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Thermo-hydraulic characterization of semi-transparent Flat-Plate Pulsating Heat Pipes in variable gravity regimes

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Pulsating Heat Pipes are thermally driven two-phase passive devices mainly based on phase change phenomena (film evaporation, flow boiling, film condensation), and influenced by capillary and gravity forces. They consist of a meandering capillary tube closed in a loop, evacuated and partially filled with a working fluid at saturation conditions. Once the heat load is applied, the fluid motion starts and an oscillating pattern of alternating vapour bubbles and liquid plugs forms inside the tube.
As it is widely accepted, complex flow patterns, ranging from slug flow to annular flow, occur in the adjacent tubes of pulsating heat pipes (PHP), initiated by local pressure instabilities ((Khandekar et al. 2003) and (Liu et al. 2007). Such flow patterns have obviously effects on the total heat flux transferred from the heated to the cooled ends of the PHP. Many parameters have also a direct influence on their operation (Charoensawan et al. 2003): number of turns, PHP dimensions, filling ratio and physical properties of the working fluid, applied heat power, etc. One of the most important parameter is the channel internal diameter permitting liquid/vapor phase division into liquid slugs and vapor bubbles separated by menisci due to capillary forces. And, more particularly in the context of this study, the inclination with respect to gravity or, generally, the change in the value of acceleration (for example, for tests on board of an aircraft during a parabolic flight campaign and/or under microgravity conditions for space application, (Gu et al. 2005), (Ayel et al. 2015) and (Mangini et al. 2015).
This paper presents some results obtained during the ESA 64th Parabolic Flight Campaign during which six similar Flat Plate Pulsating Heat Pipes (FPPHP) have been tested. One example of FPPHP can be seen on Fig. 1.The FPPHP were milled from copper plates (length: 204 mm, with varying widths and thicknesses according to the channel dimension, see below) with a single square shaped groove, forming a series of 11 U-turns in the evaporator (see Fig. 1). Every PHP channels were square shaped, with dimensions *D* varying from 1.5 mm to 3 mm. Three condenser lengths (5, 10 and 15 cm) were also tested for the 2.5 mm channel FPPHP. A containment channel link to a revervoir previously emptied has been set in order to avoid introduction of non-condensable gazes in the device (Fig. 1). Thus, considering six devices tested during 3 days of flight, each day 2 separate FPPHP were tested with doubled instrumentation. Two visible cameras (Canon® EOS 100D and 550D, 50 Hz) recorded movies allowing visualizations of fluid flow motions in the overall channels of both PHP.
Ten T-type thermocouples of 0.5 mm (±0.5 K) monitor the temperature of each section in the PHPs: three for each FPPHP evaporator (TEV1-TEV6); two in the water cooling loop and two thermocouples instrument the air temperatures. Two pressure sensors (GE PTX5076-TA-A3-CA-HO-PS, 5 bars absolute, ±200 Pa) allow recording of local fluid pressure at the top of the condenser zones. A g-sensor (DE-ACCM3D, ±0.1g) is used to measure the gravity level variations during each parabolic flight.

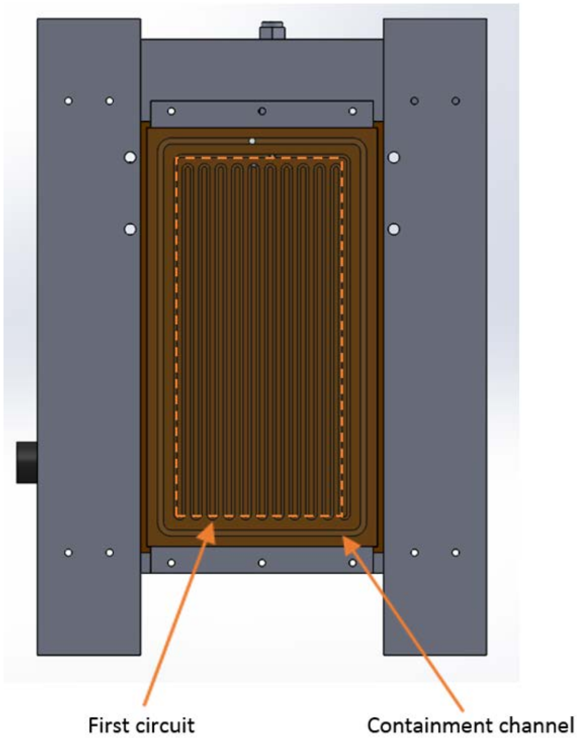

Figure 1: Schematic view of one FPPHP tested during the ESA 64th parabolic Flight campaign.

The operating conditions were the following ones: Fluid: FC72; filling ratio: 50%; heat power applied: from 20 to 150 W; cold source: plane ambient air; orientation: vertical bottom heated mode (BHM).
Foremost, in Fig. 2 are shown representative temperatures and acceleration profiles for the FPPHP tested with 100 W constant heat power during five successive parabolas (here, only two parabolas are represented). A first observation is that temperatures rise in the evaporator zone together with their decrease in the condenser zone during microgravity phases. Furthermore, the evaporator temperature curves in microgravity are subject to some oscillations that will be explained thanks to visualizations.

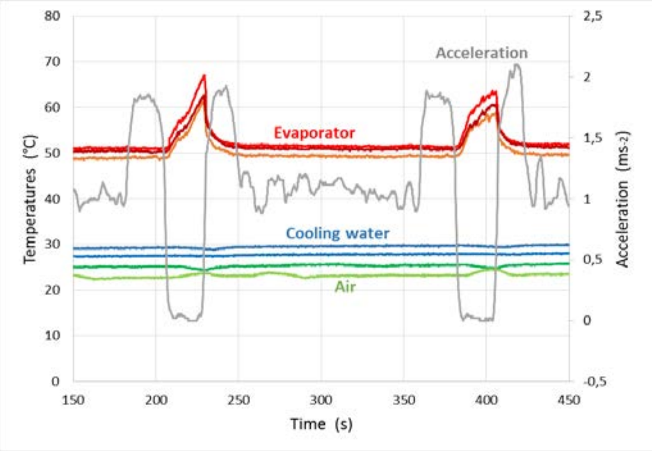

Figure 2: Transient temperatures and acceleration responses of the FPPHP to a series of 2 successive parabolas (D = 3 mm, Q = 100 W).

The major findings observed thanks to visualizations during this 64th PF campaign are: first, the fluid distribution tends spontaneously to a dry-out at the evaporator zone due to higher and homogenized vapor pressures in the channels; secondly, isolated liquid plugs can easily move under the influence of small pressure instabilities, and that whatever the channel dimensions and the condenser length. An example of visualization of an isolated liquid plug flowing towards the evaporator zone and being subjected to harsh evaporation can be seen on Fig. 3. The pressure increase due to this evaporation will be at the origin of massive mass and heat transfers which spreads throughout the whole PHP channels.

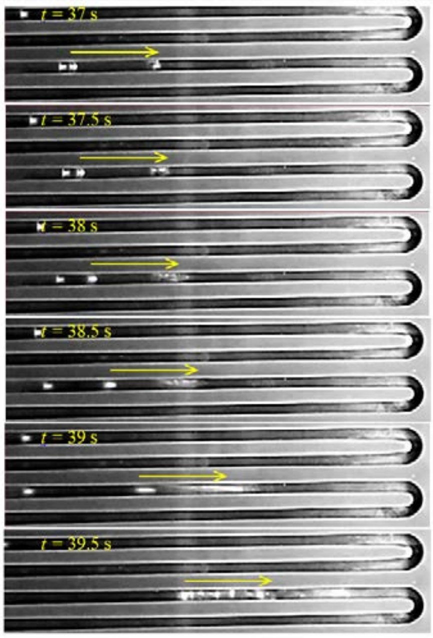

Figure 3: Sequence of macro images of isolated liquid plug during microgravity conditions flowing towards the evaporator (D = 3 mm, Q = 100 W).

Another observation was that even with no heat power applied, the liquid plugs began to move as soon as they were in microgravity condition. A video post-processing by image analysis has been done for some visualizations, allowing tracking the menisci positions as functions of time. An example of such displacement can be seen on Fig. 4 during microgravity conditions, for two menisci situated in adjacent channels, linked by a liquid plug, without heat power applied. The condition of incompressibility of the liquid plug make the displacements symmetrical between both menisci. If the motions were short for the lower channel dimensions (1.5-2 mm), their amplitude was of the order of magnitude of the length of the channels for the bigger diameters (2.5-3 mm). Obviously, the fluid movements were slower and less high amplitude for the lowest channel diameters. This point remains to be clarified.

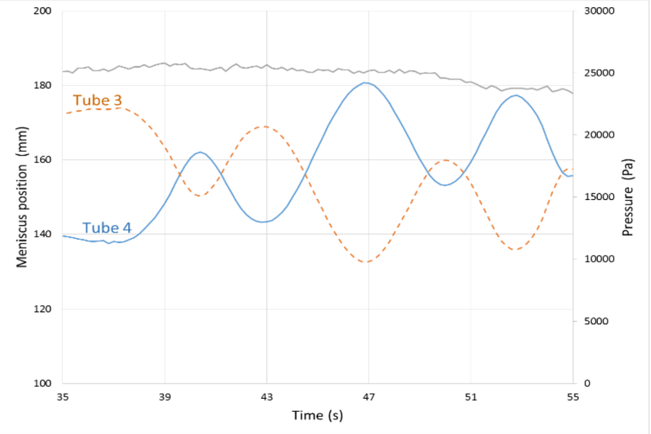

Figure 4: Motion of two adjacent menisci during microgravity conditions (D = 3 mm, Q = 0 W).

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