EVALUATING LOOP HEAT PIPE PERFORMANCE IMPROVEMENT USING CIRCUMFERENTIAL GROOVES

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Abstract

The loop heat pipe (LHP) technology development has to deal with the growing need of high heat flux dissipation and several issues related to space qualification and integration, along with the miniaturization of this device. As some design limitations are faced related to the maximum heat flux able to be managed by LHPs, improvements on their capillary evaporator design can result on a gain on its capability of heat management along with a substantial decrease on the heat source temperature, which is very desirable, as well as the use of alternative working fluids. Thus, this work presents an investigation of LHPs that operate with acetone as working fluid, for maximum operational heat loads of 80 W, where the results of life tests performed in laboratory conditions are presented. Two identical LHPs were designed and tested, where one presents the classic design of a capillary evaporator primary wick with axial grooves, while the other presents the design of circumferential grooves. For the same active length, there has been a gain of 20% on the contact area when using circumferential grooves on the primary wick, resulting in better thermal performance. Upon operating at its maximum designed heat load, the heat source temperature for the evaporator with a primary wick with circumferential grooves shows temperatures up to 50% lower than when using the one with axial grooves, which is a major gain on the overall LHP performance.

Loop Heat Pipe Design Considerations

The development of the loop heat pipe (LHP) technology for specific space applications has resulted in great advances regarding the design of capillary evaporators able to promote the heat management at lower heat source temperatures. As informations regarding the capillary evaporator design and optimization is not easily available, some features have to be implemented and tested in order to verify whether they will give the required results.

One of the most used configuration in capillary evaporators with an integral compensation chamber (CC) applies axial grooves on the primary wick outer diameter. Depending on the design of the primary wick a certain number of grooves can be implemented in order to result in a better thermal performance for the LHP. Several authors have reported this kind of primary wick configuration and how reliable the thermal behavior in LHPs can be achieved (Delil et al., 2003; Ku and Rodriguez, 2003; Riehl, 2004; Maydanik, 2005, Vlassov and Riehl, 2005). However, details on the primary wick exact geometry and features are rare as this represents the most important component of the capillary evaporator itself. Other characteristics on the evaporator design are also important, such as the secondary wick geometry and the internal surface of the capillary evaporator. In this case, micro-machining of the internal surface of the evaporator can promote a better heat transfer capability to this device. The secondary wick, being a challenging component to be simulated in order to obtain the correct influence of this part on the entire LHP behavior, also requires an special design as presented by Ku et al. (2001) when an arterial secondary wick was applied. Even though great advances on the development of LHPs have been observed during the last decade, the design of those devices still rely on the designer experience.

With the continuous development of the LHP technology performed in this institute, geometric features were applied to the capillary evaporator design in order to obtain a better thermal performance. Some geometric changes were applied in order to compared the results with classical capillary evaporator design. The features applied are related to circumferential grooves machined on the primary wick outer diameter, as well as microgrooves on the evaporator inner diameter and a secondary wick made of stainless steel screen mesh with arterial grooves. The results gathered with this new capillary evaporator design implemented in a LHP were compared to the results previously presented for another LHP that has axial grooves machined on the primary wick outer diameter (Riehl and Siqueira, 2005). Extensive life
tests using this new geometry were performed for a LHP using acetone as the working fluid with an interest in qualifying this fluid for future space applications. Thus, this paper presents the performance improvement achieved with this new capillary evaporator design, as well as presents the comparison with previous results related to the life tests of another LHP.

**Improvement on the Capillary Evaporator Design**

The most used internal configuration for capillary evaporators for both loop heat pipes and capillary pumped loops presents axial grooves machined on the primary wick outer surface. In this case, the groove geometry must be able to give a reliable operation to the device, collecting the vapour properly and not presenting localized dryout. However, depending on the primary wick outer diameter, it is not possible to make the required grooves and, sometimes, capillary evaporators with axial grooves can present a thermal behaviour that is not in agreement to what has been expected. Such a behaviour was found on a previous design named TCD-LHP2 where axial grooves were machine on the primary wick outer diameter. Even though the device would present a reliable operation, the capillary evaporator and operation temperatures were very close to the limit imposed by the project (Riehl and Siqueira, 2005 and 2006).

As a better thermal performance was necessary, some modifications on the internal geometry of the capillary evaporator were performed for this new device that has been under life tests in laboratory conditions, named here as TCD-LHP3. The capillary evaporator for this LHP presents the following features: primary wick with circumferential grooves machined on its outer surface with a single axial groove for vapour collection, microgrooves machined on the evaporator inner diameter and arteries made on the secondary wick structure. Differently from the TCD-LHP2 capillary evaporator design, which presented around 1,500 microgrooves per meter, the new design, here called as TCD-LHP3, was considerably improved as it presents around 2,500 microgrooves per meter (0.2 mm wide, 0.2 mm in depth). This change was considered necessary after some calculations in order to improve the heat transfer mechanism between the evaporator housing and the saturated working fluid. However, the most important change made on the TCD-LHP3 capillary evaporator was related to its primary and secondary wick structures. Even though the arteries of the secondary wick and micro-grooves on the evaporator inner surface seem to increase the thermal performance of the LHP, the circumferential grooves were found to highly contribute to this improvement. The geometry with circumferential grooves machined on the wick’s outer surface and only one axial groove responsible for the vapor collection was simulated and implemented in the capillary evaporator design. The characteristics of the circumferential grooves were also changed in order to accommodate a more effective geometry, which was proved to show better thermal behavior during the simulations (Riehl, 2002; Vlassov and Riehl, 2006). The machining process was much easier with the circumferential grooves as well as the wick’s insertion in the evaporator housing. With this new geometry, more grooves and greater contact area between the wick and the evaporator housing were achieved for the same active length used with the TCD-LHP2 design as well. Figure 1a presents the circumferential grooves machined on a UHMW polyethylene and sintered nickel. It is very important to point that after the machining process to make the grooves, the wick structures were verified in microscope to certify that the pores were not closed. Figure 1b shows the arteries made on the secondary wick structure.

![Figure 1](image1.png)

Figure 1: Geometry characteristics for both primary and secondary wick structures.
The changes on the LHP geometries are presented on Table 1. As both TCD-LHP2 and TCD-LHP3 present the same active length as well as the same lengths for the liquid and vapour lines and condenser, it becomes important to perform a comparison regarding the thermal behaviour of those devices.

![LHP Schematic](image)

**Figure 2: LHP schematic.**

### Performance Tests and Discussion

For a primary comparison between both LHPs tested, a power step routine was performed where the devices are started at low heat load and then it is increased until a certain level that does not represent harm to the materials used to build the LHPs. In this case, for both devices, the power step test was performed for a sink temperature of 0 °C at a controlled room temperature varying within 18 and 20 °C. Figure 3 presents the power step tests for both LHPs.

From Fig. 3 it is possible to observe that the TCD-LHP2 maximum heat load was 100 W for the evaporator body (Tevap) temperature around 110 °C, while the TCD-LHP3 presented a maximum temperature around 82 °C for 120 W. This primary performance test shows that the TCD-LHP3 presents, for 100 W of heat load, the evaporator temperature 36% lower than the TCD-LHP2 which represents a remarkable gain on the overall thermal performance for the LHP. On the same way, tests with the TCD-LHP3 present the possibility of applying higher heat loads to this device while presenting better thermal performances associated with lower heat sources temperatures even when using an alternative and less efficient working fluid such as acetone. However, to better analyse the LHP improvement with the circumferential grooves life tests have to be performed and compared with the TCD-LHP2 results.

<table>
<thead>
<tr>
<th>Capillary Evaporator</th>
<th>Liquid Line</th>
</tr>
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<tbody>
<tr>
<td>Total Length (mm)</td>
<td>100</td>
</tr>
<tr>
<td>Active Length (mm)</td>
<td>67</td>
</tr>
<tr>
<td>Outer/Inner Diameter (mm)</td>
<td>19.0 / 16.5</td>
</tr>
<tr>
<td>Material</td>
<td>316L SS</td>
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<table>
<thead>
<tr>
<th>UHMW Polyethylene Wick</th>
<th>Condenser</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pore Radius (µm)</td>
<td>Outer Diameter (mm)</td>
</tr>
<tr>
<td>Permeability (m³)</td>
<td>Inner Diameter (mm)</td>
</tr>
<tr>
<td>Porosity (%)</td>
<td>Length (mm)</td>
</tr>
<tr>
<td>Diameter (OD/ID) mm</td>
<td>Material</td>
</tr>
<tr>
<td>Number of grooves (TCD-LHP3)</td>
<td>21 (circumferential)</td>
</tr>
<tr>
<td>Number of grooves (TCD-LHP2)</td>
<td>14 (axial)</td>
</tr>
</tbody>
</table>

<table>
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<tr>
<th>Vapour Line</th>
<th>Compensation Chamber</th>
</tr>
</thead>
<tbody>
<tr>
<td>Outer Diameter (mm)</td>
<td>4.85</td>
</tr>
<tr>
<td>Inner Diameter (mm)</td>
<td>2.85</td>
</tr>
<tr>
<td>Length (mm)</td>
<td>550</td>
</tr>
<tr>
<td>Material</td>
<td>316L SS</td>
</tr>
</tbody>
</table>

The condenser of both LHPs was the cover plate (300 mm x 300 mm x 4 mm thick) of a heat exchanger with embedded channels circulating a mixture of 20% of water and 80% of ethylene-glycol so condensation temperatures of ~20 °C could be achieved during the tests. The heat loads were administrated to the capillary evaporator using a kapton skin heater (70 x 25 mm, 14 Ohms), attached to an aluminum saddle (alloy 6061), which were controlled by a DC power supply. Twenty type-T thermocouples (deviation of ±0.3 °C at 100 °C) are used to monitor the temperatures, which are read and recorded by LabVIEW software. The working fluid inventory was 25 grams of acetone for a compensation chamber with 50% of void fraction in the cold mode. An schematic of the LHPs used in this investigation is presented in Fig. 2.
During the TCD-LHP3 operation, it has been observed that at higher heat loads administrated to the capillary evaporator, the evaporator and operation temperatures could be up to 50% lower than those found during the tests with the TCD-LHP2, even when using an alternative and less efficient working fluid such as acetone, as presented by Fig. 4 where heat load profiles were performed. During all tests, reliable start-ups were observed with the TCD-LHP3 and considerably reduced time to reach the steady state was necessary. Upon comparing the TCD-LHP3 results with those for the TCD-LHP2, it is clear that the evaporator temperatures were considerably lower, for some power level, around 50% lower than what it was observed for the TCD-LHP2, as presented by Fig. 5.
From the experimental results, it can be said that as the microgrooves machined at the evaporator’s inner wall are very small, when the primary wick structure is in place, the microgrooves hold liquid prior to the capillary evaporator start up. As the circumferential grooves and the microgrooves are on the same direction, most of the liquid that is held in the microgrooves internal volume cannot be displaced when the evaporator starts its pumping activity. As the liquid is trapped in the microgrooves, this effect seems to represent an important parameter that contributes to reduce the contact thermal resistance between the primary wick and the evaporator housing, which contributes to reduce the evaporator temperature. On the same way, the secondary wick structure with its arteries is efficiently promoting the liquid exchange between the compensation chamber and the evaporator core, which also represents an important parameter. As lower heat leaks seem to be in effect in this new design, all these factors contribute to lower the evaporator and compensation chamber temperatures resulting in a better thermal performance for the LHP. Also, this effect is highly influenced by the increase on the heat transfer area achieved with the circumferential grooves. Even with the increase on the design complexity presented by this investigation, the results show that the effort is well worthy in order to have a LHP that presents lower evaporator and operation temperatures. The effects on the capillary evaporator temperature can be better seen on Fig. 6a where the evaporator temperatures for both TCD-LHP2 and TCD-LHP3 can be directly compared, showing the efficiency achieved when using the circumferential grooves. From this comparison, it is clear that the TCD-LHP3 presents considerable lower capillary evaporator (heat source) temperatures which highly influence the overall LHP performance when compared to the TCD-LHP2. As mentioned before, the other improvements on the LHP geometry resulted in reduced heat leaks that greatly contributed to decrease the thermal resistances between the capillary evaporator and compensation chamber observed during the tests, as represented by Fig. 6b. Even though the simulation model could predict such an improvement on the thermal performance, the experimental tests showed outstanding results.

![Figure 6: Overall performance comparison: (a) evaporator temperature slope and (b) thermal resistances.](image)

From the overall experimental results presented for different condensation (sink) temperatures, it can be easily noted that the TCD-LHP3 with the improved geometric characteristics specially with the circumferential grooves shows better thermal behaviour when compared to the TCD-LHP2 that presents axial grooves. The reduced thermal resistances are specially important to be evaluated as the LHP could operate at higher heat loads while keeping the evaporator temperatures at lower levels, which is very important to be considered with using an alternative and less efficient working fluid such as acetone.

**Concluding Remarks**

The current development of the LHP technology performed in this institute for future space applications, specially for satellites, has resulted in several advances towards the achievement of a reliable system able to promote the passive thermal control of electronics, structures and other equipments. Important advances have been obtained upon using alternative working fluid, specially acetone, to substitute the so-used ammonia due to its high hazard and costs. Life tests performed in laboratory have demonstrated the possibility of long-term use of acetone with acceptable behaviour of the LHPs tested. This development
has presented several advances, which were showed in this paper and the summary of the conclusions that
could be taken from this investigation are as follows:

- the life tests have demonstrated the possibility of using acetone as working fluid in LHPs for future
  space applications;
- the improvements on the geometry for the capillary evaporator used on the TCD-LHP3 proved to be
  extremely efficient, resulting in reduced evaporator (heat source) temperatures as well as reduced
  thermal resistances between the evaporator and compensation chamber;
- upon using primary wick with circumferential grooves and arteries on the secondary wick, along with
  microgrooves on the evaporator’s internal diameter, the TCD-LHP3 presents substantial improvement
  on its thermal behaviour when compared to the TCD-LHP2.

As the development of a reliable LHP continues, a device that uses the configuration of the TCD-LHP3
has been considered for future space applications. Following this path, the LHP has to undergo the
qualification tests (launching vibration tests, thermal vacuum performance tests and cycling, etc.) required
to certify it as a system that could be used in the satellite thermal control.

Acknowledgments

The authors wish to thank the financial support given by Fundação de Amparo a Pesquisa no Estado de
São Paulo (FAPESP), grants 03/08365-6, 03/11477-0 and 04/45578-9.

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