LOOP HEAT PIPES AND HEAT PIPES TECHNOLOGIES DEVELOPMENT AND QUALIFICATION FOR SPACE APPLICATIONS

Roger R. Riehl♠, Nadjara dos Santos♣
National Institute for Space Research – Space Mechanics and Control DIvision
Av. dos Astronautas, 1758, São José dos Campos, SP, Brazil, 12227-010
Phone 55 12 3945-6178 / 3945-6226 (fax)
♠rriehl@dem.inpe.br; ♣nadjara@dem.inpe.br

Abstract

The loop heat pipe (LHP) technology has been under development by this institute over the last 5 years, focusing on future applications for this passive thermal control device, specially related to instruments and components thermal control in satellites. Such a development has been focused on designing, manufacturing, assembling, charging and testing LHPs for Space applications using acetone as working fluid. Several procedures were specially conceived during the development program, which resulted in reliable apparatuses that have been extensively tested for potential applications. Repeatability on the processes used during the manufacturing of the LHPs was established as the key parameter to qualify this technology, as well as suppliers and techniques for charging and testing procedures. As a result, several LHPs were manufactured and are operational, presenting reliable results related to the thermal control according to the parameters established by the project. In parallel, two transient mathematical models were developed based on the experimental data gathered in laboratory conditions, which were then validated and have been applied on the design of LHPs for Earth orbit operation, Also, new wick materials composites are under development for application in the near future.

KEYWORDS: loop heat pipes, thermal control, technology development, Space qualification.

INTRODUCTION

As reliable two-phase passive thermal control devices, loop heat pipes (LHPs) have been extensively investigated for application in Space conditions during the last years by many researchers, with the aim to use them in satellites and spacecrafts that have been already launched and their missions were accomplished [1-6]. Several other applications for LHPs are also interesting and have been already presented [5] and this technology has shown to be important for the future of satellites that require high heat transport capabilities and considerable advances on de-freezing methods of working fluid in Space radiators have been made [7].

Loop heat pipes operate by means of capillary pressure generated in the capillary evaporator, which is in thermal contact with the heat source. Heat is transferred by conduction through the evaporator wall to the working fluid that is in its saturated condition, which evaporates instantly. The vapor generated in the evaporator flows towards the condenser by the vapor line, where it is condensed back to the liquid phase flowing towards the evaporator by the liquid line to complete the cycle. Coupled to the capillary evaporator there is the compensation chamber, which is an integral part of the evaporator and used to self-regulate the working fluid inventory in the loop according to the heat loads applied to the evaporator, as well as establishing the operation temperature that the entire device will operate [8-9]. Even though the characteristics of LHPs and their thermodynamic behavior are well known [8], some constructive and manufacturing details are considered proprietary information, specially on the case of wick materials manufacturing processes, machining and insertion methodologies

Focusing on the need to use LHPs for future satellite applications, a development program was established by this institute to understand how these thermal control devices operate and the needs to manufacture them for Space applications. In such a way, this program generated the necessary information to design, manufacture and apply LHPs for Space applications, resulting in the control of all steps necessary for such a technology, which was expanded to several other configurations (multiple evaporator, reversible, miniature LHPs, etc). Other areas have also been under development, specially related to materials in ceramics and composites with zirconia [AL_2O_3-ZRO_2 (3Y-TZP)] for primary wick structures.

Thus, the objective of this paper is to present an overview of the LHP development program, as well as some results obtained related to Space qualification, life and performance tests. Also, options on the LHPs design and a brief presentation regarding new primary wick structures is shown.

LOOP HEAT PIPE REQUIREMENTS

The LHP development program was focused in specific requirements for the current needs for heat dissipation, which should be present in geo-stationary and telecommunication satellites that shall be designed and built in the future by this institute. The requirements were first established as follows:

- heat loads: up to 150 W
- capillary evaporator temperature: up to 80 °C
- capillary evaporator active length: maximum 75 mm
- alternative working fluid (ammonia and propylene not allowed)

According to the above mentioned requirements, a development program was initiated in 2003 in order to determine the constraints that should be expected for the LHPs design. As a final product, a LHP must be qualified for Space applications for a minimum lifetime of 8 years using an alternative working fluid. Due to the restrictions, ultra-pure acetone was chosen as a potential working fluid but it has to go through an extensive testing program to prove its capability to handle the required power levels as well as the expected lifetime.

For such a development program, an extensive literature survey was performed in order to verify the available standards used to qualify two-phase thermal control devices, as well as the required procedures that had to be used in order to have a high-quality LHP. Such a survey generated an important document [10], which is based on NASA [11,12] and ESA [13] standards. Following this document, the LHP technology program could be initiated according to what was required for the device's application.

DEVELOPMENT PROGRAM AND PROCEDURES

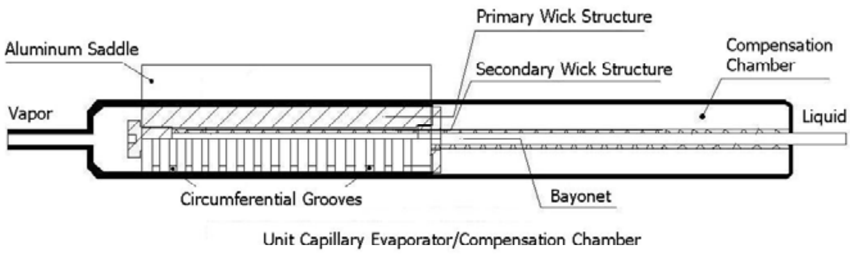
The LHP development program was divided in several steps in order to have a complete control of the entire process. First, suppliers were certified to deliver the necessary materials according to what was acceptable for the LHPs and then a prototype could be built. A first LHP prototype was built to check its operationability and to certify the designing tools that were used [14], as well as the testing procedures. Improvements on the LHP capillary evaporator design and its compensation chamber were performed constantly in order to come with a configuration that could meet the requirements for the maximum heat loads. Since acetone presents a lower Figure of Merit when compared to ammonia, the improvements on the capillary evaporator design was the option to meet such requirements. However, a parallel development program for wick structures was established, which was focused on nickel, titanium, stainless steel primary wicks as well as improvement on the already used polyethylene wick. For this final material, the development was focused on decreasing the mean pore size (diameter) while keeping the porosity (between 50 and 65%) in order to improve the polyethylene capability when its use becomes necessary. Currently, polyethylene wicks are manufactured with pore sizes of 1 micron.

Several other prototypes were then built and tested according to the established procedures to have high-quality LHPs, as defined by [10], which results were extensively published [9,15,16]. With the results obtained, refinements on the manufacturing procedures could be performed in order to improve the LHPs thermal capabilities. Repeatability on the processes used to manufacture the parts for the LHPs was highly required as a way to guarantee that the devices would present compatible performance. All procedures were repeated to the exhaustion in order to certify the processes, which were also extended to wick insertion, sealing, secondary wick manufacturing, welding, working fluid purification and charging, testing, etc. In total, more than 35 units of capillary evaporator/compensation chamber were manufactured and over 15 LHPs were built and tested in order to guarantee repeatability and reliability of all procedures. Figure 1 presents the schematics of the unit capillary evaporator/compensation chamber and a cross-section of the secondary wick configuration used in the present designs.

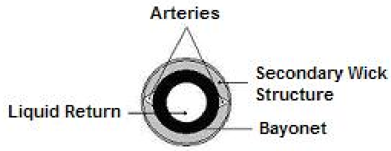
Improvements on the capillary evaporator thermal performance could be achieved when using circumferential grooves machined on the primary wick outer diameter [16], which resulted in evaporator temperatures up to 50% lower when compared to a previous design with axial grooves. Figure 2 presents some performance test results for certain heat loads profiles using different condensation temperatures. Tests have been performed for LHPs with the geometric characteristics presented by Table 1. Even though Table 1 and Fig. 2 present the data for polyethylene primary wick structure, many other units were built using other materials like nickel, titanium and stainless steel as presented by Fig. 3.

Two mathematical models were conceived and validated with the experimental data, with the objective to apply them in future LHPs design to be used for Space applications [17,18]. In total, over 8,000 hours of test results were used to validate the mathematical models in order to use them for future design of LHPs for Earth orbit operation. These test results are related to life tests performed to verify the life time of the LHP in orbit conditions, which currently is yelding to over 12 years and are still undergoing.

The models (transient approach) have been applied to predict the LHPs operation in many conditions as observed during the tests in laboratory and have shown to correlate the data very well. Both models deal with a transient behavior of the LHPs and describe the unit capillary evaporator/compensation chamber with a detailed heat flux network and the condensation area presents a refined description in order to give a more precise behavior during the phase change. All parameters related to the conductances were adjusted with the experimental data, which resulted in simulated results with a deviation of less than 3°C. More details of the mathematical models can be observed on the referred material cited above and further details regarding the experimental results and test procedures are also referenced [9,16].



(a) Capillary Evaporator/Compensation Chamber Unit.

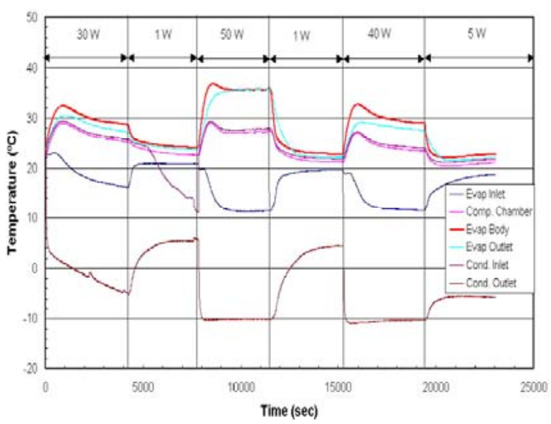


(b) Cross-Section of the Secondary Wick.

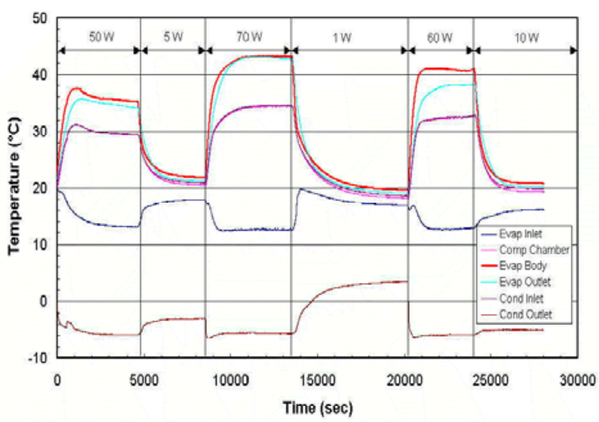
Figure 1. Schematics.

Table 1. Geometric Characteristics for the LHPs Under Tests.

Capillary Evaporator	Characteristics	Vapor and Liquid Lines	Characteristics
OD/ID/Active Length/Total Length (mm)	19.0 / 16.5 / 70 / 100	OD/ID (mm)	4.85 / 2.85
Number of circumferential microgrooves (m^{-1})	2,800	Length (mm)	550 (Vapor) / 800 (Liquid)
Material	316L ASTM Stainless Steel	Material	316L ASTM Stainless Steel
Primary Wick Structure		Secondary Wick Structure	
Number of Circumferential/Axial Grooves	21 / 1	Material	Screen mesh #200 (316L ASTM Stainless Steel)
Pore Size (μm) / Porosity (%)	4.0 / 50	Number of axial arteries	2
Material	Polyethylene		
Compensation Chamber		Condenser	
OD /ID / Length (mm)	19.0 / 17.0 / 85	OD/ID/Length (mm)	4.85 / 2.85 / 1200
Material	316L ASTM Stainless Steel	Material	316L ASTM Stainless Steel
		Plate (Alloy Al 6061)	350 mm X 50 mm X 3 mm

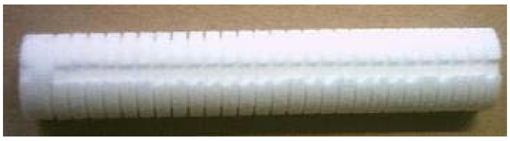


(a) Condensation at –20°C.

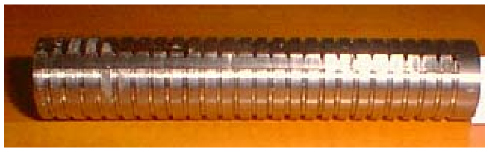


(b) Condensation at –10°C.

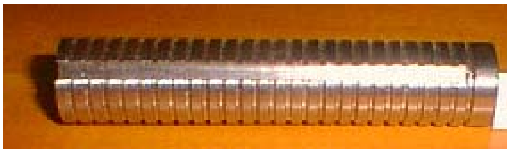
Figure 2. Performance Tests of the LHP.



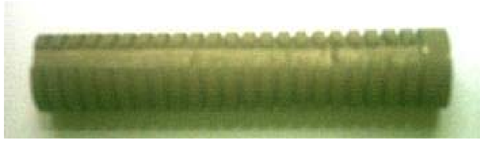
(a) Polyethylene.



(b) Titanium.



(c) 316L Stainless Steel.



(d) Nickel.

Figure 3. Primary Wick Structures Used on the LHPs.

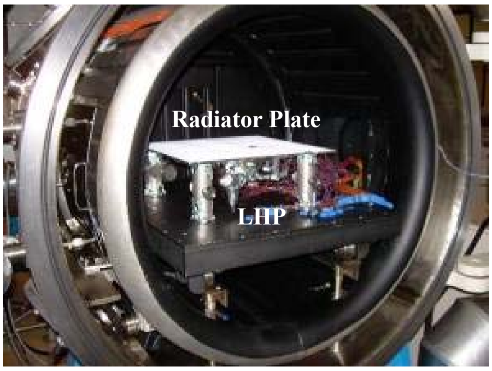
As a natural improvement, the mathematical transient models were modified to include an optimization routine. The inclusion of optimization parameters on the designing of LHP has resulted in more robust tools for future designs, as well as to include a more sensitive analysis for the parameters involved during the verification of all variables that have direct influence on the LHP design [19].

With the technological level that have been achieved, the LHP development program could be then extended to the next and more important level, which was related to a formal qualification procedure applied to a LHP. For this case, all the knowledge gathered was applied to design, manufacture and qualify a LHP, which could then be used to qualify the procedures required to apply this device in future Space missions.

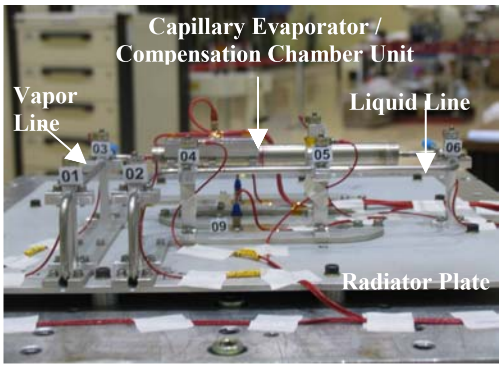
LOOP HEAT PIPE QUALIFICATION PROCEDURES

One should note that several documents were conceived in order to validate the entire technological cycle and procedures, so it could be consulted and repeated when necessary as well as it could be audited anytime by the people responsible for the quality control for devices used in Space applications. As the entire technological cycle was controlled, specially related to the manufacturing procedures (machining, assembling, sealing, welding), charging and testing, a LHP applied for geo-stationary mission was designed and built according to the parameters imposed by the thermal control devices as presented above. Such a LHP was designed following all the requirements and was built with all manufacturing procedures established so repeatability and reliability could be assured. In fact, two identical LHPs were built in order to cross-check all the necessary parameters to ensure Space qualification for such a technology. Figure 4 presents the LHP built and used to qualify all the procedures.

Structural analysis using PATRAN software was performed before building the LHPs and the vibration tests correlated well with the analysis, showing that the device is able to support launching efforts (sinusoidal) between 12 and 80-g with maximum levels of 180-g without damaging the welds or the LHP internal parts. Furthermore, the LHP was tested in laboratory conditions so its operationability could be observed under controlled conditions, operating with high-purity acetone and condensation by natural convection. Prior to this test, all the necessary tests (leak test, pressure proof, etc) were performed according to the qualification procedures for such a thermal control device. Then, the performance test had to be done again after the LHP had accomplished all the formal qualification procedures (vibration, thermal vacuum cycles, etc) so its reliability could be again verified in order to be sure that no deviation on the operation was caused by all tests.



(a) Vacuum Chamber Tests (TCT/TVT).



(b) Vibration Tests.

Figure 4. LHP Qualification Model.

Following the standards to qualify two-phase thermal control devices [10], Fig. 5 presents an schematics on the steps that shall be applied to qualify the LHP technology used during this program, which applies the principle of similarity. It is important to mention that branch #1 must be completely finished before branch #2 could be initiated and so on. For each branch, at least 2 LHPs must be built to ensure reliability on the processes.

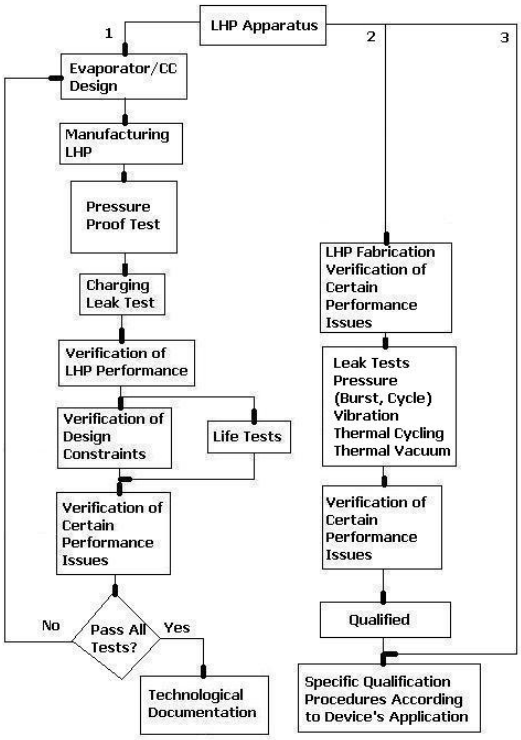


Figure 5. Qualification Procedures for LHPs By Similarity.

The experimental tests performed in laboratory conditions, as well as thermal vacuum tests, have also been used to verify the life time that the LHP would present in Space conditions, as life tests have been performed as well. In this case, the LHP shall operate at temperatures above its normal operation temperature so the system could present an aging condition and its equivalent life time could be calculated as follows [11]:

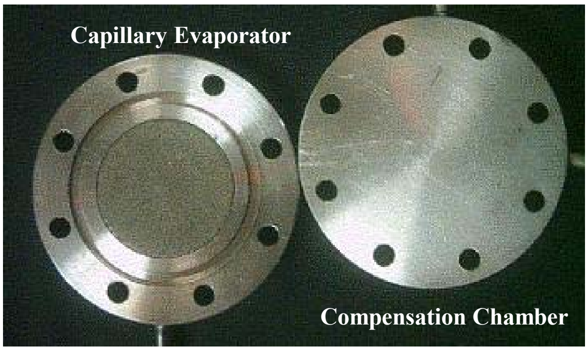
$$t_t^{1/2} = \sum_{i=1}^{D} \left[\sqrt{24i + \Delta t} - \sqrt{24i} \right] e^{-Q/(k_m T_o)} . \quad (1)$$

It is important to mention that a life test program can be shorter or longer depending on the parameters used to perform this test, specially regarding to the heat loads and *To*. Even though the life tests have given an expectancy of 12 years of continuous operation in Space so far, the aim is to guarantee a lifetime above 15 years. During the entire program, all procedures must be well documented and the suppliers need to be constantly checked in order to verify that their level of quality for the delivered materials are within the required quality, as frequent verification of materials and working fluid are performed. On the same way, testing the LHPs shall present an indication of non-condensable gases generation, which is an important information specially when acetone has been used.

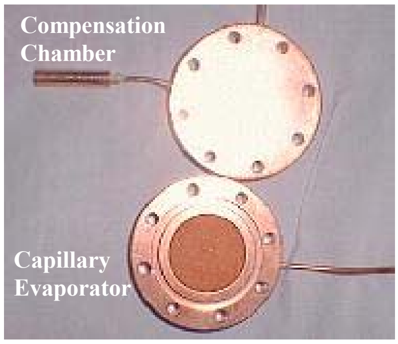
DESIGN VARIATIONS, OTHER APPLICATIONS AND DEVELOPMENTS

The development of the LHP technology has generated several other possibilities to apply it with different configurations. This has been possible as the same techniques and procedures have been applied in other LHPs projects since the technological cycle has been qualified and not only a single device. Of course, each device must accomplish all the qualification tests for the mission that has been designed for in order to comply with the project requirements. In this case, several LHPs configurations could be designed and built for different applications, such as multiple evaporator/condenser, reversible and miniature LHPs [20]. Important contributions were obtained with the development of such a technology, especially when related to the miniature LHPs with flat evaporators. Even though different procedures to manufacture the wick structure have to be developed, as well as the insertion technique, this special type of LHP can now be used when concentrated heat fluxes are a concern. The current design of the miniature LHPs can deal with heating areas of 3.0 cm^2 and presents reliable performance over time, as already presented in other publication [20]. Figure 6 presents photographs of the miniature LHPs that were built with nickel (stainless steel LHP) and copper (copper LHP) wicks.

A current project that is undergoing is called "Crystal", which stands for a geo-stationary application for two LHPs designed to operate at a maximum power level of 275 W (250 W normal operation plus 25 W of extra heat load) and a maximum heat source temperature of 45°C (+1°C) for acetone as the working fluid, using the same radiator/condenser plate. Both LHPs have been designed to operate with an active length of 100 mm, using as primary wick polyethylene with pore diameter of 1 μm and 50% porosity (minimum) and 316L stainless steel tubings.



(a) With Nickel Wick.



(b) With Copper Wick.

Figure 6. Miniature LHPs Assembling.

Since each LHP will operate 6 months at a time (due to the geo-stationary satellite orbit), the radiator had to be designed to accomplish the needs for heat dissipation according to the project requirements. Just as the above mentioned LHPs used to qualify the entire technological cycle, as well as the miniature LHPs, this current project also presents an important application, showing the variety of use for such a technology in Space and why the control of all technological steps are necessary in order to better design and build such an important thermal control device. Figure 7 presents the schematics of the "Crystal" LHPs project.

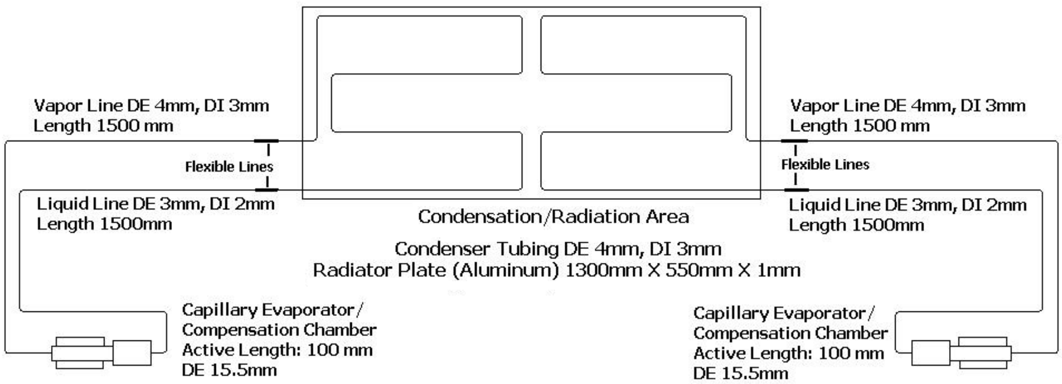


Figure 7. Schematics of the "Crystal" LHPs Project (Not To Scale).

Other projects are also undergoing, with special attention to the use of nanofluids in LHPs and heat pipes [21]. On the same way, other two-phase thermal control devices have been under development such as the pulsating heat pipes and axially grooved heat pipes, which will be integrated in honeycomb panels for satellites (Fig. 8). The entire development program shows a broad application for these devices as it represents an important parameter for the future of the institute's satellite program. This is the reason why an entire infrastructure has been created to design, build and test these devices, which are related to a 2-D testing bed, filling stations (for high and low pressure working fluids), etc.

In order to have more options for primary wick structures, a development program has been initiated to manufacture wicks with Al_2O_3 as well as its composits with zirconia - Al_2O_3-ZrO_2 (3Y-TZP), resulting in pore sizes around 2 mirons and porosity of 50% [22]. Current development has resulted in prototypes that have been tested extensively for strength, machining, chemical compatibility, as well as important properties such as pore size, porosity, permeability and thermal conductivity. Figure 9 presents the test apparatus for thermal conductivity testing. LHPs prototypes have been built and are scheduled for testing in the near future for thermal performance verification. Some other LHP prototypes will be tested for launching and TCT/TVT conditions to better evaluate the primary wick material performance. Publications describing the composits development will be released in the near future.

Figure 8. Axially grooved heat pipes for honeycomb panel insertion.

Figure 9. Thermal conductivity testing for primary wick composites.

CONCLUSION

With the objective of developing the LHP technology for the current use of this institute's satellites, a program was established in order to understand and control all the required steps to build such a device. Efforts have been made to improve the LHPs thermal capabilities focusing on design improvements and manufacturing procedures, with a special attention to the repeatability of all processes so the steps could be well controlled. Several other parameters had to be established, related to assembling, wick insertion, sealing, welding, charging, testing, etc so all the technological sequence could be understood and repeated with the required results for the thermal performance for all LHPs built. More than 35 units of the capillary evaporator/compensation chamber have been built as well as over 15 LHPs so the repeatability on the processes could be achieved and the thermal performances of all LHPs checked. The LHPs have been tested constantly, which results on more than 8,000 hours used to validate two mathematical models that are now used to design devices to operate in Earth's orbit. As a result, the technology could be well understood, documented and controlled. Currently, several other applications have been using LHPs to perform the thermal control passively focusing on the satellites' needs. Cylindrical evaporators and miniature LHPs have been extensively designed and built to be applied on the thermal control of several devices, showing reliable operation and performing according to the parameters established by the projects. The "Crystal" LHPs is the current thermal control project for geo-stationary application, which is under construction and testing shall be started soon. Also, the development of wick materials composites have lead to new options for future LHPs designs.

Nomenclature

D = number of days in operation
Δt = duration of tests (hours)
Q = heat load (W)
k_m = device's thermal conductivity (W/m °C)
T_o = average operation temperature of each test (°C)

Acknowledgements

The authors wish to thank the financial support given by FAPESP – Fundação de Amparo à Pesquisa no Estado de São Paulo/Brazil (grants 03/08365-6, 03/11477-0 and 04/15578-9) to develop the LHP technology.

References

1. Birur, G. C., Pauken, M. T. and Novak, K. S., Thermal Control of Mars Rovers and Landers Using Mini Loop Heat Pipes // *Proc. of 12th International Heat Pipe Conference*, *Moscow-Kostroma-Moscow, Russia*, 2002, pp. 189-194.
2. Figus, C., Queruel, N., Tjiptahardja, T., A. Tournemine, A. and Fournier, E., Flight Experiment of Three Miniaturized Two-Phase Technologies for Spacecraft Thermal Control // *International Two-Phase Thermal Control Workshop, Laurel, MD*, 2006.
3. Goncharov, K. and Kolesnikov, V., Development of Propylene LHP for Spacecraft Thermal Control // *Proc.* of *12th International Heat Pipe Conference*, *Moscow-Kostroma-Moscow*, *Russia*, 2002, pp. 171-176.
4. Ku, J., Ottenstein, L., Butler, D. and Nagano, H., Thermal Performance of a Miniature Loop Heat Pipe with Multiple Evaporators and Multiple Condensers // *International Two-Phase Thermal Control Workshop*, *Laurel, MD*, 2006.
5. Maydanik Y. F., Loop Heat Pipe // *Appied Thermal Engineering*, 2005, Vol. 25 pp. 635-657.
6. Swanson, T. D., Overview of Thermal Control Research at Goddard Space Flight Center // *International Two-Phase Thermal Control Workshop*, *Laurel, MD*, 2006.
7. Goncharov, K., Methods of Working Fluid De-Freezing in Radiator Manufactured on Base of LHP // *Proc. of 37th International Conference on Environmental Systems*, *Chicago, IL*, 2007, paper #2007-01-3199.
8. Ku., J., Operation Characteristics of Loop Heat Pipes // *Proc. of SAE – Society of Automotive Engineers*, 1999, paper # 1999-01-2007.
9. Riehl, R. R. and Siqueira, T. C. P. A, Evaluating Loop Heat Pipes Regarding Their Geometric Characteristics // *Proc.* of *35th International Conference on Environmental Systems*, *Rome, Italy,* 2005, paper # 2005-01-2882.
10. Riehl, R. R. and Vlassov, V. V., *Proposal of a Universal Production and Tests Procedures of Capillary Pumped Loop (CPL), Loop Heat Pipe (LHP) and Heat Pipe (HP)*, CONTER-D-G-TRP-007/2004, National Institute for Space Research, Sao Jose dos Campos, SP Brazil, 42p, 2004.
11. Tower, L. K. and Kaufman, W. B. *Accelerated Life Tests of Specimen Heat Pipe from Communication Technology Satellite (CTS) Project*. NASA TM-73846, NASA Technical Memorandum, 1977.
12. MIL-STD-1540C, *Test Requirements for Launch, Upper Stage, and Space Vehicles*, Military Standard FSC 1810, Space and Missile System Center, MC/SDFC, 126 p., 15 September 1994.
13. ESA PSS-49, *Heat Pipes Qualification Requirements*, Issues 1 & 2, March 1983.
14. Riehl, R. R., Design and Operation of Capillary Driven Two-Phase Loops as CPL/LHP // *National Institute for Intellectual Property*, Brazil, Software Register # 03003, 2002.
15. Riehl, R. R., Comparing the Behavior of a Loop Heat Pipe with Different Inclinations of the Capillary Evaporator // *Proc. of 34th International Conference on Environmental Systems*, *Colorado Springs, CO*, 2004, paper #2004-01-2510.
16. Riehl, R. R. and Dos Santos, N., Performance Improvement in Loop Heat Pipe Using Primary Wick with Circumferential Grooves // *Proc. of 36th International Conference on Environmental Systems*, *Norfolk, VA*, 2006, paper # 2006-01-2172.
17. Vlassov, V. V. and Riehl, R. R., Modeling of a Loop Heat Pipe for Ground and Space Conditions // *Proc. of 35th International Conference on Environmental Systems, Rome, Italy*, 2005, paper # 2005-01-2935.
18. Vlassov, V. V. and Riehl, R. R., Modeling of a Loop Heat Pipe with Evaporator of Circumferential Vapor Grooves in Primary Wick // *Proc. of 36th International Conference on Environmental Systems*, *Norfolk, VA*, 2006, paper # 2006-01-2173.
19. Vlassov, V. V., Souza, F. L., Riehl, R. R., Design Optimization of Loop Heat Pipes With Cyclindrical Evaporator and Integral Reservoir for Space Application // *Proc. of the Space Technology and Applications International Forum (STAIF), Albuquerque, NM USA*, 2008, Vol. 969, pp. 138-145.
20. Riehl, R. R., Extensive Development of the Loop Heat Pipe Technology // *Proc. of 36th International Conference on Environmental Systems*, *Norfolk, VA USA*, 2006, paper # 2006-01-2169.
21. Riehl, R. R., Performance Evaluation When Using Nanofluids in Loop Heat Pipe and Pulsating Heat Pipe // *Proc. of 37th International Conference on Environmental Systems*, *Chicago, IL*, 2007, paper #2007-01-3193.
22. Hirschmann, A. C. O, *Alumina-Zirconia Porous Ceramic Composits For Application in Satellite Thermal Control Devices*, PhD Thesis, National Institute for Space Research, São José dos Campos, SP Brazil, 2008.