International Communications in Heat and Mass Transfer 88 (2017) 28–36

Contents lists available at ScienceDirect

International Communications in Heat and Mass Transfer

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

Operational characteristics of oscillating heat pipes under micro-gravity condition

Qin Sun[a], Jian Qu[b,*], Qian Wang[b], Jianping Yuan[a]

[a] National Research Center of Pumps, Jiangsu University, Zhenjiang, Jiangsu, China
[b] School of Energy and Power Engineering, Jiangsu University, Zhenjiang, Jiangsu, China

ARTICLE INFO

Keywords:
Oscillating heat pipe
Oscillating motion
Contact angle hysteresis
Startup
Micro gravity

ABSTRACT

A mathematical model to investigate the oscillating motion characteristics of liquid slugs and vapor plugs/bubbles in oscillating heat pipes (OHPs) was developed considering the contact angle hysteresis (CAH) and interconnected-tube induced pressure fluctuations. Results show that a short period less than 1 s is available to attain the steady state after startup and then the oscillation amplitudes and frequencies for both of slug/bubble displacement and velocity are kept fixed. The slug/bubble displacement and velocity display quasi-sine oscillating waves with small pressure fluctuations induced by the interconnected-tube. However, small oscillation waves are superimposed on a main quasi-sine oscillation wave and cause a chaotic oscillating behavior of slug/bubble inside the OHP if the induced pressure fluctuation is large enough. Besides, the effects of filling ratio, tube length, inner diameter, temperature difference between the evaporator and condenser sections, and working fluid on the oscillating motion were numerically analyzed and discussed. The numerical model provides a physical insight to understand the operational mechanism of OHPs under the microgravity condition.

1. Introduction

With the ever-increasing demand for space-based communications and the evolution of space electronics, satellite thermal control subsystem (TCS) through radiation heat rejection with limited surface area becomes more challenging. As a result, the thermal control of satellite and spacecraft electronics is a fundamental issue and requires advanced thermal management solutions. To enable effective cooling of spacecraft electronics, heat pipes integrated into the radiator panels of TCSs provide efficient and low mass thermal solution because of their capability of transport and reject high heat loads from 100′s of Watts to greater than 1000 W [1,2].

The oscillating (or pulsating) heat pipe (OHP) is a contemporary wickless heat transfer device and attracted considerable attention due to the simple construction, low cost, and excellent heat transfer performance. Typically, an OHP consists of a loop-sealed serpentine capillary tube with multiple turns and partially filled with a working fluid after evacuation. During the operation, thermally driven self-sustained oscillation of liquid slugs and vapor plugs, initially random distributed in the capillary tube, occur and transfer both sensible and latent heat from the heating section to the cooling section. Compared to conventional heat pipes, there is no additional capillary structure in OHPs and thus not being subject to some limitations affecting the heat transport capability such as the entrainment limit. Consequently, OHPs offer a potential application for the thermal management of spacecraft electronics and other space-systems [3–6].

In the past two decades, OHPs have been extensively studied, both experimentally and theoretically, to investigate the influence of various parameters on the operating characteristics and thermal performance. However, due to the unique coupling effect of hydrodynamic and thermodynamic behavior, the operational mechanism of OHPs is extremely complex and underlying physical phenomena has yet to be fully revealed so far, resulting in a big challenge to model or predict accurately and thus hindering widespread applications. Among diverse OHP mathematical and physical models, the single or multiple spring-mass-damper system (SMDS) approach was early used to describe the oscillating motion of liquid slugs and vapor plugs assuming the compression action of plugs to function similarly to a linear spring [7–9]. Later, the action of damping effect due to flow resistance was added in the spring-mass-damper models by Ma et al. [10] and Qu et al. [11]. Although the SMDS approach is simple and not well considered the influence of thin film evaporation and condensation, it gives an effective tool to understand the physical behavior of OHP operation phenomenologically. To explain the experimental results qualitatively, the viewpoint of dynamic elastic system was adopted by Cai et al. [12] based on the SMDS model. The linear SMDS was also used to predict the dominant

* Corresponding author.
E-mail address: rjqu@mail.ujs.edu.cn (J. Qu).

http://dx.doi.org/10.1016/j.icheatmasstransfer.2017.08.005

Nomenclature

A	tube cross sectional area (m^2)
Ca	capillary number ($\mu U_{TP}/\sigma$)
D	diameter (m)
F	force (N)
f	friction factor, dimensionless
h_{fg}	vaporization latent heat (J/kg)
L	length (m)
m	mass (kg)
n	number of turns
p	pressure (Pa)
Δp	pressure difference (N/m^2)
R	gas constant (J/kgK)
Re	Reynolds number ($\rho U_{TP} D/\mu$)
T	temperature (°C)
ΔT	temperature difference (°C)
u	velocity (m/s)
U_{TP}	two-phase superficial velocity ($= U_l + U_v$) (m/s)
x	displacement (m)
ε	liquid hold-up
φ	volume filling ratio
τ	time (s)
μ	viscosity ($N{\cdot}s/m^2$)
ρ	density (kg/m^3)
σ	surface tension (N/m)
ω	oscillation frequency
ω_0	natural angular frequency

Subscripts

a	adiabatic
c	condenser
ca	capillary
cr	critical
e	evaporator
h	hydraulic
l	liquid
max	maximum
s	slug
t	total
v	vapor
v, c	vapor phase at the condenser

frequency component [13] and the oscillation frequency/amplitude and wave velocity [14]. Moreover, SMDS is conducive to realistic modeling schemes coupled with convection/phase-change heat transfer [15,16] in OHPs. Most recently, Yin et al. [17] theoretically investigated the operating limitation of an OHP to determine the maximum heat transport capability on the basis of SMDS. However, the dominance of surface tension in slug flows is neglected in a number of SMDS models or analysis. According to recent studies [18,19], the pressure drop occurring at the liquid-vapor interface is sometimes in the same order of magnitude or even much higher in comparison with the frictional pressure drop of liquid slug, which affects the oscillating motion behavior remarkably. The additional pressure drop created by the presence of bubble caps is mainly attributed to different surface curvatures of the nose and tail, resulting in the contact angle hysteresis (CAH) defined as the difference between the advancing and receding contact angles. Hence, the CAH effect could not be ignored simply and should be took into account in the modeling strategy of OHPs.

Generally, under the microgravity condition, the rapid bubble expansion and contraction in the heating and cooling sections, respectively, provides the pressure fluctuations to facilitate the robust oscillating motions in an OHP system, which is largely derived from the temperature difference between the hot and cold regions. However, the driving force associated with temperature difference was usually easily defined [7,10,11,15] and ignored the interconnected-tube induced meta-stable condition. Hence, the additional two-phase instability induced driving force is still yet to be revealed and took into account.

In this paper, a mathematical model regardless of the gravity action, but taking the CAH and interconnected-tube induced pressure fluctuation into consideration, has been developed based on the SMDS approach. Numerical simulation using fourth-order Runge-Kutta method was implemented to investigate the oscillating motion characteristics of liquid slugs and vapor plugs/bubbles in OHP tubes. This study provides a physical insight to understand the operational mechanism of OHPs at the hydrodynamic aspect under the microgravity condition and opens up new possibilities of space applications.

2. Theoretical analysis

In each tube of an OHP, the capillary slug flow or Taylor bubble flow usually prevails before the occurrence of operation limitation when surface tension dominates over gravitational force [17]. Fig. 1 illustrated the capillary slug flow in an OHP tube, which is used to simplify the present problem and find the primary factors affecting the oscillating motion of working fluid inside it. The OHP has three different parts, namely evaporator, condenser, and adiabatic section between them, characterized by lengths of L_e, L_c, and L_a, respectively.

2.1. Model description

In a microgravity environment, the gravity action on the OHP performance is negligible and can be ignored. Although slug/bubble oscillations in an OHP tube are essentially thermally driven and get affected by dynamic instabilities which are inherent part of two-phase boiling/evaporation and condensation systems [20], rapid bubble expansion and contraction in the hot and cold regions, respectively, is the primary factor that accounts for the driving force, facilitating the startup and then robust oscillating motions via creating larger pressure fluctuations [21]. Modeling of such a spatially and temporally varying driving potential is truly difficult and yet to be achieved. However, the pressure difference between the evaporation and condensation sections is a direct consequence of rapid liquid/vapor phase change (bubble generation/expansion and collapse) so as to provide a 'pumping power',

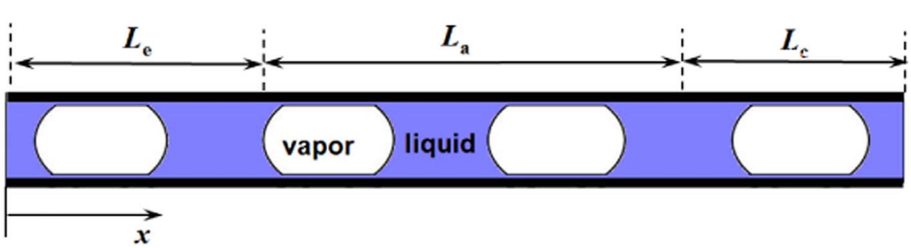

Fig. 1. Schematic diagram of Taylor bubble flow in an OHP tube.