The DEPLOY! Project: Development of a Deployable Pulsating Heat Pipe experiment on a parabolic flight

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Abstract. DEPLOY! Project aims at analysing the behaviour of Deployable Pulsating Heat Pipe (PHP) shaped as a helicoidal torsional spring in the adiabatic section on board a Parabolic Flight platform. A PHP is a passive thermal control device where the heat is efficiently transported by means of the self-sustained oscillatory fluid motion driven by the phase change phenomena. The microgravity environment allows to eliminate the buoyancy force contribution in the liquid phase momentum. Consequently, it is possible to isolate the contribution of the pressure drop caused by the 3D arrangement and infer on their effect on the PHP performance. As a result, a proper design based on the previous considerations would increase the flexibility of the PHP for use in space applications without significant reductions in efficiency. The goal of DEPLOY! is to demonstrate the functionality of a Deployable Pulsating Heat Pipe in various unfolding configurations by analysing its thermal-hydraulic response throughout a Parabolic Flight. The presented Deployable PHP is composed of an aluminium tube (inner/outer diameters 1.6mm/2.6 mm) and filled with HFE-7000. It is heated at the evaporator using a flat heater and cooled at the condenser with a water-cooled cold plate. T-type thermocouples are used to measure the wall temperature in several locations, while two pressure transducers (one located in the evaporator section and another in the condenser section of the same pipe) measure the local fluid pressure. Additionally, an IR Camera will be used to observe a section of the pipe for further analysis of the flow frequency. The device operation will be tested on ground and 0-g at different heat loads (24W, 34W), in multiple static positions corresponding to different opening angles (0°, 45°, 90°, 135°, 180°) and during its dynamic opening from 0° to 180°, thanks to a remotely controllable motion system.

Keywords: Deployable Pulsating Heat Pipe, Parabolic flight, Microgravity, infrared thermographic acquisitions, Inverse heat conduction problem

1 Introduction

In space missions, the persistent threat of irreparable damage presents an ongoing challenge. Addressing risks in the harsh deep space environment involves two primary strategies: minimizing the likelihood of risk occurrence and implementing effective risk mitigation measures. Retractable radiators play a pivotal role in reducing risks associated with micrometeoroid impacts, not only alleviating space constraints at launch but also minimizing the vulnerable surface area when inactive [1]. Passively deployable radiative panels, incorporating shape memory alloys for unfolding dynamics control, are currently under investigation as an innovative technological solution [2]. The deployable Pulsating Heat Pipe (PHP) represents a noteworthy advancement in thermal management after over two decades of research [3]. This experiment focuses on exploring the thermal response of deployable

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PHP in microgravity conditions. Limited scientific literature addresses various flexible PHP devices, such as the flexible flat plate PHP, examined in different configurations, including a polycarbonate copper multi-layer structure [4] and a polypropylene semi-flat double sheet [5]. The latter, tested during the ESA 77th parabolic flight campaign, demonstrated promise. Another flexible PHP, developed in Japan with stainless steel flexible micro pipes, yielded valuable outcomes on microgravity platforms like the REXUS ballistic rocket and parabolic flight plane [6] [7]. The device under study, tested in three unfolding configurations (0°, 90°, and 180°) and three heating power levels (14W, 24W, and 34W) during the 79th ESA Parabolic flight campaign, showed encouraging, albeit inconclusive, results. Notably, the PHP configuration had minimal impact on working conditions when the evaporator temperature exceeded 50 °C. The current experiment aims to gather crucial information on device operation, particularly under more demanding conditions with higher heating power inputs. Key novelties and upgrades from previous experiences will be explored.

i) investigation of intermediate unfolding angle configurations (45 and 135°) to produce clearer indication on the effect of the device configuration on its working conditions;
ii) implementation of a remotely controlled actuation subsystem to analyze the performances of the device during its unfolding dynamic (from closed/0°, to open/180°) in microgravity conditions;
iii) inclusion of an IR Camera which will record the temperature variation on the outside of portions of multiple channels close to the evaporator section. Such observation outcomes will be useful for future analyses.

The test campaign will take place in November 2023 and will comprehend static and dynamic conditions testing.

2 Experiments

The experimental setup, shown in **Figure 1**, comprises a containment box and a control rack, designed to satisfy the platform interfaces requirements and safety guidelines. The containment box houses the Deployable PHP (i.e., the test cell) supported by a structural framework. Additionally, the containment box accommodates components of the actuation and thermal subsystems, as well as an IR Camera. The control rack serves as the central control centre for the experiment. It incorporates power supplies, the cooling, data acquisition and actuation management subsystems. These elements provide the necessary control and measurement capabilities to tune the experiment and collect relevant data.

2.1 Test cell

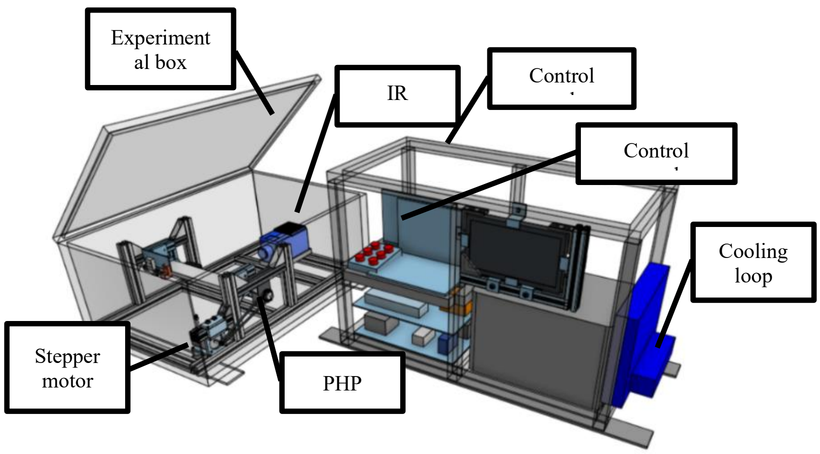

Figure 1 Experimental set up: on the right the control rack, on the left the experimental box.

The Deployable Pulsating Heat Pipe under study, depicted in **Figure 2**, features a capillary tube (1.6/2.6 mm I.D./O.D.) made of aluminum 6063. It is bent into a closed-loop serpentine with 11 U-turns in the evaporation section, resulting in 22 channels. The adiabatic, evaporator, and condenser sections are 715mm, 10mm, and 75mm long, respectively. Shaped as a torsional spring in the adiabatic section, the foldable PHP has a coil diameter (d) of 65mm, N = 3.5 coils per connection, totaling Lcoil = 715mm

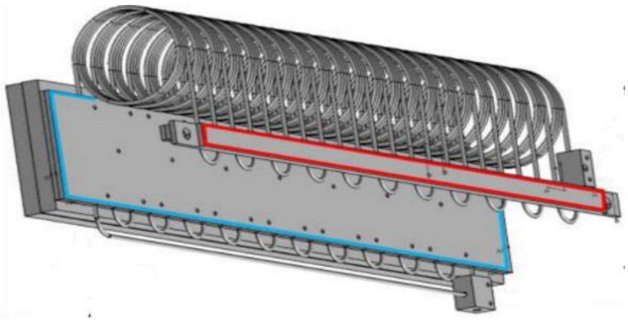

Figure 2 Deployable pulsating heat pipe (folded configuration). The heater is in red, the cold plate is in blue.

(90% of the channel length). The PHP is partially filled with HFE-7000 at a volumetric filling ratio of 70%. The evaporator section, as shown in **Figure 2**, is situated between two aluminum heat spreaders fastened to the tubes with screws. A flat, 500mm long heater (Joule Heater Hotspring®/Maxi - type WRP) connected to the spreaders provides heat input. A cold plate extracts heat from the condenser section and maintains a constant temperature, connected to a Liquid Loop System (LLS). The actuation subsystem (explained in section 2.2.2) deploys the condenser section while the evaporator remains fixed to the support structure.

2.2 Experimental setup

The experimental apparatus comprises multiple subsystems situated in two primary support structures. . As shown in **Figure 1**, the experimental setup consists of a control rack on the right and an experimental box on the left. The control rack houses the cooling loop (blue), automation and heating subsystem power supplies (small shelves on the left), a control panel with laptops (light blue), a monitoring screen (black), and control switches. The experimental box includes the Deployable PHP supported by an aluminium structure (light grey), the stepper motor with torque transmission, and an IR camera (blue).

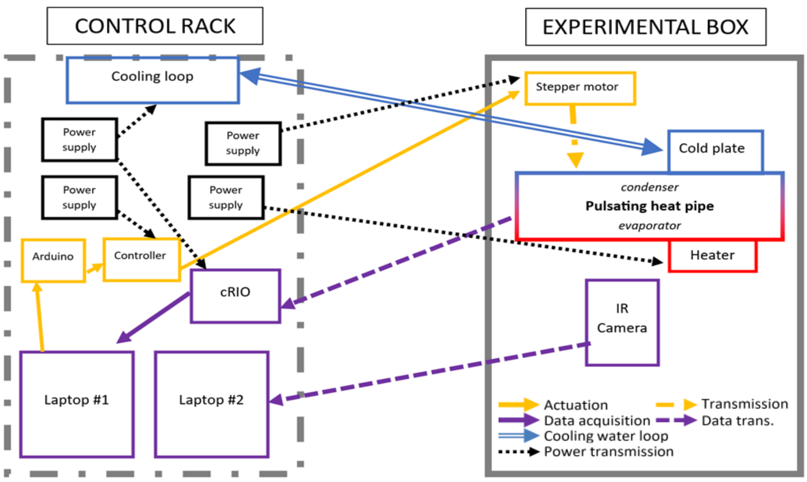

Figure 3 Experiment assembly - block description.

The main novelties of this experiment reside in the data acquisition subsystem composition and the actuation subsystem, that are described in more detail in the next sections. The block scheme in **Figure**

3 helps visualizing the connections between within and between subsystems. In red and blue the PHP and the thermal subsystem, the actuation subsystem in yellow, the data acquisition subsystem in purple.

2.2.1 Data acquisition subsystem

The system is composed by two main data paths. The first is the one connected to the IR Camera, the second one is related to the sensors connected to the PHP.

The IR Camera (Flir 7000) is in front of the evaporator section of the PHP, at 254 mm of distance. The device captures images at a 25Hz frequency, focusing on five pipes in direct contact with the evaporator section (60 mm height). Subsequently, thermal imaging data undergoes processing to extract a rectangular pixel section (approximately 20 pixels wide and 40 pixels high), representing the central image of a selected pipe. The acquired data is then filtered through the Altair acquisition program. Boundary conditions recorded during the campaign are integrated into Altair. A thermocouple (TC) strategically placed on the PHP in the observed area serves as a reference for IR Camera readings. Further processing occurs in a MATLAB script, transforming records into n-dimensional matrices, with 'n' corresponding to a single frame. Finally, the n-dimensional matrix undergoes processing using the Inverse Heat Conduction Problem (IHCP) algorithm. This algorithm estimates heat flow exchanged by the device and provides a reading on the pulsation frequency of the filling fluid, starting from a known temperature [8]. During the test campaigns, real-time sensor data are displayed and monitored to ensure the safe and optimal performance of the experimental setup. All collected data are stored for further analysis in multiple external storages. Pressure and temperature readings are plotted, and the results obtained from ground testing and parabolic flight campaign are compared to evaluate the influence of altered gravity on the PHP working conditions.

Temperature and pressure readings are performed during both the ground tests and the three parabolic flight whole duration. A total of 15 T-type thermocouples (±1 °C) are used to measure temperature. These thermocouples are positioned on the surfaces of 5 selected pipes: 5 at the evaporator section, 5 at the condenser section, and 5 at the adiabatic section. Additionally, 2 pressure transducers (Keller® PAA-33X, ± 0.5 kPa) are placed at the evaporator and condenser extremities of the same loop. To collect the data, a cRIO data acquisition system is utilized. All the collected data is transmitted to a computer equipped with data visualization software, allowing for real-time display and storage of the data. Following the completion of the parabolic flight campaign, the collected data is analysed and compared with the results obtained during the ground tests. Both the pressure transducers and the thermocouples readings are collected with a 1000Hz frequency.

2.2.2 Actuation subsystem

This subsystem is composed by a Nema 34 stepper motor (5.9 Nm torque), a transmission, a controller, and their power supplies. The motor changes the PHP configuration by opening it and closing it by 45° steps from a closed configuration (0°) to an open configuration (180°). In **Figure 4** the PHP is depicted in all the tested configurations. The stepper motor is connected to the PHP condenser section support shaft with a pulley + belt system with a gear ratio of 1 to 4. The motor is controlled by the driver board, which redirects power coming from a PSH 6066-A power supply and controls from an Arduino MEGA to the motor. The Arduino MEGA is powered and controlled by the data acquisition laptop, but its primary input source is a switch control panel located on the control rack next to said laptop. Safety measures are implemented to prevent damage to the experiment caused by accidental extra rotations of the condenser section via limit switches located at the end of the rotation span. The condenser weight is of 5.5 Kg and the maximum torque required to hold its position is of approximately 15N*m, well below the top torque transmission from the actuation of over 20 N*m. To avoid complications, no rotation is planned to happen during the hyper gravity phase of the parabolic flight, and the rotation speed is kept at lowest possible value of π/10 rad/s at the PHP shaft.

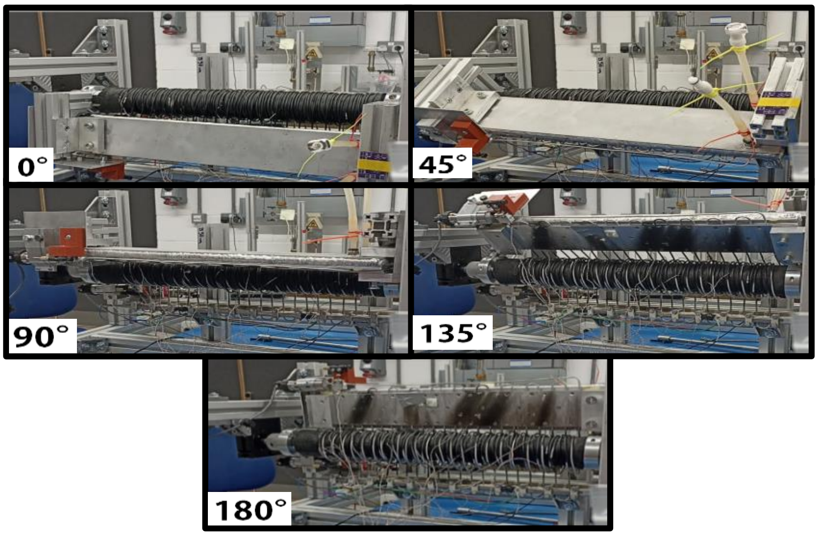

Figure 4 PHP unfolding positions. from top left to bottom: 0°-closed, 45°, 90°, 135°. 180°-open

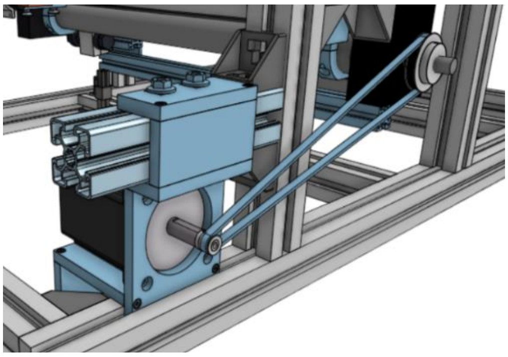

Figure 5 Actuation subsystem particular: from the left stepper motor, motor support, transmission (pulleys and timing belt), PHP shaft.

2.3 Experimental procedures

The experiment consists of two different test campaigns: a parabolic flight test and a ground test. The first is the main focus of the investigation, allowing an observation of the working conditions of the device in altered gravity, while the ladder is performed before it to set up a baseline for the tested values and establish the most functional test matrix to be designed for the PFC.

Ground tests serve as a baseline for subsequent Parabolic Flight Campaign tests. The objective is to establish a consistent comparison framework and all activities performed during the flight will be simulated.

The Parabolic Flight Campaign (PFC) is scheduled to take place in November 2023 aboard the Airbus A310 Zero-G aircraft of Novespace. The campaign is designed to be conducted over a span of three flight days, with each day consisting of 30 microgravity intervals lasting for 20 seconds each, interspersed with hyper-gravity intervals of 20 seconds at 1.8g. During a Zero-G flight, the parabolic maneuver is divided into three stages. Firstly, there is the pull-up stage, where the pilot lifts the nose of the A310 Zero G airbus to an angle of 45 degrees. This action subjects the experimental apparatus to hyper gravity, a pull that is 1.8 times than Earth's gravity. The pull-up, or "nose-up," lasts for approximately 20 seconds. Next is the parabola stage. As the aircraft ascends, the pilots reduce engine speed, and the aircraft follows a ballistic trajectory. Weightlessness begins when the aircraft enters a parabola, during which it experiences free fall for about 20 seconds. Finally, there is the pull-out stage. The nose of the plane is tilted downward by 45 degrees, and the pilots gradually level off the aircraft by increasing engine speed. Like the pull-up stage, the experimental apparatus is subjected to hyper gravity, 1.8 times stronger than Earth's gravity. After 20 seconds, the A310 Zero G returns to a horizontal trajectory. This maneuver is performed 30 times for each flight, in groups of 5 parabolas each. After performing 5 maneuvers, the aircraft enters a phase of 5 to 10 minutes of steady horizontal flight before proceeding to the next stage.

The PFC test sessions follow a predefined procedure to ensure compliance with safety and technical requirements in the environment. All experiments, including the assembly for this experiment on the plane, are powered up after take-off and must be shut down before the landing maneuver begins. The first set of 5 parabolic flight maneuvers begins 20 to 30 minutes after take-off, which aligns with the expected preparation time for the experiment to become fully operational before the injection of the first maneuver. Ground tests are conducted to verify this expectation. If the system takes longer than the allocated interval, the first 1 or 2 parabolic maneuvers of the first set may not be used for data collection, but 3 to 4 parabolic maneuvers will still be available for testing. Additionally, the parabolic flight consists of six groups of maneuvers, and the experiment is planned to be tested in five different configurations, reserving one group of parabolic maneuvers for a backup attempt.

On the first and second day, the tests resemble the static tests conducted during ground. The system is powered up, and the PHP is in its initial position (closed at 0°). When operational conditions are achieved, the test session begins, and data from the first set of 5 parabolic maneuvers are collected. At the end of this batch, the actuation subsystem adjusts the PHP angle from 0° to 45°. It is expected that the system will be minimally affected by this change, and the PHP should reach new steady-state conditions in a few seconds. The second set of parabolic maneuvers is used to test the device in the second configuration. This procedure repeats until the end of the fifth batch. The last parabolic session can serve as a backup in case any of the previous measurements were not optimally recorded. At the end of the final batch, the PHP is returned to its closed starting position, and the system is shut down before landing. This process is repeated similarly on the first and second flight days. The difference between the two flight tests lies in the thermal conditions to which the PHP is subjected. On the first day, the evaporator input power is 34W, resulting in a heater temperature of 110°C, while the cold plate temperature remains at 23°C throughout the test. The thermal conditions for the second day are expected to be different, with specific values determined after analysing data from the ground test campaign.

The third test session, on the final day of PFC, focuses on analysing the behaviour of the PHP in a dynamic situation. The pre-test procedures are the same as on previous days, with the system expected to reach nominal conditions within the same timeframe. The dynamic action is described in **Figure 6**. At the start of the first viable microgravity interval, the automation subsystem unfolds the device by rotating the condenser section 180° around the coil axis, transitioning the PHP from its initial position (open at 0°) to its open position (180°). This deployment occurs between 2 and 4 seconds after the injection and lasts for 10 seconds. Once the final position is reached, the PHP remains still until the end of the hyper gravity interval (approximately 30 seconds). During the subsequent steady horizontal flight interval, the condenser is returned to its starting position by the actuation subsystem. It may take several minutes for the PHP to return to its initial nominal conditions, making the following parabola unsuitable for data collection. This test is expected to be repeated during the first, third, and fifth parabolas of each batch. This test matrix allows the collection of three relevant samples in six different thermal configurations. For each batch, thermal conditions such as heating input and condenser temperature can be adjusted, creating a diverse set of data points. The initial thermal conditions match those of the first flight day, with subsequent conditions determined based on ground test results.

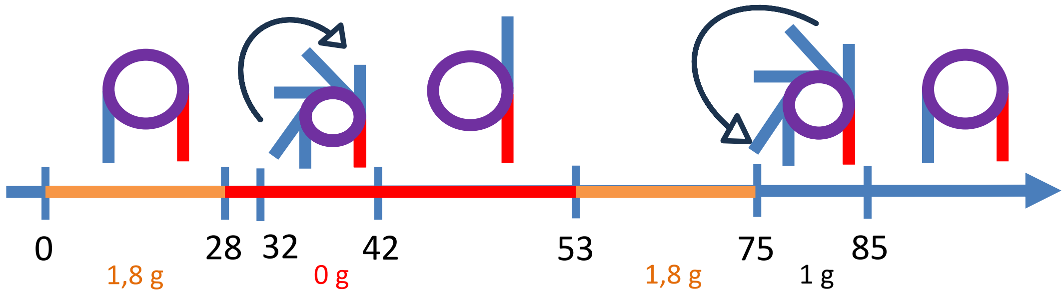

Figure 6 PFC day 3: dynamic test configuration.

3 Data analysis and expected results

The device's thermal resistance, without a working fluid, is determined to be 3 K/W based on prior measurements [6]. This resistance arises from heat conduction through the tubes and fluid flow resistance during operation. With a working fluid, the effective resistance is influenced by lower resistance from internal motions. Computation of thermal resistance involves mean temperatures at the evaporator and condenser and power input. The combined standard uncertainty considers diverse parameters, ensuring a comprehensive evaluation. The pressure drop model assumes incompressible fluid, no oscillation, full power transfer to the PHP, and 1D heat transfer. Slug motion is described by the momentum equation, considering gravity, hydrostatic pressure, and shear forces. The simplified equation includes contributions from gravity and shear forces, defining the pressure drop.

$$\Delta P = \rho\vec{g}\cos(\theta) + l(1-\alpha)\left(\frac{f_s}{2d_i}\rho_l\vec{v_l}\right)$$

To determine the fluid velocity, a wavelet analysis will be conducted [5] employing a complex Morlet wavelet. The rationale behind this selection is the resemblance between the wavelet shape and the signal profile [6]; a strong correlation between the two shapes leads to improved quality outcomes. Using the Morlet wavelet as the mother wavelet, the transformation equation, with scale factor s and time shift factor u, takes the following form.

$$WT(u,s) = \int_{-\infty}^{+\infty} f(t)\frac{1}{\sqrt{s}}\pi^{\frac{1}{4}}\exp\left[i\omega_0\left(\frac{t-u}{s}\right)\right]\exp\left[-\frac{(t-u)^2}{2s^2}\right]dt$$

Once the dominant frequency is determined, it is possible to assume that this frequency leads to the mean velocity of the individual liquid slug. It is then straightforward to calculate $\vec{v}$ as $\vec{v} = l \cdot f_z$.

Thermal imaging data is employed to extract a specific rectangular pixel section, measuring 5 pixels in width and 3 pixels in height, representing the central image of a chosen pipe. The records are filtered using the Altair acquisition programme, integrating campaign-recorded boundary conditions and referencing a thermocouple connected to a PHP point observed in the IR camera window. Processed through a MATLAB script, records transform into n-dimensional matrices (n for a single frame). This n-dimensional matrix feeds an Inverse Heat Conduction algorithm, estimating device flow and outputting the filling fluid's pulsation frequency [8].

4 Conclusions

The DEPLOY! Project aims at the technological advancement of the deployable PHP field. The device at study is an innovative foldable pulsating heat pipe which has been tested once before in a parabolic flight in 2022. This experiment is presented with novelties such as an actuation subsystem which allows to change the configuration of the device during the tests and an IR camera to analyse the behaviour of the working fluid starting from its surface temperature. This experiment contributes to enhance the knowledge on the deployable PHP, by investigating its working conditions in new configurations and at different temperatures. The dynamic deployment test, performed in simulated microgravity, is a novelty of this project; such test will shed light on an important working life condition that the device will face. The results of this test are important for a first estimate of the influence of the peculiar dynamic of this device on its working conditions and will offer insights on future testing configurations worth investigating for a complete understanding of this correlation. The experiment will be tested during a parabolic flight campaign in November 2023. The results are expected to enhance the knowledge on this device and generate further testing opportunities for the future.

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