Research Progress on Experimental Optimization for Heat Performance of Pulsating Heat Pipe

Zhehua Du1*, Xin Lin2
1 Wuhan Second Ship Design and Research Institute, Wuhan, Hubei, 430205, China
2 Hubei Province Engineering Consulting Co., LTD., Wuhan, Hubei, 430071, China
*Corresponding author’s e-mail: Jackydzh@163.com

Abstract. Pulsating heat pipe is regarded as a promising cooling technique for electronic devices. Investigations on thermal performance optimization for pulsating heat pipe will provide guideline for the utilization of pulsating heat pipe. In this paper, thermal performance optimization for pulsating heat pipe via experimental investigations is introduced. Three optimization approaches are analyzed, including the improvement of structure, the utilization of working medium, and the treatment of internal surface. The mechanism of heat transfer enhancement of pulsating heat pipe is discussed, and the potential research field of thermal performance optimization for pulsating heat pipe is predicted. On the basis of familiarity with multiple pulsating heat pipe optimization strategy, it is necessary to explore coexistence mechanism of multiple optimizing strategy and develop pulsating heat pipe coupling enhanced heat transfer method.

1. Introduction
Since the pulsating heat pipe was proposed by Akachi in the 1990s, it has attracted much attention as a new and efficient heat transfer element. Because of its simple structure, low cost, high heat exchange efficiency, optional shape, environmental adaptability makes pulsating heat pipe have its unique advantages in the fields of cells, superconducting magnet cooling, electronic product cooling, and energy collection.

2. Overview
There are many complicated gas-liquid two-phase flow and heat transfer phenomena in the pulsating heat pipe. Many factors such as pipe diameter, working medium, liquid filling rate, non-condensable gas, heat transfer, gravity, relative position of heating end and cooling end affect its flow and heat transfer performance.

This paper reviews experimental research progress on the optimization of heat transfer performance of pulsating heat pipes, analyzes the optimization strategies of pipeline structure improvement, new working medium using and internal surface modification, focuses on the mechanism of heat transfer enhancement of pulsating heat pipes, and finally explores the development trend of heat transfer performance optimization of pulsating heat pipes.

3. Pipeline structure improvement

3.1 Non uniform channel
Uniform channel pulsating heat pipe is difficult to operate in some conditions, such as horizontal placement. Non-uniform channel pulsating heat pipe has one more capillary driving force than uniform channel pulsating heat pipe. This capillary driving force can drive the flow of the working medium, thus improving heat transfer performance of the pulsating heat pipe. This is because the surface tension of liquid film at different cross sections is different, which creates an additional capillary driving force.

\[ \Delta P = 2 \sigma / R_1 - 2 \sigma / R_2 \]

In the formula: \( \sigma \) is surface tension coefficient, N/m; \( R_1 \) and \( R_2 \) are radius of curvature of pipe diameter under different cross sections, m. Working fluids in different channels with different diameters also have different flow resistances. The difference in flow resistance will also cause the working fluid in the tubes to flow in a direction with a small flow resistance. Working medium in different channels with different diameters also have different flow resistances. The difference in flow resistance will also cause working medium in the tubes to flow in a direction with a small flow resistance. Therefore, the rational use of the non-uniform channel structure will inject new driving force into the gas-liquid two-phase circulating flow in the pulsating heat pipe.

Chien, H.K. et al. [1] proposed non-uniform channel structure for the first time, and designed and manufactured 16-channel 2mm × 2mm uniform channel flat pulsating heat pipes and 16-channel 2mm × 2mm and 2mm × 1mm alternating non-uniform channel pulsating heat pipes. When placed horizontally, uniform channel pulsating heat pipe can run effectively, but non-uniform pulsating heat pipe cannot run. Tseng, C.Y. et al. [2] studied the effect of non-uniform channel structure on pulsating heat pipe, and found that it could accelerate the startup of pulsating heat pipe and reduce thermal resistance of pulsating heat pipe during operation. Liu, S. et al. [3] produced pulsating heat pipes with different diameters, and compared them with ordinary pulsating heat pipes with the same diameter, as shown in Figure 1. Visualization experiments show that a stable annular flow was easier to form inside pulsating heat pipe with different diameter, which was conducive to the return of liquid working fluid to evaporation end. Its corresponding thermal resistance was also the lowest (as shown in Figure 2), and the structure with different diameter can improve heat transfer performance of the pulsating heat pipe.

3.2 Three-dimensional distribution channel

Wang, Y.X. [4] improved traditional pulsating heat pipe into three-dimensional pulsating heat pipe, and improved condensation section into double helix structure, as shown in Figure 3. This kind of three-dimensional pulsating heat pipe could be started at 0°, 50° and 90°. When inclination angle was 90° and 50°, there was little difference in thermal resistance, and the minimum total thermal resistance could be as low as 0.117K/W. Hathaway, A.A. et al. [5] also designed a curved non-uniform pulsating heat pipe, as shown in Figure 4. The evaporation section has 14 complete elbows, while the condensation section has 14 complete elbows plus 6 local elbows. This pulsating heat pipe could also operate at minus 90° (evaporation end is on top, condensing end is on bottom), indicating that elbow uneven pulsating heat pipe could reduce gravity sensitivity. At high power, pulsating heat pipe had comparable heat transfer performance at plus or minus 90°.
Qu, J. et al. [6] designed a three-dimensional multi-layer pulsating heat pipe with layers ranging from 1 to 5, as shown in Figure 5. The results showed that, under the same operating parameters, three-dimensional multilayer pulsating heat pipe with 4-layer structure was easier to start and had a smaller thermal resistance than the other multilayer pulsating heat pipe. In addition, compared with two-dimensional pulsating heat pipe with the same number of elbows (as shown in Figure 6), it had lower thermal resistance under high heating power.

4. Improved working medium

Thermal properties such as boiling point, specific heat capacity, latent heat of vaporization, dynamic viscosity, \((dp / dT)_{sat}\) and surface tension all affect heat transfer performance of pulsating heat pipe. In the past, researchers mainly studied different pure working medium, and found that the thermal properties of pure working media had limitations, which reduced the adaptability and reliability of pulsating heat pipes under certain operating parameters. In the past, researchers mainly studied different pure working medium, and found that thermal properties of pure working medium had limitations, which reduced adaptability and reliability of pulsating heat pipe under certain operating parameters. Therefore, researchers improved thermal properties of the working medium by mixing other working medium, preparing nanocrystals and using microencapsulated fluids, thus improving reliability and adaptability of pulsating heat pipe.

4.1 Self-wetting fluid

Abe, Y.J. et al. [7] analyzed flow phenomenon of 1.5% butanol aqueous solution and 20% ethanol aqueous solution under heating conditions by using tracer particles. In both solutions, liquid flowed spontaneously to high temperature region, and fluid flow rate in butanol solution was more than 20 times that in ethanol solution. Thus, it could be known that self-wetting fluid could spontaneously flow to nucleation point of the bubble on the wall surface, hindering the occurrence of drying-up phenomenon. Cecere, A. et al. [8] also found that when non-azeotropic fluid was heated, liquid spontaneously flowed from cold side to hot side, which was opposite to flow direction in a single-component fluid. Cui, X.Y. et al. [9] experimentally studied heat transfer performance of pulsating heat pipe when using non-azeotropic fluid of water-methanol, water-ethanol, water-acetone and pentanol-acetone as working fluid. The experimental results showed that the enhancement of heat transfer performance of pulsating heat pipe by non-azeotropic fluid working medium decreased with the increase of heating power and decreased with the increase of filling rate. Pure working quality pulsating heat pipe was more difficult to dry out at low filling rate.
4.2 Nanofluid
A small amount of nanoparticles (metal particles, oxide particles, nitrogen oxides, etc.) were added to conventional working medium (water, ethanol, acetone, etc.) to obtain stable nanoparticle suspension—nanofluid. Nanoparticles in the fluid would increased fluid thermal conductivity [10], which was conducive to rapid heat absorption of working fluid in the initial stage of startup. Moreover, nanoparticles could increase vaporization core in the liquid plug and accelerate the start of the pulsating heat pipe.

4.3 Phase change microcapsule fluid
Microcapsule particles are formed by encapsulating solid, liquid, or gas inside a microcapsule. Wang, S.F. et al. [11] studied the heat transfer performance of pulsating heat pipe with microcapsule fluid as working medium. Experimental results showed that microcapsule fluid pulsating heat pipe had wider working range than pulsating heat pipe in which water and ethanol were working fluid. With high liquid filling rate, startup performance was better, and evaporation end temperature and overall thermal resistance were lower. The reason was that microcapsule particles in the fluid were conducive to the formation of vaporization core and oscillating movement of fluid in the tube, and apparent specific heat and latent heat of vaporization of fluid were both larger.

5. Channel internal surface improvement

5.1 Microstructural modification
The circulation of traditional heat pipe working medium depends on the capillary suction force of capillary core structure. The capillary core structure mainly includes two types: sintered and grooved. Introducing capillary core structure into pulsating heat pipe will inject new power into the operation of working fluid in pulsating heat pipe. Kim, W. et al. [12] prepared a silicon-based pulsating heat pipe with concave structure on the inner surface by using micromachining technology, as shown in Figure 7. Qu, J. et al. [13] introduced micro-groove structure into the inner surface of pulsating heat pipe, as shown in Figure 8. Qu, J. et al. [14] designed and manufactured flat pulse heat pipe with sintered porous copper core structure at the bottom of the channel, as shown in Figure 9. The experimental results showed that heat transfer performance of this structure heat pipe was improved.

5.2 Hydrophilic / hydrophobic modification
Ji, Y. et al.[15] coated inner surface of the heat pipe with a hydrophilic CuO layer to produce a hydrophilic surface, which significantly improved the heat transfer performance of the pulsating heat pipe, and found that the superhydrophobic surface would worsen the heat transfer of the pulsating heat pipe. Through visual experiments, Lan, Z. et al.[16] found that pulsating motion of working medium inside pulsating heat pipe with super hydrophilic and hydrophilic inner surface was greater than that of red copper pulsating heat pipe, and heat transfer performance of pulsating heat pipe was improved by 5%~15% and 15%~25% respectively compared with that of red copper pulsating heat pipe.

6. Conclusion
- Based on visual observations of gas-liquid two-phase flow and heat transfer in pulsating heat pipe, combined with theoretical analysis, it is hoped to reveal microscopic mechanism of gas-liquid phase change heat transfer in pulsating heat pipe.
- Heat transfer performance of pulsating heat pipe under different inclination conditions needs to be further studied, especially operation mechanism of pulsating heat pipe under small inclination and even negative angle.
- On the basis of familiarity with multiple pulsating heat pipe optimization strategy, it is necessary to explore coexistence mechanism of multiple optimizing strategy and develop pulsating heat pipe coupling enhanced heat transfer method.

Acknowledgments
This paper was funded by the National Key R&D Program (Item Number:2017YFC0307800).

References
[1] Chien, K.H., Lin, Y.T., Chen, Y.R. (2012) A novel design of pulsating heat pipe with fewer turns applicable to all orientations. International Journal of Heat and Mass Transfer, 55:5722-5728.
[2] Tseng, C.Y., Yang, K.S., Chien, K.H. (2014) Investigation of the performance of pulsating heat pipe subject to uniform/alternating tube diameters. Experimental Thermal and Fluid Science, 54:85-92.
[3] Liu, S., Li, J., Dong, X. (2007) Experimental study of flow patterns and improved configurations for pulsating heat pipes. Applied Thermal Engineering, 35:27-30.
[4] Wang, Y.X. (2016) Performance study for new type of three-dimensional pulsating heat pipe. Chemical Industry and Engineering Progress, 35:2367-2372.
[5] Hathaway, A.A., Wilson, C.A., Ma, H.B. (2012) Experimental investigation of uneven-turn water and acetone oscillating heat pipes. Journal of Thermophysics and Heat Transfer, 26:115-122.
[6] Qu, J., Zhao, J. (2017) Experimental investigation on thermal performance of multi-layers three-dimensional oscillating heat pipes. International Journal of Heat and Mass Transfer, 115:517-523.
[7] Abe, Y.J. (2006) Self-rewetting fluids: beneficial aqueous solutions. Interdiscip. Trans. Phenom. Space Sci, 1077:650-667.
[8] Cecere, A., Paola, R.D., Savino, R. (2011) Observation of Marangoni flow in ordinary and self-rewetting fluids using optical diagnostic systems. The European Physical Journal Special Topics, 192:109-120.
[9] Cui, X.Y., Xu, T.X. (2015) Experimental investigation on thermal performance of oscillating heat Pipe with water / methanol mixture as working fluids. Journal of Refrigeration, 36:70-75.
[10] Eastman, J.A., Choi, S.U.S., Li, S. (2001) Anomalously increased effective thermal conductivities of ethylene glycol-based nanofluids containing copper nanoparticles. Applied Physics Letters, 78:718-720.
[11] Wang, S.F., Lin, Z.R. (2009) Heat-transport capability of pulsating heat pipes for microcapsule fluid. Journal of South China University of Technology(Natural Science Edition), 37:58-61.
[12] Kim, W., Kim, S.J. (2018) Effect of reentrant cavities on the thermal performance of a pulsating heat pipe. Applied Thermal Engineering, 133:567-577.
[13] Qu, J., Li, X., Wang, Q. (2017) Heat transfer characteristics of microgrooved oscillating heat pipes. Experimental Thermal and Fluid Science, 85:75-84.
[14] Qu, J., Sun, Q., Wang, H. (2019) Performance characteristics of flat plate oscillating heat pipe with porous metal-foam wicks. International Journal of Heat and Mass Transfer, 137:20-30.
[15] Ji, Y., Chen, H.H., Kim, Y.J. (2012) Hydrophobic surface effect on heat transfer performance in an oscillating heat pipe. Journal of Heat Transfer, 134:074502-074506.
[16] Lan, Z., Ma, X.H., Zhou, X.D. (2009) Theoretical study of dropwise condensation heat transfer: effect of the liquid-solid surface free energy difference. Journal of Enhanced Heat Transfer, 16:61-71.