Study on oscillatory heat transfer performance of single loop pulsating heat pipe

Zhuang Zhi \textsuperscript{1a}, Su Lei \textsuperscript{1b,}\textsuperscript{*}, Zheng Dingming \textsuperscript{1c}

\textsuperscript{1} School of Mechanical and Power Engineering, Nanjing Tech University, Nanjing, Jiangsu Province, China.

\textsuperscript{a}Email: 201861108003@njtech.edu.cn, \textsuperscript{b}Email: 201961108011@njtech.edu.cn.

\textsuperscript{c}Corresponding author: School of Energy Science and Engineering, Nanjing Tech University, Nanjing, Jiangsu Province 210000, China Email: sulei69@njtech.edu.cn.

Abstract. The heat transfer performance of single loop pulsating heat pipe (PHP) under different filling rates (FR) was studied experimentally. The temperature oscillation characteristics of the outer wall of the tube, the start-up characteristics under different heating power and the heat transfer characteristics between the tube wall and the working fluid are analyzed. The results show that the evaporation section has the uniform temperature characteristic, the uniform temperature characteristic of the condensation section is related to FR and heating power, there is an obvious temperature change in the adiabatic section. At 50\% FR, the working fluid is easier to start. At high power, the thermal resistance of phase change heat transfer between the tube wall and the working fluid has an obvious influence on the heat transfer performance, which cannot be ignored.

1. Introduction
Pulsating heat pipe (PHP) is a new and unique high-efficiency heat transfer element, which has the advantages of simple structure, convenient operation, no power drive and so on. It is considered to be a promising heat transfer element to solve the problem of high heat flux in small space. It has potential application prospect in the fields of electronic equipment, solar cell, fuel cell and so on [1].

The working fluid of PHP is generally non-uniformly distributed as vapor - liquid slug, the heat transfer is realized by self-excited motion caused by the pressure difference between evaporation section and condensation section. Therefore, the heat transfer mechanism of pulsating heat pipe is very complex and has become the focus of current research.

Shi et al. [2] observed that the flow patterns of the PHP are mainly bubble flow, plug flow and annular flow. Kim et al. [3] in the experimental study of water and ethanol pulsating heat pipe, it is found that when the filling rate (FR) is higher or the heat transfer power is larger, the working fluid in the pipe can form a unidirectional circulation flow in the loop. Ishii et al. [4] found that when the working fluid is an oscillatory flow, the temperature in any position in the tube will fluctuate, while in the circulating flow, the temperature of the working fluid becomes stable, the vibration frequency analysis shows that the circulating flow is periodic. Yang et al. [5] found through visualization experiments that under the same instantaneous mass flow, the flow pattern of pulsating flow is basically the same as that of continuous flow. Czajkowski et al. [6] found that 75\% FR of the water working fluid at high load, the heat transfer performance is the best, while at low load, the heat transfer performance is the best at 50\% FR. Luis et
al. [7] found that with the increase of the roughness of the evaporation section, the heat transfer performance is the best at lower FR.

In this paper, the wall temperature distribution, wall temperature oscillation characteristics and start-up performance of heat pipe under different heating power and FR are analyzed, through the experimental study of single-loop PHP. The heat transfer model of condensation and boiling of working fluid in PHP is established, the effects of heat transfer power and FR on the heat transfer performance of PHP are studied.

2. Experimental apparatus
The test facility consists mainly of PHP, heating system, cooling system and data acquisition system. The cooling system includes a cooling air duct, a fan, a drive power supply and a hot wire anemometer. The heating system includes adjustable DC power supply, insulating electric heating wire and thermal insulation material. The data acquisition system includes K-type thermocouple and data acquisition instrument. One end of the thermocouple is connected to the data acquisition instrument and the other end is connected to the computer to output test data. The test system is shown in Fig.1.

The test heat pipe was a single loop PHP with structural parameters as shown in Table 1. It was filled with liquid by the heat discharge method and placed vertically. The lower end was the evaporation section, the upper end was the condensation section and the middle was the adiabatic section. The heating section was tightly wound with electric heating wire, the cooling section was arranged in the air duct and was cooled by wind. As shown in Fig.2, 10 temperature measuring points were arranged on the outer wall of the heat pipe. No.1 to 5 were measuring points in the cooling section, No.6 to 10 were measuring points in the heating section. Before the cold test of the heat pipe, check that the error between the temperature of 10 measuring points and the ambient temperature was within 0.3 ℃. In addition, all test data are taken within 3 to 6 minutes after stable operation.

![Figure 1 diagram of experimental apparatus](image1.png)

![Figure 2 Temperature distribution of measuring points](image2.png)

**Table 1 Heat pipe structure and benchmark operating parameters**

| Pipe     | inner / outer diameter (d/D) | Tube length (l) | Evaporation length (le) | Adiabatic length (la) |
|----------|-------------------------------|-----------------|-------------------------|-----------------------|
| Copper tube | 0.003/0.004 m          | 0.4m            | 0.19m                   | 0.2m                  |
| Working fluid | Condensation length (lc) | Wind speed      | Wind temperature        |
| Water     | 0.19m                        | 5.2 m/s        | 20℃                     |

3. Analysis of experimental results
The wall temperature data of 10 measuring points under each stable working condition were tested when the heating power of the heat pipe was increased from 10W to 100W under 30%, 50% and 70% filling
rates (FR). Through data processing, the distribution characteristics of measuring point temperature with the arrangement position, the oscillation characteristics of heat pipe wall temperature and the start-up performance of heat pipe are analyzed.

3.1. Distribution characteristics of tube outer wall temperature

Fig. 3 shows the temperature distribution and variation of 10 measuring points with different power. The results show that the temperature of the measuring point in the evaporation section and condensation section of the heat pipe increases as a whole with the increase of heating power. However, the temperature of the five measuring points (No. 6-10) in the evaporation section of the heat pipe is basically not affected by the position and is very uniform and tends to be fixed. Only 30% FR heat pipe has a slightly lower temperature at point 10 at the bottom of the evaporation section. It shows that the endothermic process of the working fluid in the evaporation section is uniform. On the other hand, the temperature of the five measuring points (No. 1-5) in the condensation section is obviously affected by the heating power, the position of the measuring point and the liquid filling rate. When the liquid filling rate is more than 50% and the power is more than 60W, the temperature uniformity of the five measuring points in the condensation section is better. When the liquid filling rate is low (30% FR) and the heating power is less than 60W, the temperature of the measuring point in the condensation section increases slightly with the decrease of the position. The temperature of the adiabatic section realizes the transition from condensation temperature to evaporation temperature. On the whole, the temperature uniformity of evaporation section is better than that of condensation section.

![Figure 3](image)

Figure 3 Distribution of outer wall temperature of measuring point with layout position and power: (a), (b) and (c) are the temperature changes with 30% FR, 50% FR and 70% FR, respectively.

3.2. Oscillating characteristics of outer wall temperature

Fig. 4 shows the fluctuation of the temperature of 10 measuring points on the pipe wall with the heating power when the single-loop PHP is running stably at 50% FR. The results show that when the heating power is 10W, the wall temperature of the evaporation section rises slowly and decreases rapidly. On the contrary, the condensation section is characterized by slow decline and rapid rise, the interval between oscillations is longer, so it has the characteristics of starting vibration. When the heating power is 20–40W, the wall temperature oscillation of evaporation section and condensation section is zigzag, the amplitude and frequency are larger, but the oscillation is non-uniform, which is a large oscillation stage. When the heating power exceeds 50W, the wall temperature of evaporation section and condensation section fluctuates uniformly with fast frequency and small amplitude.

Fig. 5 shows the variation of the oscillation amplitude and frequency of the wall temperature of the PHP with heating power at different FR. The results show that FR and amplitude increase when the heating power is lower. When the heating power is higher, the effect of FR on the amplitude becomes smaller, the amplitude of the heating section is smaller than that of the cooling section. When the heating power is less than 50W, the maximum amplitude of 70% FR can reach 9–11K, the maximum amplitude of 30% FR is less than 8K. However, when the heating power is greater than 80W, the temperature amplitudes of 30% FR, 50% FR and 70% FR are all about 1.5K. From the change of vibration frequency,
when the heating power is 10W~40W, the oscillation frequency shows an upward trend, then oscillates in a high position. The average oscillation frequency of 50% FR is the highest, the average oscillation frequency of 30% FR is the lowest, and the maximum oscillation frequency of 70% FR is the highest. The wall temperature oscillation is mainly caused by different heat transfer capacity when the vapor-liquid slug flows alternately through the inner wall of the tube.

Figure 4 Temperature oscillation diagram at different power (50% FR): (a), (b) and (c) are temperature oscillation diagrams of some measuring points with power of 10W, 30W and 80W, respectively.

Figure 5 Oscillation amplitude and frequency of temperature under different power and filling rate: (a) and (b) are the temperature amplitudes of the evaporation and condensation sections respectively, and (c) are the temperature oscillation frequency.

3.3. Start-up heating power
As can be seen from Fig.5, when the heating power is 10W, the wall temperature of PHP with 30% FR and 50% FR oscillates, indicating that the working fluid has been started, while the vibration frequency with 70% FR is 0, the working fluid has not been started. From the perspective of start-up power, the start-up frequency of 50% FR is significantly faster than that of 30% FR, which means that the starting power of 50% FR is the lowest, followed by 30% FR and the starting power of 70% FR is the highest. It shows that PHP with intermediate FR has the best start-up performance, and the starting performance with low FR is better than that with high FR.

4. Heat transfer performance
The working fluid in PHP forms self-excited motion under the action of cold and heat sources. When the heating power is low, the flow presents an oscillatory flow in a single tube, the flow pattern is mainly bubble flow and plug flow. When the heating power is higher, the flow of the working fluid changes into unidirectional circulation flow, the flow patterns are mainly plug flow, semi-annular flow and annular flow.

At present, in the study of the heat transfer performance of PHP, the temperature of the outer wall measured by the test is generally regarded as the temperature of the internal working fluid, ignoring the influence of the thermal conduction resistance of the pipe wall, the convection heat transfer resistance of the inner wall and working fluid on the total thermal resistance in the process of heat transfer. In this paper, the suitable calculation methods of boiling heat transfer and condensation heat transfer are
determined according to the flow pattern and heat transfer characteristics of the working fluid in the evaporation section and the condensation section. The heat conduction resistance of pipe wall, the variation characteristics of phase change heat transfer resistance and working fluid heat transfer resistance with heating power. The influence of three kinds of thermal resistance on heat transfer performance of heat pipe are studied, the evaporation temperature and condensation temperature of working fluid in pipe are calculated.

The calculation method of boiling heat transfer and condensation heat transfer in tube in the reference "heat pipe technology and its engineering application".

\[
\tilde{h}_e = 0.32 \left[ \frac{\rho_l^{0.65} \lambda_l^{0.3} \mu_l^{0.7} g^{0.2} q_e^{0.4}}{\rho_v^{0.25} \mu_v^{0.4}} \right] \left( \frac{P}{p_0} \right)^{0.3} 
\]

\[
\tilde{h}_c = 0.943 \left\{ \frac{\rho_l g \lambda_l^{0.3} (\rho_l - \rho_v) [r + 0.68 c_p l (t - t_w)]}{\mu_l c_l (t - t_w)} \right\}^{0.25}
\]

Where: \(\tilde{h}_e\) and \(\tilde{h}_c\) are the phase change heat transfer coefficient of working fluid in evaporation section and condensation section respectively. \(\rho_l\) and \(\rho_v\) are the density of saturated liquid and gas respectively. \(c_p\) is the specific heat capacity of the liquid and gas. \(g\) is the acceleration of gravity. \(\mu\) is the latent heat of vaporization. \(r\) is the latent heat of vaporization. \(\mu\) is the thermal conductivity of the liquid. \(p_l\) and \(p_v\) are working fluid pressure and atmospheric pressure respectively. \(t\) and \(t_w\) are the working fluid temperature and the pipe wall temperature respectively.

Thermal conduction resistance of pipe wall:

\[
R_w = \frac{1}{2 \pi \lambda_w l_i \ln D/d}
\]

Heat resistance of convective heat transfer in tube:

\[
R_h = \frac{1}{\pi d_i l_i \tilde{h}_i}
\]

Thermal resistance of self-excited motion:

\[
R_1 = \frac{t_e - t_c}{Q}
\]

Total thermal resistance of heat pipe:

\[
R = R_{we} + R_{wc} + R_{he} + R_{hc} + R_1
\]

Where: \(\lambda_w\) is the thermal conductivity of the pipe wall. The subscript \(i\) represents the evaporation section \(e\) and the condensation section \(c\).

Figure 6 Change of heat transfer performance at different power: (a) and (b) are phase change heat transfer coefficients and different types of thermal resistance in evaporation and condensation sections at 50% FR, respectively. (c) is the thermal resistance at different FR.

As shown in Fig.6 (a), with the increase of heating power, the boiling heat transfer coefficient of pulsating heat pipe (PHP) with 50% filling rate (FR) increases, while the condensation heat transfer coefficient decreases. Meanwhile, the condensation heat transfer coefficient is much higher than the boiling heat transfer coefficient. In Fig.6 (b), the thermal resistance of self-excited motion is the largest.
which is the main thermal resistance of the total thermal resistance, and its change is consistent with the total thermal resistance. The phase change heat transfer thermal resistance of the tube wall increases with the increase of heating power, the proportion of the total thermal resistance increases and the proportion of more than 50W reaches 19%~25%. The influence cannot be ignored. On the other hand, the thermal resistance of the pipe wall is very small. Moreover, the change with power is very small, which can be ignored. In Fig.6 (c), the total thermal resistance of pulsating heat pipe decreases rapidly with the increase of heating power, and then tends to be stable. At low power (less than 50W), the effect of FR on the heat transfer performance of PHP is obvious, the thermal resistance increases with the increase of FR. When the power is more than 50W, the total thermal resistance of the three FR tends to be the same and reaches the minimum.

5. Conclusion
In this paper, the temperature uniformity, wall temperature oscillation and start-up performance of single-loop pulsating heat pipe (PHP), as well as the variation of heat transfer resistance with heating power and filling rate (FR) are studied. The conclusions are as follows:

1) The temperature uniformity of the evaporation section of the heat pipe is obvious, the temperature of the condensation section is affected by the power and FR and the temperature of the adiabatic section changes obviously.

2) With the increase of heating power, the tube wall temperature shows four stages: no oscillation, start oscillation, large oscillation and small uniform oscillation. The temperature amplitude in the stage of large oscillation increases with the increase of FR. The average vibration frequency of 50% FR is the highest, and that of 30% FR is the lowest.

3) The start-up power with 50% FR is the lowest, the start-up performance with 30% FR is better than that with 70% FR.

4) The total heat transfer resistance of PHP decreases with the increase of heating power and tends to be stable. At low power, the thermal resistance increases with the increase of liquid filling rate. Among them, the thermal resistance of self-excited motion is main thermal resistance of the total thermal resistance. At high power, the share of thermal resistance of convective heat transfer increases obviously, which cannot be ignored.

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