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EXPERIMENTAL ANALYSIS OF THE FLUID FLOW IN THE FLAT PLATE PULSATING HEAT PIPE UNDER MICROGRAVITY CONDITIONS

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ABSTRACT

An experimental study of a flat plate pulsating heat pipe has been performed under various gravity conditions during ESA 69th parabolic flight campaign. A molybdenum plate, with 14 milled rectangular channels with cross-section of 3×3 mm^2, was covered with a sapphire window, and tested in vertical position with ethanol as working fluid. If operation in normal and hyper-gravity conditions were characterized by nucleate boiling regime, FP-PHP working like in looped thermosyphon mode, transition into microgravity was accompanied by a flow pattern change into slug/plug regime with thin film evaporation, due to absence of buoyancy forces. Hydrodynamic instabilities, accompanied with short-term periods of emergence of nucleate boiling under microgravity, were observed during several parabolas. Formations of long vapor slugs in the channel lead to thin film evaporation. Combined optical and infrared visualizations showed velocity and amplitude increase of the menisci motions.

KEYWORDS: Flat plate pulsating heat pipe, Microgravity, Infrared thermography, Parabolic flight

1. INTRODUCTION

In recent years, miniaturization of the electronics components has induced high heat fluxes generation. This fact coupled with strong requirements as compactness, massless and small energy consumption for the aerospace applications lead to challenging issues in the thermal management sector. Among high efficiency passive thermal management devices for electronic equipments [1], one of the most promising cooling technology under the ray of research and development is the pulsating heat pipe (PHP) [2-3]. PHPs are thermally driven two-phase passive devices based on phase change induced liquid motion and capillary forces. Pressure instabilities in the evaporation zone initiate complex liquid flow, ranging from bubbly flow to slug/plug flow [2]. Due to this fact, hydraulic regime is determinant to characterize the heat transfer efficiency of PHP, but many parameters, such as channel diameter, influencing the vapor/bubble interface and menisci formation, wettability of the channel walls, filling ratio and thermophysical properties of the fluid have significant impact on the PHP operation.

Due to absence of the buoyancy forces under microgravity conditions, predomination of the Taylor flow (slug flow regime) promises high efficiently operating regime. Surface tension plays the key role in the formation of the vapor-liquid interfaces, keeping the slugs from breakdown and preventing transition into annular flow. *Hosoda et al* [3] defined the maximal channel diameter based on the Bond number as $D_{cr,Bo} \approx 1.84(\sigma/g(\rho_l - \rho_v))^{1/2}$ for the stable slug flow regime [3]; but this criterion is obviously not applicable for microgravity conditions. In this case, a new criterion based on the Weber number was proposed by *Gu et al* [4]: $D_{cr,We} \approx 4\sigma/\rho_l U_l^2$, the liquid inertia being the predominant forces between the two phases due to its higher density. Most relevant criterion based on Garimella number: $D_{Ga} = ((160\mu_l/\rho_l U_l)(\sigma/g(\rho_l - \rho_v))^{1/2})^{1/2}$, more capable to define the diameter limitation for space applications was proposed by *Harichian* and *Garimella* [5]. Nervetheless, a lack of criterion cannot allow to define clearly which working conditions could guarantee stable slug flow regime [6], particularly considering flat plate PHPs (FP-PHP), whose milled channels are usually square or rectangular, inducing supplementary capillary forces in the corners, which makes the criterion even more difficult to evaluate [7].

In this study, a molybdenum FP-PHP with square channels, covered by a sapphire window permitting both visible and infrared fluid flow visualizations, was tested during ESA 69th parabolic flight campaign.

2. EXPERIMENTAL SET-UP

The device consists of a molybdenum flat plate (80×200×3 mm^3), milled with a unique channel forming a closed serpentine with 7 U-turns in the evaporator zone (Fig. 1). The plate is covered by a transparent sapphire glass (80×200×5 mm^3) for video and IR analyses, using epoxy glue to guarantee perfect sealing at the plate boards, and between adjacent channels relative to one-another. The channel cross-sectional area is of 3×3 mm^2 including the glue thickness. A heater, composed of metallic plate (80×40 mm2) with milled serpentine channel in which is inserted a heating wire (Thermocoax® Type NcAc15) has been glued on the bottom-back face of the plate. Condenser (80x100 mm^2) is cooled by a water serpentine channel milled in a copper plate, glued on the top-back face of the plate. This condenser is connected to a closed secondary flow loop, connected to a massive aluminum plate cooled by 15 integrated block fans. Finally, the cold source is the plane ambient air.

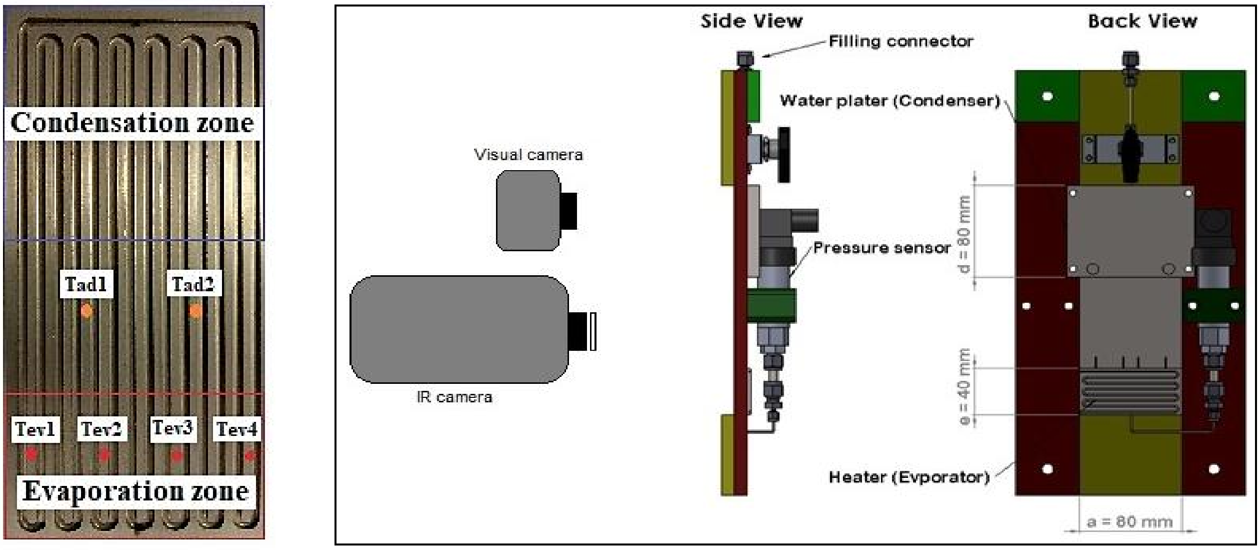

Fig. 1 Schematic view of the FP-PHP (left) and experimental system (right).

10 T-type thermocouples monitor temperatures at different locations (Fig. 1): four in the evaporation zone (T_{ev1}-T_{ev4}); two in the adiabatic zone at mid-distance between evaporator and condenser (T_{ad1}, T_{ad2}); two at inlet and outlet cooling water in the condenser (T_{inlet}, T_{outlet}); last two thermocouples are used for the confined zone ambient temperature (T_{amb}) and the external air temperature (T_{fan}). A pressure sensor (GE® PTX5076-TA-A3-CA-HO-PS, 1.5 bars absolute, ±200 Pa) is used to record the fluid pressure fluctuations at the bottom of the evaporator zone (connected to the middle U-turn), with a sampling period of 0.2 s.

A numerical camera is used for visualizations (Canon® EOS 550D, 60 fps), while an infrared camera is used for IR thermography (FLIR® SC7200, 60 fps, wavelength band 1.5-5.1 μm, ±1K accuracy and 25 mK thermal sensitivity). Accelerometer (DE-ACCM3D, ±0.1 g) records gravity level during each parabolic flight. All recorded parameters are synchronized thanks to LABVIEW® software and a visible LED is used for camera synchronization.

Ethanol is used as working fluid, with the volumetric filling ratio of 50% (at 20°C). Choice was focused on this fluid due to its opacity to infrared radiation (emissivity close to one beyond 2 mm thickness [8]), as already used by *Mangini et al* [9]. The whole system is incorporated in a double containment box preventing leakage to the aircraft cabin.

FP-PHP was tested in vertical bottom heated mode and applied heat power ranging from 20 W to 200 W. Each parabolic flight consists in 31 successive parabolas: each parabola implies a duration of around 22 s of microgravity (around 0.01g, with an average gravity normal to the aircraft floor), preceded and followed by around 20 s duration of hypergravity (of approximately 1.8g).

3. RESULTS AND DISCUSSION

An example of temperature evolution during a single parabola for a heat power applied of 150 W is presented in Fig. 2, in parallel with the flow pattern occurring at selected times during operation. The main observations are:
Normal and hypergravity conditions: visual observations demonstrate the predomination of the annular flow regime with periodic transitions into semi-annular flow pattern that can be explained by the channel diameter closed to the critical one (here, $D_{cr,Bo}$ = 3.1 mm for ethanol at 20°C). FP-PHP operated as interconnected thermosyphons in such conditions.
Microgravity conditions: transition into microgravity induces a transition into slug flow pattern and following dry-out of the evaporation zone during each parabola (noticeable thanks to evaporator temperature increase during this period, Fig. 2). Thin film evaporation and slight menisci motions can characterize such flow pattern. Menisci motions were characterized by small amplitude and low frequency during stable slug flow regime. Fluid mass transfer in the channels lead to high efficient heat transfer due to combined thin film evaporation and sensible heat transfer by cold liquid plugs (see temperature fluctuations highlighted by the red dashed circle in Fig. 2).The latter fluctuations are better explained above (see Fig 3 (right)).

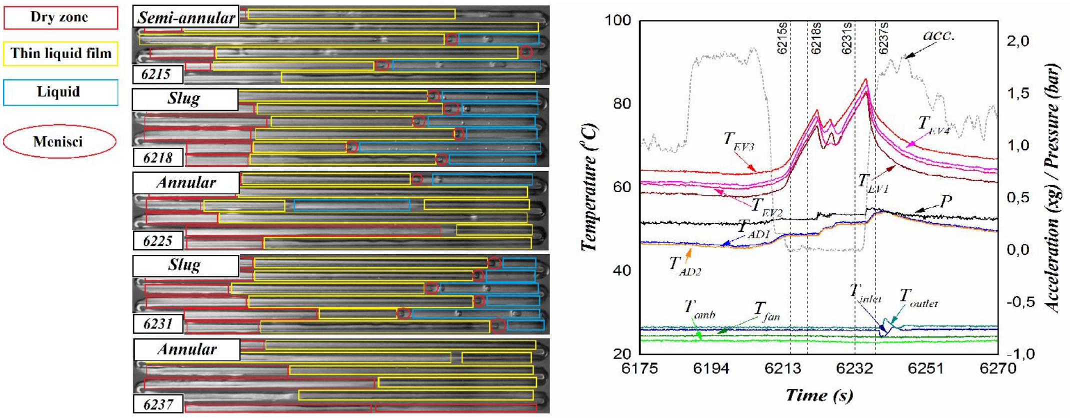

Fig. 2 Flow patterns in half FP-PHP and temperature fluctuations during one parabola (Q = 150 W).

Transition from slug flow into annular flow (the channel dimension exceeds the critical diameter for velocities of 0.2 ms^{-1}, and 0.05 ms^{-1}, according to Weber and Garimella numbers, respectively, with ethanol at 20°C) was characterized by evaporation zone rewetting due to channel rectangular shape and capillary flow in the channel corners. Explosive evaporation, resulting in the generation of local pressure differences between channels, led to significant displacement of the menisci accompanied by bubble collapse and establishment of the annular/semi-annular flow regime, as it was observed during several parabolas. After that, flow stabilization and transition into slug flow, accompanied by the decreasing of the menisci amplitude and frequency, were observed. However, the duration of 22 s microgravity does not allow to be confident in the definition of clear established regimes with regular fluctuations or the instance case of instabilities. Future experiment aboard the ISS will allow to describe deeply these instabilities.
Thanks to infrared visualizations, menisci positions in an interconnected channel pair (channels 6-7) in the central part of the FP-PHP are plotted in Fig. 3 (in blue), together with the evaporator temperatures and pressure, for both stable slug flow regime (left, with continuous increase of evaporator temperatures) and flow with hydraulic instabilities (right, with temperatures fluctuations). Microgravity phase is characterized by the slug flow regime establishment accompanied by the decrease of the amplitude and frequency of menisci motions (Fig. 3, left). However, one-directional movement of the menisci or movement with different velocities and amplitudes is observed. This phenomenon can be explained by the non-uniform evaporation-condensation processes in the separated channels due to local pressure drops. Figure 3 (left) shows decrease of the menisci motion amplitude and frequency resulting in continuously increasing temperature in evaporator. In figure 3 (right), the hydraulic instabilities are characterized by the spontaneous transition from slug flow regime to annular/semi-annular regime, with high velocities fluid flow motion leading to the break of the menisci, which cannot be followed during their

motion (“Instability zone”), and resulting in the temperature fluctuations at the evaporator due to better fluid-to-wall heat transfer.

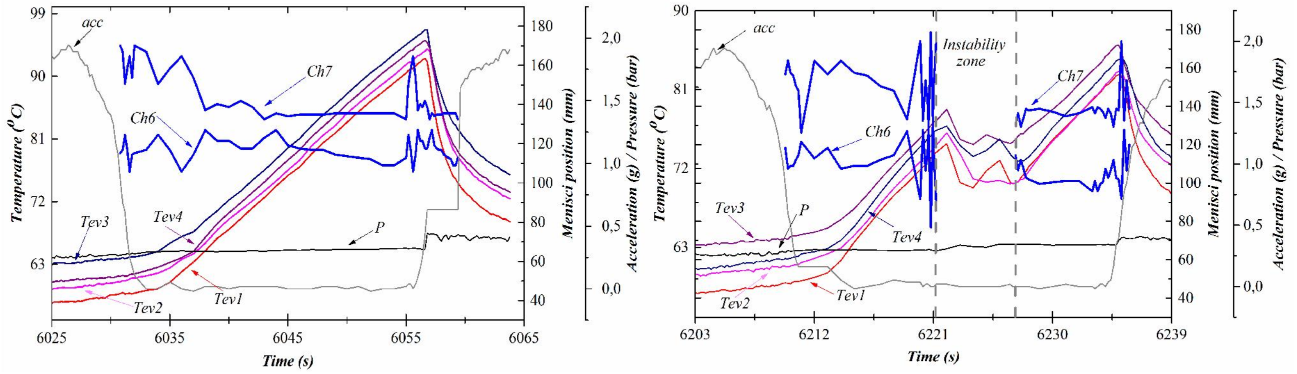

Fig. 3 Menisci positions for stable slug flow regime (left) and for flow with instabilities (right).

4. CONCLUSIONS

Thermohydraulic evaluation of a flat plate pulsating heat pipe has been performed during ESA 69th Parabolic Flight Campaign. Visualization study showed that FP-PHP with channel dimension above critical diameter operates like loop thermosiphon under normal and hypergravity conditions, but transition to microgravity leads to occurrence of stable slug flow. Capillary rewetting of the evaporator walls leads to explosive evaporation, spontaneous pressure drops and, as a result, to bubble collapse and transition from slug flow into annular flow. This phenomenon of instabilities and unsteady flow needs to be investigated under long-term microgravity conditions. Infrared analysis allowed to study displacement of the menisci, their amplitude and velocity for the slug flow regime which will be helpful for the modeling approaches.

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