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Heat and mass transfer mechanisms of a self-sustained thermally driven oscillating liquid–vapour meniscus

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ABSTRACT

Self-sustained thermally-induced oscillations of a meniscus in a two-phase system, consisting of a liquid plug and a vapour bubble in a capillary tube, are studied. This system represents the simplest 'unit-cell' version of a pulsating heat pipe (PHP). An experimental setup has been built to visualise and record the meniscus oscillations and the thin liquid film that is laid on the wall when the meniscus leaves the evaporator. The pressure and temperature of the vapour are also simultaneously measured. When the temperature difference between the heat source and the heat sink increases, different meniscus dynamics, having excellent repeatability, is observed. The experimental results clearly demonstrate that evaporation of the liquid film is responsible for these patterns. The different components of evaporation and condensation processes are critically analysed. Two different modes of evaporation are observed inside the system: one at the triple-line and one at the liquid–vapour interface. Considering that no comprehensive model of PHP system is available, the conclusions and directions provided in this study are important for building a broader understanding.

1. Introduction

A pulsating heat pipe (PHP) is essentially a passive two-phase heat transfer device, which also belongs to a special category of wickless heat pipes [1,2]. From a technological point of view, this thermal transport system is very simple and can be considered as almost costless [1] compared to other heat transport devices. Therefore, research on PHP as a system has been a point of interest in the recent past and its potential applications in many passive heat transport situations has been extensively studied [3–7]. However, in contrast to large availability of system level studies on PHPs in the literature, the nuances of its operating principles and associated physics are not well understood, which thwarts the large scale industrial acceptability of PHPs.

A PHP consists of a simple capillary tube, with no wick structure, bent into many turns, and partially filled with a working fluid. When the temperature difference between the heat source and the heat sink exceeds a certain threshold, the vapour bubbles and liquid plugs present inside the capillary tube begin to auto-oscillate, back and forth, which leads to unique heat transfer characteristics. Heat is thus passively transferred, not only by latent heat exchange like in conventional heat pipes, but also by sensible heat transfer between the wall and the fluid. This complex internal thermo-hydrodynamic transport process is known as the self-sustained thermally driven oscillating two-phase Taylor bubble flow.

Research on PHPs has seen an unprecedented increase during the last 15 years, almost 25 years after the system has been patented in its most popular layout by Akachi [8,9]. Unfortunately, major part of the literature does not provide universally applicable generic knowledge base on these systems; it generally focuses on one particular PHP structure or type, designed for a specific application. In these type of works having a system level approach, the PHP is usually characterised by the temperature difference measured between the condenser and the evaporator section, for a given applied heat flux. Every such PHP design has its own geometrical and thermophysical properties (inner and outer diameters, length, closed or open-loop devices, evaporator, condenser and adiabatic lengths, number of turns, material of the tube, etc.) and is filled with a specific working fluid having its own thermophysical properties (latent heat, wettability and for both vapour and liquid phases: thermal conductivity and capacity, density, viscosity, etc.), and is tested in specific experimental conditions (heat load at the evaporator, ambient and condenser temperatures, etc.). The number of relevant parameters to characterise a PHP is therefore so large that it is difficult to

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Nomenclature

$\hat{a}$	average acceleration of meniscus (m/s^2)
Bo	Bond number ($\rho \cdot \hat{a} \cdot D^2/\sigma$)
Ca	Capillary number ($\mu U/\sigma$)
D	diameter (m)
h	heat transfer coefficient (W/m^2 K)
h_{lv}	latent heat (J/kg)
K	thermal conductance (W/K)
L	length (m)
m	mass (kg)
$\dot{m}$	mass flow rate (kg/s)
$\overline{M}$	molecular weight (kg/mol)
P	pressure (Pa)
R	radius (m)
$\bar{R}$	universal gas constant (J/mol K)
t	time (s)
T	temperature (°C or K)
x	coordinate (m)
U	velocity (m/s)
V	volume (m^3)

Greek symbols

δ	film thickness (m)
λ	thermal conductivity (W/m K)
μ	dynamic viscosity (Pa-s)
ρ	density (kg/m^3)
σ	surface tension (N/m)

Subscripts

a	adiabatic
c	condenser
$cond$	condensation
e	evaporator
f	film
i	internal
l	liquid
max	maximum
sat	saturation
v	vapour
0	initial

explicitly discriminate the effect of one parameter among the others in this type of experiments. As a result, one can find several papers [1] dealing with the same parameters and often having conflicting or repetitive conclusions. To overcome these difficulties, some authors developed non-dimensional expressions based on different numbers like the Jacob, the Karman, the Prandtl or the Kutateladze numbers and taking into account the number of turns [10]. Nevertheless, this approach has also failed so far to provide a universal understanding of the PHP because the basic physical phenomena and the extent of parameters responsible for system dynamics are not yet well understood.

Research at the local scale (i.e., at the scale of one bubble and one liquid plug), although few, were addressed quite early, in order to augment the knowledge on basic phenomena which are responsible for the oscillations and the heat transfer in the system. From a modelling perspective, this approach was initiated by Zhang et al. [11,12] and Dobson [13,14], who studied theoretically the governing mechanisms of a single branch of the PHP, consisting of one vapour bubble and one liquid slug. Das et al. [24] developed a more sophisticated approach which included the two-phase equilibrium physics that occurs locally at the liquid vapour-interface, especially along the time-varying wetting thin film. Such a film gets laid down by the liquid plug during its journey from the evaporator towards the condenser and through which the major part of heat and mass transfer occurs. This film was shown to be one of the major phenomena responsible for the large amplitude oscillations observed in the system. In this work, an instability analysis of this system was also performed. The local scale modelling has now been extended to several PHP branches with many liquid plugs and vapour bubbles [15–19].

Looking at the literature related to experimental studies on PHPs, the local approach to study its characteristics is comparatively even scarcer. Local heat transfer measurements in non-boiling Taylor bubble flow, in the context of pulsating heat pipes have been recently addressed. Many research groups have shown that the flow field in single-phase liquid flows gets significantly modified by slipping Taylor bubbles of gas/vapour through it, which eventually leads to enhanced heat transfer [20–22]. Continuing on these lines, Mehta and Khandekar [23] recently studied the heat transfer characteristics of pulsating Taylor bubble-train flow in square mini-channels using infra-red thermography, the frequency of imposed flow fluctuations being similar to those encountered in PHPs. The main objective of the study was to observe the effects of externally imposed pulsations on local heat transfer taking place in a unit cell, comprising of a Taylor liquid slug trapped between two adjacent gas bubbles. The controlling parameter of the study was liquid and gas flow rates and imposed flow frequencies. The study indicated that the distribution of liquid-slugs and vapour bubbles is one of the important parameter for improving thermal performance of PHPs. Perturbing the Taylor bubble-train flow with imposed frequencies may conditionally lead to enhancement in the heat transfer, in comparison to steady continuous Taylor bubble-train. The sensible heating/cooling transport capability of the liquid slugs can be altered by controlling the wake generated by the adjoining Taylor bubbles. Interfacial slip created by intermittent flow conditions, was the major cause for heat transfer enhancement.

Earlier, in 2010, Das et al. [24] presented the first experimental data of the simplest 'unit-cell' version of a pulsating heat pipe, consisting of one liquid plug and one vapour bubble. Their experimental setup was closer to a real-PHP and also, the theoretical configuration previously studied by Dobson [13,14]. It consisted of a capillary tube closed at one end and connected to a reservoir maintained at a constant pressure at the other end. A single liquid plug adjoining a vapour bubble was made to thermally auto-oscillate inside this tube, which was heated on one side and cooled down on the other side, thereby creating a continuous cycle of evaporation and condensation. The movement of the meniscus was recorded in the cooled section of the tube, while the heated section, made of copper, was opaque. The vapour pressure was also measured during the oscillations. A similar experiment performed in cryogenic conditions was presented by Bonnet et al. [25] in 2011 and Gully et al. [26] in 2013. Compared to the previous experiment, their system was totally opaque; a thin micro-thermocouple was used to measure the time-varying temperature of the vapour, which showed that the vapour plug is superheated in this single branch PHP experiment. This is a major result as this hypothesis had never been verified before, although it was proposed earlier by Khandekar et al. [27]. Some important experimental limitations were present in the work of Das et al. [24]. The experimental setup