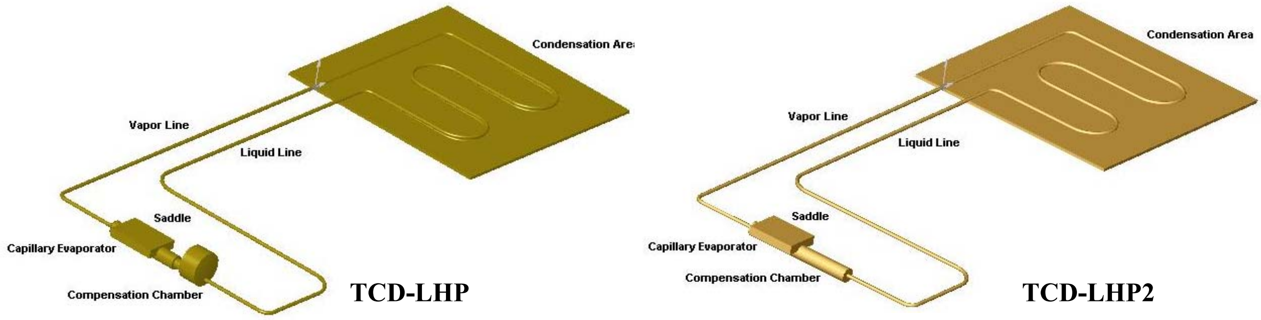

Figure 1. LHPs under development.

The LHPs differ from each other on their compensation chamber (CC) geometry as the TCD-LHP has a CC detached from the evaporator body while the TCD-LHP2 has an integral CC (same diameter as the evaporator), as presented by Table 1. In both LHPs, the condenser tubing is in thermal contact with an aluminum plate (300 x 300 mm x 4 mm thick, 6061 alloy) which is the cover plate of a heat exchanger that circulates a mixture of 50% ethylene glycol and 50% water at a flow rate of 9 L/min. The saddle, positioned at the capillary evaporators, is made of aluminum (6061 alloy) and a kapton skin heater (70 x 25 mm, 14 Ohms) is used to administrate the heat loads, which are controlled by a DC power supply. Twenty type-T thermocouples (deviation of ±0.3 °C at 100 °C) are used to monitor the temperatures throughout each loop and the readings are recorded on a spreadsheet file for further analysis.

According to the geometric characteristics presented by both LHPs, they are able to promote the heat management of up to 100 W for heat source temperatures below 110 °C for sink temperature of 0 °C, as presented by Fig. 2 when the LHPs were tested on a power step mode.

Table 1. Geometry of the LHPs under development.

Capillary Evaporator		*Liquid Line*	
Total Length (mm)	100	Outer Diameter (mm)	4.85
Active Length (mm)	67	Inner Diameter (mm)	2.85
Outer/Inner Diameter (mm)	19.0 / 16.5	Length (mm)	850
Material	Stainless steel grade 316L (ASTM)	Material	Stainless steel grade 316L (ASTM)
UHMW Polyethylene Wick		*Condenser*	
Pore Radius (μm)	6	Outer Diameter (mm)	4.85
Permeability (m^2)	10^{-13}	Inner Diameter (mm)	2.85
Porosity (%)	50	Length (mm)	1000
Diameter (OD/ID) mm	16.5 / 7.0	Material	Stainless steel grade 316L (ASTM)
Grooves height, width, angle	2.0 mm/2.5 mm/26°		
Number of Grooves	15		
Compensation Chamber		*Vapor Line*	
Volume (cm^3)	20	Outer Diameter (mm)	4.85
Screen mesh	# 200 Stainless steel grade 304L (ASTM)	Inner Diameter (mm)	2.85
TCD-LHP OD/length (mm)	45/25	Length (mm)	550
TCD-LHP2 OD/length (mm)	19/95	Material	Stainless steel grade 316L (ASTM)
Material	Stainless steel grade 316L (ASTM)		

It can be observed that due to the fact that TCD-LHP2 has an integral CC, the heat source and operation temperatures are higher than for those observed with TCD-LHP. As there are reduced thermal resistances between the capillary evaporator and CC with the TCD-LHP2, this directly affects the operation and heat source temperatures as more heat leak will be verified between these two components. Figure 3 presents tests performed with each LHP on a power cycle where it shows the heat management capability of each device.

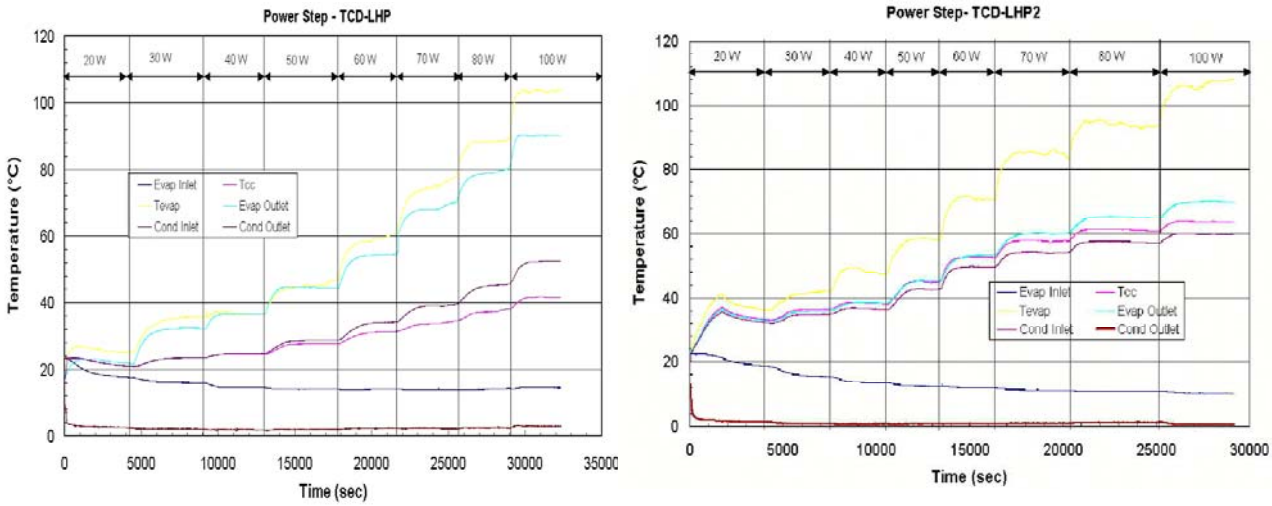

Figure 2. Power step tests performed with both LHPs – sink temperature at 0 °C.

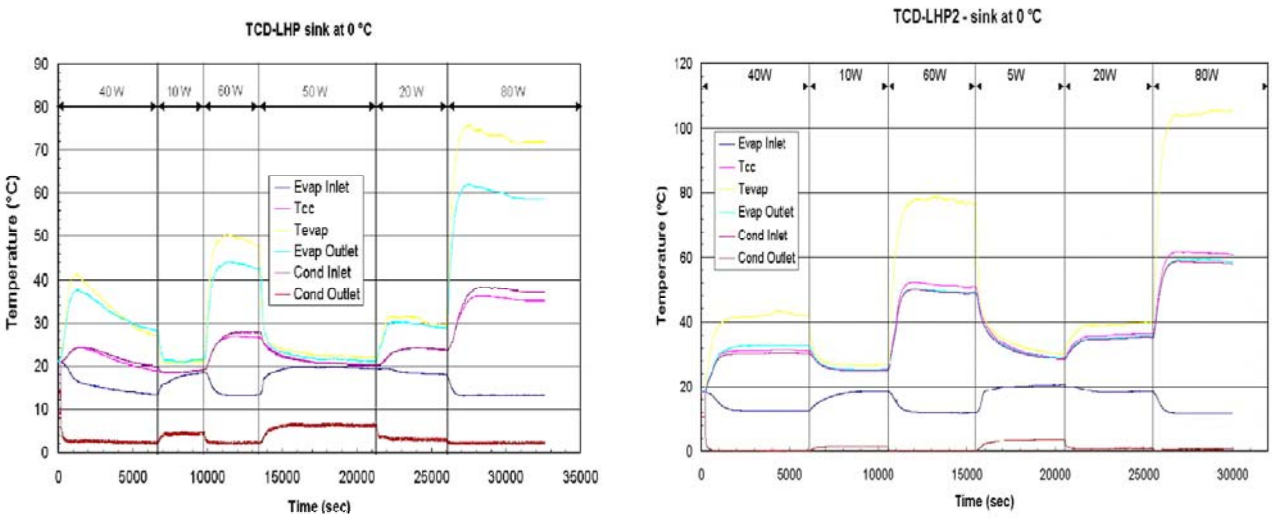

Figure 3. Power cycle on both LHPs – sink temperature at 0 °C.

Figures 4 and 5 presents the experimental results for both LHPs regarding their heat source temperatures and thermal resistances, respectively. From these data, it can be observed the clear influence of the sink temperature on the overall performance of each LHP. On the same way, the geometric characteristic difference between TCD-LHP and TCD-LHP2 regarding their CC directly affects the thermal resistances as the TCD-LHP2 presents lower values of this parameter. Both LHPs have compatible operation capabilities when comparing their results, which is important to certify the design parameters and better improve future LHPs depending on their application.

Tests were also performed with each LHP to check the gravity vector influence, where the capillary evaporator was located above and below the condenser. This type of tests are important when considering the use of LHP in commercial applications where the evaporator must operate with a tilt angle from the condenser. In this case, all tests performed so far have showed that the LHPs temperatures are dependent on the gravity vector. Lower heat source and operation temperatures are observed when the evaporator is below the condenser as there are less hydraulic restrictions and thermal losses are minimized contributing to decrease the temperature. However, when the evaporator is above the condenser, higher heat source and operation temperatures are verified which are mainly related to an increase on the hydraulic restrictions as the evaporator must overcome the height difference also contributing to increase the thermal losses (Riehl, 2004). In any case, the proper LHP design would be able to promote the desirable heat management even when adverse angle must be applied to the operation of this device and the heat source temperature can be controlled within the desired range without major concerns.

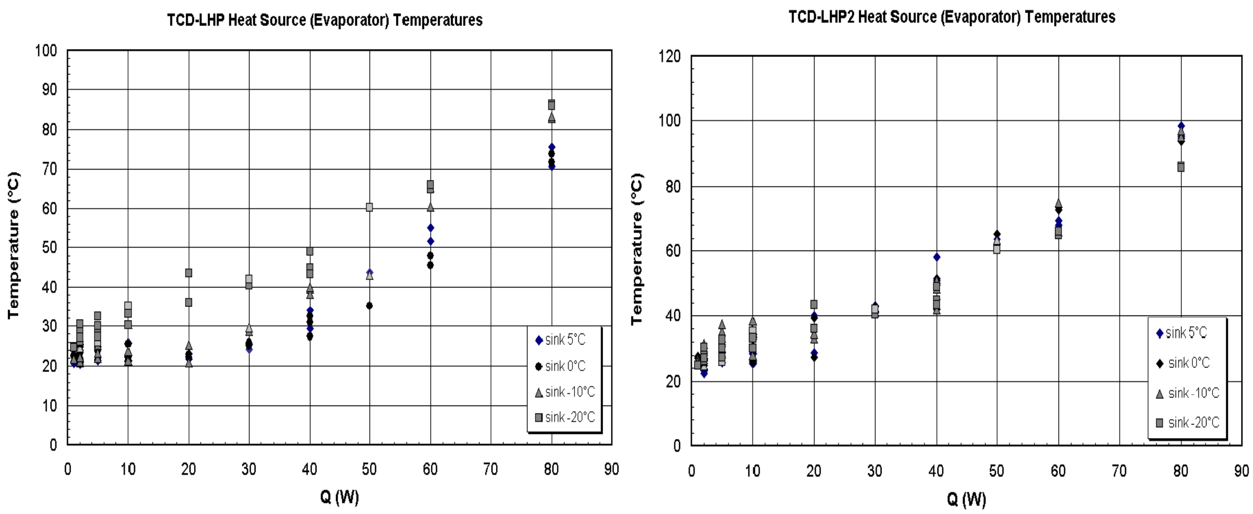

Figure 4. Overall results of the heat source temperatures.

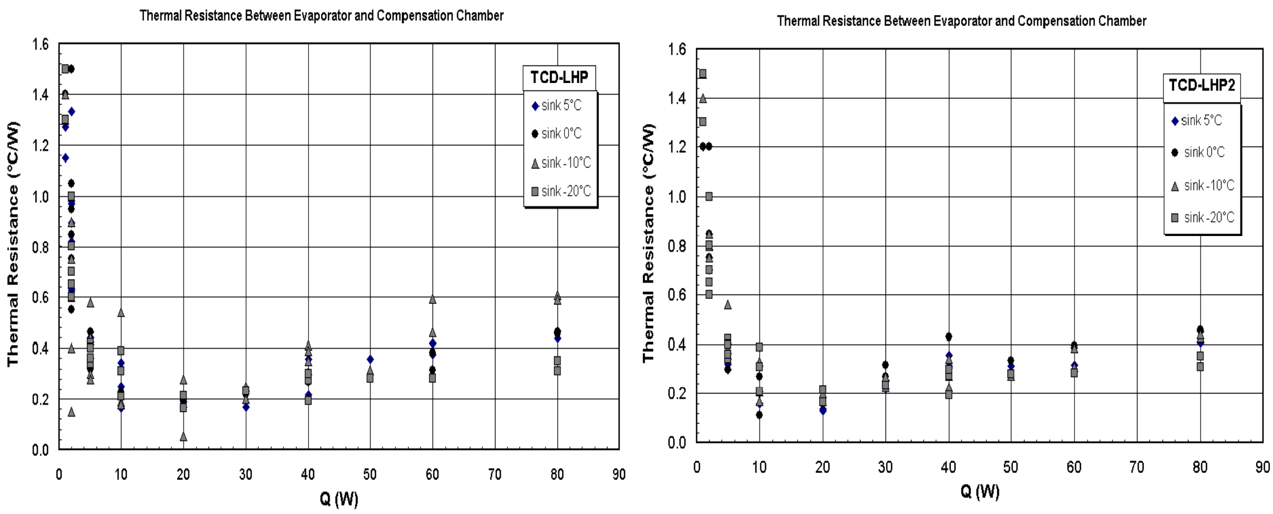

Figure 5. Overall results of the thermal resistances.

2.2. Reversible Loop Heat Pipe

As a special type of LHP, the reversible LHP presents both the evaporator and condenser with the same characteristics and internal parts, i.e. with a primary and secondary porous structure where the grooves are machined on the primary wick outer diameter. This type of LHP is important to be applied where the thermal control of a given component is required but it needs to be switched frequently and the heat source becomes the heat sink and vice versa. Such an operation is found in many aerospace applications and the development of this LHP becomes very important. However, some issues related to the condensation in channels where a porous structure is present might represent an extra hydraulics resistance to the capillary evaporator and the design of such a device must consider this variable.

Very few investigations have been performed with this special type of LHP (Delil et al., 2003; Maydanik, 2005) but they have proven that this kind of LHP is perfectly possible when considering that the characteristics of the primary wick must be a slightly different from those used in the classical LHPs design.

Following the wish to develop such a device, a reversible LHP (r-LHP) was designed, built and tested in order to prove its capability in transporting heat efficiently and open the potential of applying it in future applications either for space or commercial. The r-LHP was developed showing the same geometric characteristics for both capillary evaporator and condenser as presented by Table 2, which representation is shown in Fig. 6. Tests were performed in laboratory conditions on both power step and power cycles for the proposed device. The r-LHP was fully instrumented with 20 type-T thermocouples (deviation of ±0.3 °C at 100 °C) and the temperatures were read by a data acquisition system. On the evaporator, an aluminum saddle (6061 alloy) was placed on its top and a kapton skin heater (80 x 35 mm, 15.2 Ohms) was used to administrate the heat loads, connected to a DC power supply. On the condenser, an aluminum heat exchanger (80 x 60 mm x 10 mm thick, 6061 alloy) was placed, where channels were machined to allow the flow of a coolant at a rate of 12 L/min (50 % water and 50 % ethylene glycol) which was refrigerated by a cooling bath. The r-LHP was charged with 85 grams of high grade acetone that was twice distilled and out-gassed.

Table 2. Geometric characteristics of the reversible LHP.

Evaporator/Condenser	**Liquid and Vapor Lines**
Total Length: 185 mm	Length: 600 mm
Active length 85 mm	Outer/Inner Diameters (mm): 6.35/4.85
Inner/Outer Diameters (mm): 16.5/19	Material: 316L stainless steel
Material: 316L stainless steel	
Wick: polyethylene	**Compensation Chambers**
Mean pore radius: 4 μm	Length: 100 mm
Porosity: 55%	Inner/Outer Diameters (mm): 19/16.5
Number of grooves: 15	Material: 316L stainless steel

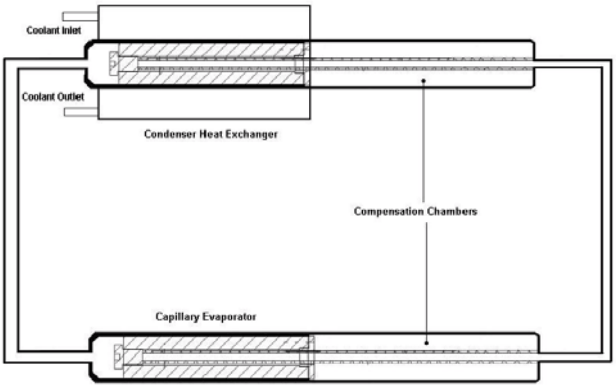

Figure 6. Reversible LHP representation.

The performance tests for this r-LHP followed the same principles as the ones done with the TCD-LHP and TCD-LHP2, where power step and power cycles were applied to the capillary evaporator to check its performance. Then, the evaporator was switched to become a condenser and then the condenser became the evaporator and the tests were resumed. Either way, the r-LHP presented acceptable operation being able to manage heat loads up to 130 W, as presented by Fig. 7. Some flow oscillations are observed during the tests, which are basically due to the draining effect of the porous wick present in the condenser. As the vapor that is condensed back to the liquid phase needs to be drained by the wick structure, some flow oscillations are expected specially when considering wick structures with fine pore radii. However, this behavior does not represent an issue for the r-LHP overall performance.

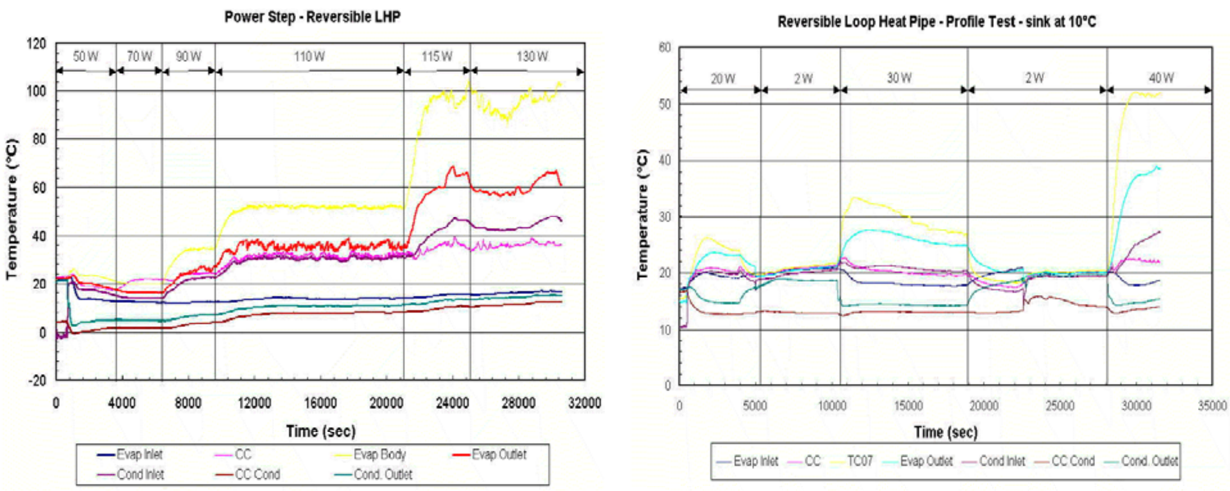

Figure 7. Power step and profile test with the r-LHP.

Even though the experimental tests have proven that r-LHPs are devices able to administrate the heat load with reliable operation, further investigations are still required in many aspects. Extensive tests have been undergoing for the r-LHP in laboratory conditions in order to better evaluate the parameters that could be improved to make this innovative device to be fully operational for commercial and space purposes in a real short time. Investigations related to the primary wick structure and its geometric characteristics must be carefully analyzed in this application as well.

2.3. Ramified (Multiple Evaporator and Condenser) Loop Heat Pipe

The ramified or multiple evaporator and condenser LHP (ramLHP) is another variation of LHPs that find interesting applications and potential use. In some cases, placing a single high-power management capillary evaporator in a heat source is not possible due to the high heat flux that need to be dissipated. In this case, several parallel evaporators could be used so the heat flux would be split and thus the thermal management could be better administrated. There were some applications in the past when CPLs were investigated to operate with several parallel evaporators (Ku and Hoang, 1997). During the first attempts to make multiple evaporators-condensers LHPs to operate, there was always an issue related to the interaction between the several parallel evaporators, which becomes a complex issue to be solved. Usually, the systems would operate in such a way that one of the compensation chambers would control the entire LHP operation temperature containing a two-phase mixture while the others would be full of liquid. Also, the evaporator that would be responsible for the thermal management of the highest heat load would establish the heat source temperature and all other evaporators would seek an equilibrium close to this one (Maydanik, 2005). However, it was noted that the ramLHP could present an acceptable operation if some steps could be taken prior to its startup. Recently, Ku and Birur (2001) have presented tests related to a multiple evaporator-condenser LHP where its operation was possible mainly due to the active thermal control of the compensation chambers and Delil et al. (2003) have shown tests of an operational ramLHP which did not use any active control to promote the thermal management of up to 1000 W of heat load using ammonia as working fluid.

As this special type of LHP presents several potential applications, specially when the thermal management of high power levels are required, a device that presents two parallel capillary evaporators and two condensers was built and has been tested in laboratory conditions. Just as all other LHPs tested and presented in this work, the working fluid used was high grade acetone, on the of amount 130 grams, and the ramLHP has been tested to better define its limits during continuous operation. The geometric characteristics of the ramLHP are presented in Table 3 and its representation is in Fig. 8. The condensers were tube-in-tube heat exchangers where the outer tube was a 19 mm OD stainless tube, circulating a mixture of 50% water and 50% ethylene glycol at –10 °C at a rate of 12 L/min on a counter-current flow. The entire LHP was built with 316L stainless steel and was instrumented with 20 type-T thermocouples (deviation of ±0.3 °C at 100 °C) which were connected to a data acquisition system responsible for monitoring the temperatures. Figure 8 presents the ramLHP sketch and the location of the most important thermocouples.

Table 3. Geometric characteristics of the ramLHP.

Capillary Evaporators	**Compensation Chambers**	**Condensers**
Total Length (mm): 185	Length (mm): 100	Outer/Inner Diameters (mm): 6.35/4.85
Active Length (mm): 85	Inner/Outer Diameters (mm): 16.5/19.0	Length (mm): 250 mm
Inner/Outer Diameters (mm): 16.5/19.0		
Vapor Line	**Liquid Line**	**Wick: Polyethylene**
Outer/Inner Diameters (mm): 6.35/4.85	Outer/Inner Diameters (mm): 6.35/4.85	Mean radius: 4 μm
Length (mm): 550 mm	Length (mm): 1250 mm	Porosity: 55 %
		Number of grooves: 15

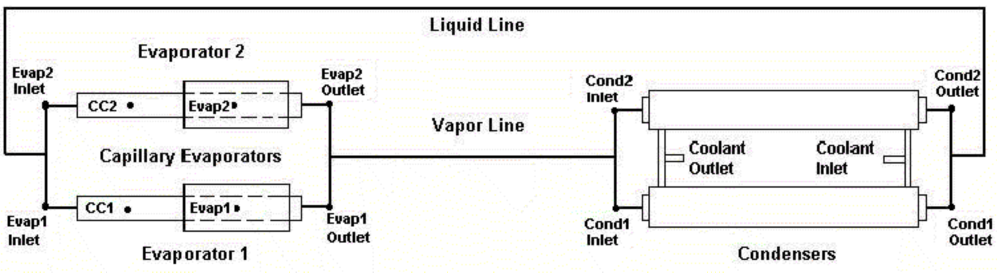

Figure 8. Representation of the ramified LHP test bed.

Testing the ramLHP requires some previous observations on how the device behaves when power is administrated to a capillary evaporator or another as no active control of the compensation chambers was available. Usually, the ramLHP did not present failure during the startup procedure but it was noted that a given evaporator that was under test would have its startup if its compensation chamber presented a temperature very close to the other one. In this case, both compensation chambers would present the same condition of 50 % of void fraction in the cold mode and the startup would be always successful. Figure 9 presents the startup procedure for the ramLHP operating in two different conditions. It can be noted that the device presents fast response and reliable operation over time which indicated its potential use in several applications were high power management become necessary.

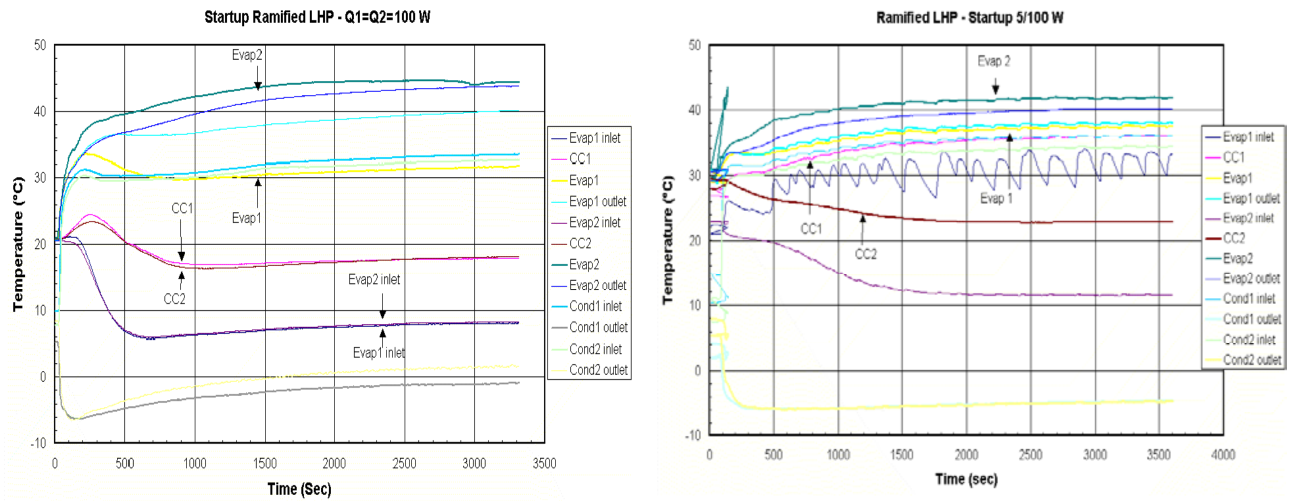

Figure 9. Startup procedures of the ramLHP.

It can be observed from the test when both capillary evaporators have the same heat load that the ramLHP seeks for a steady-state condition fast and one evaporator (Evap2) is dominating the operation as it presents higher temperature than Evap1. In this specific test, both compensation chambers present very close temperatures as well as the evaporators' inlet temperatures. This operation condition is a characteristics of this device when both evaporators have the same heat load. On the second test where the Evap2 has 100 W of power while Evap1 presents 5 W of heat load it is clear that the evaporator with greater heat load dominates the operation along with its compensation chamber, which presents the lowest temperature. Oscillations at the Evap1 inlet are mainly due to the reduced flow that enters in this specific evaporator and represents a characteristics of the operation of ramLHPs.

While testing the ramLHP over power cycles it can be noted its capability in handling the heat load even when it is suddenly changed from a power level to another, as presented by Fig. 10. Either evaporators operating at the same heat load conditions present compatible behavior showing that the thermal control of different heat sources can be performed alternatively without potential of failure of the evaporators.

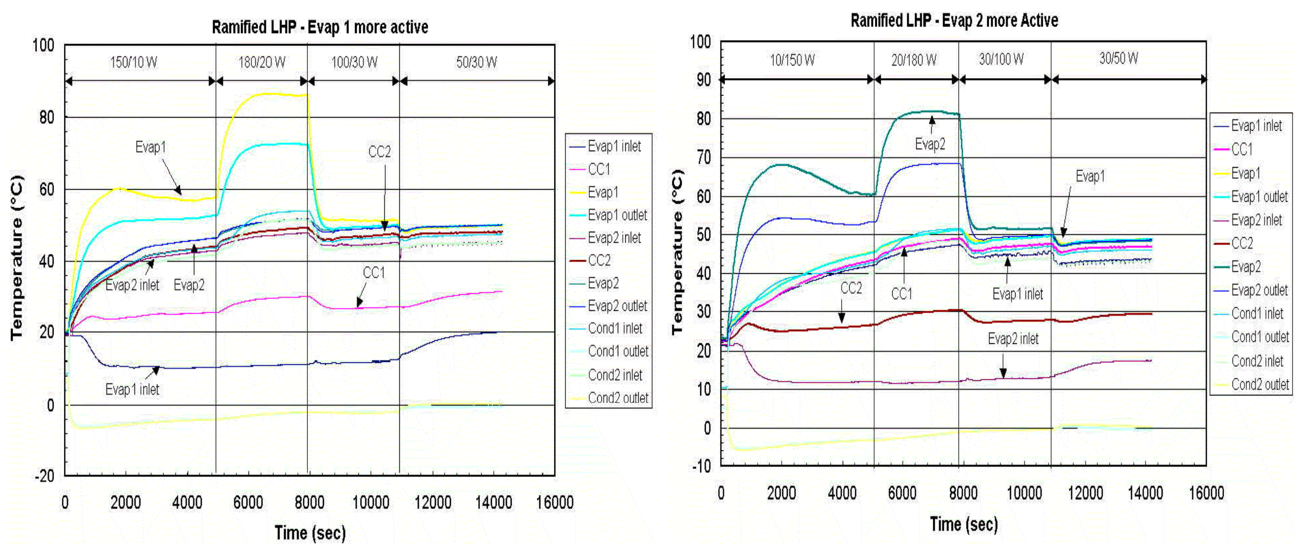

Figure 10. Power cycle applied to the ramLHP.

Once again, the evaporator that presents higher heat loads controls the entire ramLHP operation and its compensation chamber, which presents the lowest temperature, controls the operation temperature of the loop. As the heat loads are higher, even at the evaporator that presents less power applied to it, no temperature oscillations at the evaporator inlet are present as it was observed in Fig. 9. This behavior indicates that such temperature oscillations are a characteristics for very reduced heat loads.

3. Conclusions

The development of a novel technology of loop heat pipes (LHP) have been presented and discussed. As the levels of heat fluxes increase and the demand for passive thermal control becomes more important, the development of devices such as LHPs becomes an interesting option. The use of LHPs in space application has found several issues to be solve but they can be properly addressed according to each design requirements. The LHPs that have been tested and developed for future space applications are dealing with the requirements for actual heat loads and have shown reliable operation along time as they present over 24 months of continuous operation without indication of NCGs influence. The reversible LHP has presented to be an interesting option for applications where the evaporator must be switched to a condenser frequently and the experimental results have presented its reliability during operation. The ramified LHP has been presented as an option when high heat loads are required to be managed but the application of a single evaporator becomes inadequate. Testing the ramLHP has shown reliability during its operation and stable behavior as the power levels were suddenly changed. The continuous development of the LHP technology becomes important for the future of thermal control where passive devices are required not only for space applications but also for commercial applications.

4. Acknowledgements

This work has been supported by Fundação de Amparo a Pesquisa no Estado de São Paulo (FAPESP), grants 03/08365-6, 03/11477-0 and 04/45578-9.

5. References

Ku., J., 1999, “Operation Characteristics of Loop Heat Pipes”, SAE – Society of Automotive Engineers, 1999, paper # 1999-01-2007.

Swanson. T. D., Birur, G. C. , 2002, “NASA Thermal Control Technologies for Robotic Spacecraft”, Proceedings of the 12th International Heat Pipe Conference, Moscow-Kostroma-Moscow, Russia, 19-24 May, pp. 26-34.

Birur, G. C., Pauken, M. T., Novak, K. S., 2002, “Thermal Control of Mars Rovers and Landers Using Mini Loop Heat Pipes”, Proceedings of the 12th International Heat Pipe Conference, Moscow-Kostroma-Moscow, Russia, 19-24 May, pp. 189-194.

Goncharov, K., Kolesnikov, V., “Development of Propylene LHP for Spacecraft Thermal Control”, Proceedings of the 12th International Heat Pipe Conference, Moscow-Kostroma-Moscow, Russia, 19-24 May, 2002, pp. 171-176.

Delil, A. A. M., Maydanik. Y. F., Gerhart. C., “Development of Different Novel Loop Heat Pipes within the ISTC-1360 Project”, International Conference on Environmental Systems – 33rd ICES, July 7-10, 2003, Vancouver, CA, paper 2003-01-2383.

Faghri, A., 1996, “Heat Pipe Science and Technology”, Taylor&Francis, Bristol, PA-USA, 874 p.

Riehl, R. R., 2004, “Comparing the Behavior of a Loop Heat Pipe with Different Inclinations of the Capillary Evaporator”, 34th International Conference on Environmental Systems, Colorado Springs, CO, July 19-22, paper #2004-01-2510.

Maydanik, Y. F., 2005, “Loop Heat Pipe”, Applied Thermal Engineering, Vol. 25, pp. 635-657.

Ku, J., Hoang, T., 1997, “Testing of a Capillary Pumped Loop with Multiple Parallel Starter Pumps”, Proceedings of the 27th International Conference on Environmental Systems, Lake Tahoe, NVm July 14-17, paper # 972329.

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