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Thermally induced two-phase oscillating flow inside a capillary tube

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ABSTRACT

This paper deals with thermally induced meniscus oscillations in a two-phase system consisting of a liquid plug and a vapor bubble in a capillary tube of circular cross-section. This system represents the simplest version of a heat transfer device called "pulsating heat pipe" (PHP). Our purpose is to gain fundamental understanding of the physical processes that cause self-sustained thermally driven oscillations. A visualization experiment is performed and the oscillations of the liquid–vapor meniscus and the vapor pressure are observed. We propose next a theoretical model. It differs from existing models by the account of the two-phase equilibrium that occurs locally at the vapor–liquid interface and by introduction of the time varying wetting films through which the major part of the heat and mass transfer occurs. Results from the proposed model show a good agreement with the experiment.

1. Introduction

The pulsating heat pipe (PHP) [1] is a long capillary tube bent into many turns and partially filled with a two-phase, usually single component, working fluid. The tube is simple, with no wick structure. When heated, the fluid spontaneously forms many vapor bubbles separated by liquid plugs inside the tube. Evaporation of liquid in the hot (evaporator) sections and subsequent condensation in the cold (condenser) sections creates oscillations of the bubble-plug structure. These oscillations are very important because they lead to a substantial increase of the heat transfer rate in comparison with other types of heat pipes [2]. In addition to the latent heat transfer characteristic for them, the sensible heat transfer occurs in PHP. While sweeping an evaporator section, a liquid plug accumulates the heat, which is then transferred to the condenser section when the plug penetrates there.

Because of their simplicity and high performance, PHPs are often considered as highly promising. Their industrial application is however limited because their functioning is not well controlled. Multiple parameters affect its thermal performance. During the last decade, researchers have extensively studied PHPs [3]. Tong et al. [4], Miyazki and Arikawa [5], Xu et al. [6] and Gi et al. [7] conducted flow visualization studies. Ethanol, methanol, deionized water and R142b were used in their studies. Their experiments confirmed the existence of self-sustained thermally driven oscillations in PHPs. Charoensawan et al. [8] and Yang et al. [9] performed experiments with different tube diameters, configurations, orientations and filling ratios and studied the thermal performance of PHPs in different conditions.

However, the functioning of PHPs is not completely understood. Unlike other types of heat pipes, the functioning of PHPs is nonstationary and thus difficult to model. A complicated interplay of different hydrodynamic and phase-exchange phenomena needs to be accounted for.

There are only few modelling approaches available in the literature. Zhang et al. [10], Dobson [11,12] studied the governing mechanism of the PHP using simple models. They studied a U-shaped miniature tube (i.e. single bend PHP) with a single liquid plug or a vapor bubble. The evaporation/condensation rate is assumed to be proportional to the difference of the temperatures of the vapor and the walls in contact with it. In the vapor bubble evolution equation this leads to terms analogous to those of sensible heat transfer between the vapor and the tube walls. The approach [10] has been extended by Shaffi et al. [13] to model both looped and unlooped PHPs with multiple vapor bubbles, liquid plugs and tube bends. This model has been used later by another team [14], also for multi-bubble PHP modelling.

It is well known from general considerations of thermal resistance that during the meniscus evaporation, an important contribution to the heat and mass transfer comes from thin liquid films that may cover the interior of the capillary. The local two-phase equilibrium exists at the interface of microscopically thin

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Nomenclature

C_f	friction coefficient
c_vv	vapor specific heat at constant volume (J/(kg K))
D	vapor heat diffusivity (m^2/s)
d	tube diameter (m)
F	force (N)
h_lv	latent heat (J/kg)
K	coefficient in Eq. (15)
k	heat conductivity (W/(m K))
L	length (m)
m	mass (kg)
P	oscillation period (s)
p	pressure (Pa)
q_sens	sensible heat flux (W/m^2)
R_v	vapor gas constant (J/(kg K))
Re	Reynolds number
S	tube section area (m^2)
T	temperature (K)
t	time (s)
U	heat transfer coefficient (W/(K m^2))
V	meniscus velocity (m/s)
x	meniscus position (m)
x_f	film edge position (m)

Greek symbols

α	coefficient in Eq. (15)
β	coefficient in Eq. (15)
δ	thickness (m)
γ	coefficient
ν	kinematic viscosity (m^2/s)
ρ	liquid density (kg/m^3)
τ	characteristic time scale (s)

Subscripts and superscripts

bl	boundary layer
c	condenser, characteristic
e	evaporator
eff	effective
f	friction, film
i	inertial
l	liquid
m	meniscus
o	open end
p	pressure
r	reservoir
sat	at saturation
t	total
v	vapor

films [15] so that the interface is at saturation or very close to it. This effect was completely neglected in the above mentioned modelling approaches. Dobson [11,12] has included a film in his single-bubble model. However the film mass exchange in his model was not related to the liquid–vapor equilibrium and the mass exchange was proportional to the difference of temperatures of the vapor and the wall, just like in the other works that did not treat the films at all. The single-bubble model of Zhang and Faghri [16] has taken a step forward by rigorously showing that most part of heat and mass exchange occurs via the films in the PHP. The shape of the curved meniscus including the film has been calculated.

Globally, the existing models describe oscillations of small amplitude. During these oscillations, the meniscus is located almost all the time in the condenser section. This contradicts most cited above experimental results where strong amplitude meniscus oscillations are observed. At each oscillation the meniscus sweeps both the condenser and evaporator. The objective of the present work is to propose a model that accounts for the two-phase equilibrium at the vapor–liquid interface and can explain such large amplitude oscillations. Some experimental results will be presented and compared with the model.

2. Experiments

2.1. Experimental setup

The main part of the experimental setup (Fig. 1) is a capillary tube of 2 mm internal diameter. The evaporator section of the tube (of length L_e = 15 cm) is made inside an opaque copper cylindrical block. Three heating coils are wound around it. Power rating of each coil is 88 W. The temperature of the evaporator is regulated to a constant value T_e with a tolerance of ±1 °C. The 25 cm long condenser section is made of transparent glass. It is enveloped by a transparent heat exchanger so that the coolant (silicon oil with low freezing temperature) flows around the condenser. Two ends of the exchanger are connected to a thermostatic bath (MINISTAT CC with operating range −25–150 °C). This bath operates with a maximum flow rate of 18 l/min at 600 mbar. The flow rate is 12 l/min at 300 mbar. It allows the condenser temperature T_c to be maintained constant within ±0.1 °C. A small section of 1 cm between the condenser and the evaporator is insulated, and acts as the adiabatic section. Such a setup provides the fluid visualization only inside the condenser.

The closed left end of the evaporator section is connected to the KISTLER® piezoresistive absolute pressure sensor (type 4005 B and operating range of 0–20 bar). The pressure sensor is calibrated in the pressure range 0–3 bar with an accuracy of 2 mbar. A vacuum line, isolated from the main capillary tube through a shut-off valve, is also connected to the left evaporator end. This vacuum connection serves two purposes. First, it helps to remove any non-condensable gases present in the capillary tube before charging it with the working fluid. Second, it helps to control the position of the liquid–vapor meniscus in the beginning of the experiment.

The open right end of the capillary tube is connected to a large reservoir filled with the working fluid. A heating coil is wound around this reservoir to control the reservoir pressure. The entire system is first evacuated completely to remove any non-condensable gases. The liquid reservoir is then filled with the working fluid (*n*-pentane), which is convenient because of its low saturation temperature at the ambient pressure. A pressure gauge and two thermocouples serve to measure the pressure and the temperature in the reservoir. The meniscus displacement x, counted from the left end of the evaporator, is measured from the condenser images acquired with a high speed (3000 frames/s) digital camera.

2.2. Experimental results

The oscillations in the system (i.e. its instability) appear when the difference between the temperatures T_e and T_c exceeds a threshold value. At small T_c, the meniscus does not move out of the condenser (towards the fluid reservoir) which is convenient for the visualization; small T_c values (0–10 °C) are used. Fig. 2a