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UPGRADED PULSATING HEAT PIPE ONLY FOR SPACE (U-PHOS): RESULTS OF THE 22nd REXUS SOUNDING ROCKET CAMPAIGN

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Abstract. A large tube may still behave, to a certain extent, as a capillary in a micro-gravity environment. This very basic concept is here applied to a two-phase passive heat transfer devices in order to obtain a new family of hybrid wickless heat pipes. Indeed, a Loop Thermosyphon, which usually consists of a large tube, closed end to end in a loop, evacuated and partially filled with a working fluid and intrinsically gravity assisted, may become a capillary tube in space condition and turn its thermo-fluidic behavior into a so called Pulsating Heat Pipe (PHP), or better, a Space Pulsating Heat Pipe (SPHP). Since the objective of the present work is to experimentally demonstrate the feasibility of such a hybrid device, a SPHP has been designed, built, instrumented and tested both on ground and microgravity conditions on the 22nd ESA REXUS Sounding Rocket Campaign. Ground tests demonstrate that the device effectively work as a gravity assisted loop thermosyphon, whether the sounding rocket data clearly reveal a change in the thermal hydraulic behavior very similar to the PHP. Since a microgravity period of approximately 120s is not sufficient to reach a pseudo steady state regime, further investigation on a longer term weightless condition is mandatory.

Keywords: Large Diameter Pulsating Heat Pipe, Sounding Rocket, Milligravity.

1. INTRODUCTION

In the wake of electronic components miniaturization, and the consequent increase in excessive heat, two-phase heat transfer devices are becoming the predominant thermal management solution. The electronic cooling issue is even more demanding in space applications, where sintered wick Heat Pipes (HP) and Loop Heat Pipes (LHP) are generally preferred because of their lightweight, reliability and, most of all, their ability to operate without the assistance of any acceleration field (Gilmore, 2002). This ability is obtained using a capillary structure which is also the most complex and expensive element inside the system. In a cost reduction perspective, Akachi (1990, 1993) introduced the concept of Pulsating Heat Pipe (PHP), which is basically a wickless two phase loop, consisting in a capillary diameter tube bended in several turns so that the fluid resides inside the tube as an alternation of liquid slugs and vapor bubbles: when the vapor formed in the heated zone expands, it pushes the adjacent fluid to the condenser zone, where the heat is released and the vapor condenses. Generally, in the PHP literature, the capillary limit is evaluated in ground static conditions by the Kew and Cornwell (1997) criterion:

$$Bo < 4 \tag{1}$$

where the Bond number is defined as $Bo = \frac{g(\rho_l - \rho_v)d^2}{\sigma}$, σ is the liquid surface tension, g is the gravitational acceleration and ρ_l and ρ_v are the liquid and vapor density, respectively. From the simple formula shown, it seems evident that the microgravity condition allows for a bigger critical diameter and consequently for higher thermal flux dissipation as also suggested by Gu *et al.*, (2004). On the other hand, the previous criterion may not be the most suitable in microgravity conditions since it does not consider the inertial and viscous effects. Baldassari and Marengo (2013), propose a more comprehensive criterion based on the Garimella number:

$$Ga = \sqrt{Bo}Re < 160 \tag{2}$$

where where $Re = \rho_l U_l d/\mu_l$ is the Reynolds number related to the liquid phase. The static and dynamic critical diameters, d_{Bo} and d_{Ga} are calculated respectively with equation 1 and 2 for C_6F_{14} at 20°C, considering a typical average velocity of the liquid phase equal to 0.1 m/s (Fig. 1). Indeed, even considering the most conservative criterion (eq.2) it should be theoretically possible to develop a two-phase loop working as a Pulsating Heat Pipe (slug/plug flow pattern) even if the tube diameter is bigger than the critical value calculated in ground conditions.

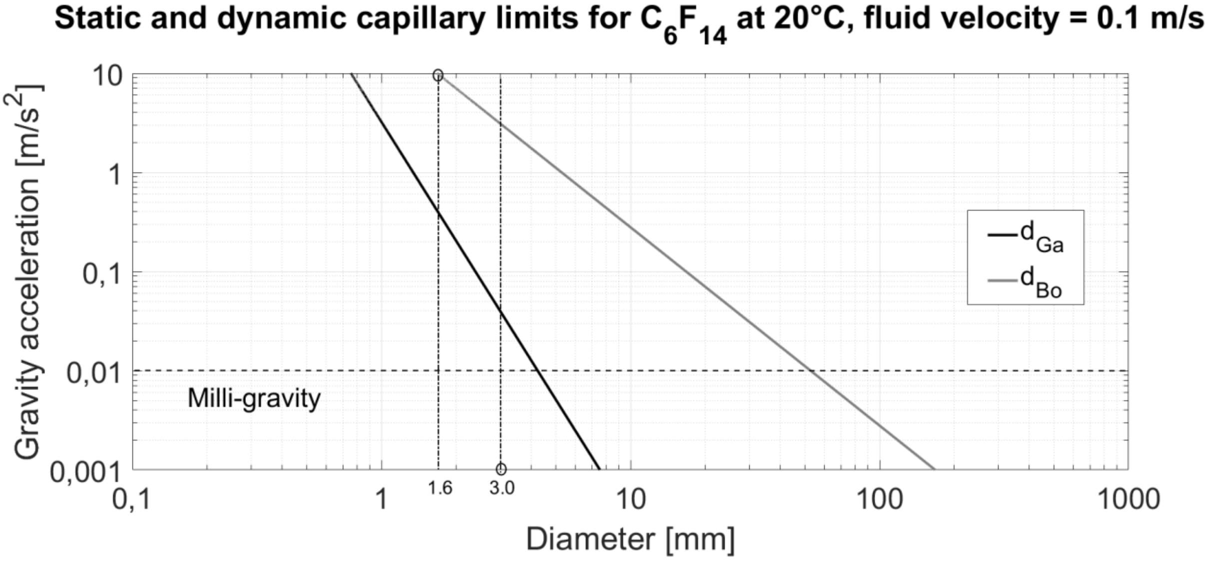

Figure 1: Static and dynamic capillary limits for C6F14 at 20°C, fluid velocity = 0.1 m/s.

Many experiments in microgravity condition (i.e. by means of parabolic flight or sounding rockets) have been carried out on capillary PHPs (Gu *et al.*, 2004, 2005; De Paiva *et al.*, 2010, 2013, Mameli *et al.*, 2014; Taft *et al.*, 2015; Ayel *et al.*, 2015, 2016) and most of them clearly revealed a self-sustained two-phase flow motion in microgravity, while few experiments have been performed when the tube diameter is bigger than the capillary limit on ground. The Space PHP concept feasibility has been already successfully tested by Mangini *et al.* (2015, 2017), who tested a PHP with an inner diameter of 3mm charged with C_6F_{14} (not capillary on ground, see figure 1), both on ground and in milli-gravity condition during ESA 61 and 63 Parabolic flight campaign. They noticed that a sudden transition of the flow pattern from stratified to slug flow takes place as the mlligravity occurs, showing that the device may work as a capillary tube PHP in space conditions. The reduced gravity ambient experienced during the parabolic flight (about 20 s) was too short to reach a steady state conditions, which would be useful to characterize the thermal performances of the device. Considering the above, the first experiment on the Space PHP onboard a sounding rocket was performed (REXUS 18) to obtain data on a longer microgravity duration (120s) but it failed due to a problem in the rocket de-spinning system (Creatini et al., 2015). An updated experiment on the Space PHP has been designed, built and tested in the next REXUS campaign (Nannipieri *et al.*,2016, 2017); the present work is devoted to describing the experimental outcomes both on ground and microgravity conditions.

2. EXPERIMENTAL SETUP

2.1 Test cell and peripheral facilities

The PHP test cell is a single loop aluminum tube (6060 alloy) folded in a staggered configuration with fourteen U-turns at the evaporator and thirteen U-turns at the condenser, as shown in Figure 2a. The device is evacuated and then partially filled with the working fluid (n-perfluorhexane, brute chemical formula: C_6F_{14}) with a volumetric ratio of 0.5 ± 0.025 (corresponding to 8.3 ml), via a T-junction. The PHP condenser section is embedded into a heat sink, consisting of a PCM (octadecane paraffin wax) doped with a metallic foam (ERG®, aluminum, 40 Pores Per Inch, 12% relative density). In order to avoid any leakage of PCM, the condenser section of the PHP and the heat sink are contained inside an airtight box. Two ceramic heaters are mounted on the heating plates brazed just above the U-turns in the evaporator zone shown in Figure 2b. A battery pack (8s1p SAFT® Li-Ion cells, 28 V, 54.4 Ah) provides an electric power input up to 200 W (corresponding to a radial wall-to-fluid local heat flux of 12.6 W/cm^2). A custom electronic PCB, provided with a PWM at 225 Hz**,** is employed to supply a wide range of power levels to the ceramic heaters. The same board has the role of exploiting power measurements, with an estimated accuracy of about 5%.

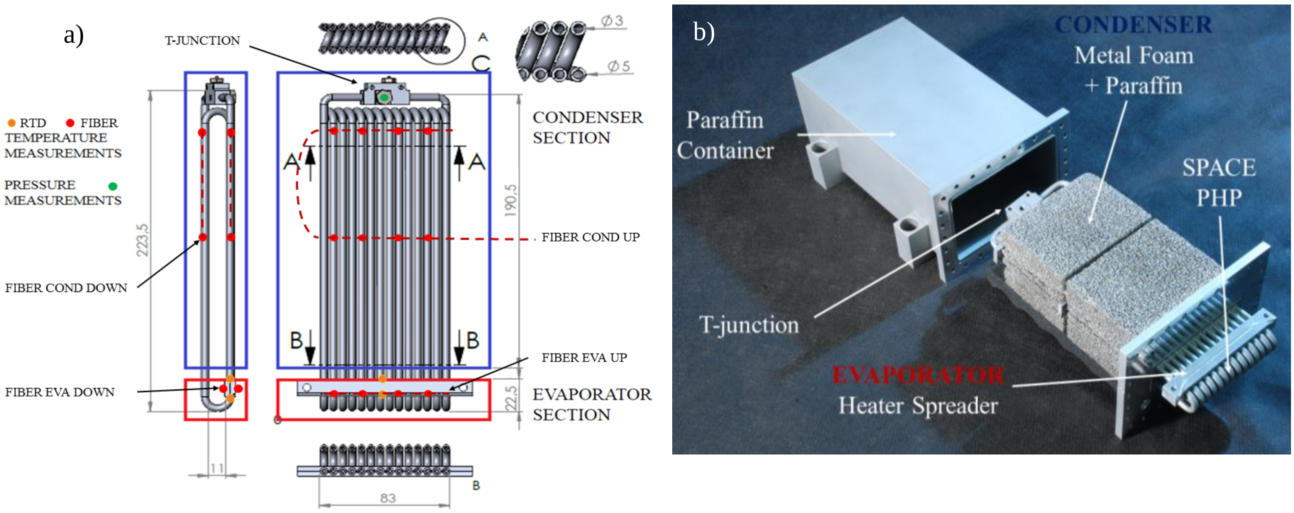

Figure 2: a) PHP Test Cell Layout, geometry and measurements location; b) PHP test cell actual shape and main components.

A pressure transducer (Kulite®, XCQ-093-1.7 bar A, max error 0.5% FSO), is located in the T-junction at the condenser end of the PHP.

A Fiber Bragg Grating (FBG) temperature measurement system (SmartScan® series realized by Smart Fibres® and Infibra Tec. ®) acquires temperatures in 24 points by means of optical sensors, with an accuracy of ± 0.1 K. This system has many technological advantages such as the intrinsic immunity to electromagnetic interference, compactness, easy integrability and accuracy. Up to the authors' knowledge, this is the first time that this system is used to test a PHP and the first time that it is actually used on board a space vehicle as temperature sensor (Nannipieri *et al.* 2017). The FBG interrogator can handle a maximum scanning frequency of 2.5KHz for all sensors simultaneously. Moreover, two PT-100 (±0,06Ω @ 0°C) are placed in the evaporator section for FBG calibration and redundancy. A data handling system records the output of the optical sensors (at 10Hz), pressure transducer (at 100Hz) and g-sensor (at 10Hz).

Gravity variations during the flight are detected by means of a three-axis g-sensor (Dimension Engineering®, DE-ACCM3d, sense range: ±3g, sensitivity 333mV/g). This sensor is needed only to detect the switching from hyper gravity to milligravity condition at burnout of the engine and the accelerations on the three axes when the de-spin has taken place, thus the range is reduced to obtain better accuracy on acceleration levels when in milligravity as shown in figure 3.

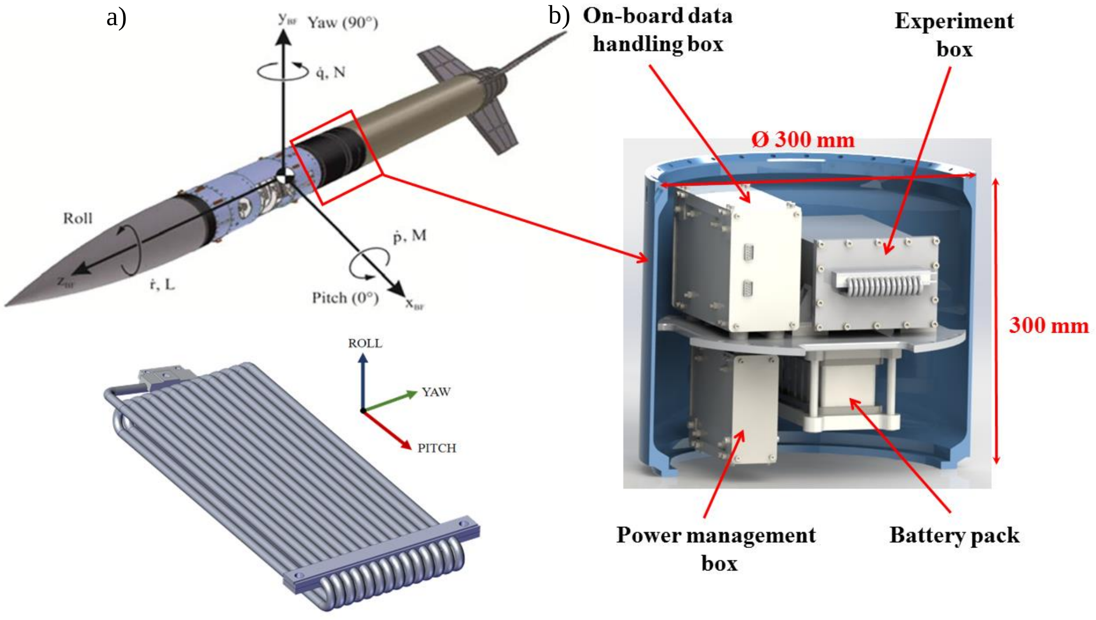

Figure 3: a) Rocket scheme and acceleration references; b)U-PHOS module scheme.

2.2 Test procedure and data analysis

The experiment time line is structured as follows:

- From t = -900 s to the lift-off (t = 0 s): a preheating system is activated. A low percentage of the nominal power (80 W) is provided by the batteries to the heater to keep the PCM temperature as close as possible to the melting point (28°C) and keep other experiment components within their temperature operative range. This percentage is adjustable at need, via uplink while the rocket is on the launch pad, in order to prevent liquefaction of the PCM or, instead, excessive temperature decrease of it, so that during the experiment the PCM might not melt.
- From t = 0 s to t ~ 65 s: immediately after the lift-off, the PHP is heated at full power (200 W). Data acquisition, data storage and downlink are switched on. Burnout of engine at t =26s, after that the experiment is in milli-g conditions, but spinning. At t~65s the de-spin system is activated.
- From t ~ +65 s to t = +190 s: in this phase, the whole experiment is in milligravity condition. Due to the low thermal inertia of the heating system and the device, pseudo-steady state condition is expected;
- At t = +300 s, the experiment is switched off and all the data are once again sent to ground for redundancy.

A custom-made ground software developed with LabVIEW®, controls the experiment during the pre-launch phase and it receives, displays and stores data during the test. Data are post-processed and analysed in order to detect the external wall temperature evolution in evaporator and condenser, the fluid pressure frequency and amplitude. All recorded data are plotted against time:

- Tube wall temperatures in the evaporator and condenser zone are plotted together with the acceleration and heat power input. The local fluid pressure in the condenser zone is plotted together with the acceleration and heat power input allowing to determine and estimate the time response of the system to milligravity.

3. RESULTS

Flight results will be compared to ground tests in vertical bottom heated mode. As better explained in the sections here below, this is the best operative condition on ground for the device, and is a good benchmark to assess about the performance of the Space PHP.

3.1 Ground tests

In the vertical operation on ground, the surface tension forces are not able to overcome the buoyancy forces, so the liquid phase initially wets the whole lower part (evaporator section) and the vapor phase accumulates in the higher part (condenser section). The liquid phase boils continuously and the generated vapor rises towards the condenser dragging liquid batches in the so-called "bubble lift" mode as widely described by Mameli *et. al.* (2016). The loop configuration allows to obtain a very efficient flow circulation.

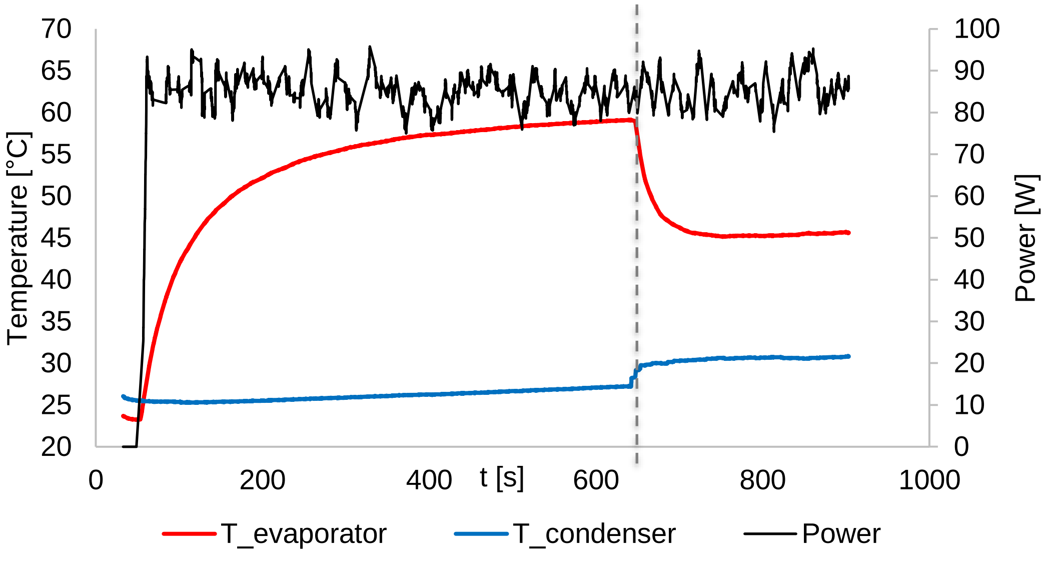

Figure 4: Start-up in ground conditions, bottom heated mode, 90W.

As shown in Figure 4, a preliminary test has been performed on the actual device in bottom heated mode at 90W. The red line represents the average temperature in the evaporator section, the blue line is the average temperature in the condenser zone, while the black line is the actual power provided to the evaporator zone. The dashed line indicates the start-up time: as the boiling process occurs, the gravity assisted two phase flow motion enhances the device thermal performance and the overall thermal resistance halves from 0.33 K/W to 0.16 K/W.

Preliminarily, it is clear that when the device is gravity assisted it may work fairly good, opening to a very promising perspective of having an hybrid device that works effectively on ground as a thermosyphon and switch to a Space PHP in zero gravity conditions.

3.2 Flight test

A first milli-gravity test was carried on a similar device during a previous flight sounding rocket campaign (Creatini *et al.* 2015). Unfortunately, the rocket de-spinning system malfunctioned and the consequent centrifugal acceleration compromised the experiment outcome, significantly affecting the working fluid distribution. In that occasion, it was not possible to observe the expected sudden transition in the temperatures and pressure trends associated with the occurrence of the slug and plug flow pattern within the device as shown by Mangini *et al.* 2015, 2017 and in the present case as shown by the results shown here below. In figures 5 to 8 the temporal trends of the three acceleration components is coupled with the main parameters of interest: the temperatures in the evaporator zone (Fig. 5 b), the temperature in the condenser zone on the upper and lower tube rank (Figs. 6b, 7b) and the local fluid pressure in the condenser zone, to appreciate how they are eventually affected by the variation of the acceleration field during the different launch phases. The secondary y-axis of all the parameters of interest is always showing the heating power profile.

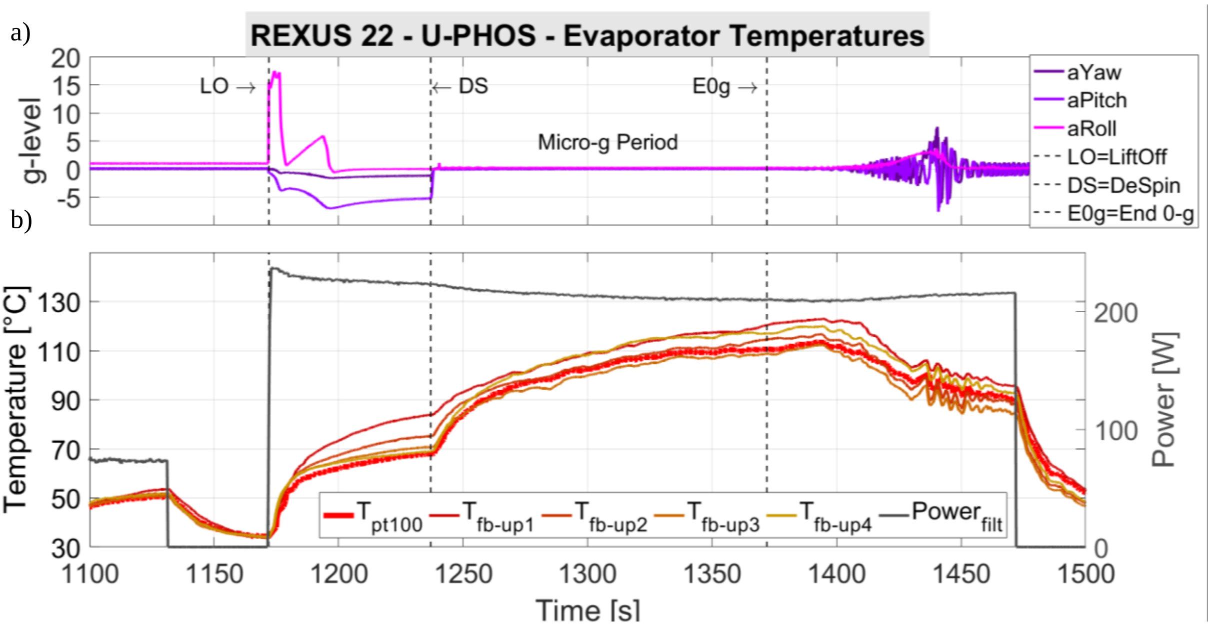

Figure 5: a) Accelerations during the different phases; b) Evaporator temperature trends (left y-axis) and Heating power (right y-axis).

Before the Lift Off (LO in the figures), the rocket is standing still in vertical position, and so only the Roll acceleration component is equal to 1g, the device is preheated at 80W to keep the PCM temperature as close as possible to the melting point (28°C), and the condenser temperatures are successfully maintained very close to that point as shown in figures 6 and 7. Since the device is horizontally oriented and the internal diameter is bigger than the capillary limit on ground, the two-phase fluid is stratified, meaning that liquid phase recollects in the lower tube rank. Furthermore, since the evaporator zone is located on the upper tube rank, it is wide known in the literature that such a two-phase loop thermosyphon where the heated zone is above the condenser, does not work and the heat is transferred only by means of conduction. Long as the preheating system is working, the evaporator temperature is indeed rising homogeneously (fig.5) and the fluid pressure signal (Fig. 8) is not showing any variation rather than its white noise (+/- 500 Pa). From the Lift Off the device is supplied with the regime heating power input (200 W) indeed both the evaporator and condenser temperatures rise.

Between the Lift Off and the De-Spin (DS in the figures) the rocket experiences nearly 20g of vertical acceleration due to the motor thrust and up to 6g of centrifugal acceleration due to the rocket spinning: the first is perpendicular to the flow path direction pushing the liquid phase once more in the lower tube rank; the second pushes the liquid phase on the two ends of the device. The effect of this acceleration field on the thermo-fluidic behavior is unpredictable but, on the overall, it is certainly assisting the fluid motion. This is clear by comparing the temperature trends in the subsequent microgravity period. After the rocket De-Spin, the three acceleration components decrease and the milligravity condition is reached. During this period, the fluid motion is only related to thermocapillary effects and the evaporator temperature exhibits a sudden increase while the condenser temperature decreases meaning a sudden decrease of the overall heat transfer performance with respect to the previous period.

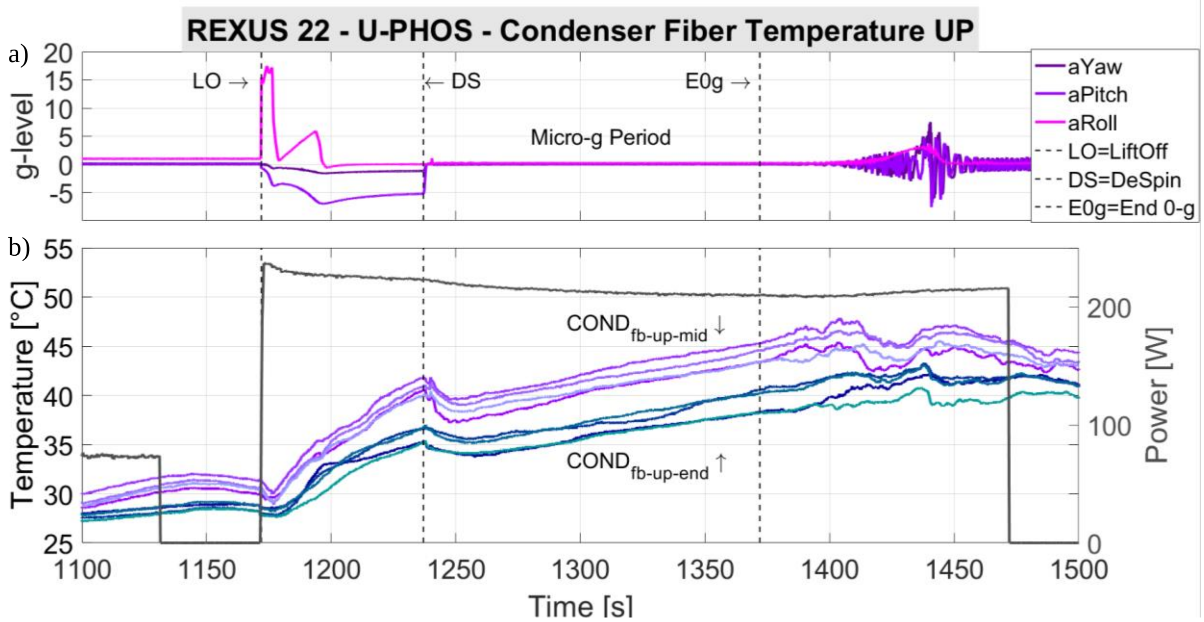

Figure 7: a) Accelerations during the different phases; b) Condenser temperature trends on the upper tube rank (left y-axis) and Heating power (right y-axis).

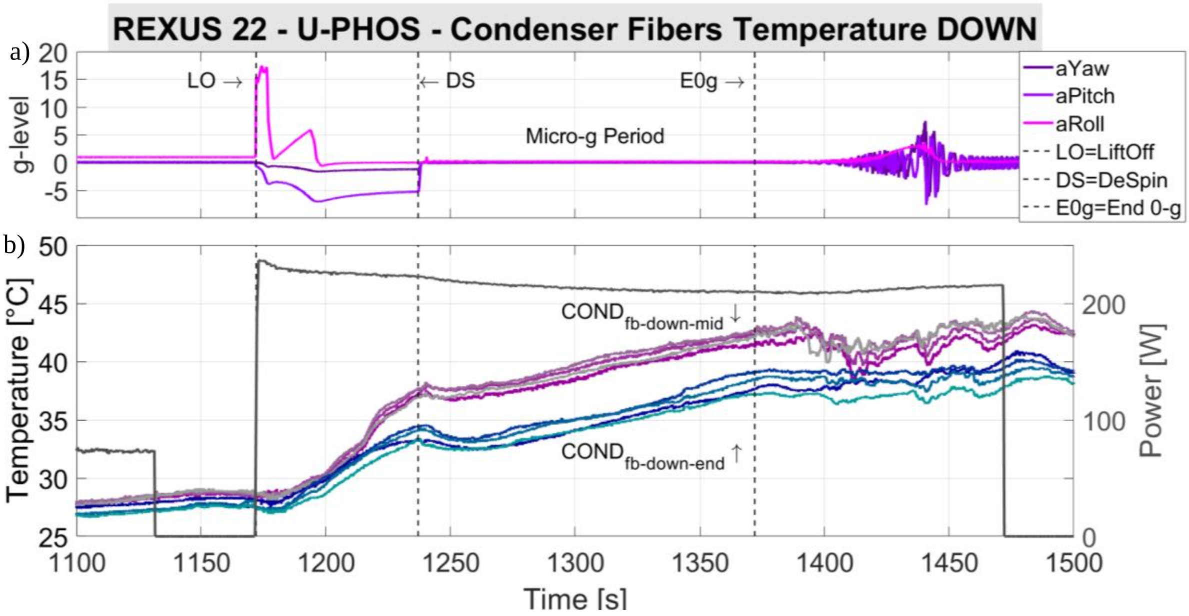

Figure 6: a) Accelerations during the different phases; b) Condenser temperature trends on the lower tube rank (left y-axis) and Heating power (right y-axis).

It is reasonable to assess that the acceleration field during the launch phase has positive effect on the fluid motion and consequently on the device heat transfer rate. On the other way, even if the device performance seems to degrade during the milligravity period, both the temperature and fluid pressure trends shows that the fluid motion is still active inside the device. Temperatures both in the evaporator and condenser, as well as the fluid pressure exhibit an oscillating component for the whole zero gravity duration and this is one the most important outcome of the present work since it is basically confirm that a multi-turn two phase loop is able to work as a Space PHP in milligravity conditions. Unfortunately, it was not possible to reach a pseudo-steady state probably because of the thermal inertia of the heat sink, stressing the fact that, a longer term micro gravity period is needed in order to infer about the actual heat transfer performance.

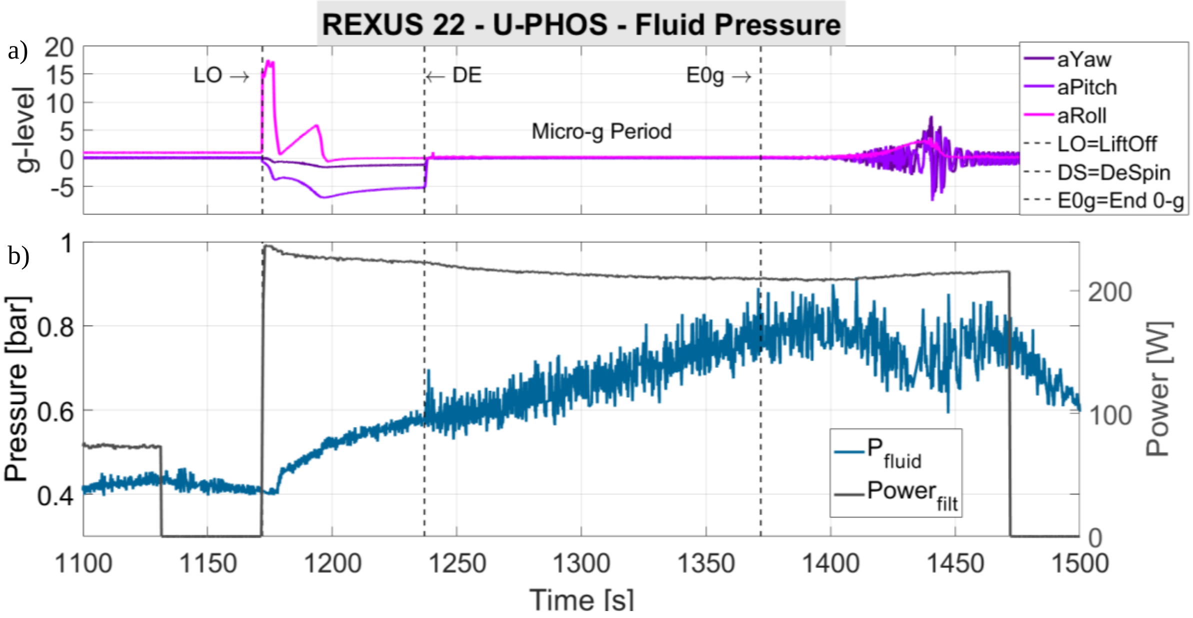

Figure 9: a) Accelerations during the different phases; b) Local fluid pressure trend (left y-axis) and Heating power (right y-axis).

As the reentry phase starts, the milli-gravity condition ends (E0g in the figures). In this period, the rocket experiences a complex acceleration field that, once again unpredictably, assists the fluid motion: the evaporator temperatures indeed decrease. The Fluid pressure signal shown in figure 8 is one of the most interesting since it clearly reveals a change in the trend immediately after the occurring of milligravity. By matching the actual results (Fig. 9a) with the one obtained in microgravity conditions during the 63rd Parabolic Flight Campaign by Mangini *et al.* 2015 (Fig. 9b) on a very similar device with five U-turns at the evaporator, same tube inner diameter (3mm), very similar working fluids (FC-72 and pure perfluorhexane), same wall to fluid heat flux (12.5 W/cm^2), it can be noticed that the pressure absolute mean level and amplitude is comparable.

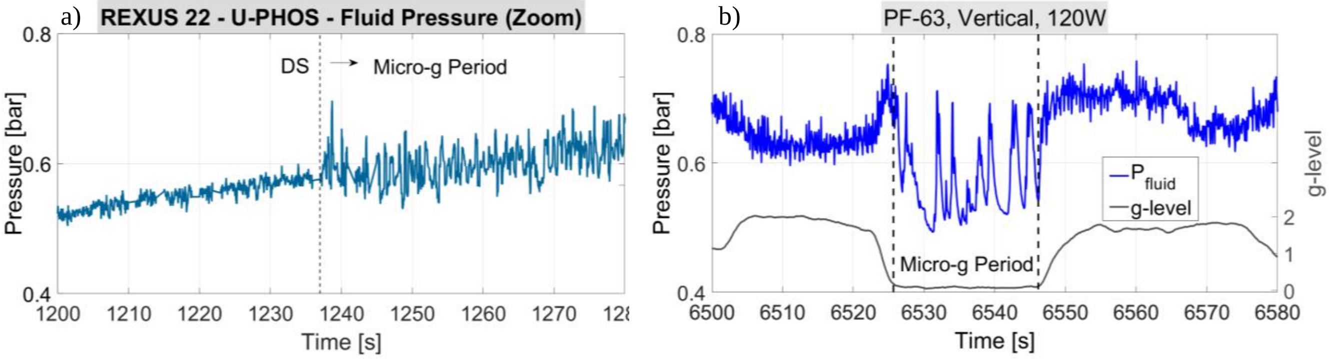

Figure 8: Local fluid pressure trend a) 63rd Parabolic flight campaign (Mangini et al. *2015); b) Actual results zoomed on the De-Spin event.*

In particular, the pressure trend recorded during the parabolic flight exhibits a slightly higher amplitude and it is characterized by some stop-over periods; interestingly the sounding rocket experiment is characterized by a slightly lower amplitude without stop-over periods.

4. CONCLUSIONS

The U-PHOS Project aims at characterizing the thermal behaviour of a large diameter Pulsating Heat Pipe (Space PHP), a promising device for thermal management in space applications. The experiment is an upgrade of a previous experiment (PHOS) that was launched on board REXUS 18 sounding rocket (Creatini *et al.* 2015). The main novelties with respect to PHOS consist of a new optimized staggered geometry, the enhancement of the heat sink thermal conductivity using a metal foam directly brazed on the PHP tubes and filled with a paraffin wax; the implementation of a temperature measurement system based on optical fibres, which is characterized by a better accuracy, reliability and integrability.

Preliminary ground tests confirmed that the device successfully works as a two-phase loop thermosyphon if gravity assisted, with an overall thermal resistance of 0.16 K/W at 90W.

The experiment has been successfully tested in milligravity condition, on board REXUS 22 sounding rocket in March 2017. Immediately after the de-spin phase, all the temperature signals both in the evaporator and condenser exhibit an oscillating component for the whole zero gravity duration. The amplitude of the fluid pressure signal is evidently increased under the occurrence of the microgravity period, and, differently from similar experiments in the literature, is not characterized by stop-over phenomena. Unfortunately, it was not possible to reach a pseudo-steady state because of the thermal inertia of the heat sink, emphasizing the fact that, a longer microgravity period is still needed in order to measure the potential heat transfer performance. Anyway it is clear that the perspective of having a hybrid device that works effectively on ground as a thermosyphon and switch to a Space PHP in zero gravity conditions is promising. Furthermore, aside the potential applications, the complexity and variety of the physical phenomena inside a SpacePHP under varying gravity conditions, together with the challenge to be able to model the device, are an excellent opportunity for a further, deeper understanding of the thermodynamics of two-phase systems and liquid/vapour interfaces.

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