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Experimental study of a closed loop flat plate pulsating heat pipe under a varying gravity force

V. Ayel [a,*], L. Araneo [b], A. Scalambra [b], M. Mameli [c,e], C. Romestant [a], A. Piteau [a], M. Marengo [c,d], S. Filippeschi [e], Y. Bertin [a]

[a] Institut Pprime CNRS – ENSMA – Université de Poitiers, UPR 3346, Département Fluides, Thermique, Combustion, ENSMA, 1 av. Clément Ader, BP40109, 86961 Futuroscope-Chasseneuil Cedex, France
[b] Politecnico di Milano, Dipartimento di Energia, Via Lambruschini 4A, 20158 Milano, Italy
[c] Università di Bergamo, Dipartimento di Ingegneria e Scienze Applicate, Viale Marconi 5, 24044 Dalmine, Italy
[d] University of Brighton, School of Computing, Engineering and Mathematics, Lewes Road, BN2 4GJ Brighton, UK
[e] Università di Pisa, DESTEC, Largo L. Lazzarino 2, Pisa, Italy

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ABSTRACT

This paper reports on an experimental study of a closed loop Flat Plate Pulsating Heat Pipe (FPPHP) tested on ground and on board of an aircraft during the 60th ESA parabolic flight campaign, during which hyper- and microgravity conditions were reproduced. The tested FPPHP consists of two brazed copper plates, into one of which a continuous rectangular channel (1.6 × 1.7 mm^2) with 12 bends in the evaporator is machined. The channel is filled with FC-72 as working fluid with a volumetric filling ratio of 50%. Tests have been conducted with the FPPHP positioned both horizontally and vertically (bottom-heated). The FPPHP presents an innovative design, involving the milling of grooves between the channels. Experimental results on the ground show that the thermal device can transfer more than 180 W in both inclinations, and that the horizontal operation is characterized by repeated stop-and-start phases and lower thermal performance. The FPPHP can operate under microgravity conditions and with a transient gravity force, with global thermal resistance reaching 50% and 25% of that of the empty plate (or around 66% and 35% of a full copper spreader of same overall dimensions), in horizontal and vertical orientation respectively. The temperature homogeneity remains within 10 K in the evaporator section and 3 K in the condenser section with thermal power transfer up to 180 W. Minimum thermal resistance of 0.12 K W^{-1} was recorded, with its value rising as heating grew more powerful. A parabolic flight test demonstrated that the FPPHP in vertical inclination is rapidly influenced by variation of gravity field, even if, due to the novel geometry, it continues to operate under microgravity. In horizontal inclination, on the other hand, there was no observable parameter change during gravity field variations.

1. Introduction

Pulsating heat pipes (PHP) have been widely studied since the patent of Akachi [1] assigned them the configuration now largely adopted in many current works. A PHP can be defined as a single capillary channel bent in several turns between a heated zone and a cold source consisting of several interconnected turns. The tube is partially filled with a working fluid at the liquid/vapour saturation state, which is distributed by means of surface tension effects in the form of liquid slugs and vapour plugs. Under the effect of the heat source in a zone called evaporator, phase change phenomena occur in the form of liquid film evaporation or flow boiling. On the other hand, condensation occurs in the zone called condenser, which is in contact with the cold source. Complex flow patterns ranging from slug flow to annular flow are initiated in adjacent tubes by local pressure instabilities, and they have effects on the total heat flux transferred by the PHP from the heated to the cooled end [2–4].

When the flow patterns are considered in conjunction with related heat transfers, many parameters have a direct influence on PHP operation [5,6]; while the most important is obviously the channel internal diameter that allows liquid/vapour phase division into liquid slugs and vapour plugs separated by menisci [6,7], other parameters deserve mention: number of turns [8], PHP length,

* Corresponding author. Tel.: +33 5 49 49 81 12; fax: +33 5 49 49 81 01.
E-mail address: vincent.ayel@ensma.fr (V. Ayel).

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Nomenclature

Bo	Bond number
D	diameter, m
FR	filling ratio, %
g	gravity acceleration, m s^{-2}
P	pressure, Pa
$\dot{q}$	heat flux, W m^{-2}
$\dot{Q}$	heat power, W
R_{th}	thermal resistance, K W^{-1}
Re	Reynolds number
T	temperature, K
u	velocity, m s^{-1}
We	Weber number

Greek symbols

ρ	density, kg m^{-3}
σ	surface tension, N m^{-1}

Subscripts

air	ambient air
c	condenser zone
crit	critical
e	evaporator zone
h	heater, hydraulic
l	liquid
v	vapour

filling ratio, the physical properties of the working fluid or, indirectly, the cold source temperature [6,9], heat power applied or heat flux, the inclination with respect to gravity [3,9,10] and the closure or not of the overall loop [11,12]. Among the above-mentioned parameters, orientation is known to strongly affect the performances of such systems by the effect of gravity on fluid momentum; Charoensawan et al. [6] pointed out that the number of turns also affects performances at the level of internal temporal and spatial dynamic pressure perturbations. The direction of the gravity vector with respect to the 3D symmetry axis of a PHP influences not only the thermo-hydraulics of two-phase flow inside the device, but also thermal performances: a PHP always shows better operation in vertical bottom heated mode than in horizontal position, that is to say with the gravity vector oriented in the same direction or perpendicularly to the channels respectively. However, Yang et al. [8] have shown that with a sufficient number of turns and a small tube diameter, a PHP proves to be practically independent of its orientation. This last point is of particular interest in this study, since pulsating heat pipes not only remain suitable as highly efficient passive heat transfer devices for ground applications, but also show promise for space applications.

The present study can be considered as a continuation of the study previously conducted by Mameli et al. [13], in which the authors carried out an experimental investigation on a tube CLPHP tested both on the ground and under micro/hyper gravity conditions during the 58th ESA Parabolic Flight Campaign. The PHP consisted in a copper tube with an internal diameter of 1.1 mm (just under the critical diameter for FC-72, calculated with the static criterion based on the Bond Number at 1 *g* and 20 °C: $D_{\rm crit} = 2(\sigma/g(\rho_l - \rho_v))^{1/2} \approx 1.68$ mm), bent into a planar serpentine, for a total of 16 U-turns in the evaporator zone. Tests during the parabolic flights showed that the vertical operation was affected by hyper- or micro-gravity phases, the first of them slightly assisting the flow motion, and the second one leading to a sudden increase of temperature in the evaporator zone. This abrupt heightening was quite similar to the thermal dynamic response of vertical-to-horizontal tilt manoeuvre on ground. The horizontal operation does not seem to be affected by variations in the gravity field.

Gu et al. [14] have experimented two flat plate aluminium PHP models (250 × 60 × 2.2 mm^3 outer dimensions) during parabolic flights. The PHP was filled with R114 as working fluid with filling ratio of approximately 50–60%. The single continuous channel, engraved on the bottom plate, had a cross section of 1 × 1 mm^2 and was laid out with 48 turns at both ends of the closed loop. Their specificity consists in the configuration of hot (55 × 16 mm^2 Kapton® heater) and cold (80 × 80 mm^2 fan) sources: the first was heated in the middle position and cooled at one end, while the other was heated and cooled at the two opposed ends. The authors concluded that both pulsating heat pipe models operated more effectively under reduced gravity than under normal or hypergravity phases. One may note that these conclusions have been confirmed only for top-heated mode data, which obviously yield less successful performance under unfavourable orientation than under micro-gravity or horizontal orientation. However, according to Gu et al. [14], a dimensional analysis based on Weber number ($We = \rho_l u_l^2 D/\sigma$, ratio between inertial and surface tension forces) has shown that PHPs can operate satisfactorily under microgravity with larger channel diameters (up to 5 mm with R114), i.e. with internal diameters that eventually impede operation on ground. They hypothesized that PHPs could apply larger channel diameters in space and transport more heat without gravity, but there was no experimental validation to confirm their hypothesis.

In this study, a Flat Plate Pulsating Heat Pipe (FPPHP) is designed and tested in order to meet a twofold objective: (i) to determine whether an evolving geometry with very similar boundary conditions as those in Refs. [10,13,14], but with a hydraulic diameter of about 1.65 mm, just below the critical one at ambient temperature for FC-72, can effectively work in microgravity, and (ii) to optimize the FPPHP with respect to a microgravity transient environment. Aspects concerning the inner diameter optimization will be discussed in Section 2. It is essential to keep in mind two issues that may differentiate a FPPHP from a capillary tube PHP; they have already been discussed by Khandekar et al. [15] and thereafter by Yang et al. [16], Ayel et al. [17], as well as Qu et al. for micro-pulsating heat pipes [18]. On the one hand, square shape channels engraved in one plate of the FPPHP have sharp angles in the corners, acting like capillary grooves assisting the liquid flow. Capillary pumping from one side helps the liquid to flow back to the evaporator zone; on the other hand it may provoke rupture of the cross-sectional menisci, resulting in flow regime transition into an annular flow. Operating in favourable vertical inclination, the FPPHP works very effectively under capillary-assisted thermosyphon mode even for the lowest heat power levels, which is not the case for circular shaped channels [15,18]. On the other hand, due to geometry continuity, thermal spreading occurs and tends to strongly decrease transverse thermal resistance between channels, leading to lower temperature gradients in the gap between the channels. This causes homogenization of the pressure differences in the channels, which are the main driver of oscillations under slug flow, particularly in horizontal inclination. The FPPHP tested under this latter inclination consequently often shows premature dry-out [15,17]. To sum-up, with respect to capillary tube PHPs, FPPHPs work more effectively in the favourable inclination, while they may come to a complete stop when functioning in a horizontal position.