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Effect of tube heat conduction on the single branch pulsating heat pipe start-up

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ABSTRACT

The oscillation inception in the single-branch pulsating heat pipe (PHP, called also oscillating heat pipe) has been studied in the presence of the heat conduction along the PHP tube, with the imposed both evaporator heat power and condenser temperature. A start-up regime caused rather by the meniscus/film evaporation than boiling has been considered. The dynamic equilibrium system state has been analyzed, where the liquid film is absent and the meniscus is located at a position where the tube temperature corresponds to the saturation temperature. The temporal evolution of the system responding to an initial fluctuation shows a non-linear response even for small fluctuations. The stability of the equilibrium state has been analyzed. The stability threshold corresponds to the start-up criterion. The main result of the above analysis is the independence of the start-up criterion of the liquid film properties (film shape and thickness). This result applies to the multi-branch PHP too. Due to the large tube thermal inertia, influence of the temporal variation of the tube temperature on the threshold can be neglected; only the equilibrium spatial temperature distribution along the tube matters. The start-up threshold value is determined for the temperature gradient along the tube, more specifically, its equilibrium value at the equilibrium meniscus location. It depends only weakly on other system parameters like condenser temperature or adiabatic section length. An analytical expression for the threshold has been obtained. The start-up power scales like square root of the tube heat conductivity. The liquid viscous dissipation is found to be much less important than the energy dissipation via the fluid and solid heat transfer.

1. Introduction

The pulsating (or oscillating) heat pipe (PHP) is a looped capillary tube that meanders between hot and cold spots that form evaporator and condenser sections, respectively. The tube is filled with a pure fluid in such a way that liquid plugs and gas bubbles coexist inside. When the temperature difference between the evaporator and condenser exceeds a threshold, the self-sustained oscillations of the plugs and bubbles appear. The PHP is extremely attractive for various industrial applications because of high thermal performance and manufacturing simplicity. However the PHP functioning is not completely understood; the absence of predictive tools that would allow their dimensioning is a substantial obstacle to their development. The reason for that is, on one hand, a multitude of complicated physical phenomena involved into their functioning [1,2], and on the other, its intrinsic non-stationarity. Because of the PHP complexity, their one-dimensional (1D) modeling has been applied initially [3] where only liquid and gas plugs with dry tube walls were modeled. The model has been extended later [4] to account for the liquid films (on the internal tube walls) through which most of the heat and mass exchange occurs.

The crucial question about the PHPs concerns their start-up, i.e. the oscillation inception. One can approach this question by direct simulation [4]. Because of the multitude of parameters that influence the start-up and different start-up modes [5], direct simulation of the multi-branch PHP is not the best way to study the start-up criteria. To gain understanding of the PHP start-up, one needs to begin with simple PHP geometries. In this article we consider the start-up of the simplest, single branch PHP (Fig. 1) for which some analytical results are possible to obtain [6,7]. It is a straight capillary with a sealed end, which is heated (evaporator). The gas bubble is confined between the sealed end and a liquid plug. The condenser end of the capillary is connected to a large reservoir filled partially with the liquid at constant pressure p_r.

One can distinguish two main start-up modes: via boiling inside liquid plugs situating in evaporator or via evaporation from liquid menisci [5,8]. The first regime is often associated with a strong evaporator temperature overshoot that appears between the power switching-on and the oscillation beginning after which the

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Nomenclature

c	specific heat [J/(kg·K)]
D	thermal diffusion coefficient [m^2/s]
d	tube diameter [m]
e	dimensionless volume element length, base of the natural logarithm
f	dimensionless viscous friction
h_{lg}	latent heat [J/kg]
j	volume heat supply [W/m^3]
k	heat conductivity [W/(m·K)]
L	length [m]
m	mass [kg]
N	number of volume elements
P	heat power [W]
p	pressure [Pa]
q	heat flux [W/m^2]
R	gas constant for gas [J/(kg·K)]
r	dimensionless velocity amplitude
S	cross-section area [m^2]
T	temperature [K]
t	time [s]
U	heat transfer coefficient [W/(K·m^2)]
V	meniscus velocity [m/s]
x	abscissa [m]

Greek symbols

α	dimensionless evaporator length
β	dimensionless heating power
χ, ξ, ζ	dimensionless constants defined in Eq. (25)
δ	liquid film thickness [m]
η	reduced condenser temperature
γ	adiabatic index
λ	dimensionless coordinate
ν	liquid kinematic viscosity [m^2/s]
Ω	dimensionless parameter characterizing the tube thermal inertia
Π	oscillation period [s]
ψ	dimensionless gas temperature
ρ	density [kg/m^3]
σ	dimensionless saturation curve slope
τ	dimensionless time
θ, μ, ϕ	dimensionless constants defined in Eq. (36)
ε	reduced adiabatic length
φ, κ	dimensionless phase shifts

Subscripts

c	condenser
e	evaporator
f	film
g	gas
l	liquid
m	meniscus
o	outer tube wall
r	reservoir
s	solid tube wall material, internal tube wall
sat	saturation
$sens$	sensible
t	total
V	at constant volume and for gas phase
0	at $t = 0$

temperature drops. It is related to the energy barrier required for the bubble nucleation. The second regime exhibits a smaller temperature overshoot (if any) and for this reason is more advantageous because it provides a better temperature stability. For this reason, in this article we study this latter regime that we call "soft" to distinguish from the "hard" regime with a bigger temperature overshoot.

The "film evaporation–condensation" (FEC) model introduced in [6] is used here. It is a 1D model. The heat/mass exchange is controlled mainly by the thermal conduction in the liquid films described by the terms $\propto (T_s - T_{sat})$, where T_{sat} is calculated for the current gas pressure p and T_s is the temperature of the *internal* tube wall. The FEC model describes large amplitude oscillations during which the meniscus sweeps both the condenser and the evaporator. The FEC model agrees quantitatively with the experimental results [6] on the single branch PHP. Recently, the FEC model has been validated against the data obtained with another experimental set-up [9]. It described most features observed experimentally (like the intermittency of oscillations observed by both [6,9]).

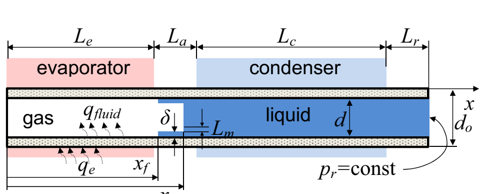

Fig. 1. Single branch PHP within the lumped meniscus approximation. The total tube length $L_t = L_e + L_c + L_r$ includes an effective length L_r representing an amount of the liquid in the reservoir that takes part in the oscillating motion; L_e and L_c are the lengths of the respective tube sections.

In the preceding article [7], the start-up has been studied for the simplest thermal boundary conditions: the imposed temperature at the internal tube walls both in the condenser and the evaporator. The temperature varied stepwise along the tube (from condenser to evaporator) for the case of PHP without adiabatic section. In the present article, we consider a more realistic case of the smooth temperature variation in the presence of adiabatic section. The thermal boundary conditions approach the experimental situation. While the condenser temperature T_c is imposed at the internal tube walls, the thermal conduction along the tube is introduced so that the tube temperature is allowed to vary both spatially and temporally. A constant evaporator heat power P_e is imposed.

When experimentalists consider the PHP start-up, they speak usually of what happens after the power switching-on. Two situations are then possible: either PHP begins to oscillate or it comes to some stationary non-oscillating state of dynamic equilibrium. One does not need to consider the switching-on procedure when approaching the start-up problem theoretically. One needs to find instead an equilibrium state and see if it is stable or unstable with respect to a small fluctuation. The stable state corresponds to that found experimentally and means the absence of oscillation while the instability corresponds to the oscillation start-up.

The article is structured as follows. The model is summarized in Section 2. The equilibrium state for such a system is identified in Section 3. The stability of the equilibrium state is studied in Section 4. The oscillation threshold (i.e. start-up criterion) is analyzed in Section 4.3. The results are summarized in Section 5.