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Research Paper

Reprint of: Effect of tube heat conduction on the pulsating heat pipe start-up ☆

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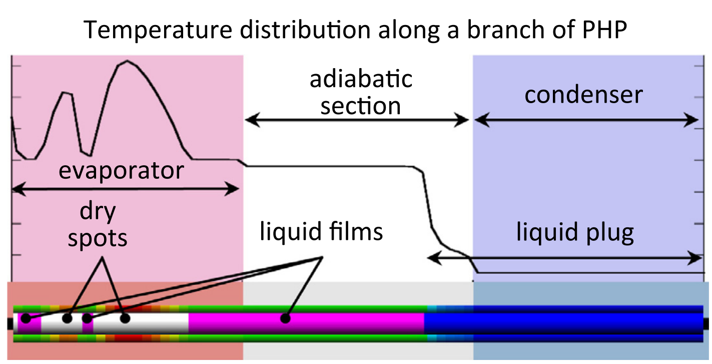
HIGHLIGHTS

- Pulsating heat pipe numerical simulation with bubble generation is presented.
- It describes dynamics of liquid plugs, liquid films, and dry spots on tube walls.
- Evaporator power is imposed, temperature varies smoothly along the tube.
- It is shown that the multibranch PHP does not start up without bubble generation.
- Description of multiple dry spots allows simulating the complete PHP halt by dry-out.

GRAPHICAL ABSTRACT



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ABSTRACT

In this work, we present our first simulation results on the start-up, functioning and stopping (dry-out) of the multi-branch pulsating heat pipe (PHP) accounting for the fluid-tube thermal interaction and bubble generation (boiling). A theoretical model that generalizes an earlier proposed approach is described. It is shown that the account of tube heat conduction changes substantially the simulated PHP behavior. In particular, in the presence of tube heat conduction, the PHP cannot provide stable oscillations without bubble generation. While the bubble generation may not be directly involved in the development of first oscillations, its role is crucial in preventing the oscillations halt. The mechanism of the oscillation sustainment by bubble generation is discussed. The PHP simulation shows basic phenomena of bubble interaction and regimes observed experimentally in transparent PHPs. The PHP ceases functioning when the evaporator power is larger than a threshold. The liquid films are evaporated so the evaporator dries out completely and the oscillations stop; the evaporator temperature rises steeply.

1. Introduction

Pulsating (or oscillating) heat pipe (PHP) is a simple capillary tube bent into branches meandering between hot and cold spots and partially filled with a two-phase, usually single component working fluid. During PHP functioning, a moving pattern of multiple vapor bubbles separated by liquid plugs forms spontaneously inside the tube. Because of their simplicity and high performance, PHP's are often considered as highly promising [1]. Their industrial

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Nomenclature

c	specific heat at constant pressure [J/(kg K)]
D	heat diffusivity [m^2/s]
d	tube inner diameter [m]
h_{lv}	latent heat [J/kg]
L	length [m]
M	total number of bubbles or plugs
m	mass of vapor [kg]
N	total number
Nu	Nusselt number
P	power [W]
p	pressure; p_i: in the bubble i [Pa]
q	heat flux [W/m^2]
S	cross-section area [m^2]
T	temperature [T_i: of vapor] [K]
t	time [s]
U	heat transfer coefficient [W/(m^2 K)]
x, X	abscissa measured along the PHP tube [m]

Greek symbols

Δ	difference
δ	thickness [m]
λ	heat conductivity [W/(m K)]
ϕ	volume fraction of liquid in PHP
ρ	density [kg/m^3]

Superscripts

l	left
r	right

Subscripts

c	condenser
e	evaporator
f	liquid film
fb	feed back section (vertical in Fig. 1)
i	bubble or plug identifier
l	liquid
m	meniscus
$next$	next bubble
$nucl$	nucleation
p	PHP spatial period
sat	at saturation
t	total
thr	threshold
v	vapor
w	internal tube wall

application is however limited because the functioning of PHPs is not completely understood; the absence of calculation tools that would allow their dimensioning is a substantial obstacle to their development.

During the last decade, researchers have extensively studied PHP [2,3]. It has been observed by many researchers that the main flow pattern inside the PHP is the slug flow, i.e. the flow of the "Taylor bubbles" where the gas is surrounded by liquid films. A major part of mass exchange occurs on their interface with the vapor like in the conventional heat pipes. Since the mass exchange provides both a moving force for the oscillations and the heat exchange, the films are extremely important for the PHP functioning.

Because of complex bubble and plug interactions and non-stationary dynamics, correlation-based system level approaches fail to predict the heat transfer in multi branch PHP and its direct numerical simulation seems to be the only possibility. One dimensional (1D) simulation models is the best choice because they are the simplest and at the same time are capable to describe the relevant physical phenomena. The pioneering approach [4] introduced basic principles for the 1D modeling. The PHP meander was represented by a straight tube with periodic boundary conditions; the evaporator, adiabatic and condenser sections followed each other sequentially. A coherent thermodynamic description of vapor has been introduced. The vapor was described as a compressible ideal gas which allowed its spring-like action. The heat conduction in the liquid plugs has been introduced. The imposed fixed temperatures T_c, T_e at the internal tube walls were assumed. Periodic oscillations were encountered. However, their amplitude was weak (smaller than the evaporator size), which contradicts the experimentally observed behavior.

One knows that the strongest heat and mass exchange occurs from thin liquid films. The films with uniform thickness δ_f, but varying length were introduced into the modeling [5] of the simplest, single branch PHP so that a partial evaporator dry-out could be described. The introduction of the heat conduction inside the tube walls [6] enabled the fluid-solid thermal interaction. The latter is quite important because it accounts for such effects as e.g. transfer of the heat from hot liquid plugs to the walls, heat accumulation in the solid and its later reinjection into the fluid. Besides, much realistic imposed heat power thermal boundary conditions become possible to simulate. The approach [6] has been reused with some improvements by another group [7] without correcting the crucial default in the model [6]: unlike [4], the vapor heat exchange was described with an inconsistent equation (cf. [8]), without which it was apparently impossible to obtain large amplitude oscillations. The vapor phase modeling problem has been analyzed and a new, "film evaporation/condensation model" (FEC) has been developed [9] for the single branch PHP. The FEC model is deprived of the above mentioned shortcomings and truthfully reproduces the experimental behavior both qualitatively and quantitatively, at least for the single branch PHP [9–11]. The FEC model has been generalized later to the multi-branch PHP [12] with the imposed temperatures T_c, T_e of the internal tube walls. An alternative film description where the film is divided by the equal length pieces of variable thickness has been introduced [13]. Within such an approach, it is also possible to describe the evaporator dry-out [14]. The bubble generation has been introduced by the same group, which is an important step forward. Indeed, such an approach is much heavier computationally as one needs to in addition to liquid plugs, discretize the liquid films. Probably for this reason, the wall temperature was assumed to be constant. The oscillation amplitude was small with respect to the evaporator size.

The main issue in the multi branch PHP is the oscillation start-up that one needs to master to develop reliable PHP for industrial needs. Because of multitude of parameters that may be relevant, it is a difficult task. For this reason, we began the start-up study with applying the FEC model to the simplest, single branch PHP [15,16]. First, the start-up has been studied for the stepwise variation of the temperature T_w of the internal tube wall (simply "wall" in the following for brevity) from T_c to T_e [15]. It has been found that the dimensionless control parameters for the start-up depended crucially on δ_f. The start-up in the presence of the tube heat conduction and the fluid-wall heat exchange has been considered in the subsequent work [16]. A constant homogeneously distributed heat power P_e applied to the evaporator has been simulated while the