International Journal of Heat and Mass Transfer 74 (2014) 353–357

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ijhmt

Technical Note

Theoretical analysis of maximum filling ratio in an oscillating heat pipe

D. Yin [a], H. Rajab [b], H.B. Ma [a,b,*]

[a] Institute of Marine Engineering and Thermal Science, College of Marine Engineering, Dalian Maritime University, Dalian 116026, China
[b] Department of Mechanical and Aerospace Engineering, University of Missouri, Columbia, MO 65211, USA

ARTICLE INFO

Article history:
Received 6 October 2013
Received in revised form 5 March 2014
Accepted 7 March 2014
Available online 12 April 2014

Keywords:
Oscillating heat pipe
Filling ratio

ABSTRACT

The filling ratio significantly affects oscillating motion and heat transfer in an oscillating heat pipe (OHP). When heat is added to the evaporating section, temperature and pressure increase. The pressure wave travels through both vapor and liquid phases. In the current investigation, focusing on the difference in pressure wave speed in the liquid phase compared to the pressure wave speed in the vapor phase led to the development of a mathematical model that predicts the filling ratio effect on the start-up power of a one-turn OHP. Results show that the heat input needed to start the oscillating motion in an OHP depends on the filling ratio. When the filling ratio increases, the heat input required to start up the oscillating motion increases; furthermore, there exists an upper limit. This upper limit of the filling ratio is dependent on the properties of the working fluid.

1. Introduction

Oscillating heat pipes (OHPs) are passive two-phase heat transfer devices. In the last decade, extensive investigations on OHPs have been conducted and have resulted in better understanding of the OHP fluid flow and heat transfer mechanisms. For an OHP, when heat is added to the evaporating section, liquid becomes vapor producing volume expansion. In the condensing section, vapor condenses into liquid producing volume contraction. Due to the pressure difference between the evaporating section and condensing section, this expansion and contraction produces the oscillation and/or pulsation of a train of liquid plugs and vapor bubbles in an OHP. In addition to the pressure difference between the evaporator and condenser and thermal energy to be used to generate the oscillating motion, the spring constant of vapor volume plays a key role in the startup of oscillating/pulsating motion of fluid in the OHP. Clearly, the vapor volume or filling ratio will significantly affect the startup of the oscillating motion and heat transfer performance in an OHP.

Extensive investigations [1–17] on the filling ratio as it pertains to the heat transfer performance have been investigated. Kim et al. [1] experimentally found that at a filling ratio of 40%, OHP heat transfer performs best at a titled angle of 90°. An experimental study was performed by Im et al. [2] to investigate the heat transfer performance of a non-loop type OHP. The results showed that the heat transfer performance at a filling ratio of 40% was higher than that at 50% for all working fluids. Cao and Cheng [3] designed a novel OHP with improved performance and found that at a filling ratio of 20%, the OHP worked like a gravity heat pipe and the oscillating flow could not be started. Qu et al. [4,5] investigated the chaotic behavior of wall temperature oscillations in a closed-loop OHP (CLOHP) and found that the OHP reached the best thermal performance at a filling ratio of 50%. Jia and Li [6] conducted an experiment for flow visualization of an OHP and found that the OHP reached the highest heat transfer performance with a filling ratio of 50%, and if the filling ratio is further increased, the thermal resistance decreases. With an energy equation for the liquid slug built with the aid of Lagrange method, Yuan et al. [7] developed a fluid flow and OHP heat transfer model and found that the amplitude and frequency of the slug oscillation is mainly determined by the geometry of OHP and the filling ratio. Ji et al. [8] studied the effects of filling ratio on the heat transport capability. Results showed that the thermal resistance of the OHP depended on the filling ratio, and a filling ratio higher than 50% leads to a higher thermal resistance. Chien et al. [9] found that the thermal resistance largely depended on the filling ratio while the thermal resistances were comparatively insensitive to the heat input. The study of Khandekar et al. [10–13] indicated that an operationally better performing and self-sustained thermally driven pulsating action is only observed when the filling ratio range is about 20–80% depending on the working fluid [12] and gravity [13]. Soponpongpipat et al. [14] presented a theoretical model to

---

[*] Corresponding author at: Department of Mechanical and Aerospace Engineering, University of Missouri, Columbia, MO 65211, USA. Tel.: +1 573 884 5944.
E-mail address: mah@missouri.edu (H.B. Ma).

http://dx.doi.org/10.1016/j.ijheatmasstransfer.2014.03.018
0017-9310/

Nomenclature

h	the height between two position in OHP, m
h_{lv}	the latent heat, J/kg
k	adiabatic coefficient
K	bulk modulus, N/m
l	the length of section of OHP, m
L	the length of OHP, m
m	mass, kg
p	pressure, N/m^2
q	heat load, W
r	radius, m
R	gas constant, J/mol-K
t	time, s
T	temperature, K
u	speed, m/s
V	volume, m^3
x	axial position, m

Greek letters

α	contact angle, rad
β	inclination angle of OHP, rad
ρ	density, kg/m^3
σ	surface tension, N/m
ϕ	filling ratio
Δ	the difference

Subscripts

a	adiabatic
b	bottom
c	condensation
e	evaporation
h	heat
i	inter
l	liquid
v	vapor

predict the filling ratio effect on the start-up power and indicated that the start-up power depended on the filling ratio. Based on the experimental visualization, Qu and Ma [15] presented a mathematical model for the startup of oscillating motion in the OHP and showed that the OHP startup performance is affected strongly by surface condition, vapor bubble type, working fluid, and filling ratio. Ma et al. [16] developed a mathematical model and their study indicated that the frequency increased significantly, which results in an unrealistic value of OHP oscillating motion when the filling ratio is too high or too low.

The vapor bubble plays a key role as the spring constant for the oscillating motion in an OHP. When an OHP has no vapor volume, the OHP cannot start up the oscillating motion. This paper's objective is to theoretically determine the highest ratio or the smallest vapor volume for an OHP to start up the oscillating motion. In the current investigation, a system consisting of one vapor bubble and one liquid plug is considered. By considering the pressure wave speed in the vapor phase, which is different from that in the liquid phase, a mathematical model is developed to determine the filling ratio effect on the startup power and the highest filling ratio, which can generate the oscillating motion in an OHP.

2. Theoretical modeling

Consider one OHP consisting of only one liquid plug and one vapor bubble, which is shown in Fig. 1. When one end of the liquid plug is on the evaporating section, liquid vaporizes and the quantity of vapor increases significantly. Increasing quantity of vapor directly increases the vapor pressure. Considering Laplace–Young equation [17], the pressure difference across the liquid–vapor interface can be found as

$$\Delta p_{v,1} = p_v - p_1 = \sigma\left(\frac{1}{r_1} + \frac{1}{r_2}\right) \tag{1}$$

Because the tube radius, r_b, is very small, the meniscus radius at the liquid–vapor interface can be assumed to be constant. Considering the pressure difference across the liquid vapor interface and the hydraulic pressure difference due to the gravitational force, and notice that the meniscus radii, r_1 and r_2, can be found as $r_1 = r_2 = \frac{r_b}{\cos\alpha}$, the pressure difference, $p_{v2} - p_{v1}$, can be expressed as

$$p_{v2} - p_{v1} = \frac{2\sigma(\cos\alpha_2 - \cos\alpha_1)}{r_b} + (\rho_l - \rho_v)g(h_2 - h_1)\cos\beta \tag{2}$$

Consider vapor as an ideal gas, i.e.,

$$p_v = \rho_v RT \tag{3}$$

Taking the derivative on both sides of Eq. (3) yields

$$\frac{dp_v}{dt} = RT\frac{d\rho_v}{dt} + R\rho_v\frac{dT}{dt} \tag{4}$$

If the initial vapor density and temperature are $\rho_{v,0}$ and T_0, respectively, the transient density and temperature can be expressed as $\rho_v = \rho_{v,0} + \Delta\rho$ and $T = T_0 + \Delta T$, respectively. Substituting them into Eq. (4), yields

$$\frac{dp_v}{dt} = R(T_0 + \Delta T)\frac{d\rho_v}{dt} + R(\rho_{v,0} + \Delta\rho)\frac{dT}{dt} \tag{5}$$

Considering that $T_0 >> \Delta T$ and $\rho_{v,0} >> \Delta\rho$, Eq. (5) can be simplified as

$$\frac{dp_v}{dt} = RT_0\frac{d\rho_v}{dt} + R\rho_{v,0}\frac{dT}{dt} \tag{6}$$

For an OHP, the primary reason for generating the oscillating motion is the pressure difference by vapor volume expansion and contraction during the heat addition/rejection process. In order to estimate the minimum heat input needed to start the oscillating motion, it is assumed that the heat added to the evaporation section is used to generate vapor just before the oscillating motion takes place, i.e., $q_v = \dot{m}_v h_{lv}$, where $\dot{m}$ is the vapor mass generation per unit time, i.e., $\dot{m}_v = \frac{dm_v}{dt}$. Furthermore, the total vapor mass can be calculated by $m_v = \rho_v V_v$, where $V_v = 2L(1-\phi)\pi r_b^2$. For a given OHP, the filling ratio is given, and the vapor volume is almost constant. Then heat addition can be expressed as

$$q_v = \frac{d\rho_v}{dt}V_v h_{lv} \tag{7}$$

Rearranging (7) and substituting it into Eq. (6) yields

$$\frac{dp_v}{dt} = RT_0\frac{q_v}{Vh_{lv}} + R\rho_{v,0}\frac{dT}{dt} \tag{8}$$

Integrating Eq. (8) with time t, it can be found as $\int_0^t \frac{dp_v}{dt}dt = \int_0^t \left(RT_0\frac{q_v}{Vh_{lv}} + R\rho_{v,0}\frac{dT}{dt}\right)dt$ or

$$\Delta p_v = RT_0\frac{q_v}{Vh_{lv}}t + R\rho_{v,0}\Delta T \tag{9}$$