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Understanding the self-sustained oscillating two-phase flow motion in a closed loop pulsating heat pipe

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ABSTRACT

In the framework of efficient thermal management schemes, pulsating heat pipes (PHPs) represent a breakthrough solution for passive on-chip two-phase flow cooling of micro-electronics. Unfortunately, the unique coupling of thermodynamics, hydrodynamics and heat transfer, responsible for the self-sustained pulsating two-phase flow in such devices, presents many challenges to the understanding of the underlying physical phenomena which have so far eluded accurate prediction. In this experimental study, the novel time-strip image processing technique was used to investigate the thermo-flow dynamics of a single-turn channel CLPHP (closed loop pulsating heat pipe) charged with R245fa and tested under different operating conditions. The resulting frequency data confirmed the effect of flow pattern, and thus operating conditions, on the oscillating behavior. Dominant frequencies from 1.2 Hz for the oscillating regime to 0.6 Hz for the unidirectional flow circulation regime were measured, whilst wide spectral bands were observed for the unstable circulation regime. In order to analytically assess the observed trends in the spectral behavior, a spring-mass-damper system model was developed for the two-phase flow motion. As well as showing that system stiffness and mass have an effect on the two-phase flow dynamics, further insights into the flow pattern transition mechanism were also gained.

1. Introduction

The European energy picture has recently undergone some major changes. In 2008 the European Union launched a ten-year growth and job strategy initiative called *'Europe 2020'* which contains specific targets for reducing greenhouse gas emissions by 20% from 1990 levels [1,2]. Moreover, in the next 10 years, 80 civilian nuclear power reactors will be shut down due to operating life or political decisions [3]. These facts, together with the intermittent nature of renewable energy sources and the depletion of fossil fuels [4], will work to shape the future European energy market. Another consequence of this initiative will be an improvement of the efficiency of power plants, industrial processes and electronics.

Recent studies [5] estimate that the energy consumption of European data centers will increase almost threefold from their 2006 levels. However, although in a state-of-the-art data center up to 45% of the total electrical energy is used for operating the cooling resources [6], the integration of new and efficient cooling technologies has been very limited in the past 20 years due to the high cost of hardware and the low cost of energy [7]. In this context represent a promising cooling solution that offers reduced production and operation costs. Furthermore, PHPs are passive thermally driven cooling systems where no mechanical apparatus, such as liquid pumps, are needed to achieve fluid flow and heat transport [8].

The PHP (pulsating heat pipe) was introduced into the literature by Akachi [9]. This comprised a sealed capillary tube bent to form U-turns with its inner volume partially filled with a working fluid. The observed self-sustained oscillatory two-phase flow, responsible for efficient heat transfer in a PHP, is achieved when a sufficiently high temperature gradient is established between the two ends of the device; namely the heated evaporator and cooled condenser ends respectively. At this instant, simultaneous evaporation and condensation of the working fluid, coupled to non-uniform heating and cooling within the hot and cold sections, and the uneven liquid–vapor distribution, produce non-equilibrium pressure conditions within the device. This then propels the liquid entrapped between the vapor plugs around the closed loop, thus transferring heat from the hot to the cold section [10,11].

The alternating local presence of vapor plugs and liquid slugs produces fluctuating evaporator and condenser wall temperatures

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whose oscillation amplitudes and frequencies change with the operating conditions of the PHP. In particular, such steady state thermal oscillations depend on the applied heat flux, liquid filling ratio, and the two-phase flow distribution and dynamics present in the device, as found by Tong et al. [12], Khandekar and Groll [13,14], Xu and Zhang [15] and Spinato et al. [16].

The heat input has been found to be the primary parameter defining the two-phase flow pattern existing within an operating PHP. The flow pattern typically observed with increasing heat input are: (a) Low amplitude oscillation, (b) oscillation, (c) unstable oscillation with circulation and direction reversals, and (d) unidirectional flow circulation [12,17,18]. The superposition of an oscillatory component on the circulating component was sometimes observed and represented as a particular case of circulating flow with 'local flow direction switch' [18], also observed by Refs. [16,19,20].

The four abovementioned flow patterns were observed and identified by Spinato et al. [16], each showing peculiar frequency spectra, present in the temperature data and in the motion of the liquid slug as computed from the time-strip technique [21].

Parametrical experimental studies were performed in order to characterize the frequency content of the steady state thermal oscillations in PHPs. Different geometries (i.e. single-turn, multi-turn, …) and a wide range of operating conditions (working fluid, heat input, filling ratio and inclination) were tested; Das et al. [22,23], in a thermally driven self-sustained oscillating PHP system, found dominant frequencies within the range 1.7–3.36 Hz for methanol and 1.69–4.14 Hz for pentane, whilst in a single loop CLPHP (closed loop pulsating heat pipe) charged with ethanol, Khandekar et al. [24] measured the system pressure to oscillate within the range 0.1–3.0 Hz. Power spectral analysis carried out in a multi-turn CLPHP by Xu and Zhang [15] displayed a quasi-periodic thermal behavior at the high heat loads, with dominant frequencies lower than 1 Hz, whilst in a different geometry multi-turn CLPHP, Kim et al. [25] observed the pressure to oscillate between 0.1 Hz and 1.5 Hz at a 40% filling ratio of R142b. Modeling and experimental measurements carried out by Zuo et al. [26] on a flat plate PHP charged with water showed dominant frequencies within the range 1–10 Hz, and frequencies within the range 1–4 Hz were provided by the 1D slug-flow model implemented and validated against a 2 mm ID (internal diameter) copper tube CLPHP charged with ethanol by Daimaru et al. [27].

Furthermore, many experimental [19,22,28] and numerical [29–31] studies concluded these frequencies to increase with heat input, thus driving temperature difference. The working fluid properties also exhibit an effect on the characteristics of the self-sustained two-phase flow in PHPs. For instance, the effect of the concentration of nanofluid in a single loop CLPHP charged with DI (deionized) water and Copper nanoparticles was experimentally investigated by Nine et al. [32]. The results of the fully non-linear thermo-mechanical finite-element model by Peng et al. [33] explained the main effect of the working fluid being due to its viscosity, in agreement with Cai et al. [30] who observed frequencies to increase at lower fluid viscosity, such as for higher system temperatures. Cheng et al. [34] developed a mathematical model of the oscillating self-sustained two-phase flow in PHPs, assuming the compression action of vapor plugs to function similarly to a linear spring: a multiple mass-spring system then represented the system stiffness. The action of the damping effect due to flow resistance was added in the mass-spring-damper models implemented by Ma et al. [29] and Cai et al. [30]. According to the results of such models the frequency increases with system temperature and pressure.

At the early stage of PHP mathematical and physical modeling, the slug-plug oscillating flow was compared to a single [35,36] or multiple spring-mass-damper [29,30,37,38] systems. FEM (finite element method) and VOF (volume of fluid) thermo-mechanical models, in which the governing equations were applied to control volumes, were later implemented. The effects of capillary phenomena in small diameter tubes and of liquid film phenomena [39–42] together with the presence of nucleation [39] are the most recent advances in the PHP modeling literature.

The large number of degrees of freedom responsible for PHP operation finally results in highly non-linear systems that are hard to model or predict. So far no comprehensive tools exist for their design, modeling and optimization and the existing theoretical models are limited and based on unrealistic assumptions [10]. Therefore, as concluded by Khandekar et al. [43], more studies on the nature of phase-change induced oscillatory flows in PHPs are needed. This provides the motivation for the present study, which attempts to gain a deeper understanding of the mechanisms governing the self-sustained two-phase flow in a single-turn CLPHP.

A time-strip image processing technique [16], previously implemented to assess the two-phase flow in a multi-microchannel evaporator [21,44], was here applied to the high speed videos of the two-phase flow in a single-turn CLPHP. Novel details of the flow regimes and their dynamics were extracted. Local temperature oscillations were measured synchronously, and their frequency spectra further helped in characterizing the self-sustained two-phase flow.

2. Experimental set-up and data reduction

The experimental set-up, the single-turn closed loop pulsating heat pipe (CLPHP) test-section, and the data analysis techniques are described in detail by Spinato et al. [16]. The geometrical specifications of the CLPHP test-section can be found in Table 1. The flow direction (z-axis) was chosen as positive in the counter-clockwise direction, with the origin of the coordinate system being the midpoint of the CLPHP left channel centerline, as depicted in Fig. 1a. The working fluid for these tests was the refrigerant R245fa.

The test-section and the camera were rigidly mounted on a tilting frame which could be set at any orientation α, defined with respect to the VED (vertical evaporator down) position. It should be noted that in this study only the VED $\alpha = 0°$ orientation was investigated. The back side of the test-section was designed to accommodate instrumentation and auxiliary apparatus. These included an electrical cartridge heater which was inserted into a customized holder, a water cooling circuit which was connected to two flat copper tubes, and two 250 μm K-type thermocouples with calibrated accuracies of 0.1 K and precisions less than 0.02 K (Fig. 1b). These thermocouples were flush-mounted to the channel wall, at $z = 200$ mm for the evaporator and at $z = 630$ mm for the condenser, in order to minimize the effects of both transient heat conduction through the channel base plate and perturbation of the flow in the channel. The local temperature oscillation of the channel walls at these locations were then measured at an acquisition rate of 20 Hz.

A high speed Photron Fastcam SA3 digital camera was used to record the two-phase flow dynamics at different locations along

Table 1
CLPHP test-section geometry.

CLPHP test-section specifications	
Number of channels in the loop	1
Channel cross-section	1 × 1 mm^2
Channel total length	830 mm
Channel spacing	13.5 mm
Bend radius	2 mm
Channel base thickness	1 mm