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Lower limit of internal diameter for oscillating heat pipes: A theoretical model

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A B S T R A C T

The upper limit of internal diameter (ULID) of oscillating heat pipes (OHPs) based on Bond number is widely accepted and considered as a primary criterion to define OHPs, whereas the lower limit of internal diameter (LLID) is still unclear. In this paper, an analytical model based on the operating characteristics and design criterion of OHPs is developed to predict the LLID. Also, a visualization investigation of glass OHP was performed to verify the reliability of the model. Comparison of theoretical LLID and actual ID for successful startup and robust operation of OHP shows a good agreement between them. In addition, the influence of several parameters on the LLID were numerically analyzed and discussed, particularly inclination angle and working fluid. This work provides useful information and understanding of traditional capillary tube OHPs (both at normal gravity and micro-gravity environment) and ultra-compact micro-OHPs to better design them.

1. Introduction

The oscillating heat pipe (OHP), or pulsating heat pipe (PHP), firstly proposed by Akachi in 1990 [1], is a relatively new member in the heat pipe family. As simple, versatile, and highly efficient two-phase heat transport devices, OHPs are becoming promising alternatives not only in the fields of electronic cooling but also heat and energy recovery [2–4]. Interestingly, the heat transfer process of an OHP largely depends on the 'self-excited' thermally driven oscillating and circulating motions of liquid-slugs/vapor-bubbles in its serpentine-arranged, interconnected capillary tubes featured by wickless structure. Therefore, the internal diameter of capillary tube that shapes the device to form such a unique flow characteristic is fundamental important for its function and performance.

Traditionally, the formation of Taylor bubbles in a capillary tube is mainly attributed to the force balance of gravity and surface tension [5]. A measure of the relative value of the two forces at a normal gravity environment is usually represented by the Bond number (Bo), defined as $Bo = D\sqrt{\frac{(\rho_l - \rho_v)g}{\sigma}}$, and $Bo \le 2$ [4,6–10] is widely accepted and even considered as a primary criterion to define OHPs. Therefore, the theoretical maximum tolerable or upper limit of internal diameter (ULID) for a capillary tube OHP is given by

$$D_{\max} \le 2\sqrt{\frac{\sigma}{(\rho_l - \rho_v)g}} \tag{1}$$

According to Eq. (1), the maximum internal diameter of an OHP charged with water and ethanol are about 5.4 and 3.4 mm at 20 °C, respectively. If $D \le D_{\max}$, surface tension dominates in comparison with gravity and stable liquid slugs are formed. Otherwise, the surface tension will be reduced and all the working fluid tends to stratify by gravity. Then, the OHP may give way to an interconnected array of two-phase thermosyphons rather than function as a pulsating device [7].

Moreover, the internal diameter of an OHP can not be too small to overcome the oscillation flow resistance of liquid slug train between the hot and cold ends. Otherwise, the OHP could not sustain robust oscillation or even fail to start up, and hence being unable to work as a high efficiency heat transfer device at tolerable evaporator temperature or internal pressure. Using pure water as the working fluid, Lin et al. [11] investigated the effect of heat transfer length and internal diameter on the heat transport capability of OHPs, and found that the OHP with an internal diameter of 0.4 mm fails to start up either at the vertical bottom heating mode or horizontal heating mode. Their

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Nomenclature

Bo	Bond number
c_p	specific heat (J kg^{-1} K^{-1})
C	friction coefficient
Ca	Capillary number
D	diameter (m)
Ec	Eckert number
g	gravitational acceleration (m s^{-2})
h_{fg}	vaporization latent heat (J kg^{-1})
Ja^*	modified Jackob number
K	loss coefficient
L	length (m)
m	number of U-bends
n	number of unit cell
p	pressure (Pa)
r	bend/turn curvature radius (m)
Re	Reynolds number
T	temperature (°C)
U	velocity (m s^{-1})
We	Weber number

Greek symbols

β	inclination angle (°)
μ	dynamic viscosity (kg m^{-1} s^{-1})
ρ	density (kg m^{-3})
σ	surface tension (N m^{-1})
ϕ	volume filling ratio
ε	liquid hold-up, filling ratio
Θ	dimensionless temperature

Subscripts

a	acceleration
b	bubble
c	condenser
e	evaporator
f	flow friction, fluid
gra	gravity
l	liquid
max	maximum
min	minima
s	slug
t	total
TP	two-phase
uc	unit cell
v	vapor
v, c	vapor phase at the condensation section
w	width

experimental study shows that it is beneficial to OHP startup when increasing the internal diameter or decreasing the heat transfer length, and suggests a minimal internal diameter of about 0.8 mm at the vertical bottom heating mode. Zhu et al. [12] conducted an experimental study to investigate the start-up and heat transfer performance of a 2 mm ID PHP using water-acetone mixtures, pure water, and acetone as working fluids. They found that the favorably startup or not of the PHP at a heat input of 10 W largely depend on the mixing ratios at 35% and 45% filling ratios, indicating that the fluid thermo-physical properties directly affect the startup performance. The experiment performed by Qu et al. [13] on silicon-based micro PHP, having hydraulic diameters in the range of 251–394 μm, also confirmed the importance of working fluid for the startup of micro PHPs. These micro devices could not start up at all when charged with water or ethanol at an allowable temperature for electronics cooling. Borgmeyer and Ma [14] experimentally investigated the effects of heat input, fluid type and inclination angle on the two-phase slug motion in a flat-grooved PHP with a square cross section of 1.5875 mm × 1.5875 mm, and found that the PHP functioned well when charged with ethanol and had large pulsation amplitude and velocity. However, slugs/plugs in the same flat-grooved PHP oscillated with much smaller amplitude and velocity (almost can be neglected) when charged with Flutec PP2 as compared to that of ethanol. Besides, numerous experimental evidences available so far demonstrate that OHPs can function well at the bottom heating mode, while it is not the case for the horizontal or anti-gravity top heating mode unless having large number of U-bends [6,15]. According to the aforementioned literature survey, it can be seen that the lower limit of internal diameter (LLID) for OHPs may vary according to the working fluid, OHP geometric structure, evaporator/condenser temperatures, gravity condition, etc. Up to now, to the best of the authors' knowledge, the available LLID for OHPs was only empirically proposed by Dobson and Harms [16] based on effective operation, which is expressed as

$$D_{\min} \geq 0.7\sqrt{\frac{\sigma}{(\rho_1 - \rho_v)g}} \tag{2-a}$$

Clearly, Eq. (2-a) can be simplified in terms of the Bond number, i. e.

$$Bo \geq 0.7 \tag{2-b}$$

Although the LLID in Eq. (2-a) is considered as an important reference to design OHPs, recent experimental studies [13,17,18] found that OHPs with non-circular cross-section could function well at much smaller hydraulic diameters as well as corresponding Bond numbers as compared to the lower limit values in Eqs. (2-a) and (2-b), respectively, implying that the applicability of lower limit of Bond number associated with the hydraulic diameter could be reduced remarkably. Hence, there naturally comes out the questions whether there is an LLID for OHPs and what is it or depend on what factors. However, little work has been focused on this problem and remains yet to be known.

In this paper, a theoretical model to predict LLIDs of capillary tube OHPs has been developed on the basis of the design criterion, namely pressure difference between the evaporation and condensation sections inside OHPs that acts on the train of liquid slugs and vapor bubbles, thermally driving them movement. To verify the reliability, a visualization investigation of glass OHP was experimentally conducted and demonstrates a good agreement between the theoretical predictions of LLID and actual value. Besides, the effects of filling ratio, temperature difference between the evaporation and condensation sections, turn number, inclination angle, heat pipe length, and working fluid on the LLID were theoretically investigated. The present model reveals important insights on the practical design and operating characteristics for traditional tube OHPs both at normal gravity and micro-gravity environment as well as ultra-compact micro-OHPs with internal diameters on the order of magnitude of ~0.1 mm.