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Inverse heat transfer analysis of a Pulsating Heat Pipe for space applications tested on board a parabolic flight

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Abstract

A Pulsating Heat Pipe specifically designed to be hosted on board the Heat Transfer Host of the International Space Station is tested in hyper-gravity and microgravity during Parabolic Flights. The device is realized bending an annealed aluminium tube with an inner diameter of 3 mm. The geometry is a three-dimensional closed loop with 14 turns. The external temperatures of the device are measured in the adiabatic zone with a high-speed infrared camera, recording images at 50 frames per second and with a spatial resolution of 1280x1024 pixel. The images are thereafter post-processed and utilized to extrapolate space and time-varying local heat fluxes on the tube internal surface in contact with the fluid, solving the inverse heat conduction problem in the pipe wall. It is found that the local heat flux can reach values up to 10 kW/m^2 during the start-up of the device in weightlessness. These results point out that in this dynamic thermofluidic system, the temperature difference between the fluid and the internal tube wall is always present even in the non-cooled/heated section. Such continuous heat transfer is beneficial for the conservation of the thermally driven oscillations of the fluid. Additionally, the synchronization of the heat flux measurements with the temperature trends and the inner flow pressure provides an overview of the device thermo-fluid dynamics at different gravity levels.

Introduction

A very promising solution in the field of passive two-phase heat transfer devices is represented by the Pulsating Heat Pipe (PHP). This device is achieving resounding interest in the heat transfer community in terms of high heat transfer capability, efficient thermal control, flexibility, low cost, and above all the ability to dissipate heat also in weightlessness. Therefore, PHPs have been extensively studied in the last years by many researchers also in microgravity and hyper-gravity conditions. Many authors have already investigated the effect of the gravity field on the flow velocity, the flow patterns, and the temperatures in the heated and in the cooled region using thermocouples fixed on the external wall tube, (Gu et al., 2004; Mameli, et al., 2014; Mangini, et al., 2015). Nevertheless, an evaluation of the local wall-to-fluid heat fluid was not yet achieved in weightlessness. A recent study (Cattani et al., 2018) demonstrated the possibility to calculate local heat fluxes of a PHP working on ground starting from the time-space distribution of the temperatures recorded by means of a high-speed Infrared (IR) Camera and solving the Inverse Heat Conduction Problem (IHCP) in the tube wall. The authors pointed out the feasibility to utilize the proposed non-intrusive technique also on PHPs, demonstrating that the fluid-to-wall heat flux in the region between the evaporator and the condenser can be calculated starting from the distribution of the temperatures obtained with a previously calibrated IR camera during real PHP operations. The main objective of the present work is to extend the proposed technique towards the analysis of a PHP operating at different gravitational levels. Therefore, the local heat flux of a PHP especially designed for space applications and tested during the 67th Parabolic Flight Campaign (PFC) promoted by the European Space Agency (ESA), has been evaluated in microgravity and hyper-gravity conditions.

The Test Cell and Experimental procedure

The PHP consists of an annealed aluminum tube with an inner/outer diameter of 3/5 mm. The tube is folded in a staggered 3D configuration with 14 turns in the evaporator zone as shown in Figure 1. Additional information of the test cell can be found in the work done by Mameli at al., 2018. The device is partially filled with 22 ml of FC-72 (50% vol.). The IR camera records images at 50 fps of the rectangular section of the device highlighted in green in Figure 1, with a spatial resolution of 1280x1024 pixel. The test rig is then mounted on an Airbus A310 and a total of 93 parabolic trajectories are performed over three days of flight. The device is oriented in bottom heated mode and tests are performed along with the overall campaign varying the heating power from 20 W up to 180 W.

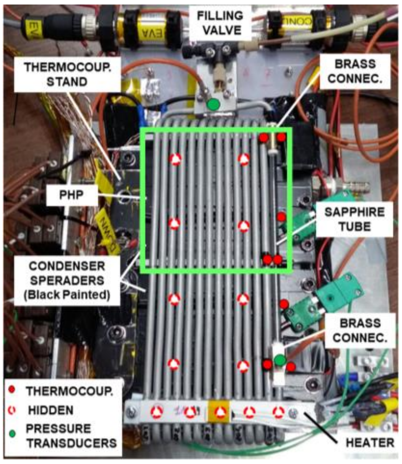

Figure 1. The Pulsating Heat Pipe. The IR camera records the section of the device within the green rectangle section.

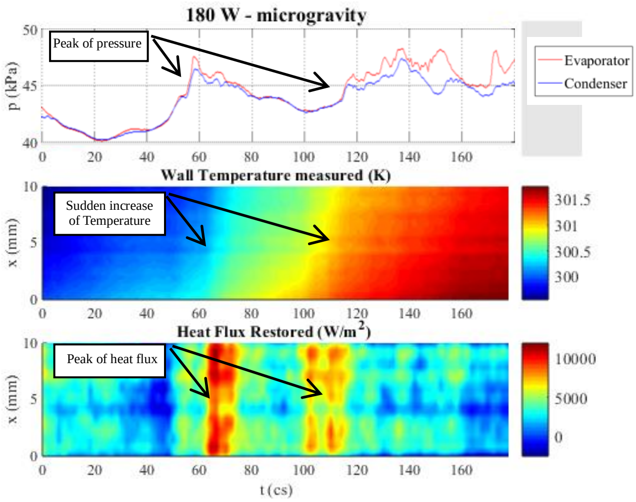

Figure 2. a) Evolution of the pressure recorded in the heated and in the cooled region; b) Time-space map of the external wall tube temperature of the second branch of the device; c) Heat flux measurements solving the IHCP.

Results and Discussion

Figure 2 shows a synchronization between the flow pressure measurements and the time-space temperature distribution of the closest aluminum branch with respect to the pressure transducers during two consecutive seconds in microgravity, providing 180W of heating power. The temperature distribution acquired on the external wall surface was employed to estimate the local heat flux at the fluid-internal wall interface by solving the IHCP in the wall (Cattani et al., 2018). During this specific test, the heat power input is provided to the device only when microgravity conditions are reached, in such a way to record the start-up of the device in weightlessness. The start-up is recognizable from the peak of pressures, synonym of a two-phase flow motion activation within the PHP. As soon as the pressure transducers detect oscillations of the flow, a sudden increase of temperatures is measured by means of the IR camera along the external wall tube. Almost instantaneously, peaks of heat flux up to 10 kW/m^2 are calculated solving the IHCP. This result points out that after the start-up, the heat firstly accumulated at the evaporator is transferred almost instantaneously on the non-heated region by the two-phase flow oscillations, and it can be exchanged conductively thanks to the temperature difference between the fluid and the wall tube also in the region usually defined “adiabatic” in the literature.

Conclusions

The heat flux of a PHP for space applications tested in hyper-gravity and microgravity conditions has been evaluated solving the IHCP, starting from IR images obtained during the flight. It is found that the heat flux of the PHP can exceed 10kW/m^2 during the start-up of the device in weightlessness. The local wall-to-fluid heat flux is thereafter synchronized in time with local pressure and temperature measurements, the heat power input and the gravity level, for several heating power inputs tested along with the campaign. The results highlight that in a two-phase passive heat transfer device, the temperature difference between the fluid and the internal tube wall, being always present even in the adiabatic section, allows to exchange heat after the start-up. These results could be also useful for updating and validating lumped parameter models aiming to simulate and predict the PHP behavior (Nekrashevych, 2017).

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