

Influence of Working Fluids on Startup Mechanism and Thermal Performance of a Closed Loop Pulsating Heat Pipe- A Review

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Abstract- In recent years, due to the fast development of integrated circuit chips and semiconductors, novel electronic cooling devices have to be developed. As a new heat transfer device, pulsating heat pipe (PHP) has been considered have a bright prospect due to its obvious advantages-simple structure, low cost and excellent heat transfer capability. A number of experimental and theoretical researches have been conducted on PHP in the past decades since it was proposed by Akachi in 1990. PHP has wide range of applications in modern electronics systems due to its capability of dissipating high heat flux. Actually, the operational mechanism of PHP is extremely complex and has not been completely revealed so far. This paper attempts to review the development of PHP on the basis of systematic summary of the latest results of both experimental and theoretical studies. This paper is expected to provide basic reference for future researches.

Index Terms- Closed loop Pulsating heat pipe, startup mechanism, thermal performance, working fluids.

1. INTRODUCTION

With the rapid development in electronic industry, including the dramatic increase in chip density and power density, as well as continuous decrease in the physical size of electronic packages, the thermal management has become, and will continue to be one of the most critical technologies in the electronic product development. The pulsating/oscillating heat pipe (PHP/OHP) first proposed by Akachi [1] in 1990 is a new type of efficient heat transfer device which has shown promising results for electronic cooling. It is drawing a great deal of attention due to its simple design, small size and excellent thermal

performance. It is different from a traditional heat pipe in working and design.

The diameter of the tube must be small enough such that liquid and vapor plugs exist. Unlike traditional heat pipes, PHPs do not need a wicking structure to transport the liquid and can work at higher heat fluxes. Due to its excellent features, such as high thermal performance, rapid response to high heat load, simple design and low cost, PHP has been considered as one of the promising technologies for electronic cooling, heat exchanger, cell cryopreservation, the spacecraft thermal control system, etc. A typical PHP is made of a long continuous capillary tube bent in serpentine manner in many turns. The PHP is first evacuated and then partially filled with the working fluid. Effects from surface tension cause the formation of liquid slugs interspersed with vapor bubbles. When one end of the bundle of turns of the undulating capillary tube is subjected to high temperature, the working fluid inside evaporates and increases the vapor pressure, which causes the bubbles in the evaporator zone to grow. This pushes the liquid column toward the low temperature end (condenser). The condensation at the low temperature end will further increase the pressure difference between the two ends. Because of the interconnection of the tubes, motion of liquid slugs and vapor bubbles at one section of the tube toward the condenser also leads to the motion of slugs and bubbles in the next section toward the high temperature end (evaporator). This works as the restoring force. The interplay between the driving force and the restoring force leads to oscillation of the vapor bubble and liquid slugs in the axial direction. The frequency and the amplitude of the

oscillation are expected to be dependent on the shear flow and mass fraction of the liquid in the tube.

The performance of a PHP depends upon many factors like the geometrical parameters of flow channel, the working fluid, the filling ratio, and number of turns, PHP configuration and the inclination angle [2]. It can be designed in three ways a) closed loop system, b) closed loop with check valves and c) open loop system.

As the name suggest, in closed loop structure, the tube is joined end to end as shown in fig.1 (a). In Closed Loop System with additional flow control check valves system the check valve is used to control the direction of flow inside the tube as shown in fig.1 (b). While in open loop system the ends are not connected to each other they are simply closed at both ends as shown in fig.1 (c).

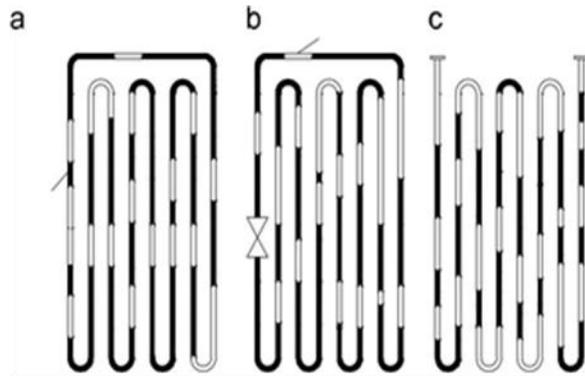


Fig. 1. Schematic of PHPs: (a) closed PHP; (b) closed PHP with check valve; and (c) open PHP.

Many experimental investigations are reported on a Closed Loop Pulsating Heat Pipe (CLPHP) out of which some are very important regarding the startup and thermal performance of closed loop pulsating heat pipe, few of which are summarized as below. The researches on the PHP before 2008 had been reviewed very well by Zhang et al. [3]. However, the influence of various parameters was mostly discussed qualitatively due to the limited experimental data and few potential applications were mentioned in the paper. After that, the local hydrodynamics of the oscillation motion were reviewed by Khandekar et al. [4] in the year of 2010, which however did not cover other aspects of theoretical investigations of PHP, such as the startup mechanism of the PHP and the theoretical models to predict the heat transfer performance of PHP under various operational conditions. In the year of 2012, Xiao et al. [5]

reviewed the experimental studies on the PHP mainly based on literatures during 2009–2011, while pay less attention to the development of theoretical studies.

Pramod R. Pachghare et al. [6] investigated the Effect of pure and binary fluids on closed loop pulsating heat pipe thermal performance. The following main conclusions can be drawn from the study: For pure and binary working fluids of PHP, thermal resistance is decreases with the increasing heat inputs. The dry-out for the water-methanol, water-acetone and water-ethanol PHPs are at 85W, 80W and 90W heat input respectively. Pramod R. Pachghare [7] experimentally study that the effect of inclination angle effect on the thermal performance of closed loop pulsating heat pipe (CLPHP), The thermal performance is scrutinized at various inclinations (viz. 0°, 20°, 40°, 60° and 90°) for different heat input. It is concluded that, the thermal performance up to 25W heat input, is more sensitive to the inclination angle; whereas above 25W heat input, less independent as pressure force dominates the inclination angle force. In comparison, vertical bottom heat mode position gives best thermal performance due to presence of inclination angle.

Vipul M. Patel et al. [8] Investigated the Influence of Working Fluids on Startup Mechanism and Thermal Performance of a Closed Loop Pulsating Heat Pipe. CLPHP is failed to startup pulsations below 20 W heat input for all working fluids. The onset of pulsations is observed at 20.5 W for acetone and methanol, 40.5 W for ethanol and 50.3 W for water. Pulsations are observed at 29.6, 40.5 and 50.3 W for water-acetone, water-methanol and water-ethanol binary fluids respectively. Startup heat input of 50.3 W is observed for 30-PPM solutions and 40.5 W for 45-PPM, 60-PPM and 100-PPM surfactant solutions. Water-acetone shows better thermal performance followed by water-methanol and water-ethanol binary fluids. Saiyan Shi et al. [9] investigated a study of the heat transfer performance of a pulsating heat pipe with ethanol-based mixtures. The mixing ratios of the ethanol-based mixed working fluids are 2:1 and 4:1, the filling ratios range from 45% to 90%. When the mixing ratio is 2:1, the heat transfer performance of PHP with ethanol–water is better than other fluids at a filling ratio of 45% because of the phase-change inhibition; at a filling ratio of 55%, PHP with ethanol–acetone shows better performance among those with mixed working fluids. When the mixing

ratio is 4:1, the thermal resistance of PHP with ethanol–water that is close to being dried out under a filling ratio of 45% rises faster than that at a mixing ratio of 2:1.

Xiangdong Liu et al. [10] Investigated Dynamic performance analysis on start-up of closed-loop pulsating heat pipes (CLPHPs). Based on such analysis, it is indicated that the optimal liquid filling ratio for start-up is about 41% for water, 52% for ethanol, and falls within the range from 35% to 41% for methanol. The startup performance is improved with increasing inclination angle from 0° to 90°. Xiaoyu Cui et al. [11] investigated Heat transfer performance of closed loop pulsating heat pipes with methanol-based binary mixtures. The volume mixing ratios used were 2:1, 4:1 and 7:1. The results showed that adding other working fluids to methanol could change the thermal resistance characteristics of a PHP. At a low filling ratio (45%), adding water to methanol could prevent dry-out at a high heating power; when ethanol was added to methanol, the thermal resistance of the CLPHP was between that with pure methanol and ethanol; when acetone was added, the thermal resistance of the CLPHP was slightly lower than that with pure methanol and acetone. At a high filling ratio (62%, 70%, 90%), the thermal resistance characteristics of CLPHPs with methanol based mixtures were not much different from those with pure fluids except for methanol-water mixture where the thermal resistance was greater than that with pure methanol and pure water.

2. INFLUENCE PARAMETERS AFFECTING PHP PERFORMANCE

Looking into the available literature, it can be seen that six major thermo-mechanical parameters have emerged as the primary design parameters affecting the PHP system dynamics. These include:

- Internal diameter of the PHP tube,
- Input heat flux to the device,
- Volumetric filling ratio of the working fluid,
- Total number of turns,
- Device orientation with respect to gravity,
- Working fluid thermo-physical properties.

2.1 Tube Diameter

The inner diameter is a parameter which closely relates to the definition of the PHP. The normal operation of PHP is based on the oscillation motions of vapor slugs and liquid plugs and whether the vapor slugs and liquid plugs can be formed in the PHP depends on the relative strength of the gravity and surface tension. The inner diameter of the pipe must be sufficiently small so that vapor bubbles can grow to vapor plugs in the tube. The theoretical maximum diameter (based on balance of capillary and gravity forces).

$$D_{cri} = 2\sqrt{\sigma / (\rho_l - \rho_g)g} \quad (1)$$

$$Eo = [Bo]^2 = 4 \quad (2)$$

Where

Bo Bond number = $d \cdot (g(\rho_l - \rho_v) / \sigma)^{0.5}$

D Tube internal diameter (m)

Eo Eotvos number = $(Bo)^2$

G Acceleration due to gravity (m/s^2)

σ Surface tension (N/m)

ρ Liquid density (kg/m^3)

If $D < D_{cri}$, surface tension forces dominate and stable liquid plugs are formed. However, if $D > D_{cri}$, the surface tension is reduced and the working fluid will stratify by gravity and oscillations will cease. The PHP may operate as an interconnected array of two-phase thermosyphons.

For the closed PHP, Yang et al. [12] compared the heat transfer performances of PHPs with inner diameters of 2 mm and 1 mm. It was found that the thermal resistance of the former PHP was lower by about 10% than that of the latter one. Yang et al. [13] concluded that the PHP with larger inner diameter showed considerably better thermal performance than that of smaller one, and it was attributed to lower dissipative losses when the inner diameter of PHP was larger. Charoensawan et al. [14] found that at each evaporation temperature, the thermal resistance of the PHP was distinctly reduced with the increase of the inner diameter. This was because that the smaller inner diameter led to larger frictional resistance. Wang et al. [15] also pointed out that the thermal resistance of the PHP increased with the decrease of inner diameter. However, some researches indicated that the thermal resistance might not decrease with the increasing of the inner diameter for the open PHP. Saha et al. [16] presented an experimental study with two open PHPs. The experimental results showed that the PHP with 0.9 mm inner diameter might have a better performance

compared with the PHP with 1.5 mm inner diameter. Besides, it should be noted that the physical properties of working fluid might have influence on the effect of inner diameter on the performance of PHP as indicated by Rittidech et al. [17].

2.2 Input heat flux to the device

The input heat flux is also a very important parameter for the heat transfer performance of the PHP. The influence of the heat flux on PHP is mainly embodied at two aspects: the startup heat flux of the PHP and the relationship between the heat flux and the heat transfer performance of PHP. For the first aspect, the experimental results [14,18] indicated that there existed a minimum heat flux to make the PHP start to operate and only when the input heat flux was greater than this minimum value that the PHP can operate successfully. Otherwise, no apparent oscillation motions of the working fluid can be observed. This minimum heat flux is usually called the startup flux of the PHP. For the second aspect, it is the pressure difference caused by the input heat flux that drives the working fluid to oscillate in the PHP, so the heat flux has a close relationship with the characteristics of the oscillation motions, as well as the heat transfer performance of the PHP. In addition, the heat flux also affected the ratio of the sensible heat to the latent heat during the process of heat transfer. When the heat flux is very low, the sensible heat will dominate the heat transfer process and the latent heat takes up when the heat flux becomes higher [3,19]. Generally speaking, the thermal resistance of the PHP decreases with the increasing of heat flux [20,21]. Hu et al. [22] presented that the thermal resistance of flat PHP reduced with the increasing of the heat flux, and the startup time was closely related with the heat flux. Meanwhile, the heat flux might have an influence on the heat transfer characteristics of the PHP.

2.3 Volumetric filling ratio of the working fluid

Filling ratio is defined as the ratio of working fluid volume to the total volume of the PHP. Due to the fact that the relative amount of liquid plugs and vapor slugs depends on the filling ratio, the filling ratio has a significant influence on the performance of PHP. If the filling ratio is too low, on the one hand, there are too many vapor slugs in the PHP and it is very hard to sustain the stable vibration; on the other hand, the heat capability of the PHP is also limited, and the

phenomenon of dry-out occurs easily. If the filling ratio is too high, there are few vapor slugs in the pipe, which causes the driving force of the working fluid decreasing and the operation of PHP will be very difficult. When the filling ratio equals to one, the PHP would become a tube full of working fluid, in which case only sensible heat transfer of the working fluid and tube wall could be applied to dissipate the heat. Experimental studies have shown that when the filling ratio is between 0.2 and 0.8, the PHP can operate normally [23,24]. However, there exists an optimal range of the charge ratio for PHP, in which the PHP shows better performance than that beyond this range. When the filling ratio of the PHP is in the optimal range, the fluctuation of pressure can promote the oscillation motions of working fluid efficiently, and the liquid plugs can dissipate enough heat from the evaporation section to the condensation section at the same time.

Some researchers have reported the existence of the optimal filling ratio. Yang et al. [12] indicated that the filling ratio of 0.50 was optimal to obtain the best performance. Liu et al. [25] investigated the heat transfer characteristics of a closed PHP with ethanol as the working fluid. It was pointed out that the optimal range of filling ratio was 0.41–0.52. Cao et al. [26] put forward a PHP with improved structure to enhance the liquid supply to the evaporation section. The PHP obtained the lowest thermal resistance when the filling ratio was 0.5. Yang et al. [13] investigated the heat transfer performance of PHP with ethanol and it was pointed out that the optimal range of filling ratio was 0.50-0.65 when the inclination angle of the PHP was 0° and 90°. While for the PHP with the inclination angle of 90°, the optimal charge ratio was about 0.15 when the heat flux was very low, and was 0.40-0.70 when the heat flux was higher.

2.4 Total number of turns

The number of turns significantly influences the internal pressure distribution and the heat transfer characteristics of the PHP. Quan et al. [27] proposed that the increasing of number of turns could improve the internal pressure disturbance and obtain a better heat transfer performance of the PHP. Researches [28,29] pointed out that there existed a critical number of turns to make the performance of PHP independent of the inclination angles when the actual number of the turns was greater than it. Akachi et al.

[30] confirmed the existence of critical number of turns and proposed that its value was 80 in his investigation. According to the work of Charoensawan et al. [31] the critical number of turns of the PHP was influenced by the properties of working fluid and the inner diameter of the tube. In another paper, Charoensawan et al. [14] also pointed out that the critical number of turns also depended on the evaporation section temperature.

2.5 Device orientation with respect to gravity

From the above contents, it can be seen that if the inner diameter of a PHP satisfies Eq. (1), the impact of surface tension of the working fluid will be stronger than the gravity. However, the gravity still has significant influence on the heat transfer performance of PHP [32]. The research methods utilized to investigate the influence of the gravity can be classified into two groups: one is by changing the inclination angle of the PHP and the other is by changing the gravity field. When the inclination angle is changing, the influence of the inclination angle on the heat transfer performance of the PHP is very obvious. Generally speaking, the PHP with the inclination angle of 90° showed better performance than the PHP with other inclination angle. Under this condition, the gravity helped the working fluid to oscillate in the PHP [33,34]. Qu et al. [35] concluded that the best performance was obtained when the inclination angle was 60°. Meanwhile, the influence of the inclination angle also coupled with the other parameters, such as the inner diameter and the properties of the working fluid. Yang et al. [12] experimentally studied the heat transfer characteristics of a closed PHP. It was found that for the PHP with 2 mm inner diameter, the best performance was obtained when the inclination angle of the PHP was 90°. While for PHP with 1 mm inner diameter, the inclination angle almost had no influence on its performance.

2.6 Working fluid thermo-physical properties

Among the numerous methods to improve the heat transfer performance of PHP, the most direct and effective one is to select an excellent functional fluid as the working fluid. The physical properties of the working fluid, such as the surface tension and wettability, latent heat, specific heat, viscosity etc.,

have profound effects on the heat transfer performance of PHP.

Surface tension: The high value of surface tension increases the interfacial force which opposes the pulsation in capillary sized CLPHP. Startup mechanism requires lower capillary resistance. Capillary resistance depends on capillary diameter, contact angles and surface tension. For the interface of copper and working fluid, the contact angles become constant. When the capillary diameter is fixed, the capillary resistance mainly depends on the surface tension of the working fluid. The decrease in surface tension reduces capillary force which decreases the evaporator temperature of surfactant solutions compared to pure water.

Latent heat: a lower latent heat will be beneficial to help the bubbles generating and rupturing more quickly, as well as shorten the startup time of the PHP. When the latent heat of the working fluid is low, lower superheat of tube wall can start the PHP [3]. So it is suggested that when the heat flux is very low, the working fluid with lower latent heat is desirable. However, when the heat flux is very high, the latent heat becomes the dominant part of the heat transfer process, so the working fluid with higher latent heat can dissipate more heat from the evaporation section.

Specific heat: when the heat flux input to the evaporation section is very low, the majority of the heat is dissipated by the sensible heat. The specific heat also closely relates to the heat capacity of working fluid.

Viscosity: it is easy to understand that the working fluid with lower viscosity is a better choice for the PHP. A low dynamic viscosity will reduce the shear stresses in the channel and decrease the pressure losses. This will reduce the required heat flux to maintain the oscillation motion.

Thermal conductivity: the effect of thermal conductivity of the working fluid on PHP is not only reflected on the temperature distribution, but also the response time of PHP. Larger the thermal conductivity is, faster the heat can transfer in the PHP. Further-more, it can also decrease the

temperature difference between the evaporation section and the condensation section.

Moreover, smaller dynamic viscosity, larger (dP/dT) ratio and smaller specific heat are favorable for the early startup of a CLPHP. Water contradicts the above properties compared to methanol, ethanol and acetone. Startup heat flux/temperature could be reduced and thermal performance could be improved when water-based binary fluids and surfactant solutions are used as working fluids in a CLPHP.

3. APPLICATIONS OF PHP

Considering the excellent heat transfer performance and the operational characteristics of the PHP, it has many potential applications. In fact, PHP has been successfully used in many occasions to enhance the heat transfer process, and the performances of various heat transfer devices were significantly improved by conjunction with the PHP. In this section, the applications of the PHP are presented.

- Applications in solar water heater
- Applications in electronic cooling
- Applications in heat recovery devices
- Applications in Cooling of fuel cell stack

4. CONCLUDING REMARKS

Learning outcomes from literature review are: i) The PHP with the inclination angle of 90° showed better performance than the PHP with other inclination angle. Under this condition, the gravity helped the working fluid to oscillate in the CLPHP. ii) The charge ratio of 0.50 was optimal filling ratio to obtain the best performance. Also the heat transfer characteristics of a closed PHP with acetone, methanol, and ethanol as the working fluid. It was pointed out that the optimal range of charge ratio was 0.41-0.52. iii) Smaller dynamic viscosity, larger (dP/dT) ratio and smaller specific heat are favorable for the early startup of a CLPHP. Water contradicts the above properties compared to methanol, ethanol and acetone. iv) The inner diameter must be less than or equal to 2 mm for early startup and better thermal performance of CLPHP. v) For early startup mechanism acetone is the best working fluid.

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