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Numerical investigation of effect of film dynamics on fluid motion and thermal performance in pulsating heat pipes

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ABSTRACT

In the present study, a one-dimensional numerical model for pulsating heat pipes (PHPs) is presented. The balance equations of mass, momentum, and energy were solved for liquid slugs, vapor plugs and also for liquid films, along with the heat conduction equation for the tube wall. The spatial and temporal variations of the liquid-film thickness were directly simulated, and the film was allowed to dry out when the local thickness decreased to the roughness height of the tube wall. The numerical results showed good agreement with the experimental data, not only for a vertical PHP but also for horizontal and inclined PHPs with various different parameters, including number of turns, working fluid, filling ratio, and operating temperature. Furthermore, the effect of the dynamics of the liquid film on flow behavior and heat transfer was examined numerically. It was confirmed that the oscillating motion of the fluid inside a horizontal PHP cannot be completely predicted when the film dynamics are ignored. For a vertical PHP, on the other hand, circulating motion was predicted regardless of the film dynamics, and the role of the film dynamics on the prediction of thermal performance was not significant. The present model is considered the first to predict the thermal performance of a horizontal PHP without introducing any fitting parameters.

1. Introduction

A pulsating heat pipe (PHP) has attracted attention as a promising heat transfer device since it was invented in 1990 [1]. It has a wide range of potential applications including electronics cooling [2] and solar thermal collectors [3]. Unlike conventional heat pipes, a PHP does not require a wick structure or an additional component to provide capillary force, making it easier to fabricate and bend. A PHP is made of a meandering capillary tube of 1–2 mm in diameter, partially filled with a working fluid after evacuation. When heat is applied, the circulating or oscillating motion of the two-phase plug flow (i.e. a train of liquid slugs and vapor plugs) conveys the thermal energy from a heat source (evaporator) to a heat sink (condenser) [4].

Despite the simplicity of its geometry, the operating mechanism is not fully understood, and hence a comprehensive design tool is still needed [2,5,6]. Some researchers proposed empirical correlations [7,8], and others applied artificial neural network [9,10] to predict the thermal performances of PHPs. However, these methods are not closely related to the physical phenomena, and their applicable ranges are restricted by the experimental data from which the models were derived [2,6].

Numerical simulations [11–17] based on one-dimensional plug flow assumptions are considered as promising candidates for exploring the underlying physics and designing PHPs. Generally, the balance equations of mass, momentum, and energy in those numerical models have been solved for liquid slugs and vapor plugs. Some researchers [12,13] successfully predicted the thermal performances of vertical PHPs with the evaporator at the bottom. However, none of those models [11–17] has been validated with experimental data for horizontal PHPs.

With a horizontal PHP, there is no buoyancy force to aid natural circulation nor manometric oscillation of liquid slugs. Therefore, the fluid motion primarily depends on the expansion and contraction of the vapor plugs, which is produced by evaporation and condensation. Rao et al. [18,19] conducted an experimental investigation on the oscillating motion of a meniscus adjoining a single liquid slug and a single vapor plug (referred to as a ‘unit-cell’). They reported that the dynamics of the liquid film are responsible for the self-sustained, thermally-driven oscillation. More specifically, the thin liquid film left behind the moving meniscus evaporates and pushes the meniscus toward the condenser. Once the liquid film in the evaporator dries out, condensation predominates and the meniscus is pulled toward the evaporator: thereby the dry portion becomes rewetted almost immediately and the process is repeated.

Most of the previous numerical models [11–13] overlooked the film

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Nomenclature

A	cross-sectional area (m^2)
c_p	specific heat at constant pressure (J/kg·K)
Ca	capillary number
D	diameter (m)
f	friction factor
g	gravitational acceleration (m/s^2)
h	heat transfer coefficient (W/m^2·K)
i	specific enthalpy (J/kg)
k	thermal conductivity (W/m·K)
L	length (m)
$\dot{m}''$	mass flux (kg/m^2·s)
N_{turn}	number of turns
Nu	Nusselt number
P	pressure (Pa)
P_r	reduced pressure, P/P_{cr}
q''	heat flux (W/m^2)
R_g	specific gas constant (J/kg·K)
R_C	cavity radius (m)
R_P	surface-roughness factor (m)
Re	Reynolds number
t	time (s)
T	temperature (K)
u	cross-sectional averaged velocity (m/s)
υ	local velocity (m/s)
v	specific volume (m^3/kg)
y	transverse coordinate from wall to center (m)
z	axial coordinate (m)

Greek symbols

δ_0	initial liquid-film thickness (m)
δ_{lf}	liquid film thickness (m)
ε	roughness height of tube wall (m)
μ	viscosity (Pa·s)
θ	angle of inclination from vertical downward direction (rad)
ρ	density (kg/m^3)
σ	surface tension (N/m)
τ	shear stress (N/m^2)

Subscripts

ad	adiabatic section
co	condenser
cool	cooling water, coolant for condenser
cr	critical state
C	flow channel
ev	evaporation, evaporator
ex	external
f	liquid
g	vapor
i	interface between liquid and vapor
I	inner
i-g	from interface to vapor-plug
lf	liquid film
lf-i	from liquid-film to interface
m	meniscus
nb	nucleate boiling
O	outer
sat	saturation state
w	wall
w-f	from wall to liquid-slug
w-lf	from wall to liquid-film
∞	surroundings

dynamics by assuming that the liquid film has a constant and uniform thickness, as illustrated in Fig. 1a. Nikolayev and his colleague [14,15] considered the film dynamics in their models with a simplifying assumption of constant and uniform thickness, but with variable length due to evaporation, as shown in Fig. 1b. The thickness of the liquid film was pre-determined and treated as a fitting parameter. Rao et al. [20] used a similar model to reproduce the oscillating motion of the 'unit-cell' [19], where the film thickness was assumed uniform in space but varies in time as a result of the evaporation. Again, several fitting parameters were used in their model [20], and the model was not validated for prediction of the thermal performance of PHPs with multiple turns. Senjaya and Inoue [16,17] presented a more realistic model of the film dynamics, where the thickness is allowed to vary in space and time, as shown in Fig. 1c. Although these models of the film dynamics [15–17] can qualitatively describe the self-sustained oscillation of the fluid inside horizontal PHPs, no quantitative validation has yet been provided.

The purpose of the present paper is to present a comprehensive numerical model valid for a horizontal PHP as well as a vertical PHP. The balance equations of mass, momentum, and energy are to be solved for liquid films as well as for liquid slugs and vapor plugs. In particular, the spatial and temporal variations of the film thickness shown in Fig. 1c were directly simulated in order to relax the simplifying assumptions of the film dynamics (such as those in Fig. 1a and b). For validation, the numerical results were then compared to the experimental data from PHPs with various different parameters, including working fluid, filling ratio, operating temperature, number of turns, and inclination angle. Finally, the effect of the film dynamics on the simulation results for both a horizontal and vertical PHP is examined.

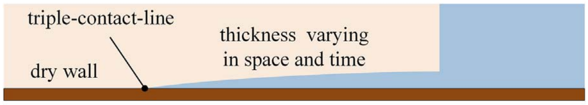
2. Numerical method

2.1. Model overview

The present numerical model is based on a one-dimensional plug flow assumption. Fig. 2a shows a schematic of a 2-turn, vertical PHP as an example. For the analysis, the axial coordinate z was defined along the loop in the arrow direction (counterclockwise) from the top-

(a) Model A (Holley and Faghri [11], Mameli *et al.* [12], Manzoni *et al.* [13])

(b) Model B (Nikolayev [14], Nekrashevych and Nikolayev [15], Rao *et al.* [20])



(c) Present (Senjaya and Inoue [16,17])

Fig. 1. Different models for film dynamics.