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THERMAL BEHAVIOUR OF MICROGROOVED CAPILLARY PUMPS FOR DIFFERENT THERMAL WORKING FLUIDS.

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Abstract. *Experimental results of a circumferentially grooved capillary pump under transient and steady state condition are presented. The test facility consists of one capillary evaporator, one condenser, vapor and liquid lines, and a reservoir to control the temperature and liquid inventory of the system. The evaporator is based on a internal circumferentially grooved aluminum tube as the capillary structure. The start up, transient and steady state behaviors, capillary limit, reprime ability are the main objective of this work, using both acetone and ammonia as working fluids. Power input up to 20 W (0.73 W/cm²) and 75 W (2.73 W/cm²) was measured for acetone and ammonia, respectively.*

Keywords: Capillary Pumps 1, Heat Transfer 2, CPL 3.

1. Introduction

Most capillary evaporators are based on porous wicks made of sintered nickel powders, stainless steel, polyethylene, nylon or other porous structures material. Capillary evaporators are also known as capillary pumps, in general used to thermally control satellites in order to assure a well function of all electronic instruments on board. Heat pipes have been first put forward as passive thermal control device to remove heat from satellites (Chi, 1976 and Dunn & Reay, 1994). In the last four decades heat pipes have been successfully used in a number of industrial and space applications as a very effective heat exchanger device in a passive mode, even at small temperature difference between the heat source (evaporator section) and heat sink (condenser section). A capillary structure was proposed as the means for returning the liquid from the condenser to the evaporator. Currently, the heat pipe technology evolved to capillary evaporators, where no wick is required along the liquid/vapor transport lines and condenser section. Heat pipes, oscillating/pulsating devices (Delil, 2003), capillary pumped loops (CPL) and loop heat pipes (LHP) are all alternative techniques, mainly to thermally control large satellites, where multi layer insulation is not sufficient. Small satellites can be thermally protected just using reflective/absorption surfaces with appropriate properties as insulation.

The CPL is a promise alternative design to be used as two phase heat exchangers loop. An important advantage of the CPL is the absence of any mechanical pump and vibrations. No external power is required to pump the working fluid inside the loop. CPL is more flexible also concerning the number of evaporators located at different positions. Design flexibility, associated to small pressure drops, may reduce the mass of the thermal control system, which is a basic requirement for airspace applications.

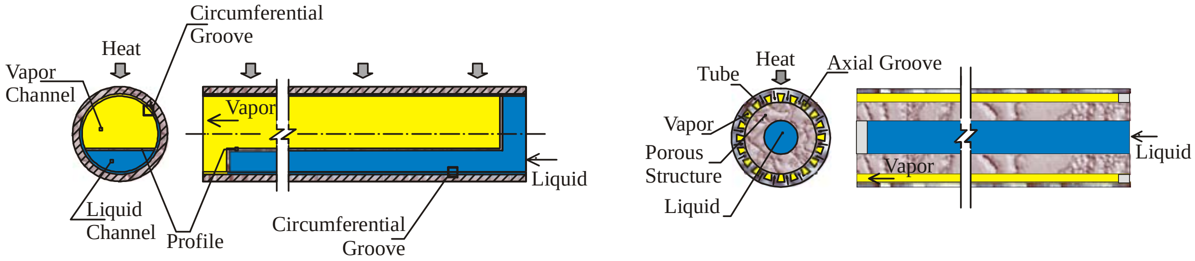
In order to assure reliability, most heat pipes have grooved surfaces as capillary structure. On their side, most capillary pumps have porous wicks as capillary structures. It is well known that the prime purpose of the wick is to generate capillary pressure to transport the wick from the condenser to the evaporator. However, porous wicks are very susceptible to dryouts due to thermal loads oscillations, non condensable gases and even during start ups (Ku, 1993). Despite their low capillary pumping pressure when compared to porous wick, in general, circumferentially grooved wicks have demonstrated unfailing startups and reliable operation even in presence of vapor bubbles or non condensable gases inside the liquid core of the capillary pump (Camargo y Bazzo, 2002). In this work, experimental results for a circumferentially grooved capillary pump under transient and steady state operation are presented. Acetone and ammonia were used as working fluids. The test facility consists of one capillary evaporator, one condenser, vapor and liquid lines, and a reservoir to control the temperature and liquid inventory of the system.

2. Capillary pumped loop

A capillary pumped loop is a two phase flow system able to transport heat even at small temperature difference. It consists of evaporators, condensers, liquid and vapor lines as well a reservoir to control the temperature and liquid inventory of the system. The working fluid flows by the superficial tension developed in the capillary structures. The capillary structure is only required at the evaporator section. CPLs are widely investigated to be trustable in thermal management of electronic panels of satellites and space stations.

A compatible and leak-proof container is required to isolate the working fluid from the outside environment. Generally, the container of the capillary pump is made of stainless steel or aluminum tube designed with liquid and vapor channels connected all the way through microgrooves or porous structure to assure sufficient force for displacing the working fluid inside the loop. In Figure 1 (a) is shown a circumferentially microgrooved capillary pump schematic. In Figure 1 (b) is shown a porous wick capillary pump schematic. Different types of porous wick material have been tested, including Teflon®, polyethylene, sintered stainless steel and sintered nickel. Only porous material or microgrooved surface have capacity to overcome the pressure drop and to assure the fluid circulation inside the loop.

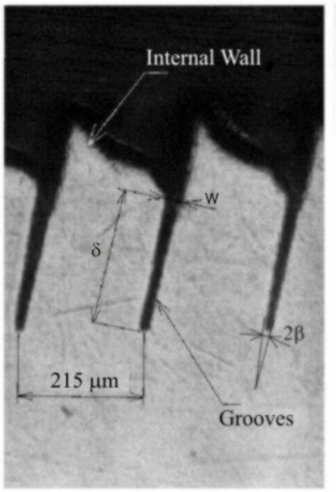
The porosity and effective porous radius are very important properties to determine the capillary pumping capacity. Metallic and ceramic porous materials have been made at UFSC with porous size between 0.3 and 12 µm. For ceramic porous material and acetone as the selected working fluid, pumping pressure up to 100 kPa have been measured (Reimbrecht, 2004).



(a) (b)

Figure 1 – Geometry used in capillary pumps: (a) Circumferentially grooved pump, (b) Porous wick pump.

Circumferentially grooved capillary pumps were proposed by ERNO – Raumfahrttechnik GmbH and IKE (Institut für Kernenergetik und Energiesysteme) from Germany and first results regarding ground testing were presented by Bazzo (1996), using Freon 11 as working fluid. First microgravity experiment was performed just in 2006, at ISS (International Space Station, in this case for safety reasons, using deionized water as the working fluid (see www.aeb.gov.br). The capillary evaporator had internally machined circumferential grooves in a ¾" diameter aluminum tubes with an average opening of 33 µm at 215 µm step, as shown in Figure 2. A flat profile is used to separate the liquid from the vapor channel, as shown in Figure 1. The smaller the opening width the higher the corresponding capillary pumping pressure. In this work, the corresponding capillary pumping pressure was measured around 1.5 kPa (Camargo, 1999).



Groove dimensions:

$w = 33 \pm 7 \mu m$
$\delta = 310 \pm 59\ \mu m$
$\beta = 0.6 \pm 0.4\ °$

Figure 2 – Micrograph image of the capillary pump groove.

A major problem is the presence of gaps at the interface between the profile and the internal wall of the tube. The presence of these gaps can significantly reduce the capillary pumping pressure. Depending on the power applied, the loop pressure drop can compromised the capillary pump mainly function by exceed its capillary pressure. This maximum capillary pressure can be found by

$$\Delta p_c = \frac{2\sigma\cos(\theta)}{r_c} \qquad (1)$$

where: σ = superficial tension of the refrigeration fluid
r_c = capillary effectivity radius
θ = angle between the capillary structure and the meniscus

In the ideal case where there are no gaps, the capillary effectivity radius can be calculated by following equation described in Bazzo et al. (1999):

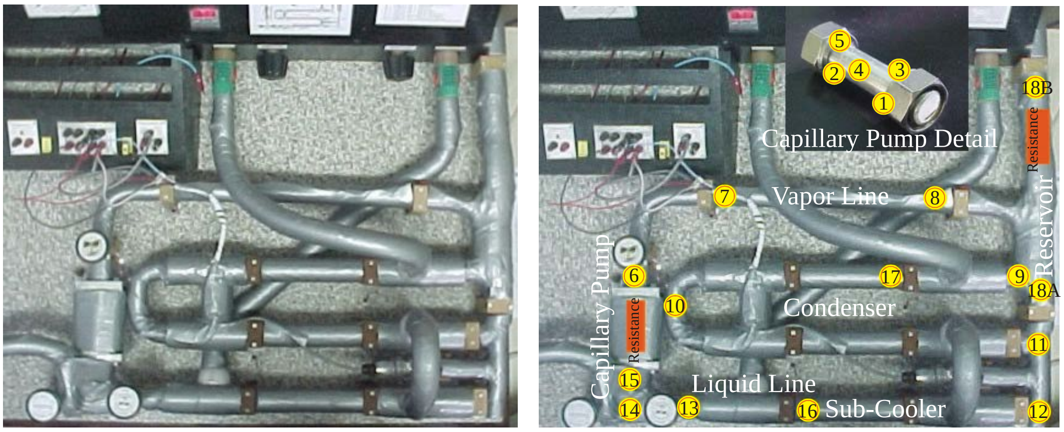
$$r_c = 2\cdot\frac{\cos\beta}{1-\mathrm{sen}\,\beta}\cdot\left(\frac{w}{2}-\delta\cdot\tan\beta\right) \qquad (2)$$

where: β = half angle of groove aperture
δ = depth of the groove
w = width of the groove

3. Experimetal setup and testing procedures

The experimental setup used for testing is shown in Figure 3. In general it is composed of the CPL controlled by one DC power supply, one cryostat and a data acquisition system connected to a computer. The cryostat is required to remove heat from the condenser to a heat sink. A vacuum pump and a pressure sensor have been used for charging the system, first with acetone and later with ammonia. The system was charged at first time with 115 g of acetone (99.5%) and at a second time with 87 g of pure ammonia (99.999%). The power input is provided by an external DC power supply.

Figure 3 – Experimental setup: general view.

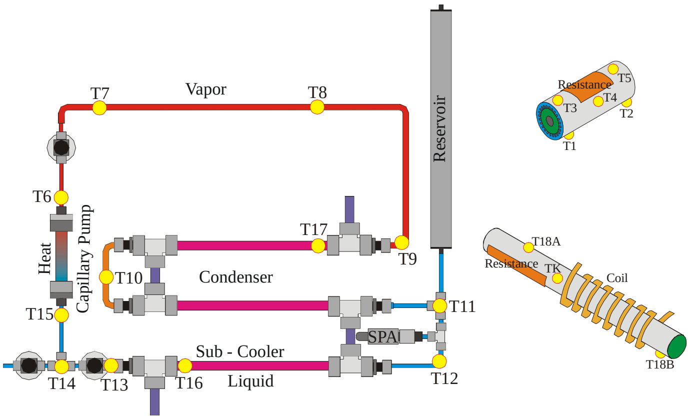


(a) (b)

Figure 4 – The CPL: Superior view (a) and thermocouples location (b).

The CPL itself is shown in details in Figure 4 and Figure 5. The CPL is composed of the capillary evaporator, a reservoir, the liquid and vapor lines, and a heat exchanger for condensing and sub-cooling the working fluid. The experimental apparatus has an absolute pressure sensor (SPA) and 18 thermocouples Omega type T (±0.5°C), all them distributed along the loop (see also Figure 5). A thermostat was used for automatic controlling of the reservoir temperature. The acquisition system is connected to a computer, for every three seconds data storing of the temperature, electrical power inputs and absolute pressure readings. According to Figure 5, following the working fluid flow direction, the thermocouples number 1 to 5 are located at the evaporator section, from 6 to 8 along the vapor line, from 9 to 12 at the condenser section, from 13 to 15 along the liquid line and 18A and 18B at the reservoir. The thermocouples 16 and 17 are located at water cooling inlet and outlet condenser, respectively.

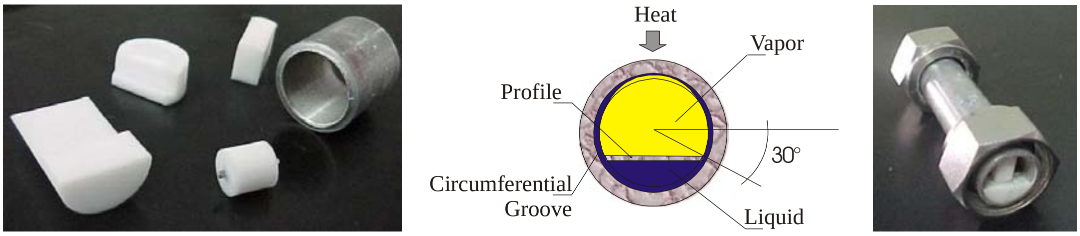
The reservoir is required to control the temperature operation and liquid inventory inside the loop. The liquid line is assembled using 915 mm stainless steel tubing with internal diameter of 4.3 mm. The vapor line is assembled using 2005 mm stainless steel tubing with internal diameter of 7 mm. The condenser (750 mm of length), followed by a sub-cooler (350 mm of length), is arranged as a counterflow heat exchanger single pass concentric tubes. The heat exchanger is assembled using 10 and 15 mm external diameter stainless steel tubes, respectively. The working fluid (hot fluid) and cryogenic water at -5°C (cold fluid) enter in the opposite ends of the heat exchanger and flow in opposite directions. The reservoir is assembled using a stainless steel tube, in this case with 1 inch of external diameter and 450 mm in length. It is located on a horizontal position to avoid any additional induced pressure inside the loop.



T1 - CP Inferior Inlet
T2 - CP Inferior Outlet
T3 - CP Superior Inlet
T4 - CP Lateral Half
T5 - CP Superior Outlet
T6 - Vapor Channel
T7 - Vapor Line
T8 - Vapor Line
T9 - Condenser Inlet
T10 - Condenser Half
T11 - Condenser / Reservoir Outlet
T12 - Sub-Cooler Inlet
T13 - Sub-Cooler Outlet
T14 - Liquid Line
T15 - Liquid Line
T16 - Cryostat Inlet
T17 - Cryostat Outlet
T18 - Reservoir Half

Figure 5 – Schematic of the CPL and thermocouples location.

The capillary evaporator has an external diameter of ¾” (18.5 mm) and a length of 95 mm. Only 55 mm was reserved to fix the resistance. The power input is applied throughout an electric resistance (13 ± 0.1 ohms) fixed on the outer surface of evaporator, as shown in Figure 5. Basically, the capillary evaporator consists of a circumferentially microgrooved aluminum tube with a metallic profile (martensitic stainless steel) inserted at an angle of 30° location, as shown in Figure 6 (b), to separate the liquid from the vapor channel. This metallic profile is fixed with Teflon® end caps (see Figure 6 (a)) to assure complete absent of gaps along the internal interface grooved wall. The presence of gaps reduces the capillary pumping capacity of the microgrooved surface. For acetone, for instance, the maximum capillary pumping pressure of the capillary pump used for testing was measured to be 1135 ± 90 Pa.



(a) (b) (c)

Figure 6 – The capillary evaporator: (a) Used pieces, (b) Internal configuration, (c) External view.

The testing procedure was planned in order to evaluate the following points:

1. The startup;

2. The thermal behavior at steady state;
3. The reprime reliability after dryout;
4. The CPL sensibility for sudden variation of power input;
5. The CPL sensibility at small power inputs.

Before any testing, the CPL has been first prepared, flooding the whole loop by heating the reservoir up to the temperature operation loop. To assure a successful startup, no vapor bubble is allowable at inlet liquid capillary evaporator. The cryostat is also turned on to provide the heat rejection from the condenser.

Once the startup is successful, the loop has been left in steady state operation, continuously, at least up to 2 hours, or up to no more variations is observed on the temperature readings.

The power input is then increase step by step, successively, up to the capillary evaporator dryout. The higher the power input the higher the vapor mass flow inside the loop and so the higher the vapor and liquid pressure drop along the whole loop. The capillary limit is reached when the total pressure drop increases up to the maximum capillary pumping pressure of the system. According to theoretical results, a significant increase in the heat exchange has been shown simply change the working fluid from acetone to ammonia (Camargo, 1999). When the capillary pressure is achieved, the fluid circulation stops and so the capillary pump is let to dryout. For safety reasons, the maximum external surface capillary evaporator temperature was limited to 100 °C.

The CPL reprime reliability after dryout has been tested, returning the loop to the normal operation just reducing the power input. This fact is crucial to qualify refrigeration systems for thermal control of satellites. In case of required shut down to return to a normal operation, the CPL will be considered inadequate.

The CPL sensibility at small power inputs and for sudden variation of power input has been also tested. To test the influence of the mass flux inside the system, low power input has been applied to the electrical resistance. Low power inputs mean low liquid mass flows reaching the capillary evaporator. At this scenario, the working fluid is susceptible for warming up to the saturation temperature and undesired bubbles formation can grow up and block the system. So, to avoid dryout and allow normal operation, very low subcooled temperatures should be required.

Temperature oscillations, non condensable gases and environmental temperature changing have been also considered for analysis.

4. Results

Experimental tests were carried out for analyzing the thermodynamic behaviors of the working fluids, concerning startup, transient and steady state operation, the reprime reliability after dryout as well as the sensibility for sudden variation of power input. During all the tests the temperature of the cryostat was fixed at -5°C. The reservoir temperature had been chosen in the range from 25 to 35°C depending of the test. The experimental results are presented for ammonia and acetone as working fluids.

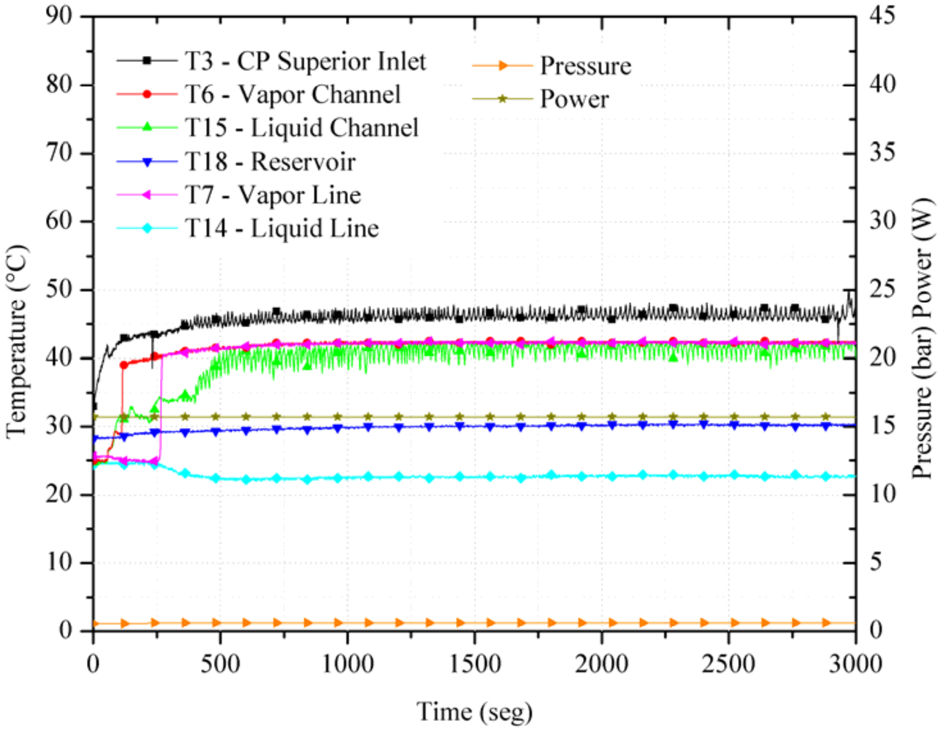


Figure 7 – Startup and thermal behavior, using acetone as working fluid.

The thermal behavior of the CPL using acetone is shown in Figure 7 for power input equal to 15 W and reservoir temperature fixed in the order of 30 °C. The start up was successful, reaching the steady state operation after 9 minutes.

The thermal behavior was satisfactory, even though the metal temperature oscillations. At steady state operation, the feeding liquid remains subcooled as desirable, but the vapor temperature is 10ºC higher than the reservoir temperature, therefore suggesting the presence of non condensable gases inside the CPL. The inlet liquid temperature is smaller than the reservoir temperature. So, it is clear that there is no vapor bubble inside the liquid channel, but on the other side it seems clear an unpleasant presence of non condensable gases and so in some measure explaining the relatively high metal temperature oscillations. An influence analysis of vapor bubbles and non condensable gases on the CPL operation has been already reported by Camargo et al (1998) and Camargo y Bazzo (2002). Unlike the porous wick capillary evaporators, circumferentially grooved wicks have demonstrated reliable operation even in presence of vapor bubbles or non condensable gases inside the liquid core of the capillary pump. Anyhow, further analysis is still required to better be aware of the physical properties influence on the capillary pump thermal behavior. For acetone, the maximum power input was 20 W or 0.73 W/cm², the point that the capillary evaporator was led to the dry out condition.

In Figure 8 is shown the thermal behavior using ammonia as the working fluid, in this case, for power input around 50 W and reservoir temperature also fixed about 30 °C. The start up was also successful, reaching the steady state operation after 30 minutes. The whole system worked properly. Unlike the previous analysis, here just slightly temperature oscillations were observed. At steady state operation, the feeding liquid remains subcooled and the vapor temperature is approximately equal to the reservoir temperature. Therefore, there is no vapor bubble and nor non condensable gases at capillary pump inlet. For ammonia, due to technical restrictions, the capillary pump was tested up to 75 W or 2.73 W/cm², below the heat load capillary limit.

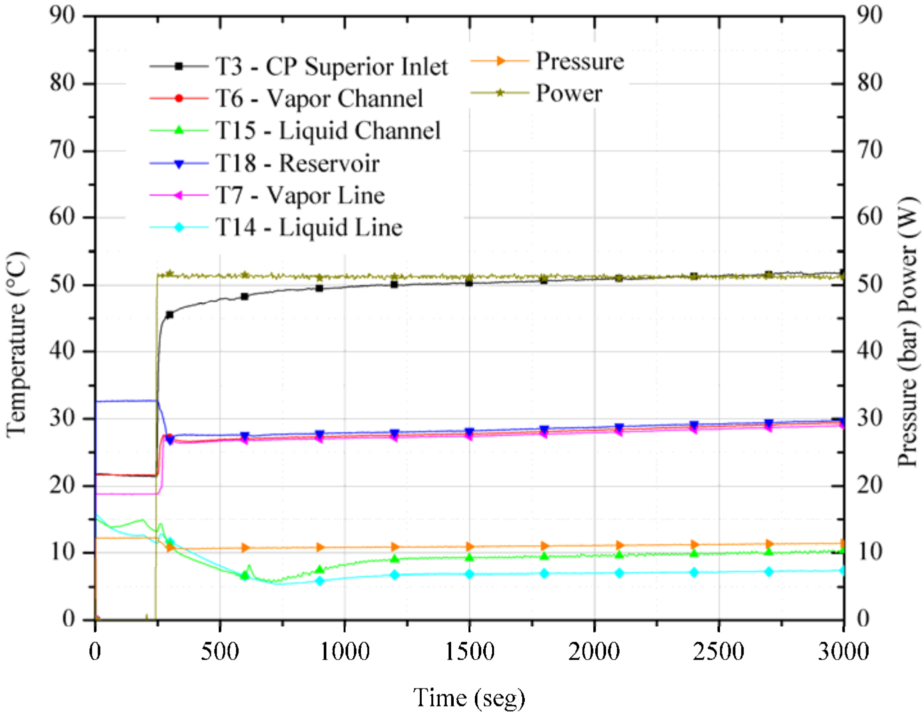


Figure 8 – Startup and thermal behavior, using ammonia as working fluid.

In Figure 9 is shown the thermal behavior corresponding to successful 6 hour steady state operations of the CPL at power inputs of 16 W and 33 W for acetone and ammonia as working fluids, respectively. The reservoir temperature was fixed in order of 30° for acetone and 32°C for ammonia. The higher heat load capability and smaller temperature differences between reservoir and evaporator are important advantages in favor of ammonia. The pressure level operation should be an advantage in favor of acetone as the working fluid.

In Figure 10 experimental results are shown, again for reservoir temperature set around 30 ºC, concerning the startup and transient operation using ammonia and acetone as working fluids. For acetone, the power input was applied stepping from 8, 16 and finally 28 W. After 300 seconds the startup was successful and the system worked suitably for 2650 seconds (approximately 45 minutes). At this time, a 28 W power input applied to the capillary pump led it up to the dryout. At steady state operation, the feeding liquid remains subcooled as desirable, despite the oscillations. The vapor temperature goes up to 20 ºC higher than the reservoir temperature. In general, no significant change on the vapor channel temperature was observed while in operation. For ammonia as working fluid, the power was applied stepping from 10 to 53 W. For 10 W power input, the reservoir, vapor channel and capillary pump temperatures remains approximately the same value. Just after 1500 seconds testing (25 minutes), a very little difference between the reservoir and capillary pump temperatures around 5 °C is observed. This fact is also an advantage and qualifies the ammonia for a number of applications where low difference of temperatures between the heat source and heat sink are design restrictions. In both cases, for acetone and for ammonia, the higher power input, the higher mass flow rate and so the lesser the inlet liquid temperature, reducing the oscillations and making a more reliable operation of the capillary pump.

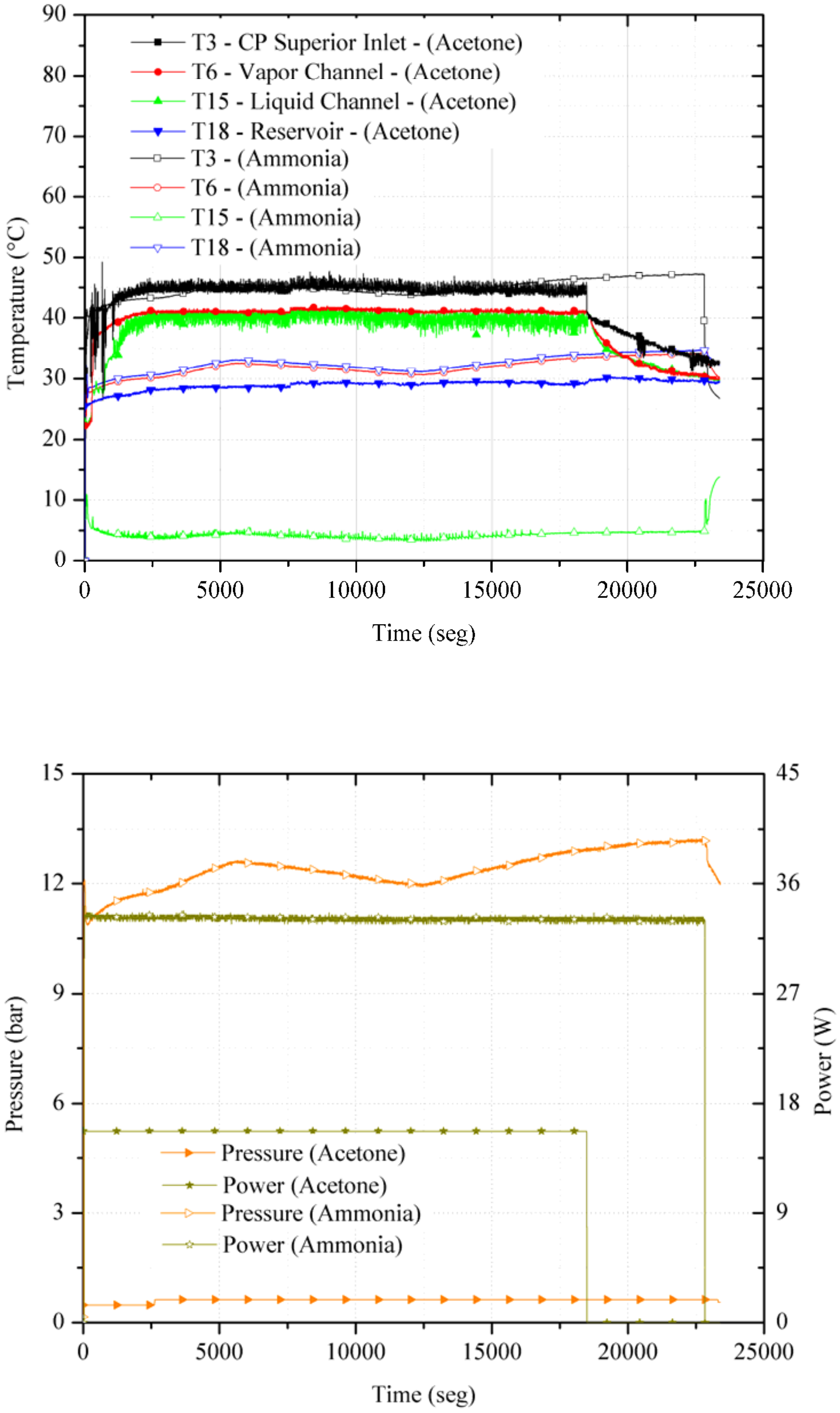


Figure 9 – Steady state operation using ammonia and acetone as working fluid.

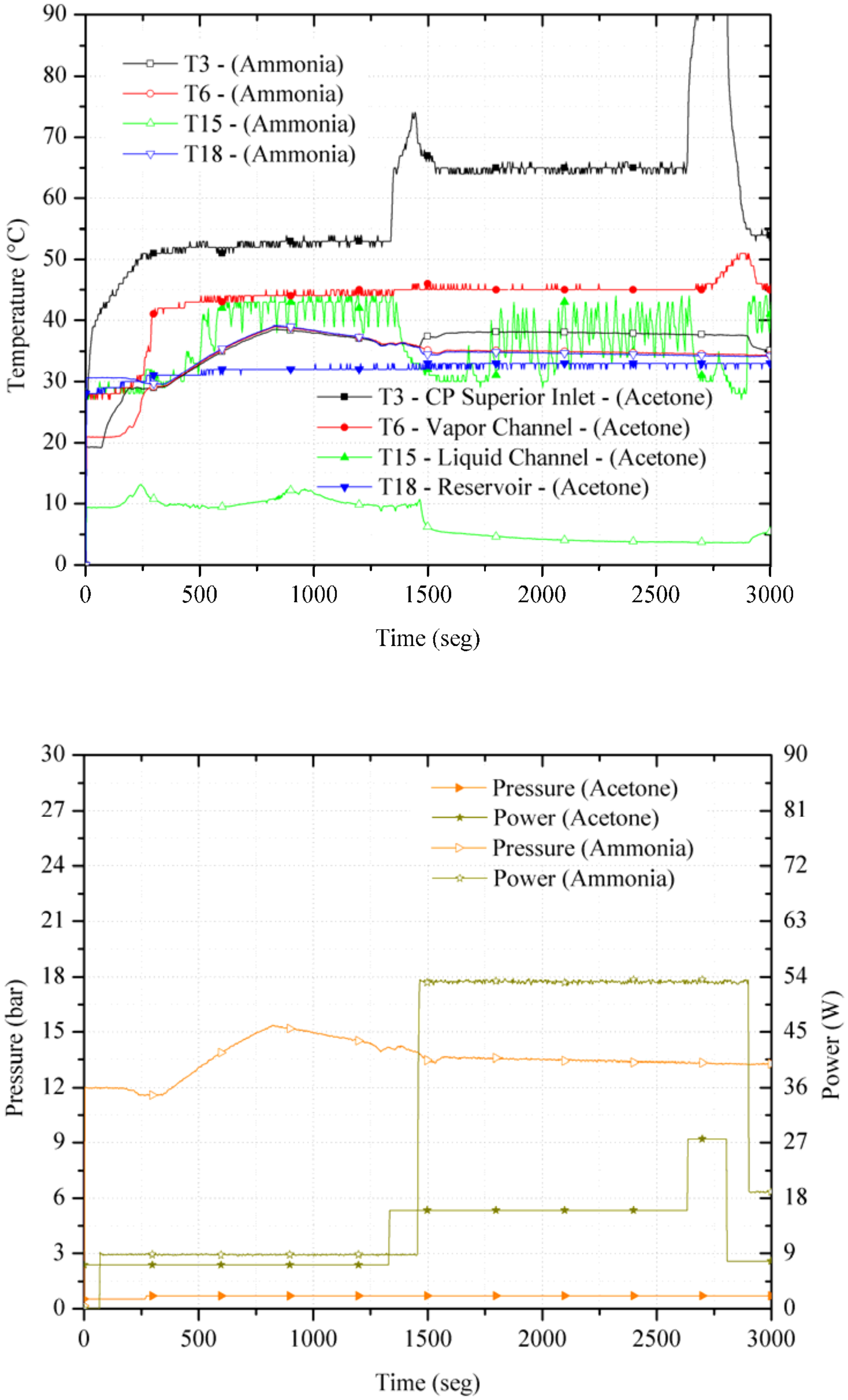


Figure 10 – Capillary pumped operation using ammonia and acetone as working fluids.

In Figure 11 is shown the transient operation using ammonia as working fluid, for power input stepping from 4 to 75 W. In this case, the reservoir temperature was set 35 ºC. The CPL worked appropriately even changing continuously the heat load. The system started up successfully after 900 seconds (15 minutes), for 4 W power input. Due to power supply technical restrictions, the capillary pump was tested up to 75 W or 2.73 W/cm², below the capillary limit. The power supply is able to provide up to 90W depending on the resistance fixed on the evaporator. For the 13 Ω resistance used the power supply provides 75 W maximum. This power was completed dissipated by the CPL.

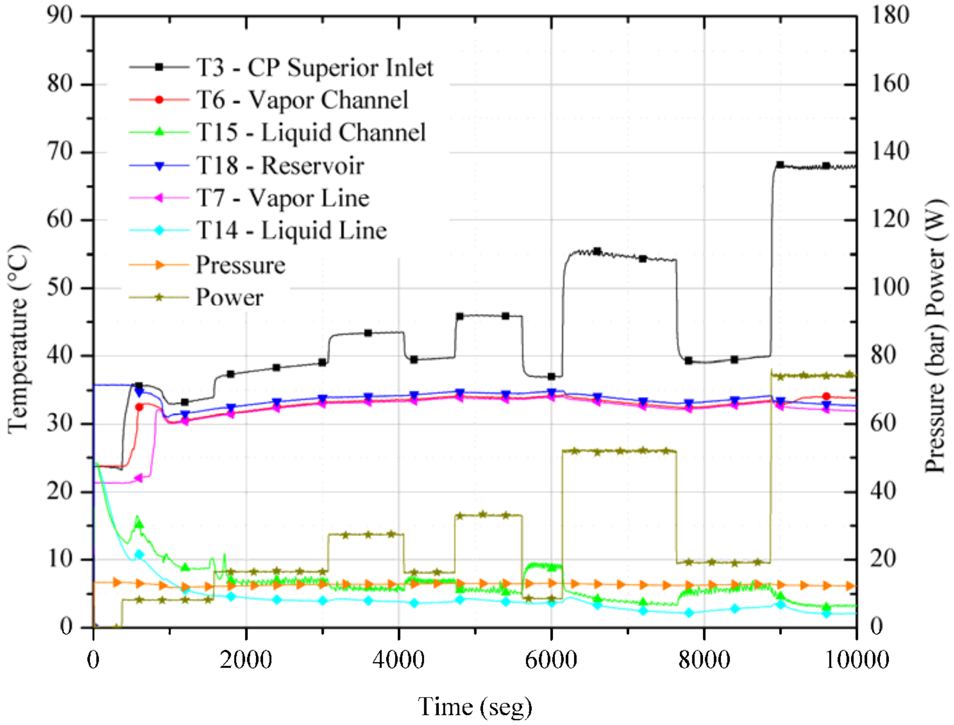


Figure 11 – Transient operation of CPL up to 75 W, using ammonia as working fluid.

In Figure 12 is shown the thermal behavior of acetone as working fluid, again for reservoir temperature set around 30 ºC, but now for power input stepping from 16 to 22 W. After 500 seconds the startup was successful and the system worked suitably for approximately 50 minutes. After this point, a 22 W power input led the capillary evaporator to dryout.

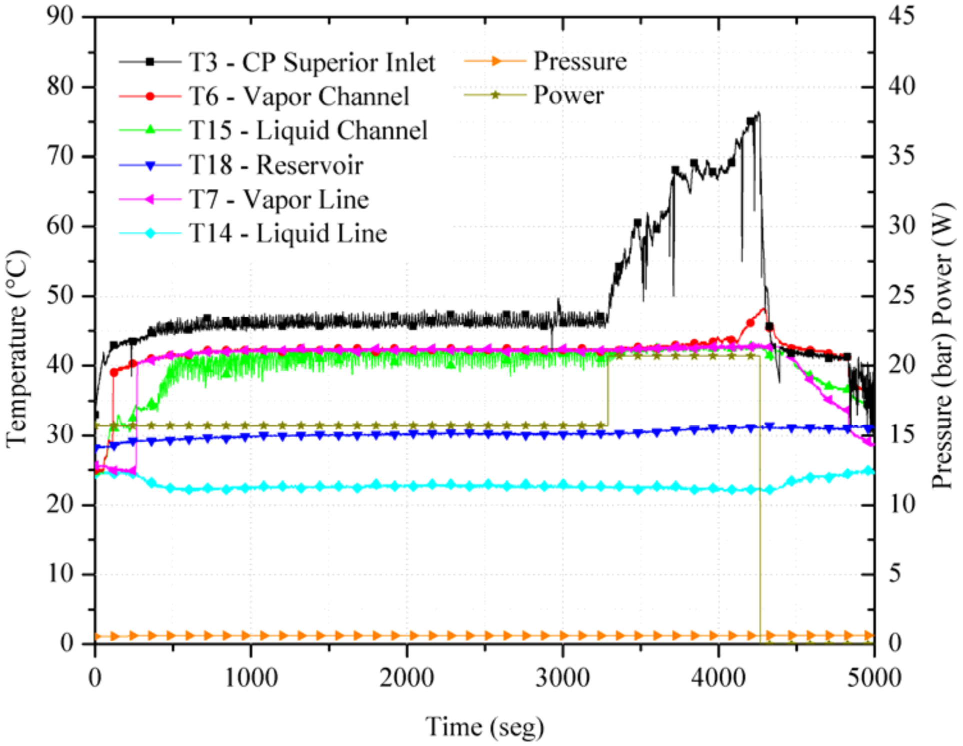


Figure 12 – Transient operation and dryout for acetone as working fluid.

Tests were carried out varying the operational temperature of the system by changing the reservoir temperature from 25, 30 and 35°C, with the purpose to verify the influence of the operational temperature into the results. In Figure 13, experimental data are shown for different reservoir temperatures and ammonia as the working fluid. In the case of 25°C, an unstable operation was noted, leading the capillary pump to dryout when the power input was increased to approximately 54 W. For 30 and 35°C, the CPL worked properly.

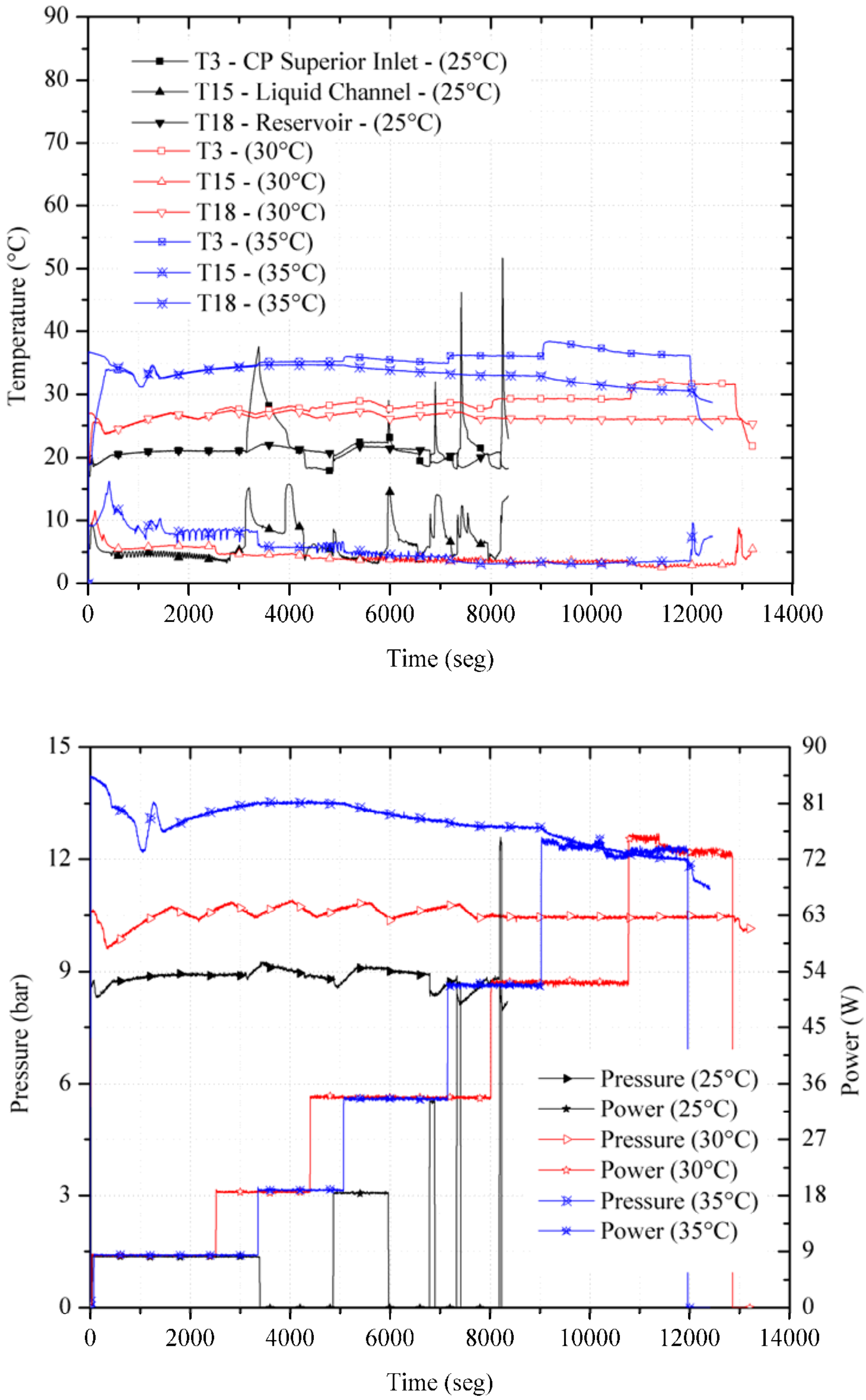


Figure 13 – Different operational temperature tests using ammonia as working fluid.

A new experimental setup is in preparation to cover power inputs up to 300 W in order to make sure the operational range of the capillary pump for any working fluid (acetone, ammonia, water etc). New tests will be carry out for searching operational limits of capillary pumps in a similar scheme for heat pipes, where capillary, sonic, viscous and also boiling limits were deeply studied (Chi, 1976). For capillary pumps, the capillary and boiling limits are more important.

5. Conclusion

The circumferentially microgrooved capillary pump has shown a successful start up and a satisfactory behavior at steady state condition, using both ammonia and acetone as the working fluid. Confirming theoretical results higher heat transfer is possible using ammonia as the working fluid. Using acetone, a maximum heat flux up to 0.73 W/cm² was measured, proving a capillary limit just around 20 W. On your turn, using ammonia as the working fluid, heat flux up to 2.73 W/cm² was measured. Higher values are still possible for ammonia, once technical limitations of the test facility did not allow power supply above 75 W. When compared to acetone, heat fluxes up to 4 times higher are expected if ammonia is used as working fluid. Ammonia is better for a number of applications where high heat loads and low difference of temperatures between the heat source and heat sink are mandatory. In general, when compared to porous wicks, circumferentially microgrooved capillary pumps presented some important advantages, concerning start up and repriming after dry out. A very easy repriming is possible, just reducing the power supply. Complementary studies are still required to better realize and establish a mathematical formulation for estimating the boiling limit in capillary pumped loops. Further testing is also still required at microgravity conditions to definitively qualify circumferentially microgrooved capillary pumps for space applications.

6. Acknowledgement

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COMPORTAMENTO TÉRMICO DE BOMBAS CAPILARES MICRORANHURADAS UTILIZANDO DIFERENTES FLUIDOS TÉRMICOS DE TRABALHO

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Resumo:

Neste trabalho são apresentados resultados experimentais de uma bomba capilar de ranhuras circunferenciais testada no seu início de funcionamento e em regime permanente. A bancada de testes consiste de um sistema com um evaporador, um condensador de tubos concêntricos, linhas de líquido e de vapor, e um reservatório para controle da temperatura e pressão do sistema. O evaporador é construído com um tubo de alumínio com ranhuras circunferenciais. O principal objetivo é comparar o comportamento térmico do CPL (CPL – Capillary Pumped Loop) utilizando diferentes fluidos de trabalho. Acetona e amônia são utilizadas como fluido de trabalho. Potências de até 25 W e fluxos de calor de até 0.73 W/cm² foram alcançadas com acetona como fluido de trabalho. Com a utilização de amônia, potências superiores a 75 W e fluxos de calor de 2.73 W/cm² foram medidas.

Palavras chave: Bombas Capilares, CPL, Transferência de Calor.