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INVESTIGATION OF A SMALL-SCALE CAPILLARY PUMPED TWO-PHASE LOOP APPLIED TO SATELLITE THERMAL CONTROL

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Abstract. *Focusing on the continuous growing of satellite and structures thermal control using capillary driven two-phase loops, this paper presents an experimental investigation of a capillary driven two-phase loop, configured on a capillary pumped loop (CPL) mode. Tests were performed with an internally grooved evaporator with a hollow polyethylene porous structure using acetone and anhydrous ammonia as working fluids. For a range of power applied to the evaporator, the system presented reliable start-ups and continuous operation for several hours for each working fluid. Comparing the operation of the CPL using two different working fluids, the system showed a better heat transport capability when anhydrous ammonia was used. The capillary evaporator depriming and re-priming was also experimentally investigated, which showed that the proposed CPL configuration is able to handle the porous structure dryout and promote its rewetting without major external interference.*

Keywords*. capillary pumped loop, thermal control, meniscus, and two-phase flow.*

1. Introduction

Capillary pumped loops (CPL) are considered reliable two-phase thermal management devices, mainly applied on satellites and structures thermal control. It operates passively by means of capillary forces generated on a porous structure present in the evaporation section, which is responsible for driving a working fluid from a high temperature source to a low temperature sink. Capillary pumped loops are part of a subject that has gained attention in research, which involve the capillary driven two-phase loops, such as heat pipes (HP) and loop heat pipes (LHP).

A CPL is basically composed of the following components: a capillary evaporator (responsible for generating capillary forces that drive the working fluid), a condenser, a two-phase reservoir (to control the loop's saturation pressure), liquid and vapor lines. The capillary forces are generated by the capillary evaporator, which acquires heat and transfer it to the working fluid. When latent heat starts being transferred to the working fluid, vapor starts being generated, which is responsible for the displacement of the liquid in the lines towards the condenser. The two-phase reservoir is used to set the operation temperature at which the entire loop will operate. The CPL works without moving parts, very little power consumption and the fluid is at its pure state without contaminants, which enables its use in microgravity. It passively promotes the thermal control, allowing fine adjustments on the operation temperature of components. A disadvantage of CPL is that it requires subcooling of the working fluid.

The CPL was first proposed by Stenger (1966) at the NASA Lewis Research Center but just received special attention in the late 70s. At this time, CPL began to be intensively investigated, which showed to be operationally reliable for using on thermal control, being able to transport heat over long distances with minor temperature difference. One issue related to the use of heat pipes in thermal control is its limitation on the maximum heat transport capability, which is mainly due to the presence of a porous wick over its entire length. In the case of a CPL, the porous wick is only presented at the capillary evaporator and the other components are usually smooth walled tubings. With this configuration, CPL is able to operate under high heat loads with very little hydraulic pressure loss.

Prior to the initiation of a CPL, the two-phase reservoir has to be heated so the operation temperature can be setup. The entire loop will then operate at this temperature with slight variations regarding some superheat or subcooling. Upon setting an operation temperature in the reservoir, the internal pressure will raise which will fill the entire loop with liquid, causing the so-called pressure priming. When the loop is filled with liquid, the CPL is ready to start operating. Then, heat is applied to the capillary evaporator and as its temperature rises, only sensible heat is transferred to the working fluid. When the evaporator's temperature reaches the same temperature as the reservoir, latent heat is transferred to the working fluid and it starts the evaporation process. A meniscus is formed at the liquid/vapor interface, which is responsible for developing the capillary pressure that will drive the working fluid. Vapor is displaced from the evaporator, which causes the displacement of the liquid in the channels allowing the vapor to reach the condenser. In the condenser, heat is removed and liquid will also present some subcooling. At the startup, the excess of liquid presented in the channels is displaced by the vapor back to the reservoir, which equalizes the right amount of working fluid for a given heat load.

With such particularities, the CPL has been used to transfer heat over long distances with small pressure drops over the entire loop, which allows its use in large systems. Capillary pumped loops have been tested over different configurations, and it is known to transport up to 8000 W when multiple capillary evaporators are used. This system is flexible to be in use if more than one heat source is present, as multiple capillary evaporators can be used. Upon setting the reservoir's temperature, a fine control of the temperature over the capillary evaporator can be achieved. This is especially important when a CPL is responsible for the thermal management of several electronics components and structural parts in satellites and the temperature must be carefully adjusted. Without moving parts and because a CPL is a thermal diode, the working fluid cannot flow from the condenser to the evaporator by the vapor line.

Great developments were achieved on CPL setups, mainly directed to the porous structures (called wick) presented in the capillary evaporator. Different materials have been used as porous wick such as sintered nickel, stainless steel, titanium and ultra-high molecular weight (UHMW) polyethylene. As the generation of capillary forces are dependent on the working fluid surface tension and wick pore size, CPL have been investigated using methanol, acetone and anhydrous ammonia as working fluids. Several investigations have been performed towards the achievement of sintered nickel components with fine pore sizes (Reimbrecht et al, 1999 and 2001). Fine pore sizes have been achieved when manufacturing wick structures using sintered components, which resulted in pore sizes as low as 3.0 μm. For such pore size and anhydrous ammonia as working fluid, capillary forces up to 15 kPa could be generated.

The working fluid must operate in its pure state, i.e. without impurities, as such condition is important to avoid the presence of non-condensable gases (NCG) in the loop. The presence of NCG in a CPL may cause a general failure of the capillary evaporator, but it is less suitable of occurring when compared to heat pipes. The presence of NGC can be minimized using compatible materials with the selected working fluid and also at the time of charging the CPL, by ensuring that a good vacuum condition is verified in the loop as well as using fluid with minimum contaminants.

Very few investigations were conducted toward to the use of small size capillary evaporator in order to manufacture a more compact CPL. Delil et al. (1997) reported that small evaporators have a tendency of depriming more easily probably due to an insufficient subcooled liquid supply to the porous wick. More information regarding this matter is not found in the open literature, but it is important to be investigated basically when more compact CPL need to be developed towards its use in microsatellites.

The objective of this paper is presenting an experimental investigation on a small-scale capillary pumped loop designed to be a payload of a microsatellite. The informations gathered in this investigation will help understand the particularities of reduced scale capillary evaporators and their potentials to be used as thermal management devices, as well as gain fundamental knowledge on the overall operation characteristics of CPL to variations on heat load applied and its capability on transferring and transporting heat when two working fluids are used.

2. Experimental Apparatus

For the present investigation, a small-scale capillary pumped loop (CPL) has been designed to accomplish the thermal management of up to 60 W transferred to its capillary evaporator. Such limitation is mainly due to the area available to the condenser that will give up to 60 W of rejected heat. This CPL was designed to be part of a payload of the Scientific French-Brazilian Microsatellite that will be launch in early 2004. The microsatellite will be placed on an equatorial orbit at 7 ° of inclination to the horizon, 700 km of altitude and will make a complete turn around the Earth each 100 minutes, being 60 minutes facing the sun and 40 minutes in eclipse. The CPL experiment had to be designed to work properly at the entire microsatellite orbit. Due to limited space, power and mass available to the CPL, some design aspects have to be considered.

Heat is to be applied to the capillary evaporator through an absorber plate and a skin heater while in orbit. The absorber plate is designed to transfer up to 30 W from the sun heat radiation to the capillary evaporator. A skin heater is responsible for delivering up to 20 W to the capillary evaporator during the eclipse period. A space radiator will reject heat from the CPL condenser to the space. A schematization of the French-Brazilian Microsatellite is presented on Fig. 1.

The characteristics of the CPL operation in orbit described above had to be carefully considered for testing it in laboratory. Thus, the CPL was designed to use a 90 mm long, 19 mm O.D, 12.7 mm I.D. internally grooved aluminum extrusion with 24 axial grooves as its capillary evaporator. A hollow UHMW polyethylene wick, with 7 mm I.D, 12.7 mm O.D, mean pore radius of 20 μm, porosity of 60 % and permeability of 10^{-12} m^2 has been used. A bayonet with 6.45 mm O.D. was place inside the capillary evaporator, delivering sub-cooled liquid direct to the liquid core in order to avoid an eventual failure of the evaporator. A representation of the capillary evaporator is shown on Fig. 2. The capillary evaporator was assembled on a test bed using 316 stainless steel tubing with 6.45 mm O.D. as liquid and vapor lines as well as condenser, on an overall length of 1200 mm. The two-phase reservoir was built with 316 stainless steel tubing with 25.4 mm O.D., 200 mm long. A screen mesh number 200 was placed at the reservoir's outlet in order to avoid that any bubble could migrate to the evaporator liquid core. The CPL test bed was placed horizontally to avoid any influence of the gravity force. Nineteen type-T thermocouples, with deviation of 0.3 K at 373 K, were used to read the temperatures throughout the CPL. An absolute pressure transducer (Omega model PX302-300AV) was used to monitor the loop's internal pressure and ensure that NCGs were not present. Comparing the respective saturation pressure related to the reservoir's temperature to the absolute pressure could show any presence of NCGs. Figure 3 presents the CPL experimental apparatus with all the instrumentation used. All instruments were connected to a HP 3947A data acquisition system, where a computer monitored the temperatures and the absolute pressure. High-grade acetone (purity of 99.95%) on the amount of 70 grams and anhydrous ammonia (purity of 99.99%) on the amount of 60 grams were used as working fluids.

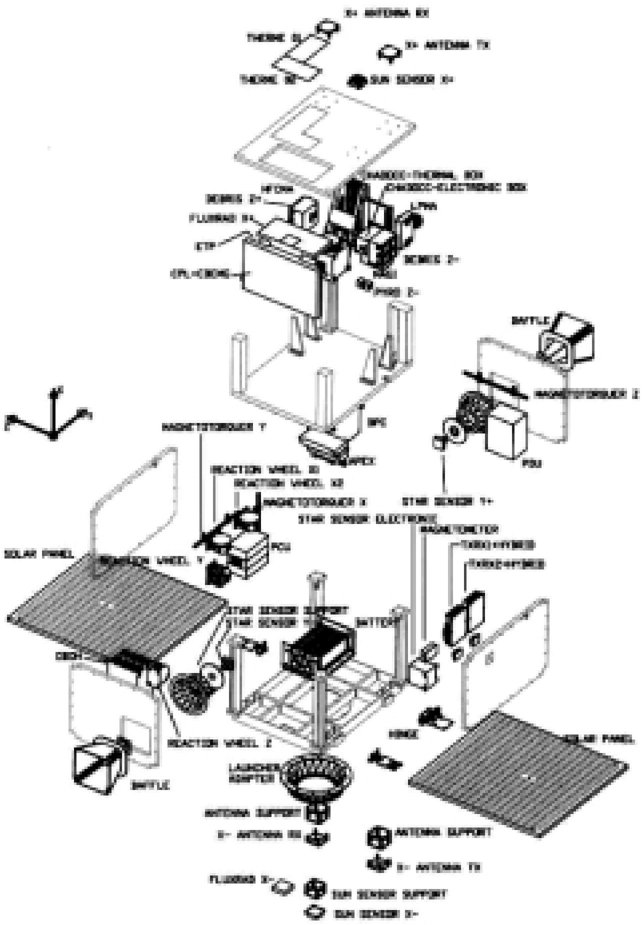


Figure 1 – The French-Brazilian Microsatellite project.

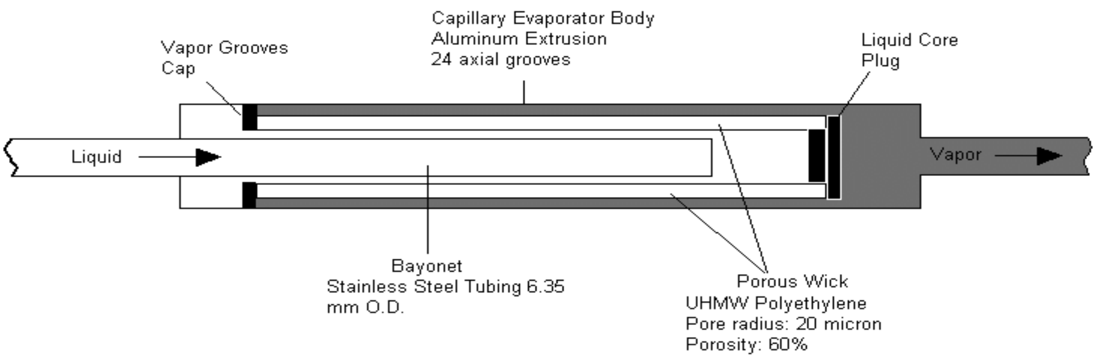


Figure 2 – Representation of the capillary evaporator used on the CPL.

The CPL design is related to the maximum capillary pressure that can be developed by the wick structure and working fluid. The maximum capillary pressure (P_{cap} in Pa) can be calculated using the Young-Laplace equation

$$P_{cap} = \frac{2\sigma}{r_p}, \tag{1}$$

where σ is the working fluid surface tension (N/m) and r_p is the mean pore radius (m). For tests performed at the operation temperature of 303 K, the CPL working with acetone could develop up to 1800 Pa of capillary pressure, while with anhydrous ammonia it could develop up to 2100 Pa.

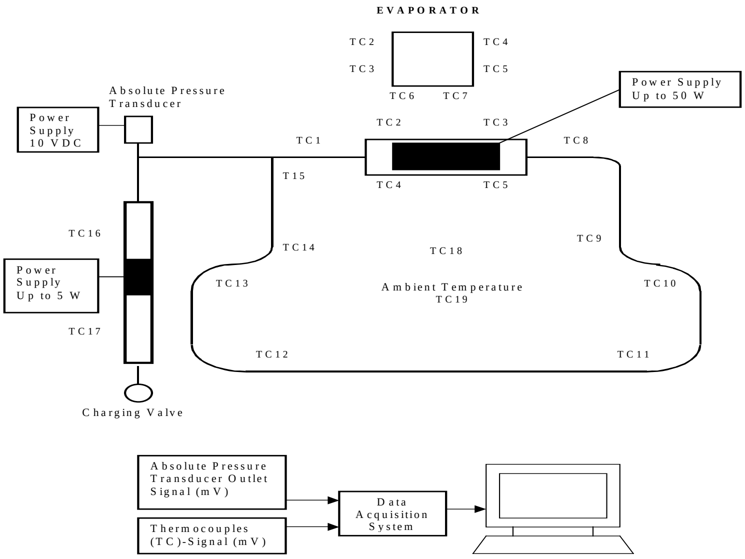


Figure 3 – CPL laboratory test bed.

The overall pressure drop present in the loop must be less than the maximum capillary pressure in order to ensure that the system will operate continuously, such as represented by the relation

$$P_{cap} \geq \Delta P_v + \Delta P_l + \Delta P_w + \Delta P_g \,, \qquad (2)$$

where ΔP_v (Pa) and ΔP_l (Pa) are the pressure drops in the vapor and liquid lines respectively, and ΔP_w (Pa) is the pressure drop in the porous material. The hydrostatic pressure drop, ΔP_g (Pa), is represented as

$$\Delta P_g = \rho_l g h \,, \qquad (3)$$

where ρ_l is the liquid density (kg/m^3), g is the gravity acceleration (m/s^2) and h is the height difference (m) between the evaporator and the condenser. The major components of the CPL pressure drop are related to the flow in the wick structure, vapor and liquid lines. The wick structure presents in the evaporator and, for some applications, present also in the condenser, causes flow restriction that affects the CPL performance, which is dependent on the wick permeability. The wick permeability (K, m^2) is a property of the porous material that describes the material ability to transport the liquid under an applied pressure gradient. The wick thickness pressure drop is calculated as

$$\Delta P_w = \frac{\mu_l \dot{Q}}{i_{lv} K \rho_l A_T} W_t \,, \qquad (4)$$

where μ_l is the liquid dynamic viscosity (Pa.s), $\dot{Q}$ is the applied heat load (W), A_T is the transversal wick area (m^2), ρ_l is the liquid density (kg/m^3) and W_t is the wick thickness (m). The liquid and vapor pressure drops are responsible for the highest-pressure resistance on the CPL operation. For either vapor or liquid lines, the pressure drop can be calculated using the following equation

$$\Delta P = f(\mathrm{Re}) \frac{\rho\, V^2 L}{2 D_h} \,, \qquad (5)$$

where L is the length (m) of either liquid or vapor line, V is the velocity (m/s), D_h is the hydraulic diameter (m) and f(Re) is the friction factor, dependent on the Reynolds number (Re) of each phase. The friction factor can be determined as follows (Chi, 1976):

$$f(\mathrm{Re}) = 64\,\mathrm{Re}^{-1} \qquad \text{if Re} < 2300, \qquad (6)$$

$$f(\mathrm{Re}) = 0.316\,\mathrm{Re}^{-0.25} \qquad \text{if } 2300 \leq \mathrm{Re} \leq 20000 \,, \qquad (7)$$

$$f(\mathrm{Re}) = 0.184\,\mathrm{Re}^{-0.2} \qquad \text{if Re}>20000. \qquad (8)$$

Using the above-mentioned equations and calculating the pressure drop for the CPL according to its geometric characteristics, the maximum pressure drop obtained for either acetone or anhydrous ammonia were less than 150 Pa, which could easily be handled by the capillary evaporator.

The liquid inventory required for the CPL operation is related to the flooded volume of the entire system as a startup condition. Additional liquid must be present in the two-phase reservoir in order to give a sustainable startup condition and supply the system with additional liquid if necessary. As a design condition, the two-phase reservoir should hold the entire loop amount of liquid in case of CPL operating on its higher capacity and it is adequate to use a charge at least 30% more than the calculated. Thus, the liquid inventory (L_{inv} in m^3) should be calculated as:

$$L_{inv} = \left(V_l + V_v + V_{evap} + V_{cond} + V_{el}\right), \tag{9}$$

where V_l is the liquid line volume, V_v is the vapor line volume, V_{evap} is the capillary evaporator volume, V_{cond} is the condenser volume and V_{el} is the volume of extra lines that might be present in the loop.

The CPL effective thermal conductivity (k_{eff} in W/m-K), which is related to the capillary evaporator design and stated the relationship between the working fluid (k_l) and the solid substrate (k_s) thermal conductivities, plays an important role on the CPL performance, can be determined by the relation given by Alexander (1972) as:

$$k_{eff} = k_l\left(k_l / k_s\right)^{-(1-\varepsilon)^{\alpha}}, \tag{10}$$

where ε is the porous wick porosity and α is the thermal diffusivity.

Experimental tests were carried out for one fluid at a time. Prior to charging the CPL with either working fluid, vacuum had to be performed in the loop. The quality of this vacuum was related to both removing any moisture present in the loop and checking for any leak that might lead to compromise the CPL operation along the time. A vacuum of at least 5 x 10 $^{-6}$ torr had to be accomplished and sustained by the experimental apparatus. Reliability on keeping this level of vacuum could ensure the CPL operationability over the time without the necessity of removing the fluid or performing a recharging.

All tests were performed observing the characteristics that the microsatellite will face in orbit, such as power availability and temperature. Such characteristics were defined as having an internal temperature of 293 K and regarding the power availability to the CPL experimental, a total of 25 W is to be used for applying in the capillary evaporator (20 W) and two-phase reservoir temperature control (5 W). A skin heater with a resistance of 9 Ω was placed at the reservoir wall, and another skin heater with resistance of 10 Ω was placed at the capillary evaporator wall. Each skin heater was connected to and manually controlled by a DC power supply. A constant temperature cooling bath was used to remove heat from the working fluid in the condenser, using a mixture of 60 % ethylene-glycol and 40 % water, set at 258 K.

After charging the CPL with either working fluid, a check on the absolute pressure of the CPL was performed in order to verify whether NCGs were present. Then, the reservoir temperature was raised until the desired operation temperature. Following the power availability and the internal temperature of the microsatellite, the reservoir temperature was raised until 303 K by the skin heater. After reaching the desired temperature, the CPL was ready to start operating. The experimental tests were performed for two situations: startup of the capillary evaporator for heat loads from 20 to 50 W and profile tests with different heat loads. Further tests were carried out with the CPL in a so-called failure mode, where the ability of the capillary evaporator on recovering its operationability from a depriming condition was analyzed. Specific details on the design and integration on the microsatellite are presented by Riehl et al. (2001), Riehl and Bazzo (2001) and Riehl et al. (2002).

2.1. Experimental tests using high-grade acetone (CH_3COCH_3)

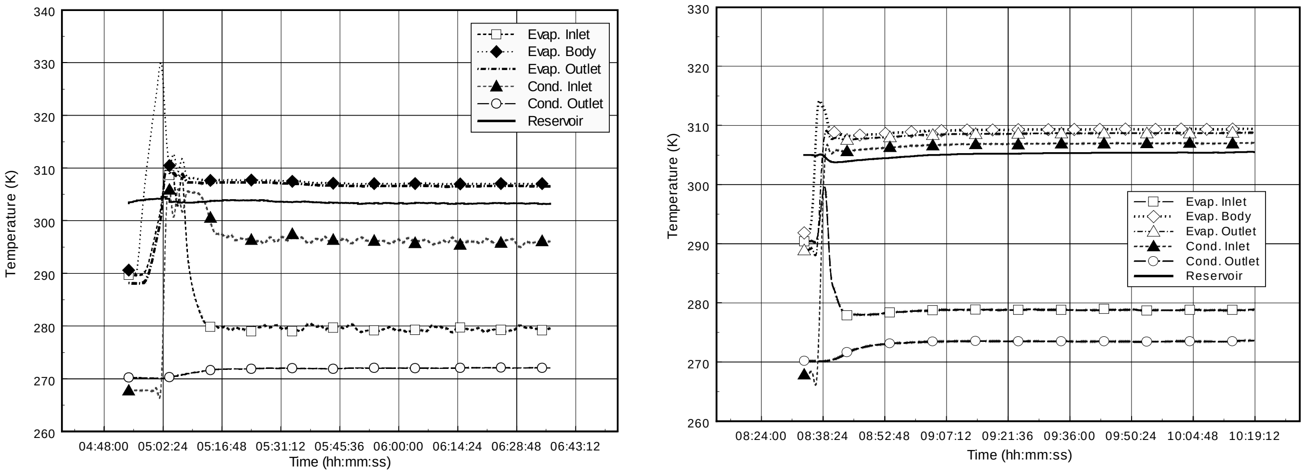
2.1.1. Startup tests

After all the steps to start testing the CPL were accomplished, several tests could be performed. The CPL startup tests were the most critical for evaluating the capillary evaporator reliability on transporting heat from a source to a sink. For reduced scale capillary evaporators, there is a stronger tendency on occurring the depriming than in larger sizes. Although, for all tests carried out, such tendency was never observed. For startups at either low or high heat loads, the capillary evaporator presented to be very reliable. Figure 4 presents the startup tests for low heat load (20 W and 30 W) and Figure 5 presents the startup tests for high heat load (40 W and 50 W).

At either test, it can be observed that the capillary evaporator never presented a tendency of depriming. The startup time for low heat loads were longer than those for high heat load. At low heat loads, the menisci formation in the grooves take more time as heat is slowly transferred to the working fluid, causing a longer time to start generating capillary forces. At high heat loads, the menisci form more quickly and the capillary forces begin to act faster. At low heat loads, the startup time took less than 6 minutes to occur, while at high heat loads the startup time took less than 2 minutes. This is particularly important to evaluate because the CPL has to present very fast response to the heat load applied to the capillary evaporator in order to efficiently perform the heat transport.

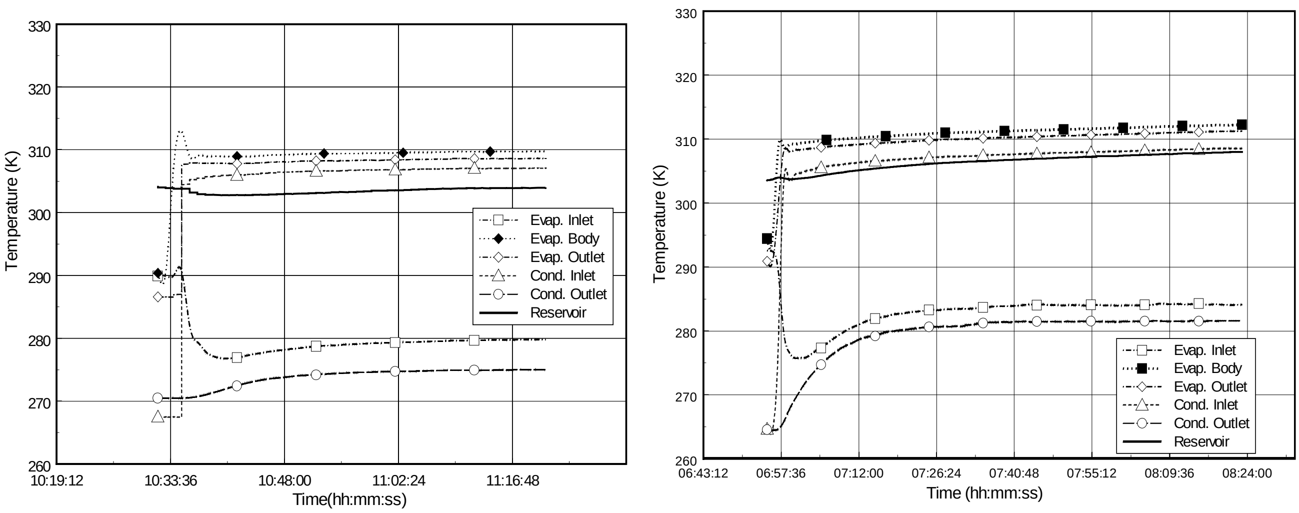
The steady state was achieved, at both low and high heat loads, in less than 20 minutes keeping the CPL operation very stable during the time. Even with a less efficient heat transport working fluid such as acetone, the CPL presented very reliable behavior as it could transport heat without presenting tendency of depriming the capillary evaporator or general CPL failure. For all tests, the superheat (difference between the evaporator body and reservoir temperature) was within a range from 4 K (for low heat loads) to 6 K (for high heat loads). The verification of the CPL superheat is important not only to verify whether the operation behavior is in agreement with the heat load to be transported, but also to analyze the CPL behavior with a certain working fluid. In the case of acetone, higher superheats were expected because this fluid is less efficient on the heat transport, due to low boiling temperature and condensing heat transfer coefficient. Also, higher superheats can lead to future deterioration of the wick structure and consequently the entire system will deteriorate.

The startup tests are important to be analyzed, as the CPL will have to start operating in orbit facing the conditions imposed by a different situation found in ground. In ground tests, such as those presented above, the CPL have to face changes with the room temperature that causes a variation on the entire system temperature, as it can be observed on Fig. 5 for tests with 50 W. On the other side, the sink temperature in space will be much lower than the one achieved in laboratory, which will contribute to a better performance of the CPL.



Power = 20 W Power = 30 W

Figure 4 – CPL startup tests at low heat load, using acetone as working fluid.



Power = 40 W Power = 50 W

Figure 5 – CPL startup tests at high heat load, using acetone as working fluid.

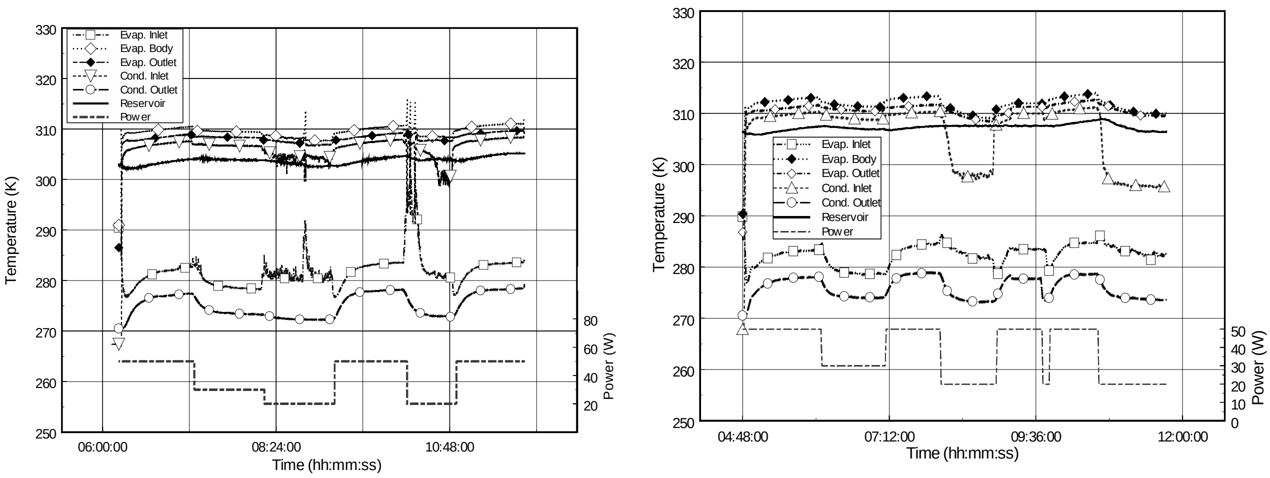
2.1.2. CPL profile tests

The profile tests were carried out in order to verify the CPL behavior for different heat loads applied to the capillary evaporator. Such tests were very important to be performed as the CPL, while in orbit, will face different heat loads.

During the 60 minutes that the CPL absorber plate will be facing the sun, a total of 30 W will be transferred to the capillary evaporator coupled with up to 20 W available from the skin heater. During the 40 minutes that the CPL is in eclipse period, up to 20 W will be available from the skin heater. Thus, the CPL must be able to handle changes on the heat load up to 50 W presenting continuous operation.

When dramatic changes have to be faced by the CPL, such as failure on the reservoir temperature control or capillary evaporator skin heater, the capillary evaporator can deprime causing a complete failure of the entire system and some procedures toward its re-priming must be performed, which will be presented later. All heat load profiles considered sudden changes on the heat load applied to the capillary evaporator and will be presented here. Figure 6 presents the heat load profiles tested.

It can be observed that at either heat load profiles tested, the CPL presented very fast response for changes with very short transients until reaching the steady state again. With very short startup periods, such as those observed on item 2.1.1, any change on the heat load for a higher or lower value showed that the CPL presented a very robust design. At no instant the CPL presented a tendency of depriming and the temperatures showed changes according to the level of heat to be transported. The system superheat, as the difference between the evaporator body and reservoir temperature, presented within a range of 4 and 6 K, which is considerably low for a CPL on a reduced scale. Despite few spikes on the liquid and vapor temperatures, such as those observed at the first profile when the heat load was changed from 30 to 20 W and 50 to 20 W, no other aspect would lead to a failure of the CPL. Even at this situation, which was probably caused by an incomplete condensation, the capillary evaporator did not present temperature overshooting and the entire system was seeking for an equilibrium for such change on the heat load. After this transient period, the CPL operated in steady state for several minutes before facing another change to 50 W. The temperature spikes can be explained by the fact that acetone is a less efficient heat transport working fluid as mentioned above, as it shows to be more sensitive to external influence. Such spikes are not expected to occur upon using a high efficient working fluid such as ammonia.



Profile 50-30-20-50-20-50 W

Profile 50-30-50-20-50-20-50-20 W

Figure 6 – CPL heat load profiles, using acetone as working fluid.

Again, the influence of the room temperature on the CPL behavior could be observed, but it did not cause any major influence other than an increase on the loop's temperature. Such influence was expected as this type of test takes several hours to be performed and the temperature during the day could vary.

From what has been observed from the tests using acetone, the proposed design for the CPL presents good thermal behavior for both startup and heat load profiles tests. The temperatures over the capillary evaporator body showed to be very stable without any indication of overshooting at any time during its operation. The proposed system proved to be able to operate for several hours continuously with very little variation on its operation conditions. Upon keeping the same heat load to the capillary evaporator, the CPL presents an expectation of working non-stop during its entire lifetime while in orbit.

2.2. Experimental tests using anhydrous ammonia (NH_3)

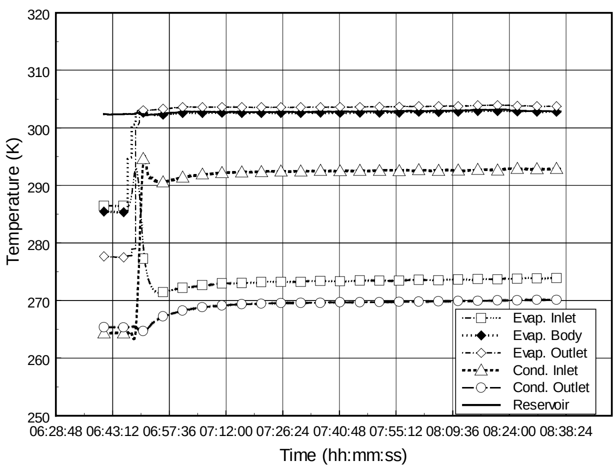
2.2.1. CPL startup tests

Anhydrous ammonia presents higher heat transport capability when compared to many working fluids, including acetone. A higher Figure of Merit for ammonia when compared to other fluids explains such better heat transport capability. The Figure of Merit is a relation between thermophysical properties and geometric factor of a capillary driven two-phase loop related to the pressure drop in the system. In the case of heat pipes, the Figure of Merit is evaluated regarding the working fluid liquid properties, as the liquid presents a major influence on the system pressure drop. For the case of CPL and LHP to be used in space applications, the major concern is related to the vapor properties and the length of the vapor line, as the vapor pressure drop can be a significant factor on the overall loop pressure drop. Dunbar and Cadell (1998) presented an investigation towards to the determination of the Figure of Merit for CPL/LHP systems where the characteristics of vapor flow were considered. An equation to determine the Figure of Merit was then proposed as

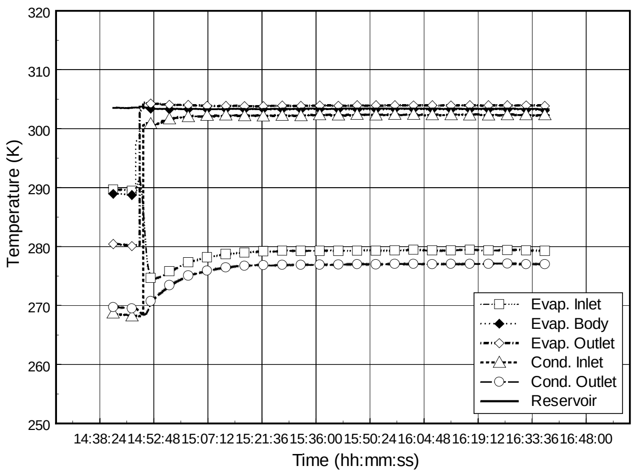
$$N = \frac{\sigma}{L^{-1.75}\mu_v^{0.25}\rho_v^{-1}}, \qquad (11)$$

where N is the working fluid Figure of Merit, L is the vapor line length (m), μ_v is the vapor dynamic viscosity (Pa.s) and ρ_v is the vapor density (kg/m^3). Using this relation, it can be verified that for the range of temperature that the CPL is operating, ammonia is the best working fluid and also presents higher Figure of Merit when compared to acetone and other fluids. As ammonia presents a higher latent heat of vaporization (i_{lv} in kJ/kg) when compared to acetone, a lower flow rate ($\dot{m}$ in kg/s) is to be verified when the CPL operates at the same heat load, i.e., $\dot{m} = \dot{Q}/i_{lv}$. Thus, better results would be expected for such tests, as well as reduced superheats are expected to occur. For the tests with ammonia, the same operation conditions used for testing with acetone were applied.

For startup tests at low heat load applied to the evaporator and using ammonia as working fluid, it could be observed that the CPL presented reliable behavior just like when using acetone. The capillary evaporator presented faster responses and lower superheat at this time, which is due to the better heat transport capability of ammonia. Such aspects are especially important to analyze because lower superheat can lead to use the CPL to transport higher levels of heat, while faster responses are important when sudden changes on the heat load are verified and the CPL must keep its operationability. Figure 7 presents the tests for low heat load applied during startups. Figure 8 presents the results for high heat load applied.



Power = 20 W



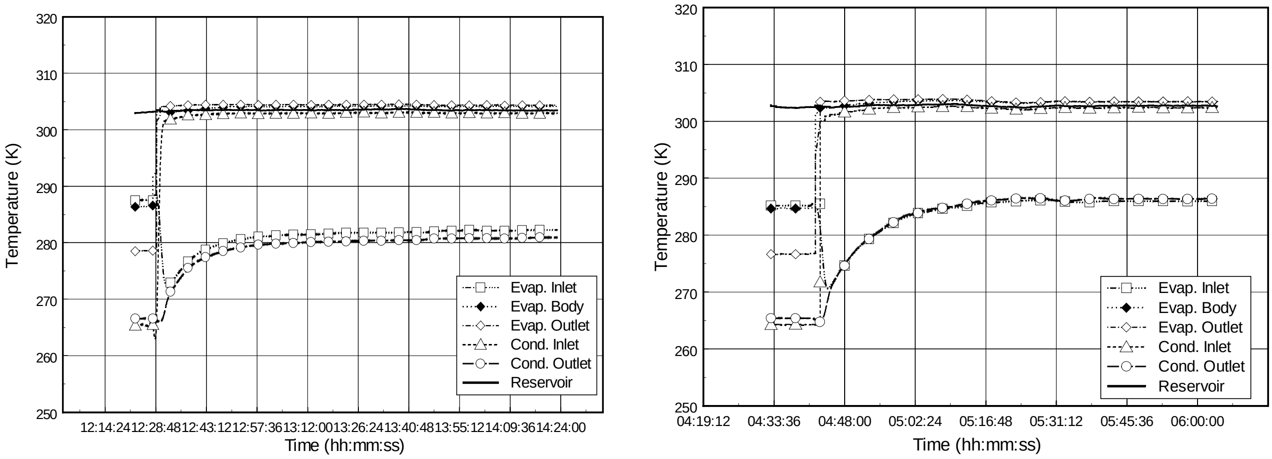
Power = 30 W

Figure 7 – CPL startup at low heat load, using ammonia as working fluid.

For all startup tests, it can be verified that the CPL takes longer time to achieve the steady state when compared to the results for acetone, but the temperatures on the vapor line reached its stability faster than with acetone. On the liquid line, the temperatures took longer time to reach stability when compared to acetone. This is due to the lower flow rate that the CPL develops when ammonia is used because of its higher latent heat of vaporization at the operation temperature (1167.5 kJ/kg) compared to acetone (544 kJ/kg). Even with lower flow rate, the CPL could reach steady state in less than 20 minutes for all tests.

Faster startups were verified at higher heat loads as the menisci were formed more quickly in the grooves at such condition. In all cases, the capillary evaporator started in a very short time, ranging from 1.5 minutes (at high heat load) to 5 minutes (at low heat load).

Comparing the tests with acetone and ammonia, the CPL presents more stable temperatures along the time when ammonia was used. Also, at the moment of startup, the capillary evaporator does not present high superheat to start operating such as observed on the tests with acetone. The levels of superheat observed during the tests with ammonia were very reduced, ranging from 0.8 K (for low heat loads) to 1.5 K (for high heat loads). Such factor is important to be evaluated as the use of ammonia can lead to more reliable startups and also can transport higher levels of heat at the same working conditions. Once again, the capillary evaporator temperature distribution showed to be very homogeneous, without showing any tendency of overshooting.



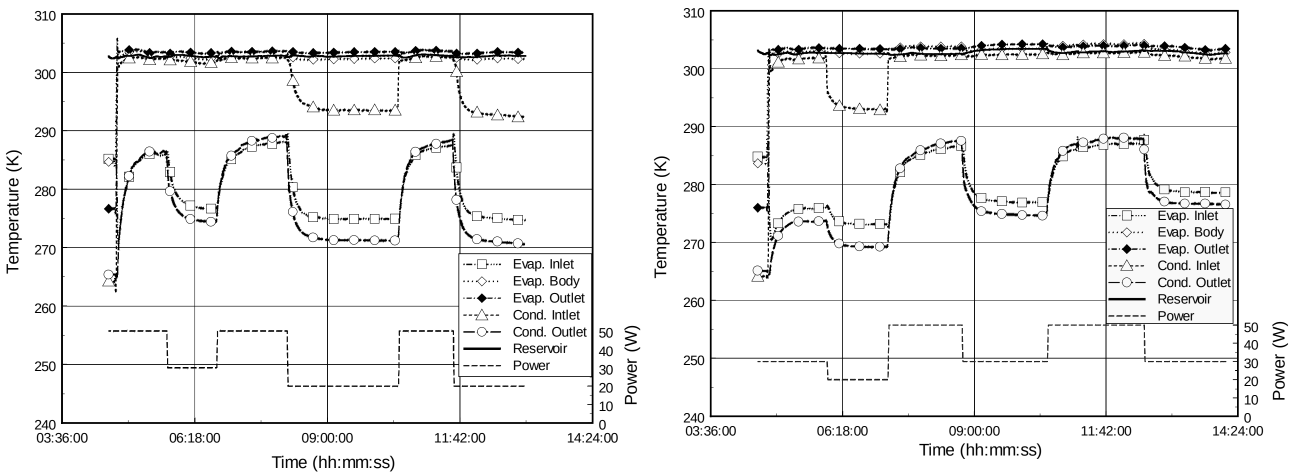
Power = 40 W

Power = 50 W

Figure 8 – CPL startup at high heat load, using ammonia as working fluid.

2.2.2. CPL profile tests

Once again with the objective of comparing the CPL behavior when operating with heat load profiles, tests were also performed using ammonia. Figure 9 presents the results for such tests.



Profile 50-30-50-20-50-20 W

Profile 30-20-50-30-50-30 W

Figure 9 – CPL heat load profiles, using ammonia as working fluid.

Comparing the obtained results, it can be verified that the temperature spikes observed during the tests with acetone were not verified for tests using ammonia, even when sudden changes on the heat load from 20 to 50 W were applied. One can say that, once again, ammonia is able to give more reliability to the CPL working operation as temperature spikes can lead to depriming the capillary evaporator and, consequently, the entire system failure. As the capillary evaporator presented faster responses and better thermal behavior using ammonia, depriming of the capillary evaporator is not to be expected.

Thus, the choice of using anhydrous ammonia as the CPL working fluid that will be placed in orbit has been proved to be the best one. For the working characteristics to be faced in orbit, the CPL using ammonia is expected to present even better thermal behavior, as the sink temperature will be lower than the one used in the laboratory.

2.3. Recovery tests for the CPL

Following the procedures for testing the CPL, some aspects related to its potential failure had to be observed and tested. As the CPL will be remote operated from the ground control in case of failure, the satellite on-board computer named Brazilian Payload Computer (BPC) needs to have a procedure to avoid the capillary evaporator temperature overshooting and consequently its depriming. Thus, some steps have to be performed as part of a software that will be loaded in the BPC. In case of temperature overshooting, the software will be responsible for performing determined steps to ensure that the CPL will start operating again.

In case of capillary evaporator temperature overshooting, the sequence for avoiding the evaporator depriming is as follows. If the difference between the evaporator body and reservoir temperature is greater than 20 K, the overshooting is about to occur. Then, two actions can be performed at the same time or one at a time. The BPC can increase the reservoir temperature to ensure that liquid has been pressurized and forced in the CPL, condensing any vapor bubbles and delivering more liquid to the evaporator liquid core, which would guarantee that the liquid/vapor interface would be present and generating capillary pressure upon keeping the wick structure wetted. Another action is related to decreasing the heat applied to the capillary evaporator, causing a decrease on the superheat and ensuring that the capillary evaporator would gain pumping capacity again.

To evaluate whether such procedures are enough to guarantee the continuous operation of the CPL, tests in laboratory were performed first to check that the capillary evaporator could really present a depriming situation and then if it would be able to be re-primed again.

During all attempts to cause the capillary evaporator depriming while using ammonia, the CPL kept working without presenting any tendency of such condition. Even when the heat load was increased coupled with a decrease on the reservoir temperature, which would be enough to cause the capillary evaporator depriming, the CPL operating with ammonia never showed any potential of failure, at least for heat inputs up to 50 W. For the case of acetone, tests could be performed to check the depriming/re-priming procedure of the CPL, as acetone is a less efficient working fluid. For such test, the reservoir temperature was decreased at the same time as the heat load to the evaporator was increased from 20 to 50 W. Figure 10 presents the results for such test.

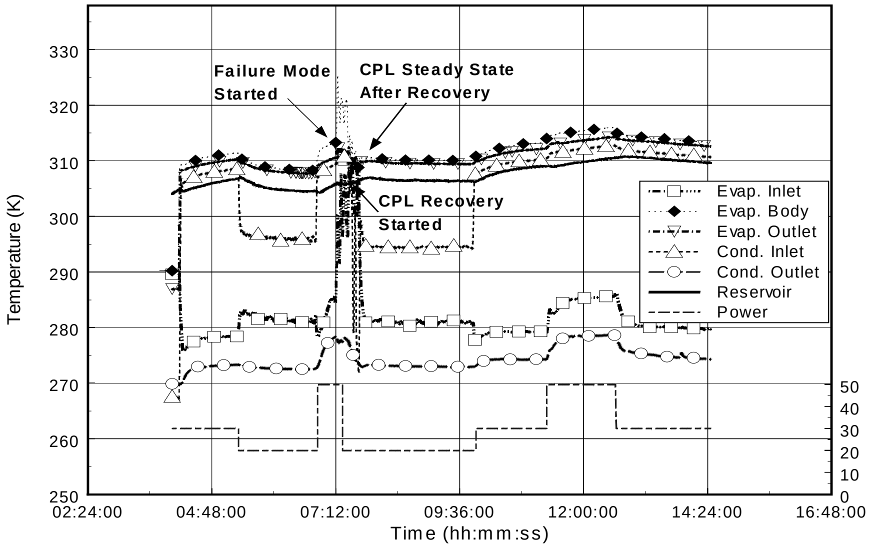


Figure 10 – CPL failure test, using acetone as working fluid.

At the time the heat load was increase from 20 to 50 W, the reservoir temperature was decreased in 1.5 K. Such change on the operating condition of the CPL was enough to promote the temperature overshooting of the capillary evaporator. Even with such overshooting of almost 20 K, the capillary evaporator presented a tendency of keep pumping fluid at such condition and seeking for a steady state. In such critical situation, the capillary evaporator never presented a tendency of depriming, causing a failure of the entire loop. The CPL was operating in such condition for more than 15 minutes when actions to re-prime the capillary evaporator were taken, such as those described above. The fact that the loop was operating for such a long time without presenting a tendency of depriming is due to the presence of a bayonet in the capillary evaporator liquid core. As this component is responsible for delivering sub-cooled liquid directly to the evaporator core, it kept supplying subcooled liquid to the wick structure even at such critical situation, giving a more robust configuration to the capillary evaporator.

The reservoir temperature was then raised in 2 K and the heat load applied to the capillary evaporator was reduced to 20 W. After less than 2 minutes, the capillary evaporator temperature decreased and returned to the same level as before. With the increase on the reservoir temperature, liquid was pressure pumped out of the reservoir direct to the evaporator liquid core. As the pumping pressure was re-established at the same level as before, the capillary evaporator re-primed and started presenting the same thermal behavior as before. After less than 10 minutes, the entire system was operating again, proving that the re-priming procedure that will be present in the BPC is able to effectively control the CPL operation.

3. Conclusion

Experimental tests of a small-scale capillary pumped loop (CPL) to the place aboard a scientific microsatellite were presented. Tests regarding a reduced scale CPL were carried out with acetone and anhydrous ammonia as working fluids, using a UHMW polyethylene wick structure in the capillary evaporator. Ground tests showed that even on a reduced scale, the CPL could present reliable thermal behavior. Discrepancies on the evaporator temperature were not observed during the tests, as other authors pointed.

Tests were performed for both working fluids in order to evaluate the CPL startup and its operationability when different heat loads were applied to the capillary evaporator. For the startup tests, the CPL presented very reliable results for both working fluid, but temperature spikes verified when testing with acetone were not verified when testing with ammonia. Such aspect could lead to more reliable thermal performance of the CPL when operating with such fluid. For the heat load profile tests, the CPL presented to transport heat efficiently with both working fluids for a long period of time. Once again, upon operating with acetone, the CPL presented temperature spikes that could lead to the capillary evaporator temperature overshooting and consequently, the entire system failure. For the tests with ammonia, such temperature spikes were not verified and the CPL presented more stable operationability, faster responses to changes on the heat load and reduced superheat.

In order to check the capability of the BPC to control the CPL in case of failure, tests were performed to promote the capillary evaporator depriming. Such test was just possible to be performed using acetone as working fluid, as attempts were done using ammonia but the CPL never presented a tendency of failure for heat inputs up to 50 W. Upon testing the CPL with acetone on a failure mode, the procedures to re-prime the capillary evaporator presented to be precise, as the capillary evaporator re-established its pumping capability after a short period of time.

The proposed CPL presented to be more robust when ammonia was used as working fluid. It is expected that the CPL will present better thermal behavior while in orbit, as the sink temperature will be much lower than that achieved in tests. As a system to be used on the satellite thermal control, the CPL presented to be a solution for such application as available area and power consumption are a concern. The thermal control promoted by such system is a technology that can solve several thermal problems in satellite, structures and electronics applications.

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