The development of Closed loop pulsating heat pipe for various geometry, shape, size and heat dissipation - A Review

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Abstract—Increasing need of electronics or micro-electronics device is one of the major reasons of heats. Thus the thermal management system with small and high efficiency heat transfer device are needed to ensure reliable operation condition. Thus the heat dissipation is one of the best approaches to increase the reliable performance and life of electronics or micro-electronics devices. And the high efficiency heat transfer device is needed. As the pulsating heat pipe (PHP) also called as oscillating heat pipe (OHP) has been considered have a high advantages. Pulsating heat pipe (PHP) consists of a single meandering capillary tube without wick structure between evaporation section and condenser section. No external mechanical power is required. So the pulsating heat pipe (PHP) has different heat transport mechanism from conventional heat pipe. Simple structure, low cost, easy manufacturer, excellent heat transfer heat capacity. The pulsating heat pipe (PHP) is a passive heat transfer device that enhance large amount of heat which works on the principle of evaporation and condensation of the working fluid. A various experiment and theoretical research have been conducted on the pulsating heat pipe (PHP) in the last decades since it was proposed by akachi in 1990. The good applications for the future, this paper attempts to review the development of the pulsating heat pipe (PHP) on the basics of summary of the latest result experimental and theoretical. This review paper is providing basic reference for future researcher.

Index Terms—Pulsating heat pipe (PHP), oscillating heat pipe (OHP), Heat transfer, Review

I. INTRODUCTION

The heat pipe is a reliable device with very high thermal conductance. The first idea was suggested by R. S. Gaugler [1] in 1942, who patented the idea, but did not develop it further. A pulsating heat pipe (PHP) or oscillating heat pipe (OHP), introduced by Akachi (1990; 1996) [2,3] consists of a plain meandering tube of capillary dimensions with many U-turns as shown in Figure 1[4]. In this design, in contrast to a conventional heat pipe, there is no additional wick structure inside the tube. There are two ways to arrange the tube, open loop and, closed loop, structure. As the names suggest, in a closed loop structure, the tube is joined end to end. The tube is first evacuated and then filled partially with a working fluid, which distributes itself spontaneously in the form of liquid-vapor plugs and slugs inside the capillary tube. One end of this tube bundle receives heat called evaporator, transferring it to the other end called condenser. 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 cry preservation, the spacecraft thermal control system, etc.

It is the unique operational mechanism of PHP that leads to its distinct advantages: when the stable operation is achieved in the PHP, the oscillation motions of liquid plugs and vapors lugs, instead of the capillary force generated by wick structures, drive the working fluid flowing in the pipe. Due to the effect of the surface tension, the liquid plugs and vapors lugs were formed and distributed randomly in the pipe. Since it was proposed, the operational mechanism and heat transfer characteristics of the PHP have been studied extensively. The theoretical researches mainly focused on the model development to simulate and qualitatively analyze the internal hydro- dynamic characteristics and the heat transfer process of working fluid. The experimental
investigations were usually carried out to quantitatively study the influence of various parameters on the heat transfer performance of PHP. The pressure imbalance in adjacent tube causes the oscillation of working fluid between the evaporation section and condensation section. No external mechanical power is required to give rise to the oscillation [5].

![Schematic of a closed loop pulsating heat pipe](image)

**Fig.1 Schematic of a closed loop pulsating heat pipe[5]**

So the PHP has different heat transport mechanism from conventional heat pipe and has attracted considerable attention for advantages of prominent thermal performance, simple structure, easy manufacture and low cost.

After more than two decades research, PHPs with different newly structures were designed, manufactured and tested to obtain good heat transfer performance and the good efficiency under different required working conditions. Some researchers designed PHPs with different tube diameters. Wang et al. [6] have tested the thermal performance of an OHP with uniform and alternating tube diameters. The results showed that the alternating tube designed OHP could start up at a low heat input with a small thermal resistance. Kim et al. [7] have designed a flat PHP with various asymmetric and aspect ratios channels and found out the optimum asymmetric ratio and aspect ratio under different heat inputs. Shyu et al. [8] have also designed a PHP with alternate channel width and found out the new design could obtain an extremely low Bond number. Some researchers designed OHPs with different geometrical structures to adopt different requirements. Qu et al. [9] have designed a hybrid flexible oscillating heat pipe (FOHP) for some spatial complicated energy utilization systems and tested its thermal performance with different structural styles under filling ratios of 50%, 60% and 70%. The results showed that the FOHP could function well and had acceptable heat transfer performance. Frijns et al. [10] have proposed a PHP with a Tesla-type valve and compared its thermal performance with an OHP without valves. The results showed that the exits of valves provided a 14% decrease in thermal resistance. Shafii et al. [11] have designed an flat OHP with interconnecting channels and found out that the interconnecting channels enhanced flow circulation and heat transfer in OHP. Shafii et al. [12] have also designed a rotating OHP and experimentally researched the charging input powers, filling ratios and rational speeds influence to the thermal performance. Ma et al. [13–14] have proposed several three-dimensional flat plate oscillating heat pipes (3D FP-OHP) with different novel designs and tested the thermal performance under different working conditions. The experimental results showed that the 3D FPOHP had better performance than conventional FP-OHP. Ma et al. [15] have also designed two three-dimensional tubular oscillating heat pipes and tested their thermal performance, respectively. The results found out that the two-dimensional OHPs (2D-OHP) could not transfer heat with a bigger heat flux. In our previous works, a three-dimensional oscillating heat pipe (3D-OHP) with three layers was designed, manufactured and tested. The 3D-OHP had good thermal performance and thermal resistance uniformity [16]. Pachghare and Mahalle (2012) conducted experiments on PHP to investigate the effect of binary mixture of working fluids on thermal performance of PHP, made from copper tube with 2 mm inner diameter and 10 numbers of turns, for different heat inputs with ethanol, methanol, acetone, water and their binary mixture with water as a working fluids at filling ratio 50%. Pure acetone is having lesser thermal resistance than working fluids methanol, ethanol, and water [17]. No measurable difference has been recorded between the PHP running with pure and binary mixture working fluids, in terms of overall thermal resistance. Working fluid behavior is strongly depends on the thermo-physical properties, but latent heat of vaporization is the main property that strongly affects the thermal performance (Borkar Pachghare, 2012). [18]
D. Torresin et al. [19] have also designed a novel pulsating heat pipe cooler based on automotive technology. The experimental results found out that the double condenser pulsating heat pipe cooler based on automotive technology having two condenser areas, above and below the evaporator. Vertical (0°), horizontal (90°), and anti-vertical (180°) the thermal resistance is decreasing with the heat load in all the orientations.

II. INFLUENCE PARAMETER

The heat transfer performance of closed loop pulsating heat pipe (CLPHP) influenced by various parameter, which is classified in to three types.

1. Geometric parameter of CLPHP [20] such as the inner diameter, cross section shape of the CLPHP, channel configuration, the number of turns, the length of evaporation and condensation etc.

2. Physical properties of working fluid [21-22] such as surface tension, latent heat, viscosity of the working fluid.

3. Operational parameters [11,23] the operational parameter such as filing ratio, heat flux, inclination angle.

2.1 Geometric parameter

The internal diameter parameter is related to the definition of CLPHP. The normal operation of CLPHP is based on the oscillation motions of vapor slugs and liquid slugs and whether the vapor slugs and liquid slugs can be formed in the CLPHP depends on the relative strength of the gravity and surface tension, as indicated by Bond number.

\[ B_o = \sqrt{\frac{E_o}{\rho}} = \sqrt{\frac{g(\rho_l - \rho_v)}{\sigma}} D^2 \]  

The theoretical maximum inner diameter of capillary tube can be calculated as:

\[ D_{cri} = \frac{\sigma}{\sqrt{g(\rho_l - \rho_v)}} \]  

\[ E_o = (Bo)^2 = 4 \]

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 CLPHP may operate as an interconnected array of two-phase thermosyphon [34]. The influence of surface tension of the working fluid would be stronger than that of the gravity, so the liquid plugs and vapor slugs could be formed in the pipe.

2.2 Cross section and channel configuration

It is an important parameter which affects the transition of flow patterns and the distribution of working fluid. When the cross section shape is not circular, such as triangular, rectangular the effect of the angle corners on the flow patterns is more conspicuous. Zhou et al. [24] conducted an experimental study on the miniature closed loop PHPs, whose hydraulic diameter \( s \) were near1mm and the shapes of cross-section were triangle and square, respectively. The results showed that the performances of tested CLPHP were also greatly influenced by gravity and the triangle cross-section CLPHP had a lower thermal resistance than that of square one.

2.3 Number of turns

Quan et al. [25] proposed that the increasing of number of turns could improve the internal pressure disturbance and obtain a better heat transfer performance of the PHP. Yang et al. [26] developed a PHP consisted of 40 parallel channels, it was found that the PHP operated successfully with all inclination angles. It was show that the above-mentioned experimental that increasing the number of turns would be help full to strengthen the internal pressure fluctuation and weaken the influence of the gravity and the critical number of turns was also influenced by other parameters, such as inner diameter, heat flux and the physical properties of the working fluids.

2.4 Physical Properties of working fluid

The numbers of method are used to improve the heat transfer rate of CLPHP. The effective one is to select excellent working fluid. The physical properties of the working fluid such as density, latent heat, surface tension, viscosity, specific heat etc. A lower latent heat is to help bubbles forming more quickly and the shorten the start up time of the PHP. If the latent heat of the working fluid is low, lower super heat of tube wall can start the PHP [27]. So it is suggested that when the heat flux is very low, the working fluid with lower latent heat is desirable. 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 [28]. Viscosity is easy to understand that the low viscosity is good choice of the PHP. A low viscosity will reduce the shear stress in the configuration and decrease the pressure losses. And hence this will reduce the required heat flux to maintain the oscillation motion [29].

2.5 Operational parameter
Filling ratio is defined as the ratio of working fluid volume to the total volume of the PHP. Yang et al. [30] indicated that the filling ratio of 0.50 was optimal charge ratio to obtain the best performance. Liu et al. [31] investigated the heat transfer characteristics of a closed loop PHP with ethanol as the working fluid. It was pointed out that the optimal range of filling ratio was 0.41–0.52.

2.6 Inclination angle
Generally 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 [32].

2.6 Heat flux
The input heat flux is 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 start up 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 [33] indicated that there existed a mini- mum 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.

III. APPLICATION OF PULSATING HEAT PIPE
The pulsating heat pipes are high efficient heat transfer passive device and operational characteristics it has many applications.

3.1 Solar water heater application
Solar water heaters normally require a large installation space. In order to reduce the device space and scale and make it more economical. Arab et al. [35] developed a new solar water heater, which was combined with two PHPs. For each PHP, the condensation section was placed in the water tank, and the eva portion section was embedded in the collector. The length of the adiabatic section varied with the position. It was found that the highest efficiency of the solar water heater was 53.79%. Rittidech et al. [36] designed a novel solar water heater. The collector tube was consisted of 10 glass tubes and in each tube there were two single loop PHPs with check valve. By this design, the efficiency could reach up approximately 76%.

3.2 Electronic cooling application
Pulsating heat pipes have superior thermal performance and the heat flux should exceed a certain value to make reliable that the oscillation motion of working fluid were stable. Shang fm et.al [37] indicates that the pulsating heat pipes are efficient method for the cooling of the electronics devices. Miyazaki et al. [38] presented a research on flexible PHP for cooling notebook, and developed a wing-type PHP. Maydanik et al. [39] designed a compact cooler using PHP for cooling electronic chips. Deng et al. [40] experimentally investigated the potential of the flat PHP for the cooling of LED. The LED array was connected with the evaporation section of the flat PHP through the substrate. It was found that the PHP could offer excellent cooling effect for LED.

3.3 Heat recovery devices application
The pulsating heat pipe applying as heat recovery of waste heat. The pulsating heat pipe has presented very good aspect. Rittidech et al. [41] designed a PHP device to recover the waste heat from the drying process. The channel arrangement was aligned in the flow direction of the hot air. The evaporation section and condensation section were arranged in the fresh air duct and hot air duct, respectively. The device showed good performance. Meena et al. [42] examined the efficiency of the PHP used in the heat recovery systems. Two sets of PHP with the check valves were embedded in to the drying system, and the air passed the evaporation section and the condensation section in order.

IV. CONCLUSION
The pulsating heat pipe superior element due to its simple in design, low cost, reliable thermal performance may find the variety of application. The pulsating heat pipe have high efficient heat transfer device has attracted great attention. The heat transfer performance of pulsating heat pipe is greatly influenced by various parameters such as
internal diameter, number of turns, inclination angle and filling ratio, and many researcher have been conducted to investigate heat transfer characteristics of the pulsating heat pipe.

The paper mainly focus on presenting a review on the technology development of various geometry and heat dissipation of the pulsating heat pipe.

REFERENCES


