Ground Testing and Thermodynamic Behavior of a Capillary Pumping Two-Phase Loop

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Abstract

Focusing on the extensive use of capillary pumping two-phase loops on satellites thermal control, an experimental investigation of a capillary pumped loop (CPL), a thermodynamic study and its integration on a scientific microsatellite has been performed. The process of manufacturing and characterization of porous structures is also presented. Results have been gathered in ground testing for different operation conditions, which show the reliability of the porous structure manufacturing and capillary evaporators construction. Experimental results showed that the proposed CPL has reliable startups and very short transients for different heat loads. From what has been observed on the experimental tests, a thermodynamic approach of the capillary evaporator behavior is presented considering the same working conditions. This investigation has shown the particularities of a CPL behavior on a reduced scale.

Keywords: porous structure, capillary pumped loop, thermal control and satellite integration.

1. INTRODUCTION

Investigations on the use of capillary pumped loop (CPL), applied to satellites and electronics thermal control have been extensively performed in the past. From what has been investigated, a CPL is considered a reliable thermal management device, as temperature control can be performed passively and heat can be transported over long distances. As the main component of a CPL is the capillary evaporator, which is the responsible for the generation of capillary forces that drive the working fluid via a porous structure, several studies have been done [1] regarding the manufacturing of different porous structures. Porous structures sinterization process of different materials have been investigated and used in capillary evaporators, which has lead to the increase of capillary pumping power and the use of CPL on different levels of temperature and heat fluxes. Several studies have also been performed on the behavior of CPL in ground and micro-gravity conditions [2, 3], in order to investigate its capability on the heat transport and temperature control. Different configurations of the capillary evaporator and the CPL itself have been attempted and many experimental results have been generated. Towards the use of a CPL on satellites thermal control, investigations have been performed considering particular working conditions on a controlled environment. Focusing on the development of a small-scale CPL to be integrated on a microsatellite, this paper has the objective of presenting several aspects related to this matter. The efforts regarding the fabrication of the porous wick by sinterization towards its use on a capillary evaporator, experimental tests of a proposed small scale CPL related to the conditions to be faced in space and its integration on a microsatellite are presented. A thermodynamic approach of the CPL behavior is also presented to better explain the experimental results. This work is also intended on showing the achievement of different technologies in order to use them on satellite and electronics thermal control.

2. THE MICROSATELLITE PROPOSAL

The CPL experiment is part of a scientific project involving France and Brazil towards the development of space technology. Other experiments will be part of the microsatellite payload, which is scheduled to be launch in early 2004 by a four-stage SLV (Satellite Launching Vehicle) from the Alcantara Launching Base, in Brazil. The integration of all experiments will be done part in France at CNES and part in Brazil at the Brazilian Institute for Space Research (INPE). Figure 1 shows a scheme of all experiments and parts of the microsatellite [7].

3. POROUS WICK DEVELOPMENT

For the development of wick structures to be used in CPL, a nickel powder carbonyl with a particle size in the range of 3 to 7 μm (specific surface area: 0.3 – 0.4 m²/g) was used as raw material and a tap powder sintering technique was employed to manufacture the porous samples.
The matrix (or mold) was designed taking into account the dimensional parameters of the capillary pump, according to the proposed CPL characteristics. The sintering process was conducted in a controlled-atmosphere-furnace JUNG (model TU-3513), with a commercial hydrogen flow of approximately 1.0 cm$^3$/s. The manufacturing parameters were fixed to be 698 K/3h in the pre-sintering part and 973 K/1h in the sintering part. Each sintering temperature schedule was repeated at least four times to increase data reliability for porosity characterization [1]. Then, the total porosity of the samples was first experimentally determined by the Arquimedes Method, according to the following relations:

$$ Pa = 100 \cdot \left| 1 - \frac{\rho}{\rho_{Ni}} \right| $$

(1)

$$ \rho = \frac{m \cdot g \cdot \rho_{Ni}}{E} $$

(2)

where, $Pa$ is the volumetric fraction of pores of the wick (%), $\rho$ is the apparent density (g/cm$^3$), $\rho_{Ni}$ is the specific nickel density ($\rho_{Ni} = 8.9$ g/cm$^3$), $E$ is the thrust of the material immerged in mercury, which density is $\rho_{Hg} = 13.6$ g/cm$^3$, $m$ is the mass (g) and $g$ is the gravitational acceleration (m/s$^2$).

To perform the measurements, an electronic scale Mars (model A1600, resolution: 0.01 g) was used. The experimental results showed that the porosity for the sintered material was 51.4%.

The total porosity and the pore size distribution are important parameters to be considered in the porous wick manufacturing. Such results are important to be considered, since the capillary pumping pressure depends on these mentioned parameters. Both were measured on images acquired by a Scanning Electronic Microscopy (SEM), from a set of samples prepared in the laboratory. The analysis was conducted with 20 images to be representative. The software Imago developed by LMPT/UFSC (Laboratory of Porous Media and Thermophysics Properties) was used.

The method to determine the pore size distribution is based on a comparison of pore images with an octagonal pattern. After each comparison, the pattern’s radius is increased and a new scanning is made. The procedure is repeated until no pores are detected and a cumulative pore size distribution curve is built, shown on Fig 2. A correlation curve is then built to indicate the level of pore organization [4]. With the correlation and the porosity, the structure can be reconstructed and mercury intrusion porosimetry can be simulated.

The reconstruction process is made with four amplifying factors (n) in order to reach a better pore structure duplication. The size of the reconstructed 3D structure used was 200x200 pixels. The reconstructed nickel structure is showed in Fig 3. The permeability was simulated in the 3D structure resulting in 31.4 mD (milli Darcy) [4].
4. SMALL-SCALE CAPILLARY PUMPED LOOP DESIGN AND DEVELOPMENT

A small-scale capillary pumped loop (CPL) has been proposed to be part of a scientific microsatellite payload, in order to use it in tests under microgravity. Due to the limited space and mass that such experiment must have, some particularities regarding the CPL design have to be faced and solved. Such particularities are in regard to the limited power available from the satellite, space radiator area and reduced geometry of the capillary evaporator. The CPL is to be assembled in a container that will accommodate two other experiments (Confined Boiling under Microgravity-CBEMG and Flux-meter of Radiation-FLUXRAD) plus all the electronic concerning control and data acquisition. All experiments and electronic will be assembled in a so-called UFSC Box container. During the time the CPL is operating, the other experiments will not be operating and vice-versa. Each experiment has its own power limitation during the mission.

The microsatellite will have an equatorial orbit at 700 km of altitude at 7° of inclination to the horizon. One orbit of the microsatellite will take 100 minutes, which is divided in 40 minutes of eclipse time and 60 minutes facing the sun. During the period that will be facing the sun, a heat radiation of 1320 W/m² will be available. To solve part of the problem concerning the power availability for the CPL, a space absorber plate was designed, which will be in thermal contact to the capillary evaporator. The absorber is designed to receive the heat radiation from the sun and transfer 30 W of power to the capillary evaporator. The heat absorbed by the capillary evaporator will be dissipated through a space radiator that will be facing the cold space all the time. Coupled to the power available through the absorber plate, a total power of 25 W is available from the satellite batteries. From this total power available, 5 W will be used during the CPL surviving period and 10 W will be used in surviving and recovery mode. For the time the CPL will be in operation, a total power of 20 W will be available to the capillary evaporator through electric resistances [5]. A schematic of the power availability is presented by Fig. 4. During the period that the CPL will be operating in space, the power available to the capillary evaporator will vary from 20 W (eclipse time, by electric resistances only) to 50 W (absorber plate plus electric resistances). According to the maximum power available, the CPL was then designed to a maximum heat load of 60 W.

4.1. Capillary Pumped Loop Design

The design of the CPL had to be related to the particularities regarding its reduced size and mass availability. Thus, the position of each component had to be carefully analyzed in order to accommodate not only the CPL but also the other experiments and electronic. Figure 5 presents the CPL layout in the UFSC Box.
The CPL design involves the fabrication of a capillary evaporator with a sintered nickel wick, as presented on item 3, and anhydrous ammonia as working fluid. As a preliminary step on the design and implementation of the proposed CPL, tests were first carried out for a capillary evaporator using UHMW polyethylene wick with mean pore radius of 20 µm and high-grade acetone as working fluid. The use of polyethylene and acetone had the purpose of verifying the CPL behavior for low performance components prior to the use of the ones proposed on its design. The capillary evaporator was assembled using an internally grooved aluminum extrusion with 24 grooves, I.D. of 12.7 mm, O.D. of 19.05 mm and length of 100 mm. The vapor and liquid lines had O.D of 6.35 mm and I.D. of 4.65 mm, on an overall length of 1200 mm and were made of 304-stainless steel tubing, as well as the reservoir. A stainless steel screen mesh number 200 was placed at the reservoir’s outlet in order to avoid that any bubble would migrate to the liquid core. A bayonet was place in the capillary evaporator, linking it with the liquid line, which was used to deliver sub-cooled liquid directly to the liquid core. Figure 6 presents the CPL test bed.

The entire loop was placed horizontally in order to avoid any influence of the gravity force during the CPL operation. A total of 19 Omega type-T thermocouples (accuracy of 0.3 at 373 K) were used to monitor the temperature throughout the CPL and an absolute pressure transducer (Omega model PX302-300AV) was used to check the working fluid operation pressure. A total of 70 grams of acetone were used to perform the preliminary tests and 60 grams of anhydrous ammonia (NH₃) were used for the final performance tests. The condenser was in thermal contact to a cold plate that was connected to a constant temperature cooling bath, which temperature was set at 258 K, using a mixture of 60% ethylene-glycol and 40% water. The other tested CPL has the same geometric characteristics described above, using a sintered nickel porous wick with mean pore size of 3 µm and anhydrous ammonia as working fluid.

4.2. Results for the Acetone Tests

The preliminary tests were performed following the same conditions that the CPL will face in orbit. Tests were conducted in a controlled room temperature environment at 293 K, which corresponds to the microsatellite internal temperature [6]. Then, the reservoir temperature was raised until 303 K to pressurize the loop and flood the capillary evaporator prior to its startup. Such procedure was closely following the power availability for the reservoir, which is 5 W maximum. A power of 3.6 W was found to be enough to raise the reservoir’s temperature to 303 K and keep it at this temperature [6]. After reaching the desired operating temperature, the CPL was tested for both startup at different levels of heat load and profiles. For the startup tests, heat loads from 10 to 60 W were applied to the capillary evaporator. For any heat load, the capillary evaporator presented fast and reliable startups even for low power. In the case of startups at 10 W, the capillary evaporator took less than 5 minutes to start and the CPL could reach steady state conditions in less than 20 minutes. For heat loads of 50 W, the capillary evaporator presented startups in less than 2 minutes and the CPL could reach steady state conditions in less than 15 minutes [6]. Figures 7 and 8 presents the startups for 20 and 50 W respectively.

Figure 7 – CPL startup at 20 W.
The heat load profiles used were 30-20-10-30-10-30-20 W (profile 1), 50-30-50-20-50-20-50 W (profile 2) and 30-20-50-20-30-50-30 (profile 3). For all profile tests, the CPL presented reliable startups and fast response to changes on the heat load, as the evaporator quickly responded to a change and the CPL could reach steady state in a very short time. Figure 9 presents a profile test.

![Figure 8 – CPL startup at 50 W.](image)

Very seldom the capillary evaporator presented a tendency of depriming under normal operation conditions. When a perturbation occurred, a slight increase on the capillary evaporator temperature was observed but quickly returned to a normal level. This was caused by the presence of the bayonet, delivering sub-cooled liquid directly to the evaporator’s liquid core, avoiding a temperature overshoot and consequently, the evaporator’s depriming. This component of the CPL was found to be extremely important for its continuous operation in space. Although the CPL would seldom present failure during its operation, its capability on recovering from such condition had to be tested and analyzed. Such analysis is important to verify whether the control procedures for the CPL recovery present at the BPC (Brazilian Payload Computer) responsible for monitoring all experiments and data acquisition, were correct. Thus, tests regarding the capillary evaporator depriming and re-priming were carried out. For such tests, a perturbation at both reservoir’s temperature and heat load applied to the capillary evaporator was performed. Figure 10 presents a test were this procedure was used while applying profile 3. Coupled to the increase on the heat load from 20 to 50 W, the reservoir’s temperature was decreased in 1.5 K. After 15 minutes, the capillary evaporator presented a tendency of having temperature overshoot, as its temperature was swinging on amplitude of 20 K.

![Figure 9 – CPL profile 2 test.](image)

It could be observed that the capillary evaporator temperature was increased from 308 to 328 K in less then 1 minute, but never presented overshoot or depriming. The capillary evaporator could operate under such conditions for a long period without presenting general failure. Following the recovery procedure presented on the BPC, the reservoir’s temperature was increased in 2 K and the heat load was decreased to 20 W. After less than 5 minutes of such changing, the capillary evaporator presented a recovery on its temperature and the entire CPL continued to operate normally. The experimental results showed that the CPL overall design and operation procedures were established correctly, which will lead to the success of the entire mission while in space.

Due to its reduced geometric characteristics and the internal configuration of the capillary evaporator, the CPL presented very fast start-ups even at low heat load. Such behavior was also verified when profile tests were performed and changes on the heat load were done. The reduced geometry of the capillary evaporator allows that heat can be promptly transferred to the working fluid, where a change on the latent heat will cause an increase or decrease on the mass flow rate. The bayonet would drain the excess of sub-cooled liquid, or a lack of fluid would be supplied by it, which is also responsible for avoiding the capillary evaporator to deprime. The bayonet presence was found to be very important to the continuous CPL operation when sudden changes...
on the heat load are verified, as it allows the capillary evaporator to operate at the same saturation line with slight changes on the superheat. The variation on the positioning of the vapor front in the condenser could be verified by the thermocouples when profile tests were performed. For low heat loads the condenser was mainly flooded by liquid, which resulted in higher sub-cooling. For high heat loads, the vapor front moved further in the condenser. For heat loads higher than 60 W, the condenser was unable of dissipating such heat and promotes the required sub-cooling to the capillary evaporator.

5. CPL INTEGRATION ON THE SATELLITE

As part of a payload that involves other two experiments and electronic, the entire payload related to the UFSC Box is intended not to exceed 5 kg of mass and each experiment has its own limitations on available power from the satellite. A schematization of all experiments and their positioning in the UFSC Box can be observed on Fig. 5. The physical integration of all experiments and electronic had to accomplish certain requirements, as one experiment could not interfere on another. The aspects related to thermal influence an electronic control were carefully considered and analyzed. Also, different levels of static and dynamic vibrations, considering the satellite launching procedure had to be verified during simulations and ground qualification tests [5, 7]. Thus, the CPL and electronic integration in the UFSC Box can be observed on Fig. 11. Further tests regarding ground qualification are also scheduled to occur.

Figure 11 – CPL and electronic integration.

6. CONCLUSION

The development of porous wick structures, a capillary pumped loop (CPL) and its integration on a scientific microsatellite, towards their use in microgravity conditions are presented. Tests in laboratory have shown the quality of the wick structure developed and its potentiality of use in capillary evaporators. The CPL presented reliable startups and great capability on transporting up to 60 W of heat load. The development of such technology and the integration on the satellite has shown the potentiality of applying it on thermal management in space applications.

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References