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2015 J. Phys.: Conf. Ser. 655 012042

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Pulsating Heat pipe Only for Space (PHOS): results of the REXUS 18 sounding rocket campaign

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Abstract. Two Closed Loop Pulsating Heat Pipes (CLPHPs) are tested on board REXUS 18 sounding rocket in order to obtain data over a relatively long microgravity period (approximately 90 s). The CLPHPs are partially filled with FC-72 and have, respectively, an inner tube diameter larger (3 mm) and slightly smaller (1.6 mm) than the critical diameter evaluated in static Earth gravity conditions. On ground, the small diameter CLPHP effectively works as a Pulsating Heat Pipe (PHP): the characteristic slug and plug flow pattern forms inside the tube and the heat exchange is triggered by thermally driven self-sustained oscillations of the working fluid. On the other hand, the large diameter CLPHP works as a two-phase thermosyphon in vertical position and doesn't work in horizontal position: in this particular condition, the working fluid stratifies within the device as the surface tension force is no longer able to balance buoyancy. Then, the idea to test the CLPHPs in reduced gravity conditions: as the gravity reduces the buoyancy forces becomes less intense and it is possible to recreate the typical PHP flow pattern also for larger inner tube diameters. This allows to increase the heat transfer rate and, consequently, to decrease the overall thermal resistance. Even though it was not possible to experience low gravity conditions due to a failure in the yo-yo de-spin system, the thermal response to the peculiar acceleration field (hyper-gravity) experienced on board are thoroughly described.

1. Introduction

Pulsating Heat Pipes (PHPs) are novel two-phase passive heat transport devices that seem suitable for the thermal management of electronics components in space related applications. Patented in their most common configurations by Akachi [1-2], PHPs basically consist of a meandering tube of capillary dimensions closed end-to-end to form a closed loop. The tube is first evacuated and then partially filled with a working fluid, which naturally resides in the form of liquid plugs alternated to vapour slugs. When input heat power is provided to the evaporator section, the vapour bubbles expand and push the adjacent liquid plugs to the condenser section, where heat is released to the cold source and condensation process occurs.

In spite of the significant efforts made in the last decades in order to create a comprehensive set of tools able to predict PHPs behaviour and facilitate their design, some issues still remain unsolved [3], such as the effect of the number of turns and the influence of the orientation with respect to the gravity



vector on the thermal performance. Nowadays, the design of PHPs is based on the so-called Bond number confinement criterion: in particular, surface tension can prevail over buoyancy and a capillary slug flow pattern can form inside the tube, if the inner tube diameter is smaller than a critical diameter formulated on Earth gravity conditions, i.e. $d_{cr} = 2\sqrt{\sigma/g(\rho_l - \rho_v)}$. If one accounts only for the aforementioned criterion it seems that, under reduced gravity conditions, the inner tube diameter may be increased to the bitter end. However, both Gu et al [4] and Mameli et al [5] asserted that viscous and inertial effects always play a significant role in the definition of the flow pattern within the device that can not be discounted. Considering the recent formulation of the dynamic confinement criterion based on the Weber and Garimella numbers, it seems that a two-phase loop device may work as a PHP under reduced gravity conditions with an inner tube diameter larger than the one evaluated on static Earth gravity conditions. In order to assert the validity of the aforementioned assumption and to decouple completely the inertial effects from buoyancy is therefore fundamental to conduct experiments directly in a reduced gravity environment.

Based on the above considerations, Mangini et al. [6] tested a planar Closed Loop Pulsating Heat Pipe (CLPHP), with an inner tube diameter (3 mm) much larger than the critical diameter value defined on static Earth gravity conditions (1.6 mm at 20 °C for refrigerant FC-72), both on ground and in the micro-gravity conditions experienced during the 61st ESA Parabolic Flight Campaign. On ground, the device works as a closed loop two-phase thermosyphon when gravity assisted and as a pure conductive medium when placed in a horizontal position. When the gravity level decreases, visualization studies reveal a sudden transition of the flow pattern from stratified to slug flow. Then, the oscillations of the working fluid suddenly activate and the device is also able to work as a PHP when placed in horizontal position.

As the time required for the device to reach an operational pseudo-steady-state is about few minutes, the available reduced gravity period in a parabolic flight (approximately 20 s) is not enough to assert anything on the device overall thermal performance. One of the alternative methods in order to obtain a longer reduced gravity period is to exploit longer flight trajectories, such that on board a sounding rocket or a satellite in an orbit around the Earth.

The aim of the present work is to investigate the thermal response of two CLPHPs with an inner tube diameter respectively smaller and larger than the critical one on Earth in the reduced gravity conditions experienced on board REXUS-18 sounding rocket. The reduced gravity period is expected to last around 90 s according to preliminary calculations based on the foreseen overall mass of the payload. The flight test results are compared with the results obtained on ground with the devices both in vertical Bottom Heat Mode (BHM) and horizontal orientations.

2. Experimental set-up

The test-cell and the peripheral facilities are mounted inside a cylindrical module, which constitutes the REXUS 18 sounding rocket casing, according to the architecture sketched in Figure 1.

The geometrical features of the module are given in the rocket manual. The test-cell consists of two CLPHPs and a phase change material that acts as a heat sink. The test-cell is mounted inside an airtight box, also termed as experiment box, in order to avoid leakages that may result in a serious hazard for launch safety. The battery cells that provide the input heat power to the heat sources are integrated inside a pack. Then, the electronic boards for the management of data and power are mounted in the on-board data handling and power management boxes, respectively.

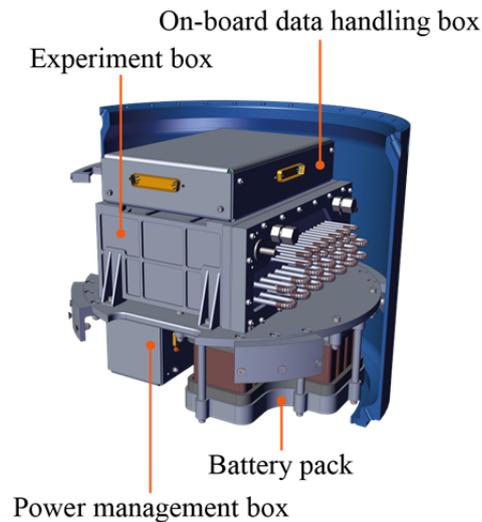


Figure 1. Experimental set-up.

2.1. Test-cell

The geometrical features of both CLPHPs are summarized in Table 1. The basic devices structure, as sketched in Figure 2, consists of an aluminium tube folded in a double-layer configuration with fourteen curves constituting the evaporator section. Two T-junction close the tube in a loop and in addition allow for obtaining two ports: the former is used for the emptying and filling procedure; the latter hosts a pressure transducer (Kulite[®], XCQ-093-1.7 bar A). The devices are equipped with T-type thermocouples that have a post-calibration accuracy of ± 0.7 K. The thermocouples are thermally linked to the aluminium tube by means of a high conductive paste. The thermocouples position on the large diameter CLPHP is sketched in Figure 2 and is symmetrical on both devices planes. The thermocouples position on the small diameter CLPHP is the same except in the evaporator section, where the thermocouples are mounted in an alternate fashion. The thermocouples position is selected in order to make assumptions on the circulation of the working fluid and does not influence the experiment in any way being a non-invasive measurement.

Table 1. Geometrical features.

	Small Diameter CLPHP	Large Diameter CLPHP
Internal Diameter (ID)	1.6 mm	3 mm
Outer Diameter (OD)	3.2 mm	5 mm
Radius of Curvature (r_c)	4.8 mm	7.5 mm
Length (L)	192.8 mm	200 mm
Evaporator Length (L_e)	6.4 mm	10 mm
Condenser Length (L_c)	145 mm	145 mm
Width (W)	128 mm	200 mm
Height (H)	12.8 mm	20 mm

The CLPHPs are evacuated by a two-stage vacuum pump (Edwards[®], XDS35i and EXT255H 24V) until a pressure level of 10^{-4} Pa is obtained. The selected working fluid, i.e. FC-72, is separately degassed in a secondary loop by continuous boiling: the incondensable gases first accumulate at the top of a tank and then are sucked away by means of several vacuuming cycles. Then, the devices are partially filled with a volumetric ratio of 0.5 ± 0.025 and sealed. The incondensable gases content results in an overpressure included within the margin of accuracy of the pressure transducer.

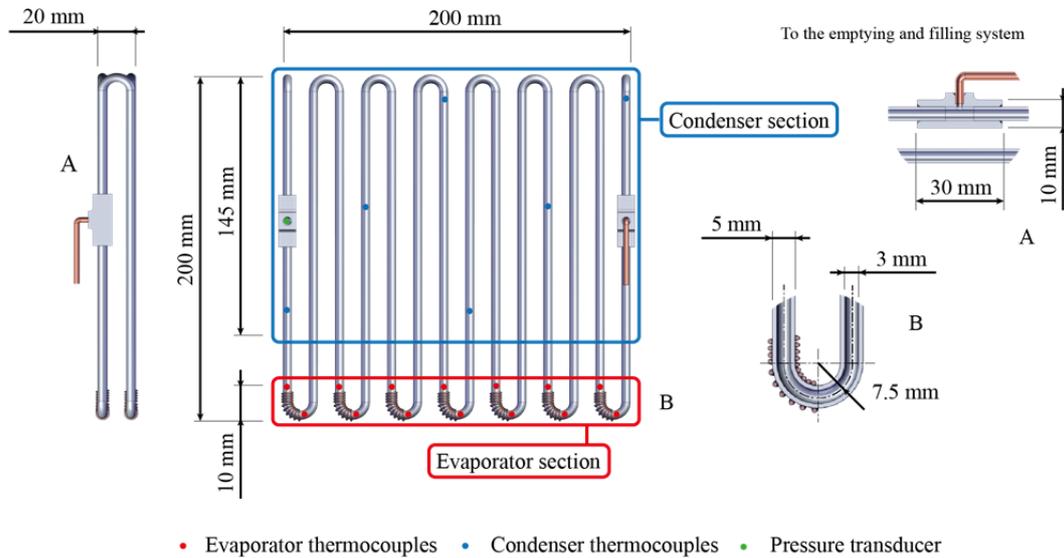


Figure 2. Structure.

2.1.1. Evaporator section. The CLPHPs evaporator sections consist of 2 wire-shaped heating elements (Thermocoax[®], 1 Nc I) 1.6 m long with a 1 mm external diameter and an equivalent line resistance of 12 Ω/m. The heating elements are connected in parallel and wrapped around the evaporator curves as shown in Figure 2: the asymmetrical position with respect to the curves is intended to promote the working fluid circulation in a preferential direction. The evaporator sections temperature is limited to 150 °C by two thermal switch (DMP[®], 11MP 160L 007E) in contact with the aluminium tube. The heating elements are powered up to 400 W by 14 battery cells (SAFT[®], MP176065): 8 DC/DC converters, each that consist of a PRM regulator (Vicor[®], P024F048T12AL) and a VTM current multiplier (Vicor[®], VTM48EF480T006A00) regulate the voltage and current coming from the cells in order to provide the power profiles shown in Figure 3.

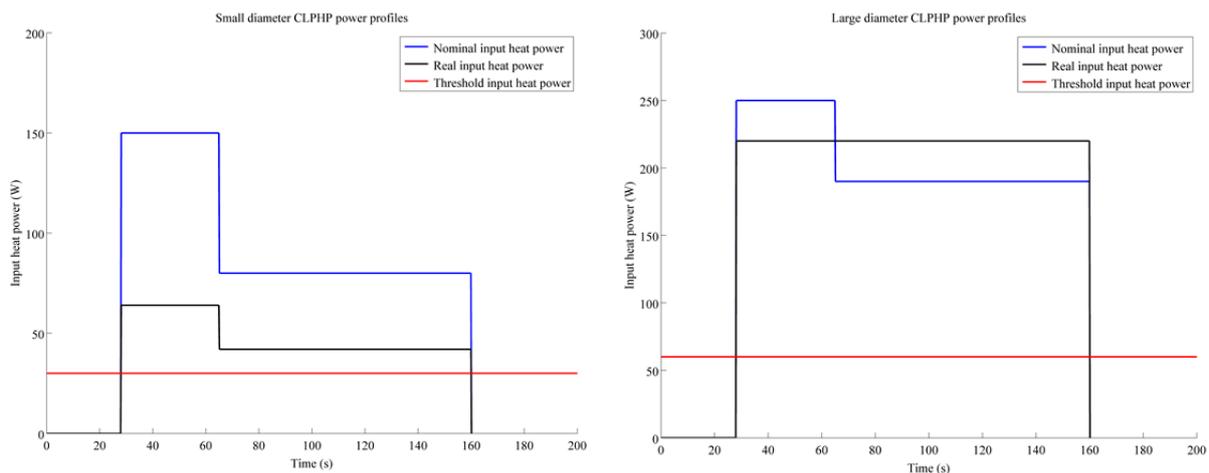


Figure 3. Power profiles: a) small diameter and b) large diameter CLPHPs.

The nominal power values provided to the heating elements are selected in order to supply the evaporator sections of both CLPHPs with an input heat flux larger than a threshold value. The threshold value (dotted line in Figure 3) corresponds to the value beyond which the device shows an unstable behaviour, i.e. it is not able to reach a pseudo-steady-state even if the heat input power is increased [8]. The threshold value is about 5 W/cm², thus, the nominal power values are sized so as to

result in an input heat flux of 15 W/cm^2 . The nominal power values are preceded by peak values intended to rapidly overcome the thermal inertia of the aluminium tubes. The power is evaluated by combining the voltage and current measurements with the imposed duty cycle values. The measurements are carried out by an instrumental amplifier (Analog Devices®, AD8221) with a minimum accuracy of $\pm 10 \%$ of the imposed power values.

2.1.2. Condenser section. The heat sink consists in a phase change material in contact with the condenser section. The phase change material is an n-octadecane paraffin wax whose thermal properties are summarized in Table 2. Theoretically, the paraffin wax should absorb heat via latent heat of fusion so as to keep constant the condenser temperature. However, as the thermal conductivity of the paraffin wax is small, after a certain time, the melting front stops and the liquid paraffin surrounding the tubes is heated up (sensible heating), thus leading to an increase of the condenser temperature. This phenomenon should be carefully taken into account and can be probably overcome by embedding a conductive structure inside the paraffin (i.e. aluminium honeycomb).

Table 2. Paraffin wax thermal properties.

Phase change material properties	
Melting point temperature	28.0 °C
Boiling point temperature	317.9 °C
Specific heat	2160 J/(kg K)
Latent heat of fusion	244 kJ/kg
Thermal conductivity	0.15 W/(m K)

2.2. Data handling system

The output signals were managed by a microcontroller, mounted on an electronic board specifically designed in order to meet the actual experimental objective. The temperatures and pressure output signals were acquired at 5 and 10 Hz, respectively, while the current and voltage output signals were acquired at 1 Hz.

3. Experimental results

The experimental results are presented in terms of temperatures and pressure temporal trends. In the graphs below, the tubes wall average evaporator and condenser temperatures are sketched together with the local working fluid pressure on the secondary ordinate axis. The input heat power provided to the CLPHPs heating elements is also reported.

The flight results are compared to that obtained on ground with the devices in vertical BHM and horizontal positions in order to provide comparison between the devices thermal performances under different operational conditions. A list of the performed tests is provided in Table 3.

Table 3. List of the performed tests.

	Small Diameter CLPHP	Large Diameter CLPHP
Ground Tests -Vertical		
Peak Power	64.5 W	218 W
Nominal Power	42.5 W	218 W
Ground Tests -Horizontal		
Peak Power	64.5 W	218 W
Nominal Power	42.5 W	218 W
Flight Tests		
Peak Power	64.5 W	218 W
Nominal Power	42.5 W	218 W

3.1. Ground tests

The ground tests results relative to the small and large diameter CLPHPs in vertical and horizontal positions are reported in Figure 4 and Figure 5, respectively.

The pressure temporal trends relative to the small diameter CLPHP in vertical (Figure 4a) and horizontal (Figure 4b) positions are different: in the former case, pressure oscillations have smaller amplitude and higher frequency while in the latter larger amplitude and lower frequency. The reason lies in the different orientation of the device with respect to the gravity vector. In vertical position, the gravity vector acts along the flow path direction and assists the working fluid motion. In these conditions, even a small pressure change is sufficient to overcome the inertial effects and to push vapour bubbles and adjoining liquid plugs towards the condenser section: as the vapour bubbles rise rather easily the resulting pressure oscillation frequency is high. In horizontal position, the gravity vector acts on a plane perpendicular to the flow path direction. As a result, a large pressure change is needed in order to displace the liquid plugs and the working fluid motion is least frequent.

The nature of the pressure oscillations results in different start-up behaviours. In vertical position, the start-up occurs suddenly as soon as a sufficient pressure difference is set up between the evaporator and condenser sections. In horizontal position, the start-up takes slightly more time, as gravity has not an influence on the working fluid motion. The working fluid motion inside the CLPHP in different orientations also affects the overall thermal performance. The heat transport capability is higher when gravity assists the working fluid motion as more liquid reaches the condenser section and releases sensible heat. Then, the average evaporator temperature moves towards a smaller value when the device is in vertical than in horizontal position.

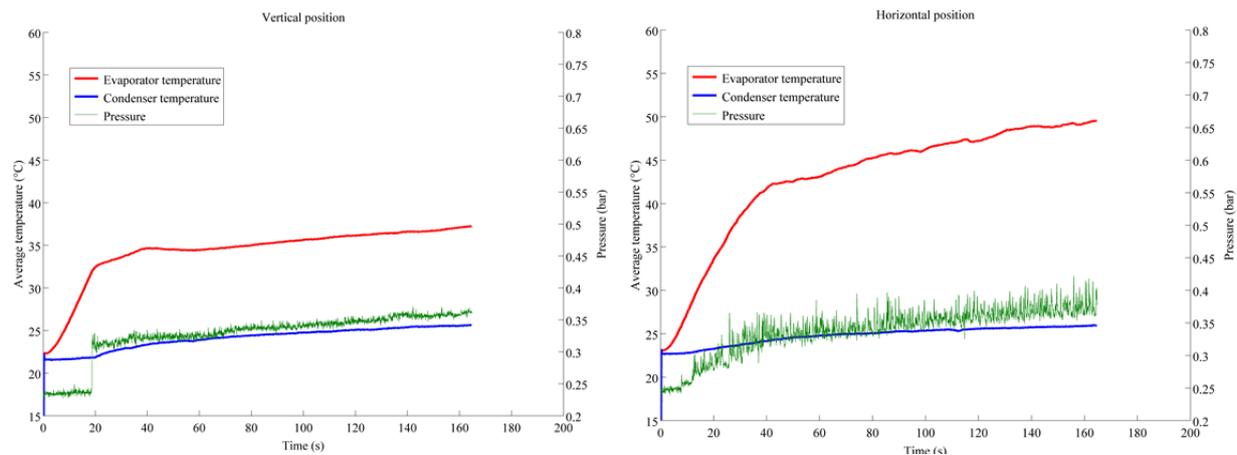


Figure 4. Small diameter CLPHP: a) vertical and b) horizontal ground tests.

The pressure temporal trends relative to the large diameter CLPHP in vertical (Figure 5a) and horizontal (Figure 5b) positions are quite similar to the ones discussed above, although the physical phenomena that occur inside the device have a different nature. In vertical position, the device operates as a two-phase thermosyphon. The liquid phase that accumulates close to the evaporator section boils continuously. The generated vapour rises towards the condenser section and, sometimes, drags on with it on some liquid batches in the so-called "bubble lift" mode thoroughly characterized by Franco et al. [8]. As the working fluid distribution inside the device is optimal, even a small pressure difference between the evaporator and condenser sections is able to trigger the working fluid motion. In horizontal position, gravity restrains the liquid phase in the bottom plane of the device while the vapour phase fills the upper plane. The resulting working fluid distribution within the device is not optimal: beyond gravity, the pressure force that ensue from the vapour expansion on the upper plane, keeps the liquid phase confined to the bottom plane. Therefore, the working fluid motion is completely absent until the vapour phase in the upper plane condenses: the associated pressure decrease in the upper plane leads to a vigorous boiling process in the bottom plane. The vapour expansion process is

almost instantaneous and traduces in a water hammer associated with high amplitude pressure oscillations. The heat transport process in such a condition is inefficient and results in a higher average evaporator temperature.

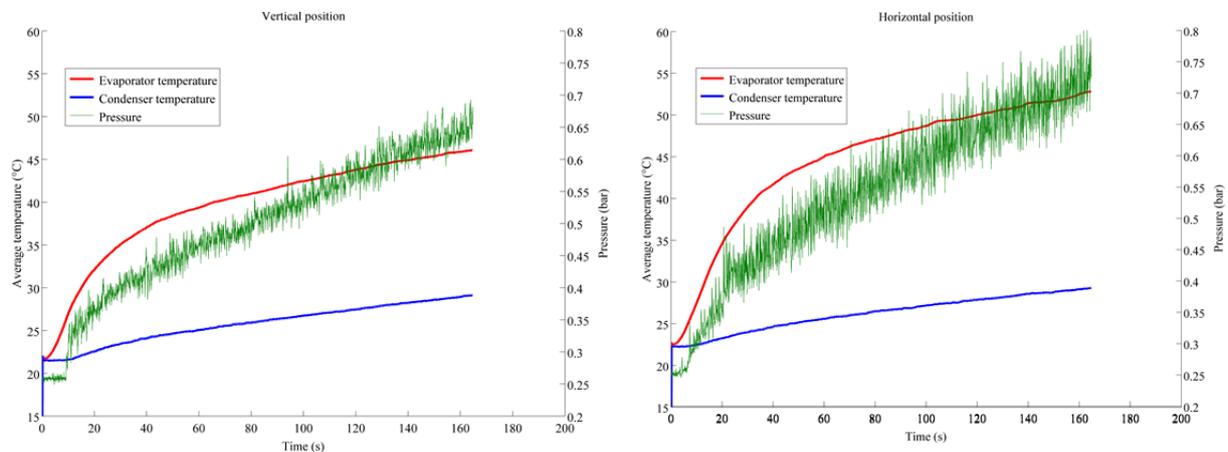


Figure 5. Large diameter CLPHP: a) vertical and b) horizontal ground tests.

3.2. Flight tests

The accelerations experienced during REXUS 18 sounding rocket flight are sketched in Figure 6. The red and blue lines represent the accelerations along the longitudinal axis of the rocket and on a plane perpendicular to it, respectively. The black vertical lines represent the timeline main events. The line that corresponds to the ordinate axis represents the rocket Lift Off (LO) and Start of Experiment (SoE). Then, proceeding to right, at LO +28 s, there occurs the Start of Data Storage (SoDS): from this time, power is provided to the heating elements and data are stored in the memory. Finally, power is switched off at LO +160 s and simultaneously the experiment ends.

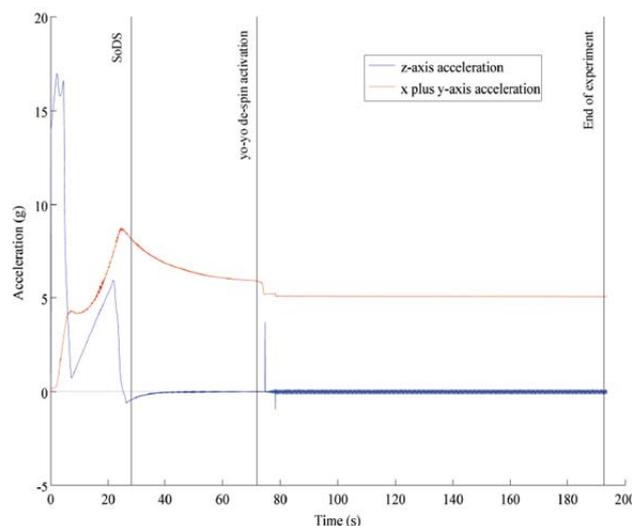


Figure 6. Accelerations.

The black vertical line at LO +70 s corresponds to the instant when the yo-yo system had to act and reduce the rotation of the rocket about its longitudinal axis. However, as can be clearly inferred from Figure 6, the yo-yo system failed and the presence of the residual centrifugal acceleration prevents

both CLPHPs to work in the expected reduced gravity environment. For this reason, the flight results are placed in the context of the hyper-gravity experiments documented in literature. An image with a series of concentric circles representing the gravity levels that act on the devices depending on their radial distance from the longitudinal axis of the rocket is sketched for clarity in Figure 7.

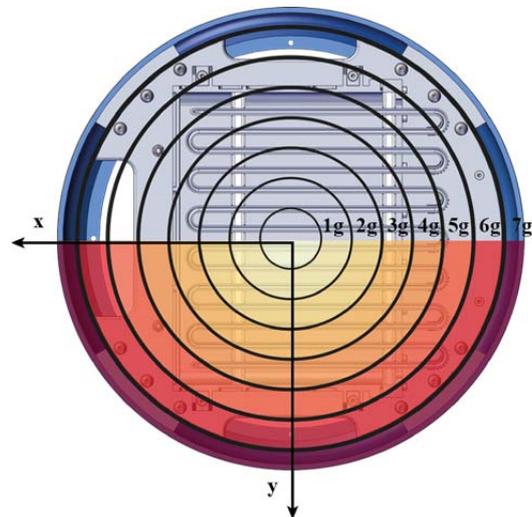


Figure 7. Gravity levels.

The flight test results relative to the small diameter CLPHP are reported in Figure 8. The centrifugal component of the acceleration promotes the working fluid motion and affects the device start-up. However, the acceleration is not oriented from the condenser to the evaporator as in the case with the device oriented in vertical position and it pushes the liquid phase from the central to the peripheral region of the device. The confinement of the liquid phase in the peripheral region of the device results in a detrimental effect on the performance with respect to the vertical ground test but not with respect to the horizontal ground test. The pressure temporal evolution is characterized by the occurrence of random pressure peaks associated with a decrease and increase of the average evaporator temperature, respectively. In fact, when the centrifugal acceleration separates phases, the working fluid motion stops and the heat transport process becomes ineffective. Then, it occurs a decrease of the acceleration level or an increase of pressure in order to allow the working fluid to redistribute properly: the standoff condition is overcome and the device restarts its operation.

The flight test results relative to the large diameter CLPHP are reported in Figure 9. The centrifugal component of the acceleration significantly affects the distribution of the working fluid within the device: the liquid phase is pushed towards the peripheral region while the vapour phase occupies the central region. As such a distribution is not optimal, the heat exchange process is not effective and the average evaporator temperature increases with respect to the vertical case. It is worth to note that, a few moments before the end of the test, a failure in one of the heating elements prevents heat power to be provided to the evaporator section and the average evaporator temperature and pressure decrease.

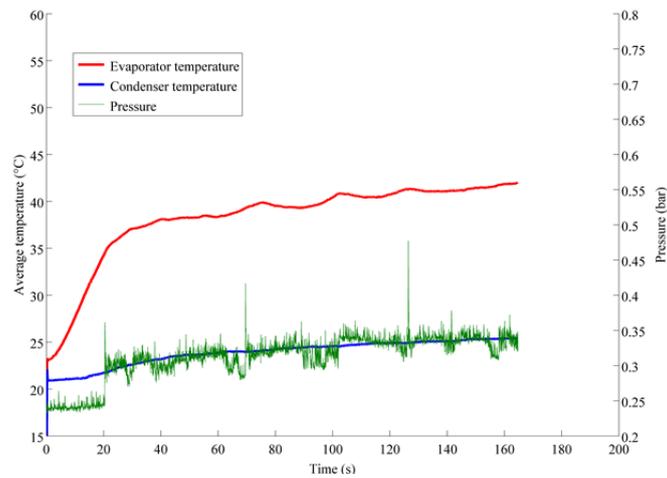


Figure 8. Small diameter CLPHP: flight test.

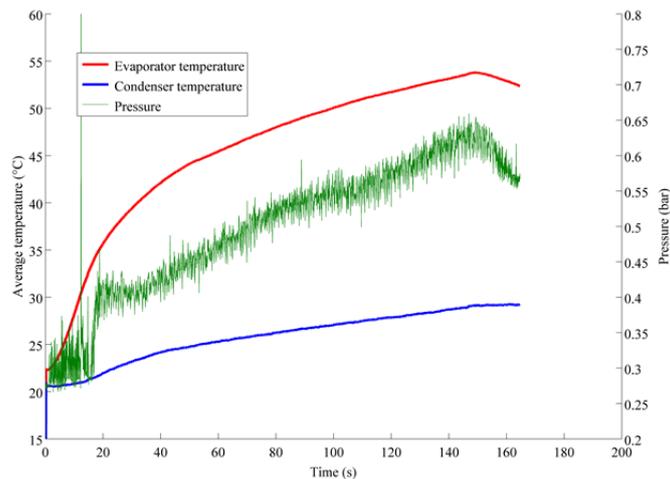


Figure 9. Large diameter CLPHP: flight test.

4. Conclusions

In the present work, the experimental results of two CLPHPs tested on board REXUS 18 sounding rocket are discussed. The devices consist of an aluminium tube folded in a double-layer configuration and filled with refrigerant FC-72. The only remarkable difference between the devices regards the inner tube diameter that is larger (3 mm) and slightly smaller (1.6 mm) than a critical diameter defined on static Earth gravity conditions. The condenser section is embedded in a phase change material, which absorbs heat via latent heat of fusion so as to keep the evaporator temperature to a nearly constant value. The evaporator section consists of 2 wire-shaped heating elements wrapped around the evaporator curves. Due to a malfunction of the rocket de-spin system, the device experienced an augmented gravity environment instead of the desired milli-gravity, so was not possible to observe the expected net transition in the temperatures and pressure temporal evolutions associated with the occurrence of the slug and plug flow pattern within the device. In the light of such considerations, the major outcomes of the present work are listed here below:

- The small diameter CLPHP confirm literature results: the hyper-gravity conditions have a beneficial effect on the overall thermal performance with respect to horizontal orientation as centrifugal accelerations promote the working fluid circulation within the device in every direction. However, the overall thermal performance in vertical position on ground is the best, as gravity acts always from the condenser to the evaporator;

- The large diameter CLPHP on ground is affected by the stratification of the working fluid within the device, as surface tension is not able to balance buoyancy. When in vertical position, the liquid and vapour phases reside in the evaporator and condenser section, respectively and the device behaves like a two-phase thermosyphon. When in horizontal position, the liquid and vapour phases reside in the bottom and upper device planes, respectively, and the device operates intermittently whenever a sufficient temperature gradient arises between the planes to push some liquid in the upper plane;
- The large diameter CLPHP in hyper-gravity conditions is more sensitive to the centrifugal acceleration: the liquid and vapour phases hold relatively in the peripheral and central parts of the device. The overall thermal performance is better than in horizontal position.

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