Experimental Study on the Starting-Up and Heat Transfer Characteristics of a Pulsating Heat Pipe under Local Low-Frequency Vibrations

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Abstract: Vibrations have attracted much attention as an effective method for enhancing heat transfer in pulsating heat pipes (PHPs). This study mainly investigates and explores the effects of local low-frequency vibrations on the starting-up and heat transfer characteristics of a PHP. The starting-up temperature and average temperatures along the evaporation section of the pulsating heat pipe were experimentally scrutinized, along with thermal performance, under local vibrations on evaporation, condensation and adiabatic sections, respectively. The following important conclusions can be derived by the experimental study: (1) The effect of vibrations at the evaporation section and at the adiabatic section during the starting-up time of the PHP were more significant than that at the condensation section; (2) vibrations at different positions could reduce the starting-up temperature of the PHP—the effect of the vibrations at the evaporation section was the best when heat power was lower, while the effect of vibrations on the adiabatic section was the best when heat power was higher; (3) vibrations at the evaporation and adiabatic sections could reduce the thermal resistance of the PHP, but vibrations at the condensation section had little effect on the thermal resistance of the PHP; (4) vibrations at the evaporation and adiabatic sections could effectively reduce the temperature at the evaporation section of the PHP, but the vibrations at the condensation section had no effect on the temperature at the evaporation section of the PHP. This paper shows that local low-frequency vibrations have positive effects on the heat transfer performances of PHPs.

Keywords: pulsating heat pipe; local vibration; starting-up characteristic; heat transfer performance

1. Introduction

A heat pipe, also known as a “thermal superconducting tube”, is a heat transfer technology developed in the 1960s. It adopts vaporization and condensation phase transformation of its internal saturated working medium to realize heat transfer. This phase transformation heat transfer mode has a very high heat transfer capacity. Compared with copper, aluminum and other metals with good heat conductivity, the heat transfer capacity of a heat pipe is several orders of magnitude higher [1]. In addition to its excellent heat transfer, a heat pipe has many other outstanding advantages, such as a good isothermal property, heat flux density variability, flow direction reversibility and environmental self-adaptability; hence, it has been widely used in the field of refrigeration and cryogenics, waste heat recovery and battery cooling, among others. Mosleh et al. [2] used a pulsating heat pipe (PHP) to replace the fins in an air-cooled heat exchanger, and found that the overall convective heat transfer coefficient could be increased by about 310%. Mahajan et al. [3] used a finned PHP in an HVAC air system to strengthen the heat exchange between airflows, and were able to improve heat exchange efficiency by about 50%. Chi et al. [4] used a PHP to solve the heating of lithium batteries in electric vehicles, and were able to greatly improve heat dissipation efficiency.
PHPs are a new type of heat dissipation device proposed by Akachi in the 1990s [5] that have increasingly studied by people due to the advantages of their simple structure, small volume, reliable operations, flexible arrangement and high heat transfer efficiency compared with traditional heat pipes. The working principle of PHPs is illustrated as follows: liquid working medium (distilled water, methanol, acetone, freon, etc.) in a serpentine capillary tube forms multiple liquid columns and a gas plug with different lengths under the action of surface tension; the gas and liquid plugs create an unstable, random pulsating flow between the evaporation and cooling sections due to the thermally heating force, which oscillates back and forth between evaporation and condensation to achieve efficient heat transfer.

Although the structure of PHPs is simple, the gas-liquid two-phase flow inside the heat pipe involves many heat transfer mechanisms, such as sensible heat transfer, latent heat transfer and expansion work. Studies have shown that the working medium, working conditions and geometric parameters of a PHP produce important effects on its starting-up and heat transfer characteristics. Kangli Bao et al. [6] and A. Gandomkar et al. [7] studied the effects of surfactants on the starting-up, operation and drying characteristics of PHPs. The results showed that surfactants could reduce thermal resistance and starting-up thermal load, and increase the heat load of burning and drying. To resolve the difficulty of starting a PHP at a low heating power, Zhang et al. [8] proposed a zeotropic immiscible mixture (HFE-7100) as the working fluid. The results indicated that, compared with water, the low latent heat of vaporization of HFE-7100 could accelerate the formation of bubbles in the evaporation section and starting-up of a PHP. In terms of working conditions, Ahmad et al. [9] investigated the influence of filling ratios of working fluid (ethanol) on the thermal performance of a PHP. The experimental results indicated that the optimal filling ratio was 50%, and the thermal resistance significantly decreased with an increase in the heat input power, for a filling ratio of 50% ethanol. Bai et al. [10] explored the effect of a vacuum on the heat transfer characteristics of PHPs charged with de-ionized water or Al$_2$O$_3$/water nanofluid. The experimental results showed that the vacuum degree had an important effect on the starting-up and heat transfer characteristics of the PHP, as the heat load was more than 90 W. Further, the starting-up heat load decreased with increased internal vacuum degrees in the PHP. Huang et al. [11] introduced a gas-liquid two-phase flow model into a heat transfer unit model with two gas plugs and one liquid plug, to study the influence of different fluid states of the PHP on its heat transfer characteristics. The results indicated that the improved model could better reflect the changes in heat transfer performance of the heat pipes under different heat load conditions. Other researchers have improved heat transfer performance by changing the structure’s form. For example, Bao et al. [12] proposed a metal foam multichannel heat pipe with distilled water as the working fluid, and studied its heat transfer characteristics. Compared with a traditional PHP, the metal foam multichannel heat pipe had superior heat transfer characteristics and superior temperature uniformity. Jiang et al. [13] proposed a novel saw-tooth corrugated structure PHP with two bends, which was proved to have much better thermal performance and shorter starting-up time than the traditional structure.

Since heat pipes have a complex gas-liquid two-phase pulsating flow, external vibrations affect the stability and thermal performance of their internal working medium to some extent. Thus, experimental research is imperative in order to fully understand the various properties and heat transfer mechanisms of heat pipes under a vibration environment. Alaei et al. [14] studied the results of low-frequency vibrations on a horizontal PHP, and found that low-frequency vibrations had a momentous effect on heat transfer performance and thermal resistance, achieving a minimum 0.05 K/W when the frequency was 25 Hz. In another study by Alaei et al. [15], the effects of low-frequency vibrations on a vertical heat pipe were experimentally investigated at different filling ratios, heat transfer rates and frequencies. A minimum thermal resistance of 0.064 K/W was achieved at a frequency of 30 Hz. Similarly, low-frequency vibrations have been experimentally proven to have a positive influence on the thermal performance of PHPs, due to the fact that low-frequency
vibrations can remove the dry-out point of a PHP [16]. Chen et al. [17] studied the influence of horizontal longitudinal vibrations on a grooved cylindrical pulsating heat pipe. The results showed that horizontal longitudinal vibrations can increase the heat flux of a heat pipe, and that the heat flux is directly proportional to the energy of vibration. Guo et al. [18] studied the influence of vertical vibrations on characteristics of liquid film flow in a vertical rectangular microgroove. The results showed that the dry-out point was raised and the wetting length was elongated as a result of the vibrations, which might be the reason for the heat transfer enhancement that occurred under the vibrations. Zhang et al. [19] investigated the influence of vibrations on convection heat transfer in a straight circular SiO$_2$–water nanofluids pipe. Experimental results showed that the forced heat transfer coefficient could be enhanced by the transverse vibration. Chen et al. [20] investigated the potential seismic vibration effect on a two-phase flow in an annular channel. In their study, an eccentric cam vibration module attached to an annular channel, the frequencies were 0.75–20 Hz. The void fraction was potentially decreased in a bubbly flow and a lower liquid flow under vibrations. In the bubbly-to-slug boundary region that was closed to transition, the void fraction was potentially increased under vibration, which could be the essential reason for the heat transfer enhancement resulting from the vibrations. Zhou [21] explored the effect of vibrations on the thermal performance of a PHP with different pipe diameters. The results revealed that the effect of the vibrations on the PHP increased with increases in pipe diameter.

The above literatures demonstrate that vibrations have an influence on the operations of PHPs. However, the current studies mainly focus on overall vibrations (i.e., transverse or vertical), including their frequencies as well as displacement. There is a lack of research about the influence of local vibrations and vibration positions on the starting-up and thermal performances of a PHP. This paper investigates the effects of local low-frequency vibrations on heat pipes through the use of micro motors. The micro motors were imposed on the external surface of the evaporation, condensation and adiabatic sections of the PHP, respectively. The starting-up temperature and the temperatures along the evaporation section, as well as the thermal resistance of the PHP, were experimentally studied under the effects of local vibrations at different positions.

2. Analysis Methods

2.1. Starting-Up Characteristics

A PHP can be deemed “starting-up” when the surface temperature of a heat pipe begins to show peak-and-trough oscillations. Meanwhile, the starting-up of a PHP can also confirmed by using the distribution theory of statistical random variables (i.e., as long as the heat pipe’s temperature exceeds $[t_0 - 3\sigma, t_0 + 3\sigma]$ (where $\sigma$ is the standard deviation of the random variable), the PHP can be considered as started).

2.1.1. Starting-Up Time

The starting-up of a PHP is a random quasi-steady state process. Before starting, the PHP needs a certain amount of time to accumulate heat and increase the temperature of the working medium in the pipe until the starting condition is reached. The time elapsed from the beginning of the input heat load to the starting-up of the PHP is defined as the starting-up time of the PHP.

2.1.2. Starting-Up Temperature

Before the PHP starts, the working medium is in a state of equilibrium. During the starting process, the working medium needs to accumulate a large amount of heat until a certain temperature is arrived at. During the experiment, the temperature required for starting-up the PHP at the evaporation section is defined as the starting-up temperature of the PHP.
2.1.3. Starting-Up Power

One of the driving forces of the working fluid in a PHP is the pressure difference caused by bubble expansion, which results from the contraction that occurs after being heated in the evaporation section then being cooled in the condensation section. The bubble needs to absorb a large amount of heat in the evaporation section to ensure the growth process, so there should be a minimum thermal power that can generate enough pressure difference to promote the flow of the working medium. The minimum power for starting the PHP is the starting-up power of the PHP.

2.2. Thermal Performance Evaluation Index

The thermal performance of a PHP mainly includes thermal resistance. Thermal resistance \( R \) of a PHP mainly consists of heat conduction resistance of the heat pipe wall, phase change heat transfer resistance and convection heat transfer resistance. This can be calculated using Equation (1):

\[
R = \frac{t_c - t_e}{P}
\]

where \( R \) is the total heat transfer resistance (K/W); \( P \) is the heating load in the evaporation section (W); and \( t_c \) and \( t_e \) are the average temperature in the condensation and evaporation sections, respectively (°C).

3. Experimental System and Accuracy Analysis

3.1. Experimental System

A PHP was made using a quartz glass tube. Detailed dimensions of the PHP are shown in Table 1. Miniature vibrating motors were installed on different sections of the PHP (i.e., evaporation section, condensation section and adiabatic section). The detailed positions of the temperature sensors and miniature vibrating motors on the PHP for the experimental study are shown in Figure 1. The working medium of the PHP was deionized water, the thermophysical properties of which are shown in Table 2. The filling rate was 45%. An enameled Ni-Cr resistance wire was used for heating the evaporation section, and heat power was controlled by a DC power supply. The product of the input voltage and the input current of a DC regulated supply is considered the heating power of a PHP. The measurement accuracies of the voltage and current were 0.1V and 0.01A, respectively. In order to reduce the heat loss caused by convection and radiation, the heating part was wrapped with a thermal insulation film. The condensation section was cooled using an axial flow fan. In order to make the cooling air speed uniform and reduce the loss of cooling air, an air duct was designed (size: 500 × 365 × 175 mm) and the PHP was vertically inserted into the air duct. The speed of air cooling was 4.7 m/s. The temperature of the indoor environment was 8.5 °C, and the air humidity was 38.2%. The experimental setup for testing the thermal characteristics of the PHP is shown in Figure 2.

Table 1. Detailed dimensions of the PHP.

| Geometric Parameter                  | Numerical Value |
|-------------------------------------|-----------------|
| Inner diameter (m)                  | 0.002           |
| Outer diameter (m)                  | 0.006           |
| Number of elbows                    | 5               |
| Elbow spacing (m)                   | 0.06            |
| Elbow outside diameter (m)          | 0.036           |
| Evaporation length (m)              | 0.1             |
| Condensation length (m)             | 0.15            |
| Adiabatic length (m)                | 0.05            |
Figure 1. Positions of the temperature sensors and miniature vibrating motors on the PHP for the experimental study.

Table 2. Thermophysical properties of the working medium (in a saturation state, the qualitative temperature is 60 °C).

| Thermophysical Parameter                       | Numerical Value |
|-----------------------------------------------|-----------------|
| Density (kg/m$^3$)                            | 983.1           |
| Specific enthalpy (kJ/kg)                     | 251.1           |
| Specific heat at constant pressure (kJ/(kg · K)) | 4.179           |
| Thermal conductivity (W/(m·K))                | 0.659           |
| Thermal diffusion coefficient (m$^2$/s)       | $1.6 \times 10^{-7}$ |
| Dynamic viscosity (Pa·s)                      | $4.699 \times 10^{-4}$ |
| Kinematic viscosity (m$^2$/s)                 | $4.78 \times 10^{-7}$ |
| Pr                                            | 2.99            |

Figure 2. Cont.
Experimental setup: (a) diagrammatic sketch; (b) photo (in order to show the heating mode and thermal resistance position, the heating part was not wrapped with thermal insulation film when shooting).

3.2. Accuracy Analysis

In this experiment, PT100 thermal resistance (class A) was used for temperature measurement, and the measurement error was ±0.15 °C. The lowest temperature measurement point in this experiment was 20 °C, so the maximum error of temperature can be calculated using Equation (2):

\[
\frac{\delta t}{t} = 0.75\% \tag{2}
\]

where \( t \) is the temperature of the PT100 thermal resistance (°C).

The voltage and current were read by the DC power supply with a display accuracy of 1%. The voltage range was 0~30 V and the current range was 0~5 A. When heat power was 40 W, the minimum voltage and current were 27.2 V and 1.47 A, respectively, and the minimum temperature difference in the adiabatic section of the evaporation section was 31.5 °C; so, the maximum relative error of the thermal resistance can be calculated using Equation (3):

\[
\frac{\delta R}{R} = \sqrt{\left( \frac{\delta t_e}{t_e - t_c} \right)^2 + \left( \frac{\delta \tau}{t_e - t_c} \right)^2 + \left( \frac{\delta U}{U} \right)^2 + \left( \frac{\delta I}{I} \right)^2} = 3.6\% \tag{3}
\]

where \( t_e \) and \( t_c \) are the temperature of the condensation and evaporation sections, respectively, and \( U \) and \( I \) are the voltage and current of the DC power supply, respectively.

4. Results and Discussion

4.1. Influence of Vibrations on Temperature Characteristics of PHP

Figure 3 shows temperature curves at the evaporation section of the PHP under different vibration positions (i.e., evaporation section, adiabatic section and condensation section) in the case of a 40 W heating power. As shown in Figure 3, the four temperature curves basically overlapped in the preheating process. This is because most of the heat during the preheating process comes from heating wire, and the heat generated by vibrations is small and negligible. As time passed, the PHP under the vibration condition started first, while the PHP under the non-vibration condition started later, showing that vibrations shorten the preheating time of the PHP and accelerate the start. This is because the pressure difference accumulated by boiling the working medium in the evaporation section cannot
push the liquid plug in the tube to the condensing section when the heating time is short, and thus the PHP cannot be started. The presence of vibrations at any section of the PHP can destroy the boundary layer of the working medium on the wall of the tube and strengthen the convective heat transfer between the working medium and the wall of the tube, while vibrations can also accelerate the escape of the bubbles generated by the boiling of the working medium and accelerate the accumulation rate of the pressure difference in the gas plug. It can be seen in Figure 3 that the starting-up temperature was the highest in the case of no vibration, followed by the case of condensation vibrations, while the evaporation and adiabatic vibrations were the lowest. This is because evaporation and adiabatic vibrations can destroy the boundary layer of the working medium on the pipe wall and reduce the resistance of the liquid plug to move from the evaporation section to the condensation section, therefore permitting it to start at a lower evaporation temperature. However, vibrations at the condensation section could only enhance the convective heat transfer between the tube wall and the cooling air, and thus the effect of the vibrations on the starting-up time at the evaporation and adiabatic sections was more significant than that at the condensation section.

![Image](image_url)

**Figure 3.** Temperature characteristics at the evaporation section of the PHP under different vibration positions (heating power 40 W).

Figure 4 presents the influence of different vibration positions on the temperature at the evaporation section of the PHP under different heating power levels. It can be seen from Figure 4 that with heat power increasing, the temperature at the evaporation section first increased, then temporarily remained unchanged before continuing to increase. This phenomenon can be explained as follows: when heat power was low, the thermal resistance of the PHP was large and the heat transfer performance was poor, so the PHP cannot effectively discharged heat, resulting in a temperature rise in the evaporation section with the increase of heating power. With heating power further increasing, the thermal resistance of the PHP decreased and the heat transfer performance improved, hence the temperature at the evaporation section did not increase any further. However, as heat power continued to increase to a certain value, the decrease in thermal resistance of the PHP was not obvious, so the temperature at evaporation section began to rise once again. Comparing the temperature at the evaporation section under different vibration positions, it can be seen that the vibrations at the evaporation section and at the adiabatic section could effectively reduce the temperature at the evaporation section under the lower heating...
power level. For example, when heat power was 40 W, the vibration had the best effect on reducing the temperature at the evaporation section. In this case, the temperature at the evaporation section could be reduced from 81 to 62 °C after the vibrations were introduced. However, with heat power increasing, the effect of vibrations on the temperature at the evaporation section became weakened until it disappeared.

![Figure 4. Influence of different vibration positions on the temperature at the evaporation section of the PHP under different heating power levels.](image)

4.2. Influence of Vibrations on the Starting-Up Temperature

In order to further analyze the impact of vibrations on the starting-up temperature of the PHP and to compare the impact of different vibration positions, the starting-up temperatures of the PHP were measured at heat powers of 40, 60, 80, 100 and 120 W under no vibration and different vibration positions (i.e., the evaporation, adiabatic, and condensing sections). The results are plotted in Figure 5. As shown in Figure 5, in the case of no vibration, the starting temperature decreased first, then increased with the increase of heating power. The phenomenon can be explained by as follows: when heat power is low, the PHP needs a long time to start until the evaporation section has heated to a high temperature. With the increase of heating power, the starting-up time of the PHP becomes shorter and shorter, and the starting-up evaporation temperature is reduced. When heat power is increased, the PHP can quickly start, and the effect of heating power on the starting-up time becomes smaller. At the same time, the increase of heating power results in a higher evaporation temperature rate. As a result, the evaporation temperature increases as the PHP is starting.

By comparing the starting-up temperatures of different vibration positions under the same heating power, it can be seen that the starting-up temperature of the three vibration positions was lower than that of the non-vibration conditions, indicating that the vibration could reduce the starting-up temperature of the PHP at all three different positions. When heat power is low, vibrations at the condensing section will reduce the starting-up temperature more effectively. When heat power is high, vibrations at the evaporation and adiabatic sections will better reduce the starting-up temperature.
Figure 5. Influence of vibrations at different positions on the starting-up temperature of the PHP under different heating power levels.

4.3. Influence of Vibrations on the Starting-Up Time

Figure 6 presents the influence of vibrations on the starting-up time of the PHP under different heating power levels (40, 60, 80, 100, and 120 W). As shown in Figure 6, the starting time decreased with an increase in heating power. This is because the higher the heat power is, the faster the bubbles are generated in the evaporation section. As a result, the pressure difference among the evaporation and condensation sections can reach the critical pressure difference of startup more quickly. Meanwhile, it can be seen from Figure 6 that the decreasing speed of the starting time decreased with the increase in heating power, until the final starting time basically did not change with any further increase in heating power. This is because it is difficult to start a PHP when heat power is low, and increasing heat power can significantly reduce the starting time. By comparing the starting time of different vibration conditions under the same heating power, it can be seen that the starting times of the three vibration conditions were smaller than those of the no-vibration condition under all heating powers, indicating that vibrations can effectively reduce the starting time.

From Figure 6, we can also see that when heat power was low, vibrations had a significant effect on the reduction of the starting time. However, with the increase of heat power, the reduction effect became worse and worse. This is because when heat power is small, the PHP is difficult to start and external vibrations can greatly reduce the start time, whereas when heat power is increased, the PHP can start faster, and the effect of the vibrations is not obvious.
4.4. Influence of Vibrations on the Thermal Resistance

Figure 7 shows the influence of different vibration positions on the thermal resistance of a PHP under different heating power levels (i.e., 40, 60, 80, 100 and 120 W). It can be seen from Figure 6 that the slope of thermal resistance decreased with increased heating power. This is because with the increase of heating power, the bubble formation rate was accelerated in the evaporation section, and the gas plug and liquid plug moved faster to the condensation section, improving the heat transfer performance. Comparing the thermal resistance of different vibration positions under the same heating power, it can be seen that the vibrations at the evaporation and adiabatic sections brought about significant reductions in the thermal resistance of the PHP, while the vibrations at the condensation section had little influence on the thermal resistance of the PHP. The reason for this is that vibrations at the evaporation and adiabatic sections can be conducive to bubble separation and enhance the convective heat transfer between the working medium and pipe wall, so as to accelerate the bubble formation rate. Although the vibrations at the condensation section can also strengthen the convective heat transfer between the working medium and pipe wall, the thermal resistance at the condensation section was itself much smaller than that at evaporation and adiabatic sections, resulting in the vibrations at the condensation section had a relatively little impact on the thermal resistance of the PHP. The results in Figure 7 also show that the influence of vibrations on the thermal resistance of the PHP became increasingly smaller with increases in the heating power level. This is because when heat power is high, the bubble formation rate in the evaporation section will be very fast, and the enhancement effect of the vibrations is not obvious.
4.5. Influence of Vibration Frequency on the Starting-Up Time and Thermal Resistance

According to the previous experimental results, the evaporation section vibration had a better start-up and heat transfer performance of PHP compared with those of the condensation section vibration, adiabatic section vibration, or without vibration. Therefore, experiments were carried out under the condition of the evaporation section vibration, with the vibration frequencies changed to 200, 250, and 300 Hz, respectively, to study the influences of vibration frequency. The changes in start-up time and thermal resistance with heating power under different vibration frequency conditions are shown in Figures 8 and 9. It can be seen from the figures that the vibration frequency did not alter the variation of the start-up time and thermal resistance which changed with heating power. However, under the same conditions, increasing the vibration frequency did shorten the start-up time and reduce thermal resistance, especially when heat power was low. This is because the greater the vibration frequency, the faster the vibration speed and acceleration, and the easier the bubbles generated in the evaporation section can separate under the action of inertial force, which speeds up the accumulation of pressure difference in the PHP, so as to speed up the start-up speed. At the same time, the increase of vibration velocity and acceleration enhanced the disturbance of the boundary layer of the working medium in the evaporation section, reducing the thickness of the boundary layer and enhancing the convective heat transfer between the working medium and the inner wall of the PHP and improving the heat transfer performance of the PHP. However, when heat power is significant, bubble generation was accelerated in the evaporation section, the pressure difference in the PHP accumulated rapidly, and the improvement effect of vibration frequency was relatively weakened, so the effect was not obvious.
Figure 8. Influence of vibration frequency on the starting-up time of the PHP under different heating power levels (vibration on the evaporation section).

Figure 9. Influence of vibration frequency on the thermal resistance of the PHP under different heating power levels (vibration on the evaporation section).

4.6. Visualization Experiments

In order to reveal the influence mechanism of vibrations on the starting-up characteristic of the PHP, a high-speed camera (shooting time interval 0.1 s) was used to film the evaporation section of the PHP, and the bubble generation and rupture states were compared at the evaporation section under a non-vibration condition and a vibration condition, as shown in Figure 10. In Figure 10, 12 pictures (i.e., a total of 1.2 s) can be seen of bubbles from generation to bursting under the vibration-free condition, while under the...
vibration condition there are only six pictures (i.e., a total of 0.6 s). These phenomena infer that the vibrations in the evaporation section can accelerate the escape speed of the boiling bubbles of the working medium, which is conducive to the start of the PHP.

![Dynamic photos (shooting time interval: 0.1 s) of bubble generation and rupture in the evaporating section of the PHP under (a) vibration-free condition, and (b) vibration condition.]

Meanwhile, the gas plug pulsating velocity under the vibration-free condition and the vibration condition were observed by the high-speed camera as well, and are shown in Figure 11. The results in Figure 11 show that the gas plug pulsating velocity under the vibration condition was significantly higher than under the vibration-free condition.
Figure 11. Dynamic photos (shooting time interval: 0.1 s) of gas plug movement under (a) vibration-free condition, and (b) vibration condition.

5. Conclusions

This experimental study mainly investigated the influence of vibration positions on the starting-up and heat transfer characteristics of a PHP, providing a reference for the selection of vibration positions in vibration-enhanced PHP heat transfer performance. The following conclusions can be made:

1. The starting-up time of the PHP decreases with increases in heating power level. The vibrations at different positions can reduce the starting-up time of PHP, and the smaller the heat power level is, the better the reduction effect will be. The effects of vibrations at the evaporation and adiabatic sections on the starting-up time of the PHP were more significant than that at condensation section;

2. The starting-up temperature of the PHP initially decreased, then increased with an increase in heat power level. The vibrations at different positions could reduce the starting-up temperature of the PHP. The effects of the vibrations at the evaporation section were best when heat power was lower, and the effects of the vibrations at the adiabatic section were best when heat power was higher;

3. The thermal resistance of the PHP decreased with increases in heat power level. The vibrations at the evaporation and adiabatic sections could reduce the thermal resistance of the PHP. The smaller the heat power level is, the better the reduction effect achieved by the vibrations at the evaporation and adiabatic sections. However, the vibrations at the condensation section had little effect on the thermal resistance of the PHP;

4. With increasing heating power, the evaporation section temperature of the PHP initially increased, after which it temporarily remained unchanged, before continuing to increase again. Under lower heating power, vibrations at the evaporation and adiabatic sections can effectively reduce the temperature at the evaporation section of the PHP, but vibrations at the condensation section have no effect on the temperature at the evaporation section of the PHP.
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**References**

1. Tuckerman, D.B.; Pease, R.F.W. High-performance heat sinking for VLSI. *IEEE Electron Device Lett.* 1981, 2, 126–129. [CrossRef]

2. Mosleh, H.J.; Bijarchi, M.A.; Shafii, M.B. Experimental and numerical investigation of using pulsating heat pipes instead of fins in air-cooled heat exchangers. *Energy Convers. Manage.* 2019, 181, 653–662. [CrossRef]

3. Mahajan, G.; Thompson, S.M.; Cho, H. Energy and cost savings potential of oscillating heat pipes for waste heat recovery ventilation. *Energy Rep.* 2017, 3, 46–53. [CrossRef]

4. Chi, R.-G.; Chung, W.-S.; Rhi, S.-H. Thermal Characteristics of an Oscillating Heat Pipe Cooling System for Electric Vehicle Li-Ion Batteries. *Energies* 2018, 11, 655. [CrossRef]

5. Akachi, H. Structure of a Heat Pipe. U.S. Patent 4921041, 1 May 1990.

6. Bao, K.; Wang, X.; Fang, Y.; Ji, X.; Han, X.; Chen, G. Effects of the surfactant solution on the performance of the pulsating heat pipe. *Appl. Therm. Eng.* 2020, 178, 115678. [CrossRef]

7. Gandomkar, A.; Kalan, K.; Vandadi, M.; Shafii, M.B.; Saidi, M.H. Investigation and visualization of surfactant effect on flow pattern and performance of pulsating heat pipe. *J. Therm. Anal. Calorim.* 2020, 139, 2099–2107. [CrossRef]

8. Zhang, C.; Xu, R.; Chen, J.; Wu, Q. Analysis of start-up characteristics of pulsating heat pipe with zeotropic immiscible mixtures. *Chem. Ind. Eng. Prog.* 2019, 38, 5279–5286.

9. Ahmad, H.; Kim, S.K.; Jung, S.Y. Analysis of thermally driven flow behaviors for two-turn closed-loop pulsating heat pipe in ambient conditions: An experimental approach. *Int. J. Heat Mass Transf.* 2020, 150, 119245.1–119245.13. [CrossRef]

10. Bai, L.; Ren, X.; Yang, W. Vacuum effect on heat transfer performance of the pulsating heat pipe. *Cryog. Supercond.* 2019, 47, 62–66.

11. Huang, X.; Lu, X.; Xu, G.; Chen, X.; Duan, Y. Analysis of flow pattern and heat transfer characteristics of pulsating heat pipes under different thermal loads. *Appl. Energy Technol.* 2019, 11, 13–20.

12. Bao, K.; Hua, C.; Wang, X.; Han, X.; Chen, G. Experimental investigation on the heat transfer performance and evaporation temperature fluctuation of a new-type metal foam multichannel heat pipe. *Int. J. Heat Mass Transf.* 2020, 154, 119672. [CrossRef]

13. Jiang, E.; Zhang, D.; Zhou, J.; Chao, S. Numerical simulation of pulsating heat pipes with two-bends in different structures. *J. Chem. Ind.* 2019, 70, 244–249.

14. Alaei, A.; Kafshgari, M.H.; Atashi, H. A new designed heat pipe: An experimental study of the thermal performance in the presence of low-frequency vibrations. *Heat Mass Transf.* 2012, 48, 719–723. [CrossRef]

15. Alaei, A.; Kafshgari, M.H.; Rahimi, S.K. A vertical heat pipe: An experimental and statistical study of the thermal performance in the presence of low-frequency vibrations. *Heat Mass Transf.* 2013, 49, 285–290. [CrossRef]

16. Alaei, A.; Kafshgari, M.H. Low-Frequency vibrations on the thermal performance of an oscillating heat pipe. *Ind. Eng. Chem. Res.* 2014, 53, 12179–12183. [CrossRef]

17. Chen, R.H.; Lin, Y.J.; Lai, C.M. The influence of horizontal longitudinal vibrations and the condensation section temperature on the heat transfer performance of a heat pipe. *Heat Transfer Eng.* 2013, 34, 45–53. [CrossRef]

18. Guo, C.; Hu, X.; Cao, W. Effect of mechanical vibration on flow and heat transfer characteristics in rectangular microgrooves. *Appl. Therm. Eng.* 2013, 52, 385–393. [CrossRef]

19. Zhang, L.; Lv, J.; Bai, M. Effect of vibration on forced convection heat transfer for SiO-Water nanofluids. *Heat Transfer Eng.* 2015, 36, 452–461. [CrossRef]

20. Chen, S.W.; Hibiki, T.; Ishii, M. Experimental investigation of horizontal forced-vibration effect on air-water two-phase flow. *Int. J. Heat Fluid Flow* 2017, 65, 33–46. [CrossRef]

21. Zhou, H. Study on Flow and Heat Transfer Performance of Pulsating Heat Pipe under Vibration. Master’s Thesis, Suzhou University of Science and Technology, Suzhou, China, 2019.