Available online at www.sciencedirect.com
ScienceDirect
International Journal of Heat and Mass Transfer 50 (2007) 2309–2316
International Journal of HEAT and MASS TRANSFER
www.elsevier.com/locate/ijhmt

Theoretical analysis of startup of a pulsating heat pipe

W. Qu [a], H.B. Ma [b,*]

[a] Institute of Engineering Thermophysics, Chinese Academy of Sciences, Beijing 100080, China
[b] Department of Mechanical and Aerospace Engineering, University of Missouri – Columbia, Columbia, MO 65211, United States

Received 25 October 2005; received in revised form 22 August 2006
Available online 28 December 2006

Abstract

A theoretical analysis is conducted to determine the primary factors affecting the startup characteristics of a pulsating heat pipe. It is found that the wall surface condition, evaporation in the heating section, superheat, bubble growth, and vapor bubbles trapped in cavities at the capillary inner wall affect the startup of oscillating motion in the pulsating heat pipe. The required superheat and heat flux level for the startup of oscillating motions in a pulsating heat pipe depend on the cavity size of the inner wall surface and the naturally-formed vapor bubbles and their shapes. When the capillary inner surface is coated or fabricated with cavities or roughness, the pulsating heat pipe can be readily started up. And it is found that the working fluid significantly affects the startup characteristics of a pulsating heat pipe. The results presented here can result in a better understanding of the startup operation of a pulsating heat pipe.
© 2006 Elsevier Ltd. All rights reserved.

Keywords: Startup; Pulsating heat pipe; Cavities; Evaporation; Vapor bubble shape

1. Introduction

With the rapid development in electronic industry, including dramatic increase in chip density and power density, as well as continuous decrease in the physical dimensions of electronic packages, the thermal management has become, and will continue to be one of the most critical technologies in the electronic product development [1]. The Pulsating Heat Pipe (PHP), which has been studied extensively by many investigators [2–9], is made from a long, continuous capillary tube bent into many turns. The tube diameter must be sufficiently small so that vapor bubbles and liquid plugs can be formed by the capillary action. Its operational mechanisms are distinctively different from those occurring in the conventional heat pipe. The PHP can be classified as looped and un-looped, and the former usually has smaller thermal resistance than the latter due to strong oscillating motions in the loop.

When the PHP reaches the required startup condition, the oscillating motion in the PHP starts. And when the required superheat or/and power input meet(s) the required condition, the stable oscillating motion can be self-sustained [10]. The startup condition is very important for the stable oscillating motion occurring in a PHP. The PHP startup depends on many factors such as the wall temperature variation, heat flux level, physical properties of working fluid, heating and cooling modes, transient heat transfer process, initial temperature, and so on.

A number of theoretical models have been developed recently [2–11] to predict the oscillating motion and heat transfer performance in the PHP [12,13] have experimentally visualized the boiling phenomenon in the heating section, which might be one reason to start up the oscillating motion in a PHP. And Khandekar et al. [14] experimentally observed that some oscillations were random and non-periodic. Xu et al. [15] visualized the flow patterns in the PHP charged with methanol and observed the long vapor plugs and dispersed bubbles including the transition process from the dispersed bubbles to the vapor plugs.

Clearly, it is necessary to do further research to determine the primary factors affecting the startup of oscillating

* Corresponding author. Tel.: +1 573 884 5944.
E-mail address: mah@missouri.edu (H.B. Ma).

0017-9310/$ - see front matter © 2006 Elsevier Ltd. All rights reserved.
doi:10.1016/j.ijheatmasstransfer.2006.10.043

Nomenclature

ΔP	pressure difference, Pa
ρ	density, kg/m^3
q	heat flux, W/cm^2
h_{fg}	latent heat of evaporation, J/kg
δ	thickness, m
λ	thermal conductivity, W/m K
P	pressure, Pa
r	radius, m
R	gas constant, J/kg K
T	temperature, °C
σ	surface tension, N/m

Subscripts

n	nucleate point
l	liquid
v	vapor of original capillary bubble
in	inner wall
globe	globe bubble
Taylor	Taylor bubble

motion in a PHP, in particular, charged with water. The objective of this study is to conduct a theoretical analysis predicting the startup of a PHP and its related conditions. In order to include the primary parameters in the mathematical model, the detailed experimental observation was conducted including the detailed flow patterns and their effect on the startup of oscillating motion occurring in the PHP.

2. Experimental investigation – startup visualization

In order to obtain a basic understanding of the startup of a PHP for a steady oscillating motion, a setup was established as shown in Fig. 1, and an experimental investigation on the oscillating motion including the vapor bubble growth was conducted. The prototype was made of glass with the total length of 300 mm from the top to the bottom. The tube inner and outer diameters are 3 mm and 5 mm, respectively. The heating section was on the bottom, where a hot water tank was used as the heat addition. The total length of heating section was 90 mm. The cooling section was placed on the top, where the cooling water was used as the heat rejection. The length of cooling section was 75 mm. During the experiment, the inlet temperature of cooling water was kept at 23 °C. The vapor bubble nucleation and vapor bubble growth near the capillary wall of heating section were recorded including their effects on the stable oscillating motion by a video camera. In order to clearly visualize the effect of surface roughness on the vapor bubble nucleation and growth and the oscillating motion, the inner surfaces of the glass tube were coated with micro particles with a diameter of approximately 20 μm. The working fluid was water.

After the heating section of the PHP was placed into the hot water tank, small bubbles appeared at some given cavities on the capillary wall. At this time, the working fluid in the PHP was almost still. As the bubble size on this cavity continuously increased until its size was large enough, as shown in Fig. 2, the working fluid in the PHP started to move.

When the inner surface was coated with micro structures, the bubble was easily generated and grew faster than the one with the smooth surface. The surface with micro particles can significantly help to obtain a stable oscillating motion and increase the operational stability of a PHP. The visualization results show that the surface roughness or microstructure added on the inner capillary tube in the heating section can improve the startup and operation of the PHP significantly.

From the experimental visualization, it was found that two kinds of vapor bubbles, i.e., small round (globe) bubbles and long column (Taylor) bubbles, were formed and

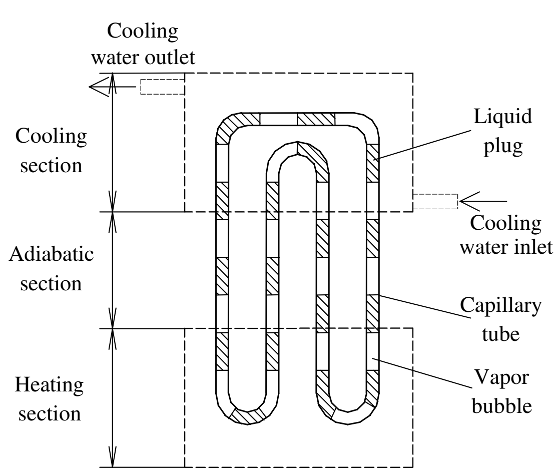

Fig. 1. Schematic setup of PHP visualization (plugs not in scale).

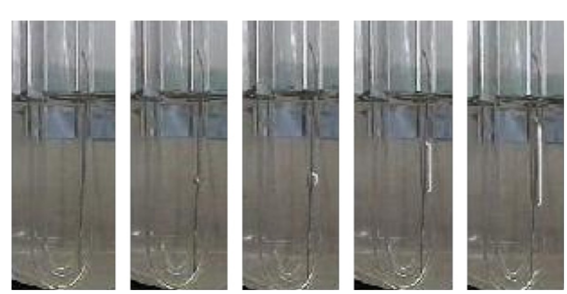

Fig. 2. Visualization of vapor bubble growth with the roughness manipulation at the capillary wall.

circulated in the whole PHP. When heat was added on the heating section, the globe bubble was easily stimulated and grew faster in the liquid plugs than those long column bubbles. And the micro structures added on the wall surface significantly help increase the boiling nucleate sites. Once heat is added to the outside wall and the required superheat was met, new micro vapor bubbles in the liquid plug were formed at some cavities on the capillary inner surface. As heat is continuously added on the surface, a large amount of vapor generated in these bubbles, and the vapor pressure increased. The sudden increase of vapor pressure would make a train of vapor bubbles and liquid plugs move quickly and durably.

From the experimental results for the PHP with a relatively large diameter, it can be concluded that the startup of pulsating heat pipe and steady oscillating motions are primarily due to the boiling heat transfer associating with several critical conditions: (1) the temperature difference between the capillary wall and the bubble in the heating section must be larger enough; (2) the vapor pressure in the heating section should be higher enough to drive a train of vapor bubbles and liquid plugs, and the driving pressure difference between the heating section and the cooling section should be high enough to overcome the pressure drops occurring in the flow channel of the bubble train and (3) after the PHP is started up, the normal operation would depend on the durable ability of the pressure difference. While the temperature difference in the heating section is the primary factor for the startup of a PHP, the heating and cooling conditions are important for a PHP operation.

If heat is applied to the heating section of a PHP, the temperature of working fluid is increased gradually. The temperature increase rate is dependent on the heat capacity and heat flux level. Before the nucleate boiling heat transfer occurs, heat transfer consists of the sensible heat to the working fluid, and the latent heat due to evaporation at the vapor–liquid interface. During this period, the vapor pressure in the existed vapor bubble was not increased significantly. And vapor bubbles and liquid plugs are kept still or snail very slowly. The snail's movement could occur at the quasi-steady situations. Clearly, a waiting period exists to start the oscillating motion. In the waiting period, the evaporation intensity is very low and it is not possible to significantly increase the vapor pressure in a short time. Before the PHP starts to have a stable oscillating motion, the sensible heat transfer is the primary heat transfer mechanism in the heating section.

After the waiting period, the vapor bubble is excited from the active cavity of the capillary inner wall and the nucleate boiling starts in the heating section. The increase of the vapor bubble volume in the heating section rapidly increases its instant pressure and results in a pressure difference between the heating section and the cooling section. This pressure difference is the driving force for the oscillating motion of liquid plugs and vapor bubbles along the capillary. After the initial vapor bubble is produced and escaped from the wall, the wall temperature will drop to a lower level. Combining with the frictional flow in the channel, the pressure difference between the heating section and the cooling section decreases depending on the heat flux level in the heating section and the heat rejection rate in the cooling section. If the heat flux level adding to the heating section is lower, it takes a longer time for the subcooled working fluid to have the nucleate boiling. The PHP could take longer time to have a sudden movement of vapor bubbles and liquid plugs. If the waiting time is too long, the PHP could not be started up normally. If the heat flux level is higher, the waiting time becomes shorter, and the pulsating heat pipe can readily start up.

3. Mathematical model

Based on the experimental visualization as stated above, it can be concluded that when the nucleate boiling occurs at the capillary inner wall, a large amount of vapor is produced. And the increase of vapor pressure in the heating section can help to start up the PHP. In order to establish the mathematical model, the following assumptions are made: (1) the working fluid wets the wall surface completely; (2) before the PHP starts to function, both liquid plugs and vapor bubbles are assumed as the quasi-steady state and there exists a snail movement; (3) the vapor is saturated and is taken as an ideal gas and (4) there exist two-types of vapor bubbles, i.e., the small round (globe) bubble and the long column (Taylor) vapor bubble [16], as shown in Fig. 3, in the PHP. The small globe vapor bubbles were sometimes described as the dispersed vapor bubbles [15].

The experimental visualization shows that the liquid film thickness formed on the capillary inner wall is much larger than the "evaporating thin liquid film". Because the working fluid is wetting the surface, the "non-wetting" phenomenon indicated by Zhang et al. [3–5] does not exist. And because the liquid film between the capillary wall and the vapor bubble is thick enough, the thin film evaporation does not occur, which is also consistent with the

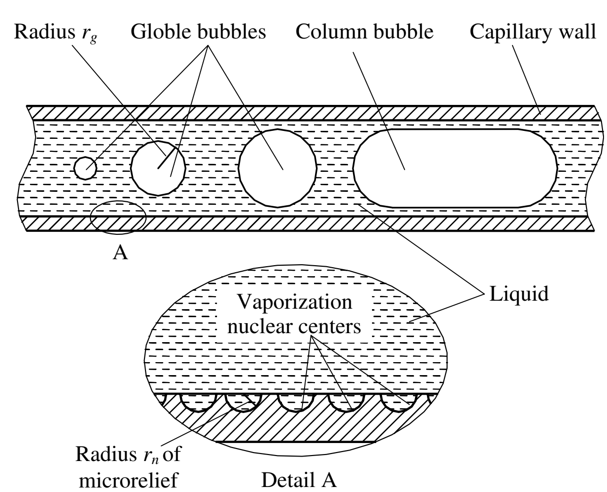

Fig. 3. Schematic of globe and column bubbles, and the exaggerated vaporization nuclear centers.

experimental visualization. For the globe vapor bubble shown in Fig. 3, the pressure difference across the liquid–vapor interface can be described as

$$P_v - P_l = \frac{2\sigma}{r_{globe}}, \tag{1}$$

where, r_{globe} is the radius of the globe vapor bubble. During the heating process in the heating section, when the superheat is higher than the required onset temperature difference, the cavity on the inner capillary wall will become active and the vapor bubble starts to grow. If the vapor bubble trapped in the cavity is a perfect sphere with a radius of r_n, the pressure difference between inside and outside can be determined as

$$P_n - P_l = \frac{2\sigma}{r_n}. \tag{2}$$

The pressure difference between the globe vapor bubble and the vapor bubble formed in the cavity on the wall can be found as

$$\Delta P_{globe} = P_n - P_v = 2\sigma\left(\frac{1}{r_n} - \frac{1}{r_{globe}}\right). \tag{3}$$

Considering the vapor phase as the ideal gas, i.e.,

$$\rho_v = \frac{P_v}{RT_v}, \tag{4}$$

the Clausius–Clayperon equation,

$$\frac{dP_v}{dT_v} = \frac{h_{fg}\rho_v}{T_v} \tag{5}$$

can be rewritten as

$$\frac{dP_v}{P_v} = \frac{h_{fg}}{R}\frac{dT_v}{T_v^2}. \tag{6}$$

Integrating Eq. (6) from the state of small vapor bubble (P_n, T_n) to the state of globe vapor bubble (P_s, T_s) yields:

$$\ln\frac{P_n}{P_v} = \frac{h_{fg}}{R}\left(\frac{1}{T_v} - \frac{1}{T_n}\right). \tag{7}$$

Considering Eq. (4), Eq. (7) can be written as

$$T_n - T_v = \frac{RT_nT_v}{h_{fg}}\ln\left[1 + \frac{2\sigma}{P_v}\left(\frac{1}{r_n} - \frac{1}{r_{globe}}\right)\right]. \tag{8}$$

When the cavity on the capillary inner surface becomes active, the superheat determined by Eq. (8) is necessary to grow the vapor bubble.

If the vapor bubble is formed as a long column one shown in Fig. 3, which is often called as a Taylor bubble, most of heat is transferred through the liquid film. If δ_l is the liquid film thickness between the Taylor bubble and the capillary wall and r_{in} is the capillary radius, the radius of the Taylor bubble in the capillary, i.e., r_{Taylor}, can be found as

$$r_{Taylor} = r_{in} - \delta_l. \tag{9}$$

The pressure difference between the vapor phase in the Taylor bubble and the liquid thin film can be given as

$$P_v - P_l = \frac{\sigma}{r_{in} - \delta_l}. \tag{10}$$

When a nucleate site becomes active and the nucleate boiling occurs at the capillary wall for this situation, the pressure difference between the vapor bubble near the wall and the Taylor bubble in the capillary can be found as

$$\Delta P_{Taylor} = P_n - P_v = 2\sigma\left(\frac{1}{r_n} - \frac{1}{2(r_{in} - \delta_l)}\right). \tag{11}$$

The superheat required to grow the vapor bubble can be determined by

$$\Delta T_{Taylor} = T_n - T_v = T_v\left\langle 1\Big/\left\{1 - \frac{RT_v}{h_{fg}}\ln\left[1 + \frac{2\sigma}{P_v}\left(\frac{1}{r_n} - \frac{1}{2(r_{in} - \delta_l)}\right)\right]\right\} - 1\right\rangle. \tag{12}$$

When the wall is superheated and higher than the one defined by Eq. (12), the cavity become active and the bubble starts to grow. Before the cavity becomes active, heat is transferred primarily by the pure conduction through the liquid film. The maximum heat transfer rate through the liquid film just before the bubble formation can be calculated by

$$q = \frac{\lambda_l \Delta T_{Taylor}}{r_{in}\ln[r_{in}/(r_{in} - \delta_l)]}. \tag{13}$$

As shown in Eq. (13), the heat flux added on the evaporating section of a PHP is directly related to the superheat, which is the required minimum heat flux (startup heat flux) to start the bubble formation in the film. Because the bubble formation is directly related to the startup of a PHP, Eq. (13) can be used to determine the heat flux level for a PHP to start up an oscillating motion occurring in a PHP.

4. Results and discussion

Using the mathematical models presented above, the effects of cavity size, capillary radius, heat flux level, working fluid, and bubble type on the startup characteristics of oscillating motion are investigated to better understand the heat transfer mechanisms of a PHP. As heat is added on the heating section of the PHP and when the wall temperature is higher than that of the required superheat, some cavities on the capillary wall become active, which can significantly affect the startup of the PHP. The superheat is directly related to the cavity size as indicated by Eqs. (8) and (12). When the cavity size increases, the superheat activating a cavity decreases. In other words, when the surface becomes rough, the PHP can be easily started up. As shown in Fig. 4, when the cavity size increases from 0.1 μm to 10 μm, the superheat to activate cavities decreases significantly. And when the cavity size increases and is higher approximately than 10 μm, the required superheat decreases gradually to one almost constant

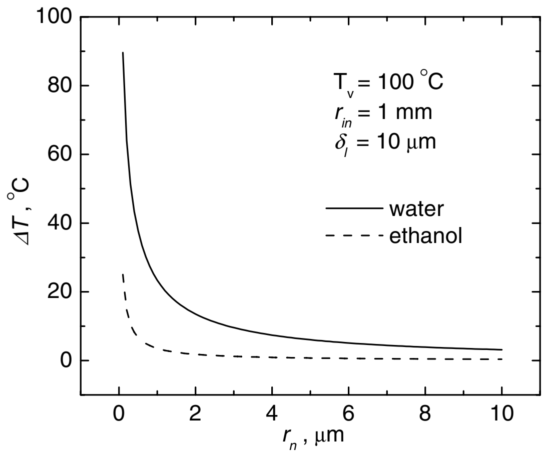

Fig. 4. Working fluid type effect on the superheat.

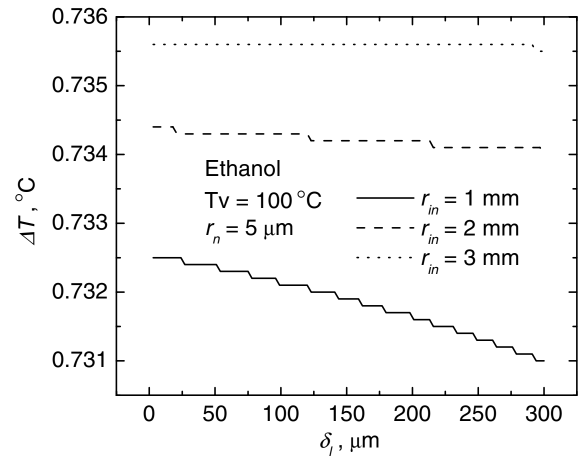

Fig. 6. Capillary radius effect on the superheat (working fluid = ethanol).

value. Fig. 5 illustrates the cavity size effect on the superheat and show that the cavity size is a key factor determining the superheat to start up a PHP. The effects of cavity size on the superheat and the startup of the PHP are also shown in Figs. 6 and 7. The results indicate that the inner radius and liquid film thickness all affect the superheat and nucleate boiling. The effect, however, is smaller than the one with the cavity size effect.

Using Eq. (13), the required minimum heat flux (startup heat flux) to activate the bubble formation and start the nucleate boiling can be calculated. With the nucleate boiling occurring in the PHP, the startup of oscillating motions can be determined. For a PHP with a capillary radius of 1 mm and methanol as the working fluid, the increase of cavity size, as shown in Fig. 8, will significantly reduce the minimum heat flux starting up the oscillating motion in a PHP. As shown, when the cavity size is less 0.5 μm, the pulsating heat pipe needs a relatively large heat flux to activate cavities for the bubble formation and startup the PHP for the steady oscillating motion. With the increase of the cavity size on the capillary inner surface, the inner surface becomes rougher, and the startup heat flux becomes smaller. When the cavity size increases and is larger than 2 μm, however, the further increase of cavity size would not significantly affect the startup heat flux starting up a PHP.

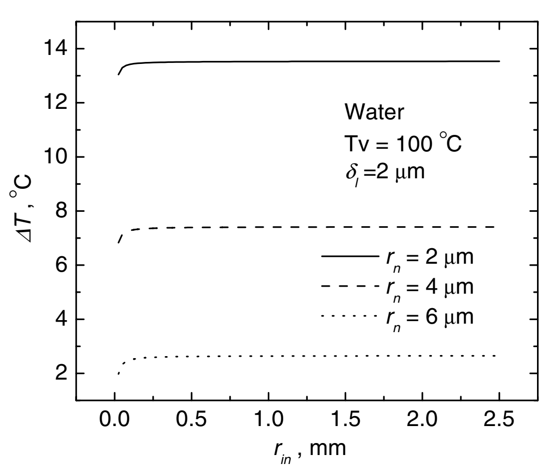

Fig. 5. Cavity size effect on the superheat (working fluid = water).

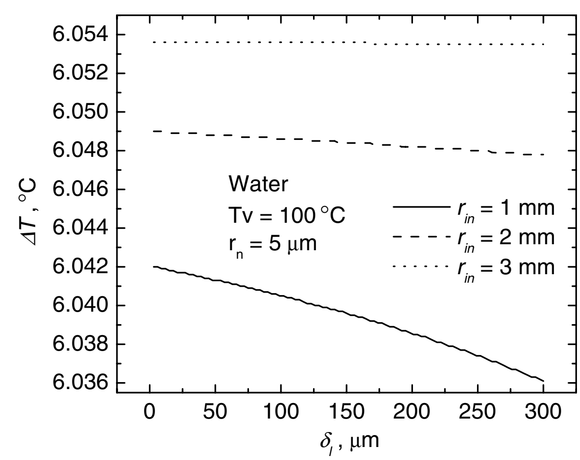

Fig. 7. Capillary radius effect on the superheat (working fluid = water).

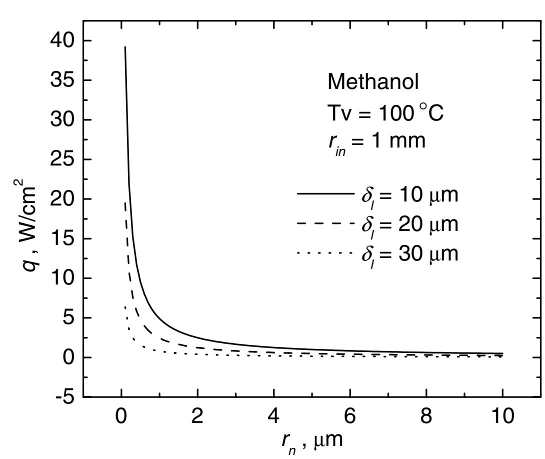

Fig. 8. Liquid film thickness effect on the startup heat flux.

As the surface roughness increases, the pressure drop due to the frictional force will increase. Based on the theoretical analysis presented by Ma et al. [10], the increase in the frictional pressure drop would require more driving force to generate the oscillating motion which will directly affect the minimum heat flux to start up the oscillating motion in a PHP. From the point of view of frictional force, the smooth surface of capillary inner wall would improve the oscillating motion in a PHP. Clearly, an optimization should be conducted in order to determine the best design for a PHP. The minimum heat flux shown in Eq. (13), however, demonstrates that the minimum heat flux to start up a PHP depends on the surface roughness (cavity size). And the cavity size on the capillary inner surface should be larger than 2 μm (for methanol as working fluid). Fig. 8 also illustrates the liquid film effect on the minimum heat flux to start up a PHP.

Fig. 9 illustrates the cavity size effect on the startup heat flux. When the capillary radius is small less than approximately 0.2 mm, the capillary radius has a relatively larger effect on the startup heat flux. When the capillary inner radius is larger than approximately 0.2 mm, the capillary radius has almost no effect on the startup heat flux. From the results presented in Fig. 9, it can be found that the cavity size significantly affects the startup heat flux. For example, if the cavity size on the capillary inner surface increases from 4 μm to 6 μm, the startup heat flux will drop from 6.0 W/cm^2 to 2.0 W/cm^2 when the PHP is charged with acetone. Clearly, it will significantly help to start up a PHP if the capillary inner surfaces are coated or fabricated with particles or other micro structures.

Fig. 10 presents the effect of working fluid on the superheat and startup of the oscillating motion in a PHP. As shown in Fig. 10, water needs much higher superheat for the startup of a PHP than methanol, ethanol and acetone. It means that the PHP charged with water needs a heat flux much higher than the one with methanol, ethanol or acetone for a PHP to start up the oscillating motion. This agrees well with the experimental investigation obtained by Dobson [6], Qu and Ma [12], lee et al. [13] and Khandekar et al. [14]. All working fluids, however, have the same trend, i.e., when the cavity size becomes smaller, the required superheat increases significantly. Fig. 11 illustrates the working fluid effect on the startup heat flux in a PHP. As shown, the startup heat flux will be very close to 460 W/cm^2 if water is used as working fluid for the current PHP. When methanol, ethanol or acetone is employed as working fluid, the startup heat flux can be dropped to between 10 W/cm^2 and 20 W/cm^2 under the same condition. It can be concluded that water should not be selected as working fluid based on the startup performance of a PHP. Water has a higher latent heat which is a couple of times higher than other working fluids. In addition, water has a relatively higher thermal conductivity. The final selection of working fluid in a PHP depends on many factors.

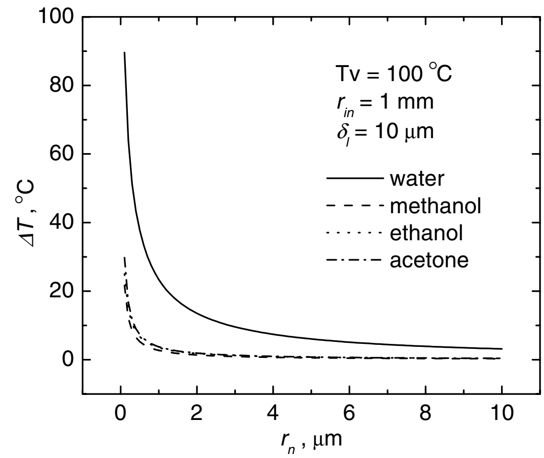

Fig. 10. Working fluid type effect on the superheat.

The one unique feature in a PHP is that the PHP is filled with vapor bubbles and liquid plugs along the capillary. The vapor bubble and liquid plug distribution, however, is not uniform, due to the surface tension, flow direction, gravity, surface energy and frictional forces. Based on the experimental observation, the globe bubble and Taylor

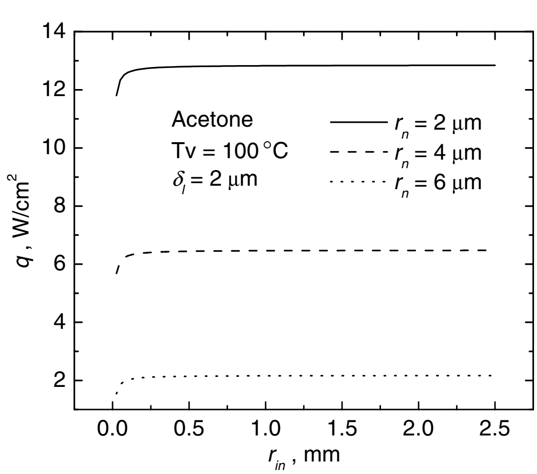

Fig. 9. Cavity size effect on the startup heat flux.

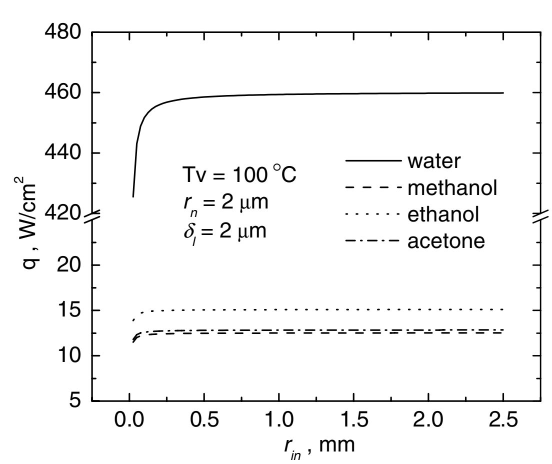

Fig. 11. Working fluid effect on the startup heat flux.

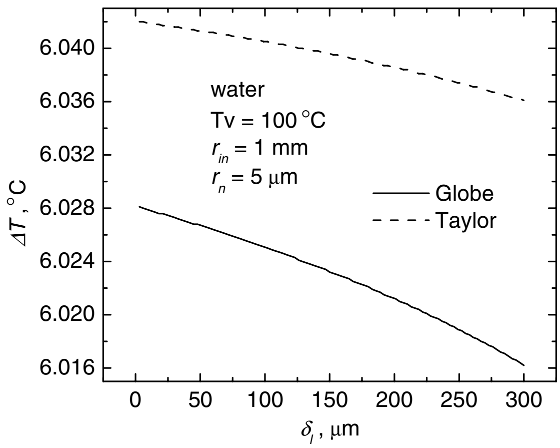

Fig. 12. Vapor bubble type effect on the superheat (working fluid = water).

bubble are two limitations of bubble types in a PHP. In the gravity field, if a PHP with a relatively larger diameter is placed vertically, most of globe bubbles are found in the bottom section, and the Taylor type bubbles are most seen in the top section.

Fig. 12 illustrates the vapor bubble type effect on the superheat. As shown, the required superheat for the globe bubble is smaller than the one with the long Taylor bubbles. In other words, smaller naturally-formed vapor bubbles will be in favor of the vapor bubble generation, which agrees well with the experimental results shown in Fig. 2. Fig. 13 presents the vapor bubble type effect on the superheat for the PHP charged with methanol. Comparing Fig. 12 with Fig. 13, it can be found that in addition to the different working fluid, results presented in Fig. 13 includes the capillary radius effect, while one can find the liquid film thickness effect in Fig. 12. When the capillary radius becomes smaller as shown in Fig. 13, the required superheat for the globe vapor bubble is smaller than the one for the long Taylor vapor bubble. Although the vapor bubble type effect on the superheat is very small, as shown in Figs. 12 and 13, this small effect might be one of the reasons why when the capillary radius becomes smaller, most of the vapor bubbles are formed in the globe-type vapor bubble.

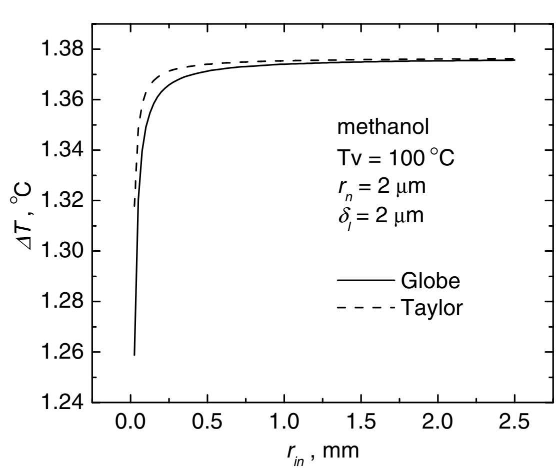

Fig. 13. Vapor bubble type effect on the superheat (working fluid = methanol).

5. Conclusions

A theoretical analysis is conducted to determine the primary factors affecting the startup of oscillating motions in a PHP. It is found that the superheat and heat flux level added on the heating section, cavity size on the capillary inner surface, and vapor bubble shapes formed in the PHP affect the startup of a pulsating heat pipe.

(1) The cavity size on the capillary inner surface strongly affects the PHP startup. When a PHP is charged with water, the cavity radius on the capillary inner surface should be larger than 2 µm, which can result in a smaller superheat starting up a PHP.
(2) The vapor bubble shape affects the superheat and vapor bubble growth. The globe-type vapor bubble needs smaller superheat than the one with the Taylor-type vapor bubble.
(3) The startup performance can be improved by using a rougher surface, controlling vapor bubble type, and selecting a right working fluid.

Acknowledgements

The authors gratefully acknowledge financial support for this work from the National Science Foundation of China (NSFC 50376065) and the National Science Foundation of United States (CTS-0507913).

References

[1] B.M. Guenin, Packaging: designing for thermal performance, Electronics Cooling 3 (2) (1997) 14–19.
[2] M. Hosoda, S. Nishio, R. Shirakashi, Meandering closed-loop heat-transport tube (propagation phenomena of vapor plug), in: Proceedings of 5th ASME/JSME Joint Thermal Engineering Conferences, San Deigo, CA, 1999, pp. 1–8.
[3] M.B. Shafii, A. Faghri, Y. Zhang, Analysis of heat transfer in unlooped and looped pulsating heat pipes, Int. J. Numer. Methods Heat Fluid Flow 12 (5) (2002) 585–609.
[4] Y. Zhang, A. Faghri, Heat transfer in a pulsating heat pipe with open end, Int. J. Heat Mass Transfer 45 (2002) 755–764.
[5] Y. Zhang, A. F Faghri, M.B. Shafii, Analysis of liquid–vapor pulsating flow in a u-shaped miniature tube, Int. J. Heat Mass Transfer 45 (2002) 2501–2508.
[6] R.T. Dobson, Theoretical and experimental modelling of an open oscillatory heat pipe including gravity, in: Proceedings of the 12th International Heat Pipe Conference, Moscow, 2002, pp. 209–214.
[7] P. Sakulchangsatjatai, P. Terdtoon, T. Wongratanaphisan, P. Kamonpet, M. Murakami, Operation modeling of closed-end and closed-loop oscillating heat pipes at normal operating condition, Appl. Therm. Eng. 24 (2004) 995–1008.
[8] Z.J. Zuo, M.T. North, K.L. Wert, High heat flux heat pipe mechanism for cooling of electronics, IEEE Trans. Compon. Pack. Technol. 24 (2) (2001) 220–225.

[9] Z.J. Zuo, M.T. North, L. Ray, Combined pulsating and capillary heat pipe mechanism for cooling of high heat flux electronics, in: Proceedings of the ASME Heat Transfer Division, HTD-Vol. 364–4, 1999, pp. 237–243.
[10] H.B. Ma, M.R. Maschmann, S.B. Liang, Heat transport capability in a pulsating heat pipe, AIAA 2002–2765 (2002) 1–7.
[11] M.B. Shafii, A. Faghri, Y. Zhang, Thermal modeling of unlooped and looped pulsating heat pipe, J. Heat Transfer 123 (2001) 1159–1172.
[12] W. Qu, T. Ma, Experimental investigation on flow and heat transfer of a pulsating heat pipe, in: Proceedings of the 12th International Heat Pipe Conference, Moscow, 2002, pp. 226–231.
[13] W.H. Lee, H.S. Jung, J.H. Kim, J.S. Kim, Flow visualization of oscillating capillary tube heat pipe, in: Proceedings of the 11th Int. Heat Pipe Conference, Tokyo, 1999, pp. 131–137.
[14] S. Khandekar, X. Cui, M. Groll, Thermal performance modeling of pulsating heat pipes by artificial neutral network, in: Proceedings of the 12th International Heat Pipe Conference, Moscow, 2002, pp. 215–219.
[15] J.L. Xu, Y.X. Li, T.N. Wong, High speed flow visualization of a closed loop pulsating heat pipe, Int. J. Heat Mass Transfer 48 (2005) 3338–3351.
[16] J.D. Bugg, G.A. Saad, The velocity field around a taylor bubble rising in a stagnant viscous fluid: numerical and experimental results, Int. J. Multiphas. Flow 28 (2002) 791–803.