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Thermal response of a closed loop pulsating heat pipe under a varying gravity force

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ABSTRACT

A Closed Loop Pulsating Heat Pipe made of a copper tube bent into a 2-D serpentine of 32 parallel channels and filled with FC-72, has been tested on ground and in micro/hyper gravity conditions during the 58th ESA Parabolic Flight Campaign. The device has been investigated both in horizontal and in vertical positions and at different heat loads (from 40 to 100 W). Beyond the standard thermal characterization, dynamic investigations have been performed on ground by changing the device orientation at constant heat input levels. Results show that in the vertical position the PHP thermal behavior is strongly affected by the variation of gravity field both on ground and on flight tests. In particular, during a parabolic flight, the first hypergravity period slightly assists the flow motion, while, during microgravity, the device undergoes a sudden temperature increase in the evaporator zone; the following hypergravity phase is then able to bring the PHP back to the previous thermal regime. The PHP in the horizontal position does not show any sensitive thermal variation during the parabola. A further analysis with a tilting bench in the ground lab proves that microgravity thermal behavior is comparable to the horizontal operation on ground: therefore for capillary closed loop pulsating heat pipes microgravity tests are not strictly necessary for the space application assessment.

1. Introduction

Two-phase passive (or thermally driven) heat transfer devices, such as heat pipes and loop heat pipes, are currently the best available technology for the passive thermal control of electronics both in ground and in space conditions. In the early 90's a new concept of heat pipe, commonly known as Pulsating Heat Pipe (PHP), was introduced by Akachi [1]. It consists in a capillary channel with alternate heating and cooling zones, evacuated and partially filled with a working fluid. The thermal-hydraulic behavior mainly depends on the interplay between phase change phenomena (film evaporation, flow boiling, film condensation), capillary forces (able to maintain the fluid confinement in terms of slug/plug flow pattern) and gravity, which may assist or damp the fluid motion. Low cost, ease in manufacturing, compactness and outstanding features in terms of maximum heat transfer capability, thermal resistance, and temperature control make PHPs suitable for ground applications and promising for space applications. On the other hand the complex physical phenomena occurring inside the device (liquid film evaporation, fluid/wall interaction, flow pattern transition) are not fully characterized and the effect of several physical parameters on the device operation (number of heating/cooling sections, external acceleration field, geometry) is not yet clear.

In particular the interrelation between the effect of orientation with respect to gravity and the effect of the number of turns and/or heating and cooling sections is still a debated issue. The two effects have been investigated separately on ground: Yang et al. [2] showed that a relatively big number of heating and cooling sections (20 turns in the evaporator) coupled with a small internal diameter (1 mm) is beneficial in making the device operation almost independent from its orientation with respect to gravity, although the device had a particular, specific staggered layout and therefore no general conclusions are possible. Charoensawan and Terdtoon [3] investigated the thermal performance of horizontal closed loop PHPs with different number of turns (5, 11, 16, 26), internal diameters (1 mm, 1.5 mm, 2 mm), fluids (ethanol, water), evaporator lengths (50, 150 mm) and demonstrated that for a

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Nomenclature

Bo	bond number [−]
d	diameter [m]
FR	filling ratio [−]
g	gravity acceleration [m/s^2]
Ga	Garimella number [−]
$\dot{Q}$	heat input power [W]
R	thermal resistance [K/W]
Re	Reynolds number [−]
T	temperature [°C]
U	fluid velocity [m/s]
We	Weber number [−]
μ	dynamic viscosity [Pa s]
ρ	density [kg/m^3]
σ	tension surface [N/m]

Subscripts

Bo	bond number
c	condenser zone
e	evaporator zone
eq	equivalent
Ga	Garimella number
l	liquid phase
max	maximum
min	minimum
Re	Reynolds number
v	vapor phase
We	Weber number

planar geometry with no gravity component in the flow path direction, the device with 5 turns never worked, and that the critical number of turns in order to achieve the device start-up is inversely proportional to the evaporator temperature and the inner diameter. Recently Mameli et al. [4] investigated the effect of orientation on the thermal performance of a perfectly planar CLPHP with 16 turns in the evaporator operated with FC-72 as working fluid. Despite the capillary inner diameter of 1.1 mm, the thermal resistance of the gravity assisted mode (bottom heated) performs more than two times better than the horizontal orientation. Probably, with a not negligible experimental effort, the coupled effect of inner diameter and thermal resistance could be better investigated with a systematic approach, even if one of the most common and fast solution for making the PHP independent on orientation in ground conditions is represented by designing three dimensional geometries [5,6], so that the device is partially assisted by gravity in any orientation. This approach is obviously not applicable when the acceleration field is absent (for example, for space applications): in this case the two effects must be investigated by creating an artificial microgravity environment (Drop Tower, parabolic Flight, Sounding Rockets) or by performing the experiments directly in orbit (for example, on the International Space Station). Gu et al. [7,8] performed experiments in normal, hyper (2.5g) and microgravity (0.02g aboard Falcon 20 aircraft flying parabolic trajectories) conditions on a Flat Plate Pulsating Heat Pipe (FPPHP) charged with R114, where square channels (1.5 mm) were engraved into an aluminum plate. One thermocouple was used to characterize the heating and cooling sections and the device is always tested in two positions: vertical gravity assisted or Bottom Heated Mode (BHM), vertical antigravity or Top Heated Mode (THM). They concluded that under reduced gravity, the heat pipes showed better operating and heat transport performances than under normal and hyper-gravity. By taking a careful look at the results in Ref. [7], the previous statement is supported by experimental evidence only for the top-heated mode. The occurrence of microgravity is naturally beneficial when the device is working in the antigravity mode, while the beneficial effect of microgravity is not evident against the top-heated gravity assisted PHP.

The present work aims at clarifying how a capillary tube PHP reacts to a variable acceleration field and proving that the thermal behavior of a symmetric 2-D PHP device working in the horizontal position on ground (no gravity component affects the internal axial fluid motion) is the most similar to the microgravity conditions, as suggested by the numerical simulations performed by Mameli et al. [9]. In Appendix A a further detailed discussion is offered to the reader in order to clarify the term “capillary tube” for the various gravity levels and the consequences in the choice of the PHP inner diameter.

A 2-D serpentine Closed Loop Pulsating Heat Pipe (CLPHP) made of a copper tube charged with FC-72 have been tested at different heat loads (up to 100 W), orientations (BHM, horizontal), transient gravity levels (0g, 1g, 1.8g). Beyond the standard thermal characterization and the hysteresis analysis on ground, an unprecedented experiment have been performed by changing the device orientation (vertical–horizontal–vertical) in order to obtain a gravity field variation with respect to the flow path direction and reproduce a (1g, 0g, 1g) gravity cycle. During the 58th ESA Parabolic Flight Campaign the device has been tested both in horizontal and vertical position throughout the parabola trajectory. The accuracy of the microgravity level obtained during the parabolic flight is ±0.05g.

The dynamic response of a symmetric 2-D PHP obtained during the ground tests shows interesting analogies to the dynamic response obtained during the microgravity tests.

2. Experiments

The pulsating heat pipe is made of a copper tube (I.D./O.D. 1.1 mm/2.0 mm) bended into a planar serpentine (32 parallel channels) where all curvature radii are 3 mm. Two “T” junctions allow to close the serpentine in a loop and to derive two ports at each side: one is devoted to the vacuum and filling procedure while the second one hosts a pressure transducer (Kulite®, ETL/T 312, 1.2bar A). The PHP is equipped with 14 “T” type thermocouples with wire diameter 0.127 mm, with an accuracy of ±0.1 °C after calibration; nine are tin soldered on the external tube surface in the evaporator and four in the condenser in order to maximize the thermal contact, a last one measures the ambient temperature. The test cell geometry as well as the thermocouple locations is shown in Fig. 1.

While evacuating the PHP by means of an ultra-high vacuum system (Varian® DS42 and TV81-T) down to 0.3 mPa, the working fluid (FC-72) is degased in a secondary tank by continuous boiling: incondensable gases accumulate un the upper part of the tank and they are sucked from above by means of several vacuuming cycles. Finally the PHP is filled with a volumetric ratio 0.5 ± 0.03 and permanently sealed by means of tin soldering. The incondensable gas content, less than 6 PPM, is estimated by measuring the difference between the actual fluid pressure inside the PHP and its saturation pressure at ambient temperature with the same procedure described by Henry et al. [13]. The present PHP is equipped with a wire electrical heater (Thermocoax® Single core 1Nc Ac, 0.5 mm external diameter) wrapped 20 times around each