

Article

Experimental Study on the Effect of Inclination Angle on the Heat Transfer Characteristics of Pulsating Heat Pipe under Variable Heat Flux

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Abstract: This paper aims to deeply explore the influence of different inclination conditions on the heat transfer characteristics and broaden the application scene of a pulsating heat pipe. A test device for the heat transfer performance of a pulsating heat pipe under different inclination angles is designed and built. Under the condition of 70% liquid filling rate, ethanol and HFE-7100 are selected to carry out the experimental test with heating power of 40–140 W and dimensionless thermal difference of 0–0.56. The heat transfer performance, the temperature in the evaporation section and the internal pressure fluctuation of the pulsating heat pipe were experimentally studied. The results show that under the condition of uniform heat flux, for ethanol working medium, when the pulsating heat pipe is heated at 40 W, the operating thermal resistance varies significantly with different installation angles. At this time, the operating thermal resistance of a pulsating heat pipe with installation angles of 45°, 70°, 90° and D90° is 1.38 °C/W, 1.60 °C/W, 1.73 °C/W and 2.07 °C/W, respectively. With the increase in installation angle, the operating thermal resistance also increases gradually, reaching the maximum at 90°. At low heating power, the effect of the installation angle on the ethanol working medium is significantly greater than that of HFE-7100 working medium. The HFE-7100 working medium showed lower operating thermal resistance at low heating power, but with the increase in heating power, the operating thermal resistance of the two working medium gradually approached a 70% filling rate. Under non-uniform heating conditions, when HFE-7100 is used as a working fluid, the operating thermal resistance of a pulsating heat pipe under different heating power was lower than that of the ethanol working medium. The operating thermal resistance is less affected by the installation angle, and the overall heat transfer performance is better. The phenomenon in which the ethanol working medium is obviously affected by the installation angle can be improved by non-uniform heating conditions. For ethanol working medium, when the dimensionless heat difference reaches 0.33 under the condition of a 45° installation angle, the average temperature fluctuation in the evaporation section appears gentle. At this installation angle, the internal working medium of the four elbow pulsating heat pipe devices used in this research more easily forms a cycle in the pipe than the 90° installation angle.

Keywords: pulsating heat pipe; thermal behavior; liquid filling rate; dimensionless thermal difference; installation angle



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1. Introduction

Pulsating heat pipe is a kind of heat transfer element. Its effective thermal conductivity is dozens of times that of common metals. Because of its simple structure, low-priced of manufacture and excellent isothermal property [1,2], it is widely used in data center

cooling [3–6], solar water heater [7,8], low-temperature refrigeration and other fields. A lot of research related to it has been applied in engineering [9]. The installation angle of the pulsating heat pipe will affect the heat transfer characteristics of the pulsating heat pipe [10]. This is because gravity causes the liquid in the pulsating heat pipe to condense back and interact with the surface tension to affect the movement of the gas–liquid plug in the pipe. The change of installation angle of a pulsating heat pipe affects the vertical gravity of the working medium in a pulsating heat pipe [11].

Since the pulsating heat pipe was put forward, scholars have studied in order to find out the influence degree of gravity on the pulsating heat pipe. Zhang Xianming et al. [12] studied the influence of inclination angle on the heat transfer performance of a pulsating heat pipe through the test-bed. It was found that the heat transfer performance changed greatly when the inclination angle was 0–30°, while the temperature and thermal resistance at the heating-up section remained at a low level when the inclination angle was 30–90°. Rao et al. [13] selected inclination angles of 0°, 30° and 60° for the experiment. The results show that the horizontal direction has a great influence on other operating parameters such as liquid filling rate and heating power. Wang Yu et al. [14] found that the heat transfer performance is the strongest when the installation angle is vertical. Especially for the single loop pulsating heat pipe, gravity has a great impact on its heat transfer performance.

Pulsating heat pipe has attracted more and more attention since it was invented due to its excellent heat transfer performance [15–19]. Pulsating heat pipes seem simple in structure, but their actual operation characteristics are very complex, mainly involving phase change heat transfer, two-phase flow, fluid mechanics and other related disciplines [20]. In order to understand the complex working mechanism of pulsating heat pipes, researchers have conducted extensive and in-depth study on them. In terms of the method and content of the research, it can be divided into three aspects: theoretical research, application research and experimental research. Among them, the theoretical research is mainly to reveal the heat and mass transfer mechanism in the pulsating heat pipe by building a theoretical model and to predict the flow and temperature state of the working medium in the pulsating heat pipe. The application research is to better combine the pulsating heat pipe with engineering practice under the support of experimental data and the mechanism revealed by theoretical research. The experimental study is to explore the relationship between the flow characteristics and heat transfer performance of a pulsating heat pipe working medium and various parameters so as to provide guidance for the performance optimization of a pulsating heat pipe in practical application.

At present, researchers at home and abroad focus on the experimental research of pulsating heat pipes, mainly focusing on the influence of various experimental parameters and on the performance of various kinds of pulsating heat pipes [21–26]. There are few studies on the influence of different inclination angles on heat transfer characteristics of pulsating heat pipes. In order to better understand the influence of gravity on pulsating heat pipes and provide data and theoretical support for the selection of pulsating heat pipes in practical applications, it is necessary to study the heat transfer performance of pulsating heat pipes in the process of inclination variation.

Based on the above reasons, the experimental platform of a pulsating heat pipe with different inclination angles was built in this paper. The heat transfer performance, evaporation section temperature and internal pressure fluctuation characteristics of a pulsating heat pipe were studied by using ethanol and HFE-7100 working medium with the heating power of 40–140 W and the dimensionless thermal difference of 0–0.56 under the condition of a 70% liquid filling rate.

2. Experimental System and Data Processing

2.1. Experimental Device of Pulsating Heat Pipe with Different Inclination

The experimental device for the effect of inclination on the performance of pulsating heat pipe is shown in Figure 1. The integral device which can adjust the angle through the steering angle piece is fixed on the aluminum alloy support. The device consists of a

heating device, cooling water circulating device, data measurement and acquisition device, four elbow pulsating heat pipes, vacuum pumping and liquid injection device. After summarizing the research of different scholars [27–31] and fully considering the influence of the number of elbows on the operation performance of a heat pipe, the number of elbows of a pulsating heat pipe is 4. The overall shape of the pulsating heat pipe is like a snake winding, which is formed by bending a copper pipe with an inner diameter of 2 mm and an outer diameter of 3 mm. The lengths of the insulation section, evaporation section and condensation section are 108 mm, 40 mm and 40 mm, respectively. Heat conductive silicone grease is evenly applied on the surface of the copper pipe in the heating section, and the surface is evenly wound with electric heating wire. The heating power is provided by two DC regulated power supplies of the same model (UTP1306S), which independently control the heating power of heating sections A and B. The power can be adjusted by the knob on the DC power supply. Two different heating sections, A and B, are shown in Figure 2. The condensation section is welded with the copper pipe by a slotted red copper block, and the outer wall of the copper pipe is directly contacted with the cooling water for cooling. The brushless DC water pump with adjustable power provides power for cooling water circulation. The rotameter monitors the circulating water flow.

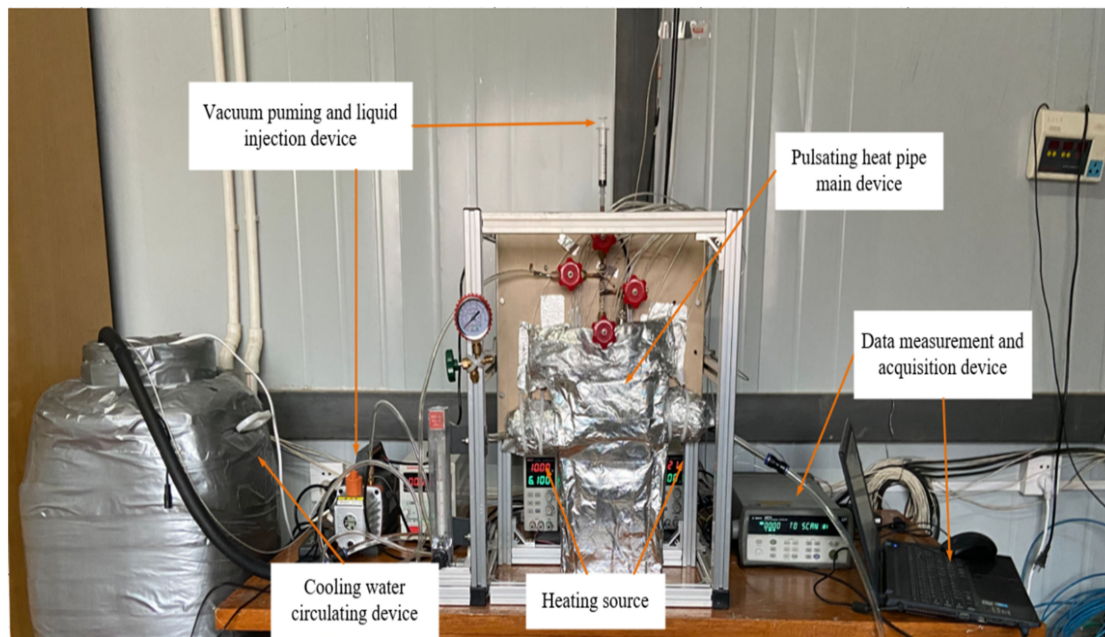


Figure 1. Physical diagram of pulsating heat pipe experimental device with non-uniform heating.

The integral device of a pulsating heat pipe which can adjust the angle through the steering angle piece is fixed on the aluminum alloy supportas shown in Figure 3. We adjust the angle between the horizontal plane and the pulsating heat pipe through the steering angle piece to 45° , 70° and 90° , respectively. At the same time, the side setting condition of a pulsating heat pipe ($D90^\circ$) is selected as the installation angle to broaden the use scene of a pulsating heat pipe. Bottom heating is adopted. In order to reduce heat loss and further ensure the accuracy of the experiment, 25 mm thick glass fiber insulation cotton is wrapped around the pulsating heat pipe and outside the cold clot.

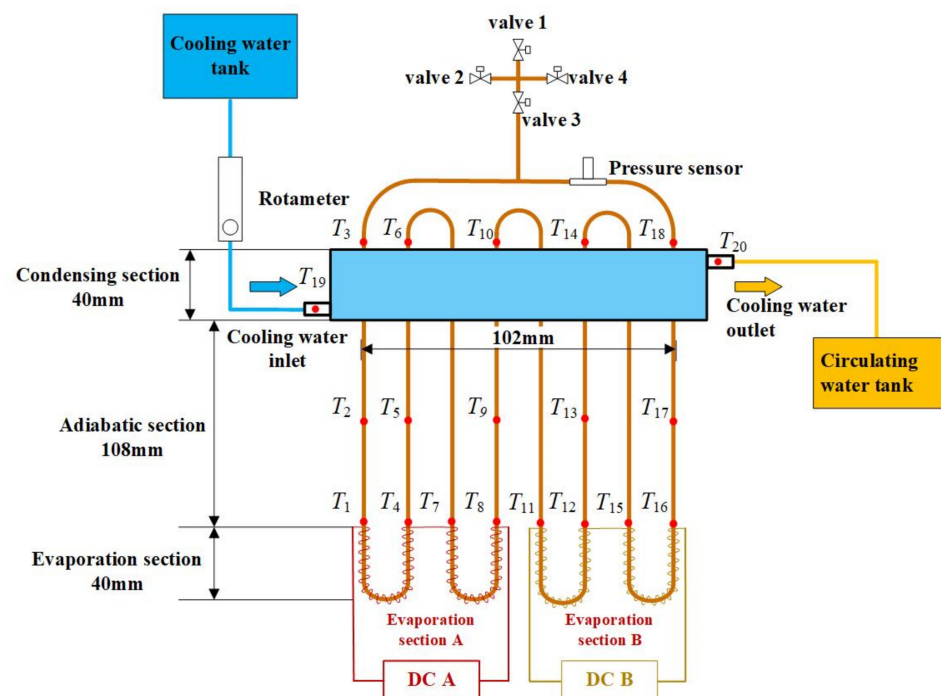


Figure 2. Schematic diagram of pulsating heat pipe experimental device with non-uniform heating.

Data measurement includes temperature measurement and pressure measurement. Temperature acquisition is a key part of the test performance. In this system, the temperature of the pulsating heat pipe is measured by the patch-type PT100 platinum resistance temperature sensor. The temperature core of the sensor and the part of the pulsating heat pipe to be installed are pasted with thermal grease and fixed with aluminum foil tape. In this experiment, a total of 18 temperature sensors are arranged on the surface of the heat pipe, including 8 at the evaporative end, 5 at the adiabatic end and 5 at the condensing section. The specific temperature measurement points are shown in Figure 2. A probe-type PT100 platinum resistance temperature sensor was placed at the geometric center point of the room to measure the indoor ambient temperature, and the indoor ambient temperature was controlled by the air source heat pump system to maintain it at 25 °C. The pressure transmitter is installed on the top of the heat pipe device and connected with the pipe channel by welding. The output signals of the pressure sensor and temperature sensor are collected by Agilent 34970A data acquisition instrument, and the collection time interval is 1 s [32].

In the national standard, PT100 has two grades A and B, and the measurement range is -200 to $+850$ °C. Grade A precision is $(0.15 + 0.002 \cdot |t|)$ °C; B grade accuracy is $(0.30 + 0.005 \cdot |t|)$ °C; where $|t|$ is the absolute value of the actual temperature. The measurement accuracy of the rotor flowmeter is level 4, that is, $(\text{measurement upper limit} - \text{measurement lower limit}) \times 4\%$. The physical quantity and accuracy measured in the experiment are shown in Table 1.

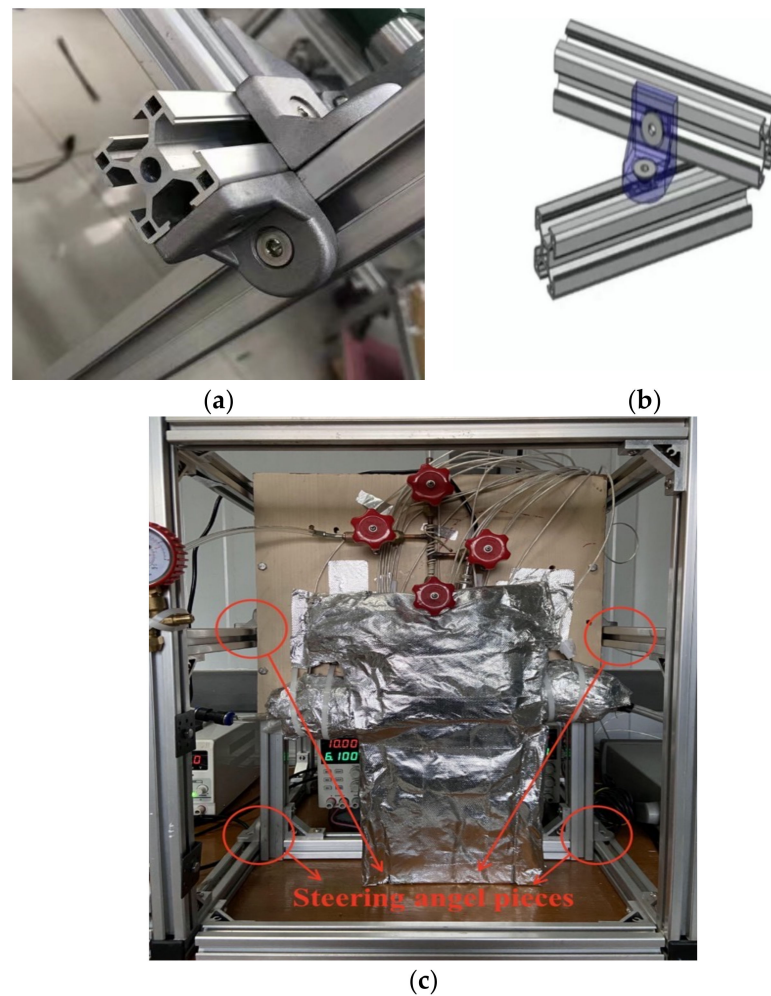


Figure 3. Angle adjustment diagram of non-uniform heat flux heating pulsating heat pipe experimental device. (a) Details of steering corner pieces. (b) Three-dimensional drawing of steering angle. (c) Installation position of multiple steering angle pieces.

Table 1. Measuring physical quantity and precision of experimental device.

Measure Physical Quantity	Temperature	Pressure	Heating Power	Flow
Measurement method	Temperature sensor	Pressure sensor	DC regulated power supply	Rotameter
Type	PT100	UNF/7/16	UTP1306S	LZB-6
Measuring range	−50 to 650 °C	−0.1 to 1 MPa	0–32 V, 0–6 A	6–60 L/h
Measurement accuracy	Level B	0.5%FS	$\leq 0.1\% + 10 \text{ mV}$, $\leq 0.2\% + 3 \text{ mA}$	Level 4

2.2. Experimental Working Medium and Working Conditions

In this experiment, ethanol and HFE-7100 are selected for the working substance. HFE-7100 is a hydrofluoroether compound, which has good thermal and chemical stability. The thermal physical properties of the two working fluids at 25 °C are listed in Table 2. The filling ratio (FR) of the working medium in the pulsating heat pipe is 70%. Due to the start-up conditions and heat transfer limit of the pulsating heat pipe used in this study, 40 W, 50 W, 60 W, 70 W, 80 W, 90 W, 100 W, 120 W and 140 W are selected as the heating power. We adjust the angle between the horizontal plane and the pulsating heat pipe through the steering angle piece to 45°, 70° and 90°, respectively. At the same time, the side setting condition (D90°) of the pulsating heat pipe is selected.

Table 2. Thermophysical parameters of ethanol and HFE-7100 at 25 °C.

Physical Properties	Ethanol	HFE-7100	Unit
Molecular formula	C ₂ H ₅ OH	C ₄ F ₉ OCH ₃	—
Molecular weight	46.06	250	g/mol
Boiling point	78.24	61	°C
Density	0.785	1.51	g/cm ³
Specific heat	2434.60	1183	J/(kg·K)
Latent heat of vaporization	920.66	112	kJ/kg
Viscosity	1.0817	0.61	Pa·s
Surface tension	21.97	13.60	mN/m
(dp/Dt)	601	1318	Pa/°C

The non-uniform heat flux condition in the experiment is set as follows: the heating power of heating section A is set to a constant value of 20 W, while the heating power of heating section B increases gradually. The power configuration of different heating sections under the condition of uniform heat flux is shown in Table 3. The power configuration of different heating sections under the condition of non-uniform heat flux is shown in Table 4.

Table 3. Heating power configuration of heating section A and B under the condition of homogeneous heat flux.

Designation	Numerical Value						Unit
Total heating power	40	60	80	100	120	140	W
Heating section A	20	30	40	50	60	70	W
Heating section B	20	30	40	50	60	70	W

Table 4. Heating power configuration of heating section A and B under the condition of non-uniform heat flux.

Designation	Numerical Value					Unit
Total heating power	50	60	70	80	90	W
Heating section A	20	20	20	20	20	W
Heating section B	30	40	50	60	70	W
Dimensionless thermal difference	0.20	0.33	0.43	0.50	0.56	—

2.3. Key Indicators of Pulsating Heat Pipe

In order to distinguish the temperature distribution at the cold and hot ends of pulsating heat pipes under different heating conditions, and to know whether there is special vibration inside the pulsating heat pipe, the temperature difference between the cold and hot ends ΔT is introduced. This physical quantity is defined as,

$$\Delta T = \overline{T_e} - \overline{T_c} \quad (1)$$

where $\overline{T_e}$ and $\overline{T_c}$ represent the average temperature of the evaporation section and condensation section of the pulsating heat pipe, respectively (°C). Its calculation formula is as follows,

$$\overline{T_e} = \frac{1}{n_1} \sum_{i=1}^{n_1} T_i \quad (2)$$

$$\overline{T_c} = \frac{1}{n_2} \sum_{j=1}^{n_2} T_j \quad (3)$$

where n_1 and n_2 represent the number of temperature sensors arranged in the evaporation section and condensation section of the pulsating heat pipe, respectively.

The whole thermal resistance of the pulsating heat pipe was analyzed.

$$R = \frac{\Delta T}{Q} \quad (4)$$

where R is the thermal resistance of the pulsating heat pipe ($^{\circ}\text{C}/\text{W}$). Q is the heat transfer of the pulsating heat pipe (kg/s). It can be calculated from the following formula,

$$Q = c_p \dot{m} (T_{20} - T_{19}) \quad (5)$$

where T_{19} and T_{20} represent the water inlet temperature and water outlet temperature of the condensate block, respectively ($^{\circ}\text{C}$). c_p is the specific heat at constant pressure ($\text{J}/(\text{kg}\cdot\text{K})$). $\dot{m}$ is the mass flow rate of cooling water (kg/s).

The dimensionless thermal difference is defined as the ratio of the input power difference of DC power sources A and B to the total input power. (Q_A in this study is a constant value of 20 W). It is defined as,

$$\varepsilon = \frac{Q_B - Q_A}{Q_{\text{total}}} \quad (6)$$

where ε is the dimensionless heat difference, indicating the degree of power difference between two input heat sources.

2.4. Error Analysis of Experiment

In order to ensure the accuracy of the experimental instruments used in this experiment, systematic error analysis of the experimental results is carried out in this paper [33]. The direct measurement errors in the experiment include: temperature (T), flow (q), voltage (U), current (I) and pressure (P). The temperature measurement accuracy is $\pm 0.3^{\circ}\text{C}$, and the minimum temperature measured in the experiment is 20°C . The measurement accuracy of the flow rate is 1 L/h, and the flow rate is set to 25 L/h in the experiment. The measurement accuracy of the pressure sensor is ± 5.5 kPa, and the minimum pressure is 60 kPa after filling the liquid. In addition, the error propagation law is used to calculate the indirect measurement uncertainty of heating power P , thermal resistance R and heat transfer Q . The details are as follows,

$$\frac{\delta Q}{Q} = \frac{1}{c_p m (t_{20} - t_{19})} \left[\left(\frac{\partial Q}{\partial t_{20}} \right)^2 \delta t_{20}^2 + \left(\frac{\partial Q}{\partial t_{19}} \right)^2 \delta t_{19}^2 + \left(\frac{\partial Q}{\partial q} \right)^2 \delta q^2 \right]^{\frac{1}{2}} \quad (7)$$

$$\frac{\delta R}{R} = \left(\frac{\Delta t}{Q} \right)^{-1} \left[\left(\frac{\partial R}{\partial \Delta t} \right)^2 \delta \Delta t^2 + \left(\frac{\partial R}{\partial Q} \right)^2 \delta Q^2 \right]^{\frac{1}{2}} \quad (8)$$

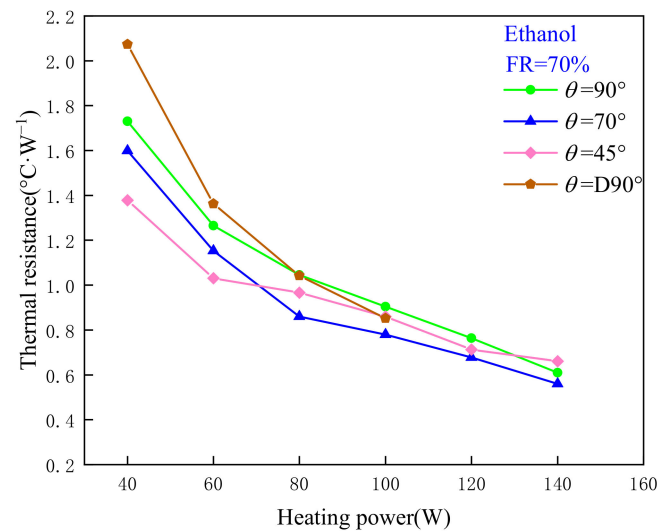
$$\frac{\delta p}{p} = \frac{1}{UI} \left[\left(\frac{\partial P}{\partial U} \right)^2 \delta U^2 + \left(\frac{\partial P}{\partial I} \right)^2 \delta I^2 \right]^{\frac{1}{2}} \quad (9)$$

Through error analysis, the maximum uncertainty of volume flow rate, temperature, heating power, pressure, heat transfer and heat transfer resistance in the experiment are 4%, 1.5%, 0.18%, 9.2%, 4.5% and 5%, respectively.

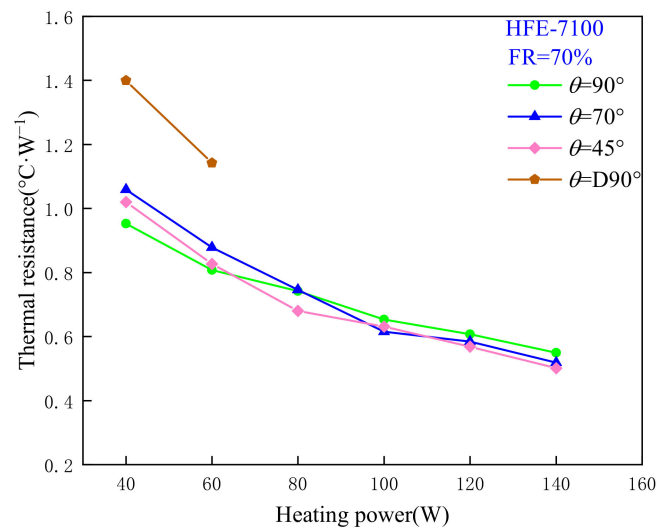
3. Analysis of Influence Characteristics of Installation Angle of Pulsating Heat Pipe

The thermal resistance comparison of pulsating heat pipes with ethanol and HFE-7100 as working fluids under different heating power and installation angles is shown in Figure 4. The filling rates of both working fluids are 70%. It can be seen from Figure 5 that the operating thermal resistance of the pulsating heat pipe filled with two working fluids is negatively correlated with the heating power. When the heating power is 40 W,

different installation angles have a great influence on the thermal resistance of the pulsating heat pipe filled with ethanol working medium. With the increase in installation angle, the thermal resistance of operation also increases gradually, reaching the maximum value at 90° . With the increase in heating power, the influence of installation angle on the operating thermal resistance begins to decrease gradually. After the heating power reaches 80 W, the influence degree is obviously reduced. When the heating power is 120 W, the installation angle has little effect on the operating thermal resistance of pulsating heat pipes.

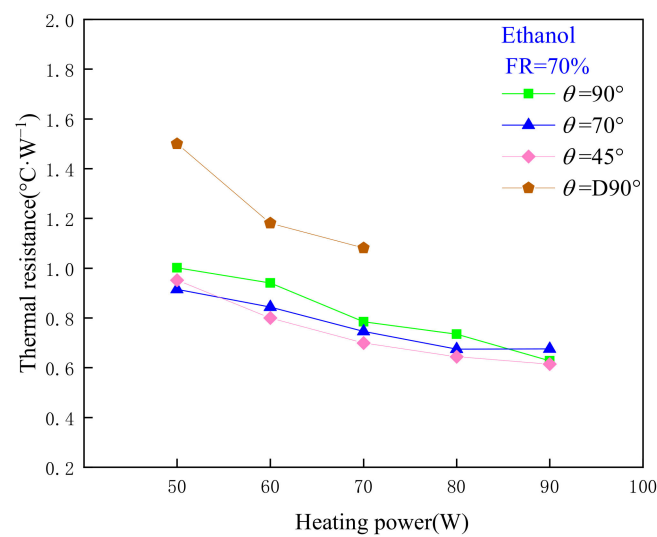


(a)

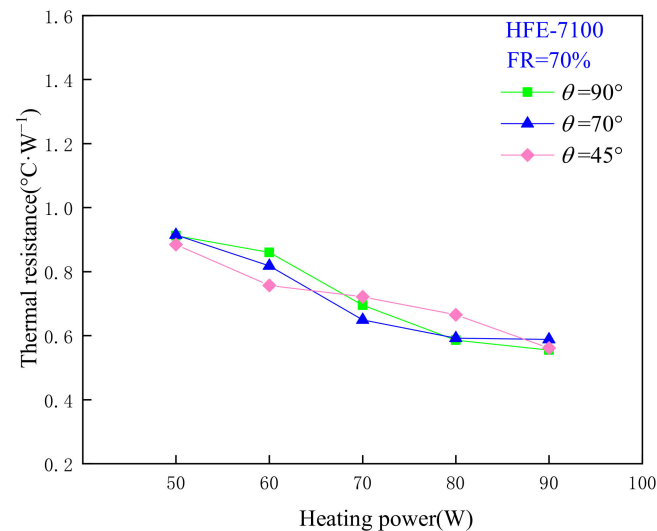


(b)

Figure 4. Variation of thermal resistance of pulsating heat pipe with installation angle under homogeneous heat flux: (a) Ethanol (b) HFE-7100.



(a)



(b)

Figure 5. Variation of thermal resistance of pulsating heat pipe with installation angle under non-uniform heat flux: (a) Ethanol (b) HFE-7100.

This is because the number of gas plugs formed in the pulsating heat pipe is related to the heating power of the heat pipe. When the heat pipe is at high heating power, the number of gas plugs formed in the heat pipe increases. At this time, the main pulsating power inside the heat pipe comes from the thermal driving force of the gas plug, which accelerates the flow of working medium in the pipe and reduces the influence of the installation angle. At low heating power, due to the long formation time and small number of gas plugs in the heating section, the thermal driving force of gas plugs is not enough to overcome the influence of gravity and surface tension, resulting in an obvious difference in thermal resistance during operation.

When the pulsating heat pipe is installed on the side (D90°), the action direction of gravity on the working medium is changed, which reduces the ability of the working medium to return to the evaporation section, reduces the working medium circulation ability of the pulsating heat pipe and increases the operating thermal resistance. The experimental results obtained in this paper under the installation angles of 45°, 70° and 90°

are similar to those obtained by Zhao Jiateng [30] in the experiment of pulsating heat pipes with three bends. With the increase in heating power, the thermal resistance of the pulsating heat pipe decreases in the angle range, which is obviously affected by the installation angle. Under the same installation angle, with the increase in heating power in the evaporation section, its thermal resistance gradually decreases: with the increase in heating power, the angle range where the thermal resistance is significantly affected by the installation angle decreases.

For the pulsating heat pipe whose working medium is HFE-7100, the installation angle has little influence on the operating thermal resistance. The overall performance of heat transfer is good. When the heating power is 40 W, the operating thermal resistance of the pulsating heat pipes installed at 45°, 70° and 90° are 1.02 °C/W, 1.05 °C/W and 0.95 °C/W, respectively. There is no obvious difference in operating thermal resistance between installation angles. The thermal resistance of the pulsating heat pipe filled with HFE-7100 working medium is lower than that of the pulsating heat pipe filled with ethanol working medium under different heating powers. The pulsating heat pipe filled with HFE-7100 working medium has good heat transfer performance. According to the physical parameters of the two working fluids, it can be inferred that compared with the working fluid ethanol, the working fluid HFE-7100 has a low boiling point and low latent heat of vaporization. So, it is easier to form a gas plug under low power and promote the internal working medium to form circulating flow faster. As a result, when the pulsating heat pipe is installed on the side (D90°), the evaporating section of a pulsating heat pipe filled with working medium HFE-7100 is easier to dry out due to the rapid formation of the gas plug. The heat transfer performance deteriorates, thus reducing the heat transfer limit.

The variation of operating thermal resistance of the pulsating heat pipe device under non-uniform heat flux with installation angle is shown in Figure 6. It can be seen from Figure 6 that under the condition of non-uniform heat flux, there is no obvious difference in the influence of installation angle on the heat transfer performance of pulsating heat pipes filled with two kinds of working medium, both of which reflect low thermal resistance in operation. By comparing the operating thermal resistance of the two kinds of working medium, it can be found that the variation range of the operating thermal resistance of the pulsating heat pipe filled with the two kinds of working medium is close to each other under the non-uniform heating condition. This is because the pulsating heat pipe device under the condition of non-uniform heat flow density has different heating powers in heating section A and B, resulting in different heating temperature rise. The high power side produces more gas plugs, which reduces the influence of gravity and resistance on the working medium and speeds up the circulating flow. For the pulsating heat pipe filled with HFE-7100 working medium, when it is under non-uniform heating, the evaporation section of the heat pipe will burn off under the condition of side installation (D90°), so that it cannot operate.

The flow resistance of the working medium in the pipe is reduced when the side position of the pulsating heat pipe is chosen as the installation angle. At the same time, the lateral position also results in a decrease in the gravitational force and a decrease in the liquid reflux capacity. The low latent heat of vaporization of working medium HFE-7100 results in the formation of a large number of gases plugs in the evaporation section during non-uniform heating. However, under such conditions, the reflux capacity of the working medium is weakened, and a small part of the reflux working medium is rapidly vaporized. The gas plug formed will squeeze the working medium in the condensation section and make it unable to reflux, resulting in heat transfer deterioration. It can be seen from the experimental results that the influence of installation angle on the liquid-filled working medium ethanol pulsating heat pipe can be improved by non-uniform heating conditions.

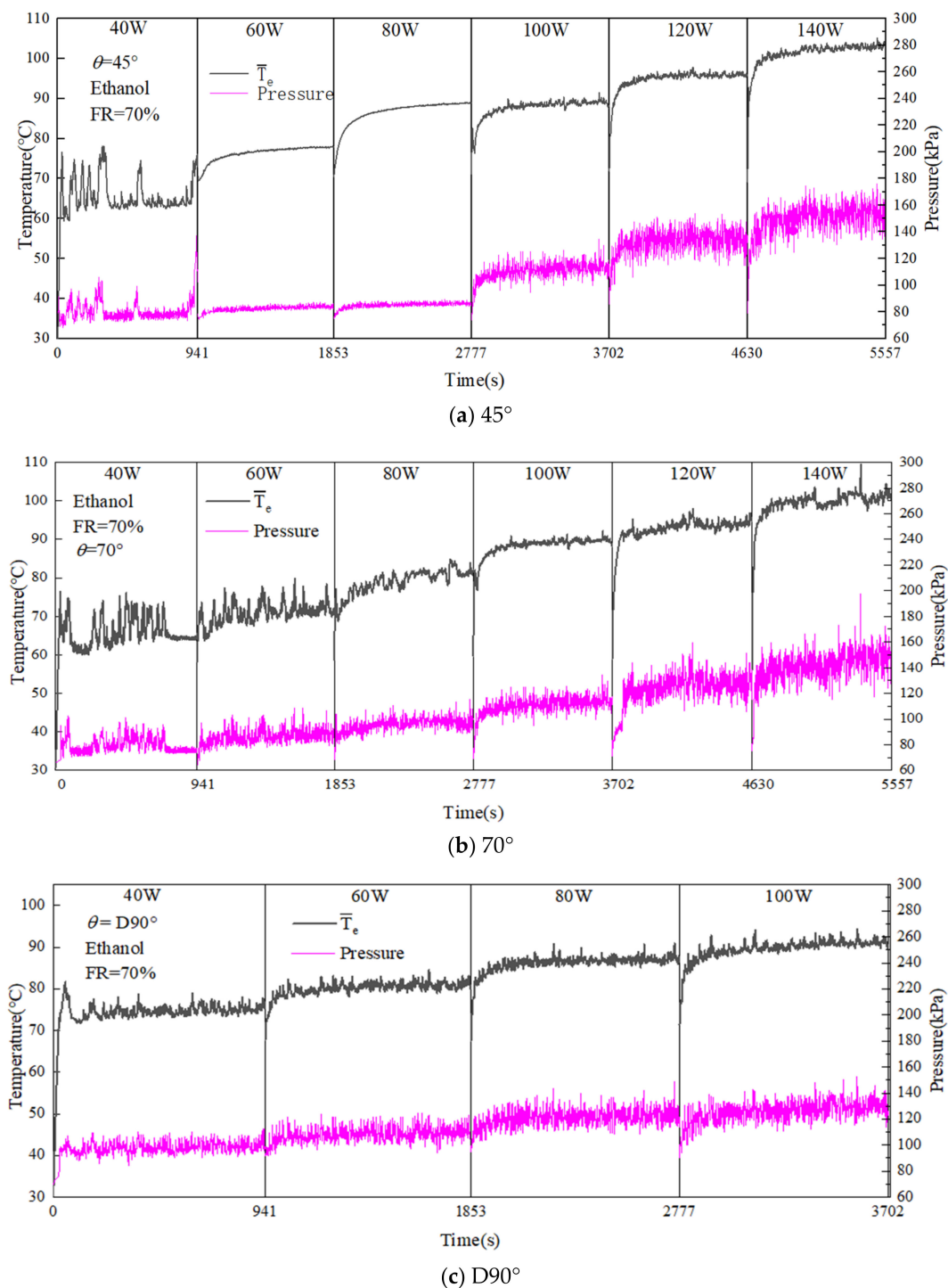


Figure 6. Variation of temperature and internal pressure of evaporation section with time under different installation angles of ethanol working medium.

4. Variation Characteristics of Temperature and Internal Pressure in Evaporation Section of Pulsating Heat Pipe at Different Installation Angles

4.1. Under the Condition of Uniform Heat Flux

The evaporation temperature and internal pressure of the pulsating heat pipe with a 70% filling rate of ethanol and HFE-7100 at different installation angles are shown in Figures 7 and 8 over time. As we can be seen from Figure 7, compared with the installation angle of 90°, the fluctuation range of temperature and internal pressure in the evaporation

section of the pulsating heat pipe is low when the installation angle of the working medium ethanol is 45° , and the average evaporation section temperature of the pulsating heat pipe is lower in the whole operating range. When the pulsating heat pipe device is at the installation angle of 70° , the temperature fluctuation degree of the evaporation section under different heating power is lower than the installation angle of 90° . When the heating power reaches 60 W, the temperature of the evaporation section of the pulsating heat pipe has shown a gentle fluctuation state, while the temperature of the evaporation section of the pulsating heat pipe under the same heating power at the installation angle of 90° still fluctuates violently. When the device is at high power, the temperature of the evaporative section of the pulsating heat pipe does not fluctuate greatly, and the temperature stays stable during operation.

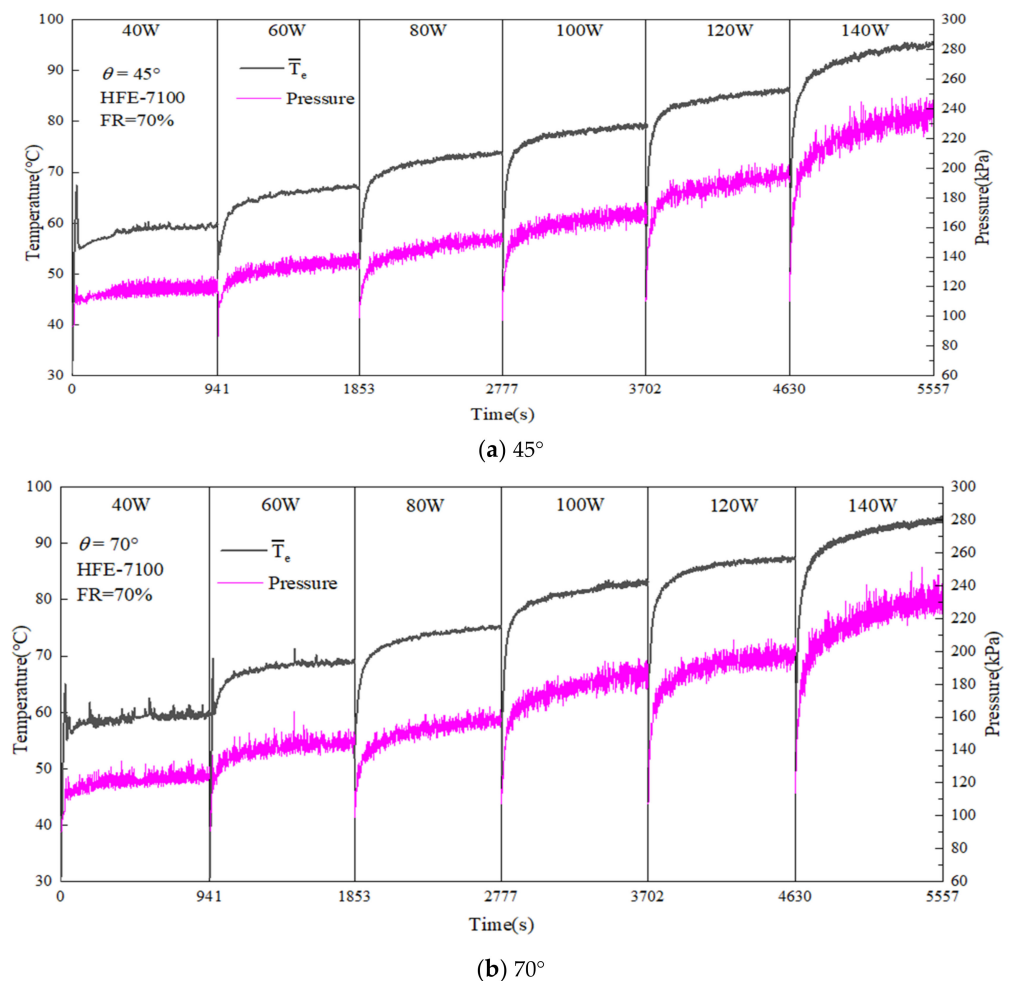


Figure 7. Variation of temperature and internal pressure of evaporation section with time under different installation angles of HFE-7100 working medium.

The pulsating heat pipes of HFE-7100 working medium also show more uniform evaporation temperature at the installation angle of 45° compared with 90° at the heating power of 40 W and 60 W. The experimental results of the two kinds of working medium indicate that the internal working medium of the pulsating heat pipe device used in this experiment is easier to form circulating flow in the pipe at the installation angle of 45° than at the installation angle of 90° . This is because when the liquid filling rate is high and the heating power is low, the working medium exists in the form of a long liquid plug due to the narrow channel in the pipe, and the gas generated in the evaporation section needs to overcome the gravity of the liquid plug to circulate heat exchange. When the installation angle is 45° , the direction of gravity on the working material is changed, reducing the

gravity that the gas plug needs to overcome. At the same time, the flow resistance of the working medium is reduced, making it easier for the internal working medium to form a cycle. Therefore, at low power, the average temperature of the evaporation section is lower when the installation angle is 45° compared with 90° , and the working medium with low surface tension shows a more stable fluctuation. When the pulsating heat pipe is installed on the side ($D90^\circ$), the fluctuation range of temperature in the evaporation section of the pulsating heat pipe is more stable than that in the installation condition of 90° , the fluctuation range of pressure is smaller, but the heat transfer limit is lower. When the experimental heating power was 120 W, the phenomenon of drying appeared. This is because the working medium in the pipe is provided with smaller reflux power by gravity, and the flow speed of the working medium is slow. The heat transfer at the lower end of the heating section in the vertical direction of the thermostat device deteriorates. Without the influence of gravity between the elbows, it is difficult to press the working medium back to the evaporation section for heat transfer, which leads to the heat transfer limit lower than the vertical installation angle. The slow flow of the internal working medium also reduces the impact on the probe of the pressure sensor, making the pressure fluctuation range in the tube lower.

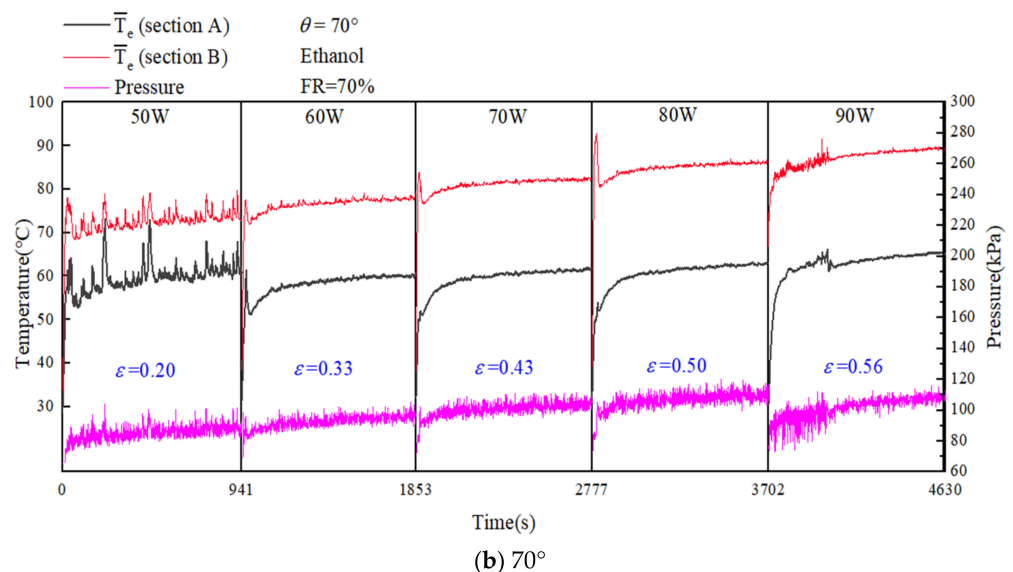
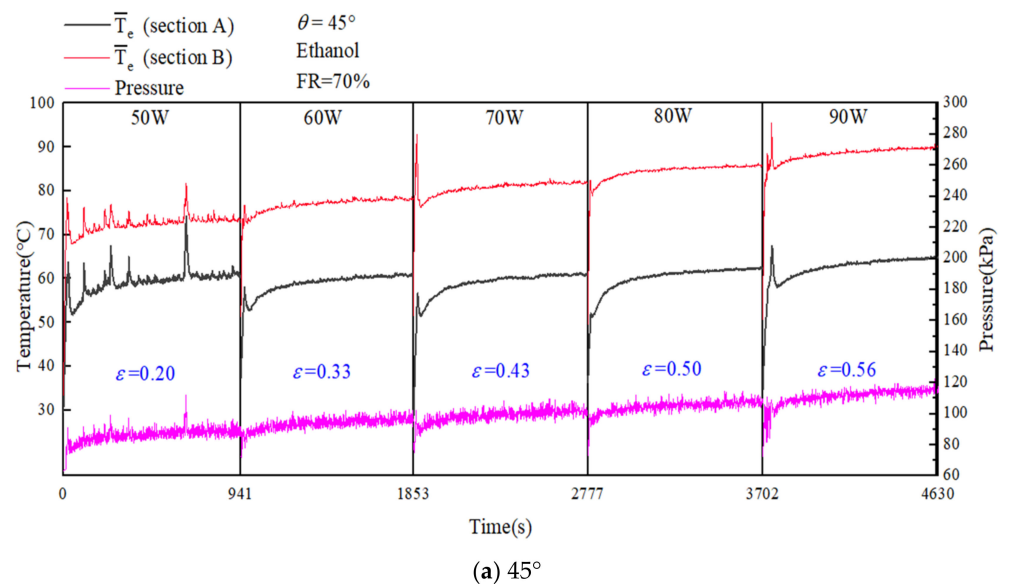


Figure 8. Cont.

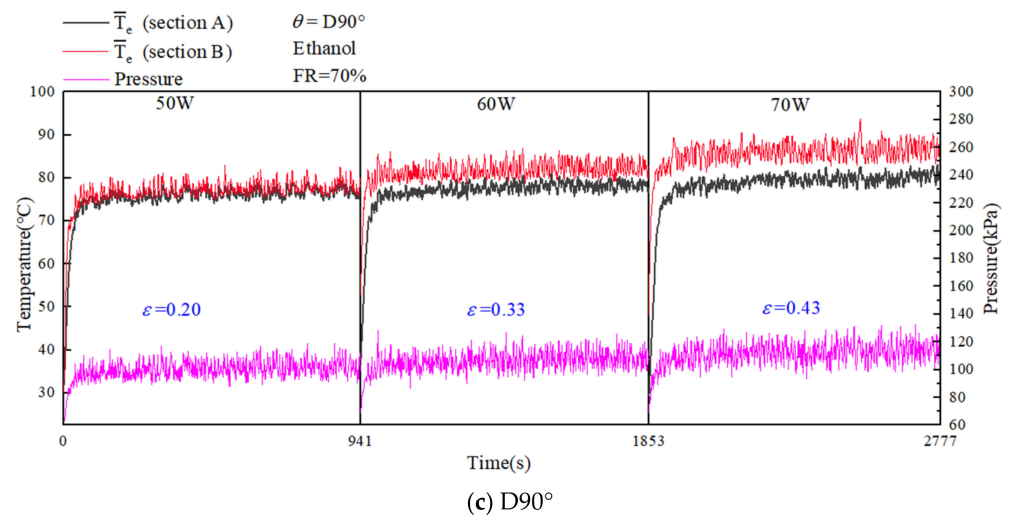


Figure 8. Variation of average temperature and internal pressure of evaporation section with time under different installation angles of ethanol working medium.

4.2. Under the Condition of Non-Uniform Heat Flux

The variation of average temperature in evaporation section of the pulsating heat pipe with running time was studied under the condition of non-uniform heat flux. Due to the different heating powers of the heating section A and B, the evaporation section A and B of the device are discussed separately.

In the case of non-uniform heat flux heating with a 70% filling rate, the average temperature and internal pressure of the evaporation section of ethanol and HFE-7100 working medium at different installation angles change with time, as shown in Figures 8 and 9. For the working medium of ethanol, when the dimensionless thermal difference reaches 0.33 at the installation angle of 45°, the fluctuation of average temperature in the evaporation section shows a gentle phenomenon. Under uniform heating, the same experimental phenomenon also appeared in ethanol working medium with a 70% liquid filling rate. This is because when the pulsating heat pipe device is placed at a low installation angle, it can reduce the flow resistance and make the average temperature fluctuation in the evaporation section more moderate.

When HFE-7100 working medium is installed at a 45° angle of pulsating heat pipe, the average temperature of the evaporation section is relatively close in different operating intervals. When the installation angle of the pulsating heat pipe is 70°, the phenomenon of high temperature start appears when the heating power is 60 W and 70 W. When the ethanol working medium is installed on the side of the pulsating heat pipe (D90°), the temperature of the evaporation section has no obvious peak in different operating intervals, but it reaches the heat transfer limit when the dimensionless heat difference is greater than 0.43. This proves once again that the flow resistance of ethanol working medium with a high filling rate is larger in the pipe. After the arrangement of reducing flow resistance is adopted, the temperature difference between the two evaporation sections can be reduced.

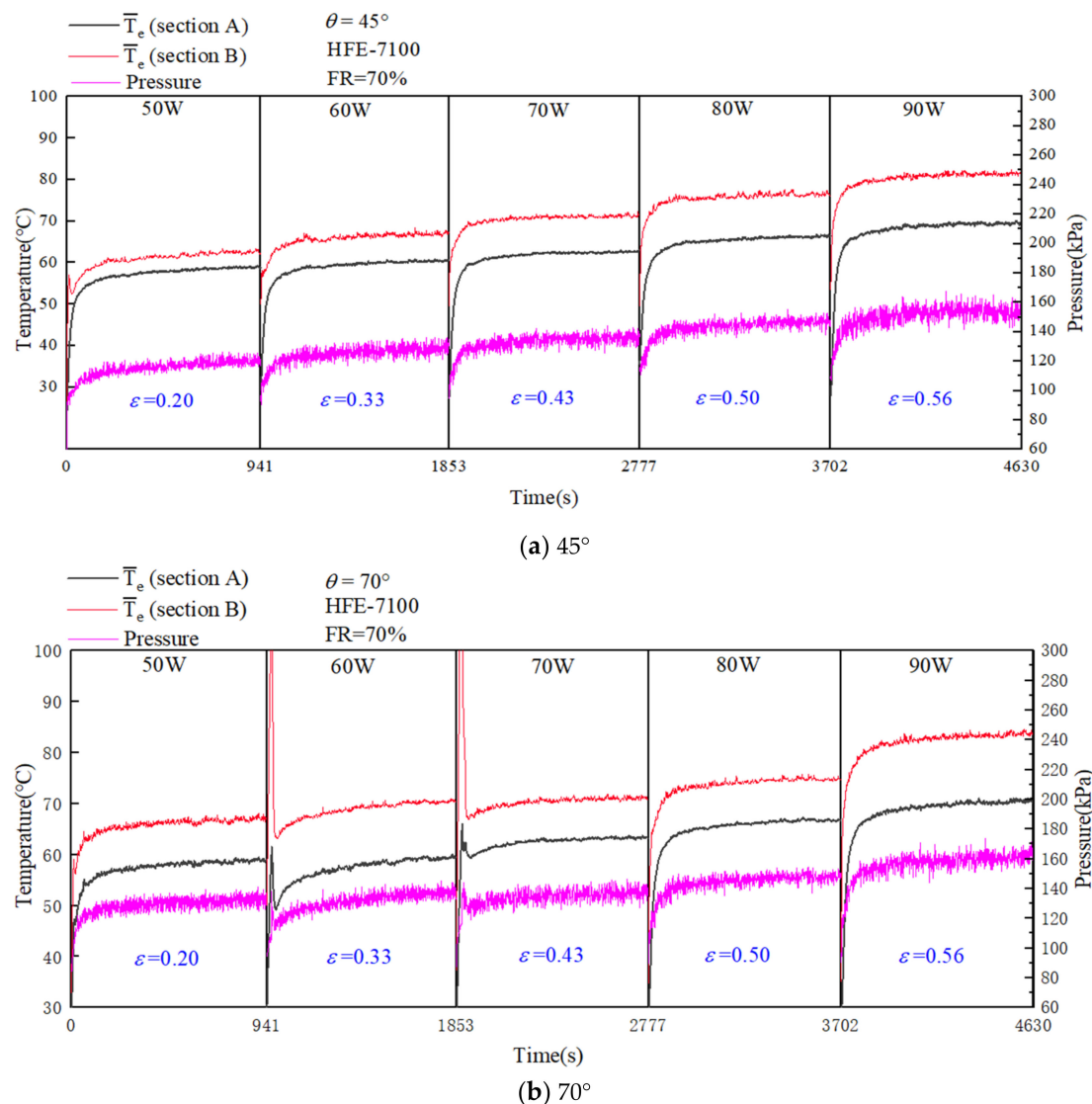


Figure 9. Variation of average temperature and internal pressure of evaporation section with time under different installation angles of HFE-7100 working medium.

5. Conclusions

In order to explore the influence of different inclination conditions on the heat transfer characteristics of pulsating heat pipes, a test device for the heat transfer performance of pulsating heat pipes under different inclination conditions was designed and built. The heat transfer performance, evaporation section temperature and internal pressure fluctuation characteristics and start-up characteristics of the pulsating heat pipe were analyzed by changing different working medium and operating parameters. The main conclusions are as follows.

(1) For the pulsating heat pipe filled with ethanol working medium, different installation angles have a great influence on the thermal resistance of the pulsating heat pipe at the heating power of 40 W. With the increase in installation angle, the thermal resistance of the pulsating heat pipe gradually increases and reaches the maximum value at 90°. When the installation angle is 45°, the internal working medium of the four-bend pulsating heat pipe device used in this paper is easier to form circulation in the pipe than the installation angle of 90°.

(2) Due to its low surface tension and low latent heat of vaporization, the HFE-7100 working medium exhibits low operating thermal resistance under different heating

modes. Compared with the uniform heating method, the operation thermal resistance of the pulsating heat pipe is not significantly affected by the installation angle when the non-uniform heating method is used.

(3) Under uniform heat flux, the thermal resistance of the HFE-7100 working medium is lower at low heating power. However, with the increase in heating power, the thermal resistance of the two working mediums at 70% liquid filling rate gradually approaches. Under low heating power, the effect of installation angle on the ethanol working medium was significantly greater than that of the HFE-7100 working medium.

(4) The non-uniform heat flux heating condition can obviously improve the phenomenon that the ethanol working medium is affected by the installation angle. Then, reducing the overall thermal resistance of ethanol working medium can broaden the application scenario of a pulsating heat pipe. This experiment also provides guidance for the arrangement of heat pipes in different heat dissipation parts.

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Abbreviations

Abbreviations

FR filling ratio

Nomenclature

T temperature ($^{\circ}\text{C}$)

R thermal resistance ($^{\circ}\text{C}/\text{W}$)

Q heat transfer (W)

$\dot{m}$ mass flow rate (kg/s)

C_p specific heat at constant pressure ($\text{J}/(\text{kg}\cdot\text{K})$)

P pressure (Pa)

Subscripts

e evaporation section

c condensation section

Greek symbols

ε dimensionless heat difference

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