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Starting and running performance of a pulsating heat pipe with micro encapsulated phase change material suspension

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ABSTRACT

Pulsating heat pipe (PHP) is an efficient heat transfer technology. The micro encapsulated phase change material (MEPCM) suspension is a novel latent heat fluid with high heat storage density. The research on the PHP with MEPCM suspension is of great significance for expanding the types of working fluids and studying the operating performance. An experimental investigation of starting and running performance was carried out on a closed loop PHP with MEPCM suspension at mass concentration of 0.5%. The results show that the PHP charged with MEPCM suspension starts unstably with irregular oscillating under lower heating power of 30–90 W, while it runs stably after starting with heating power increasing to 120 W. The start-up time of PHP charged with MEPCM suspension first drops rapidly, then flattens from 50 s to 20 s with increasing heating power and it still maintains at 20 s with the increasing of heating power from 150 W during experiments, which indicates the influence on the start-up time from further increasing heating power becomes smaller on the condition that the heating power increases to a certain level. Compared with 70% of filling ratio, conditions with 35% and 50% of that showed better performance. Gravity is very important to overcome the viscous resistance of working fluids. The running performance of PHP was slightly affected by inclination angle which was greater than 60°. When it dropped to 30°, the running deteriorated obviously. However, the PHP with 35% of filling ratio couldn't run normally at a small inclination angle of 30°.

1. Introduction

With the rapid development of higher loads and component miniaturization, the need for better thermal management systems with more effective heat flux dissipation components is increasing rapidly, which has led to a novel technology regarding to the present demands. Pulsating heat pipe (PHP) [1–2] is a new kind of heat pipe possessing not only simple structure but also low cost, which can date back to the early 1990s when potential alternatives were proposed and applied in electronic cooling fields. Nowadays, PHP has been universally investigated by scholars worldwide, and it can be widely used in a variety of applications such as heat exchangers, economizers, space applications, solar collector, waste heat utilization and so on [3–7]. PHP was prepared by a capillary tube bending into a loop, which was further filled with working fluids after vacuumizing. The fluid exists randomly in the form of gas bubbles and liquid plugs in the tube because of surface tension. When the temperature of evaporation section is different from that of the condensation section to a certain level, the gas bubbles would automatically pulsate back and forth with high amplitude. The liquid plugs flows by the same way between the condensation section and evaporation section to achieve the heat transferring via sensible heat and latent heat.

As reported previously, the factors such as working fluid, filling ratio, diameter and inclination angle emerged are the important design parameters for the PHP systems. Yin et al. [8] investigated operating limit effect of using different working fluids on the thermal performance of a CLPHP and found that the heat transfer limit is affected by working fluids, operating temperature and filling ratio. Charoensawan et al. [9] studied the heat transfer performance of PHP with internal diameters of 1 mm, 1.5 mm and 2 mm and the results showed that the optimal diameter varied with the working fluids properties. To investigate the

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Nomenclature

A	Heat conduction area (m^2)
c	specific heat capacity (J/(kg·°C))
h	thickness of double-layer asbestos (m)
i	number of thermocouple
$\dot{m}$	the mass flow rate of cooling water (kg/s)
Q	quantity of heat transfer (W)
R	thermal resistance (°C/W)
t	temperature (°C)
Δt	temperature drop (°C)
U	uncertainty
λ	thermal conductivity (W /(m·°C))
abbreviation	
MEPCM	micro encapsulated phase change material
PHP	Pulsating heat pipe
PCM	phase change material
SEM	scanning electron microscopy
subscript	
cond	condenser
evap	evaporator
p	isobaric

effect of vacuum on heat transfer performance, Bai et al. [10] charged deionized water and AL_2O_3/ water nanofluid with a diameter of 50 nm into a PHP by changing different vacuums of 0.014 MPa, 0.042 MPa, 0.070 MPa and 0.098 MPa and confirmed that there was an important effect on the performance by non-condensable gases especially with higher heat powers. They mentioned that the starting heat power of the PHP decreased with non-condensable gases decreasing. Shi et al. [11] observed the distribution and flow pattern variation of working fluids by visual experiments, and they also found that the heat transfer performance with filling ratios of 50% is higher than that of the other filling ratios. Srikrishna et al. [12] charged methanol into experimental system with different filling ratios and found the best performance of PHP was emerged in the vertical direction. Different heating inputs [13–16] have been tested to study the effects on the performance of heat systems. Higher heating enhances heat transfer because it can increase recycling rate of the operating fluid, which eventually enhances the heat transfer efficiency of the heat systems.

The thermophysical property of working fluid is one of the most important factors affecting the heat transfer efficiency of PHP. The literature review indicates that most of the studies on the heat transfer performances in the PHP by experimental measurements are from different working fluids effect. Different types of fluids, such as mixed fluids [17–19], refrigerants [20], surfactant [21], nanoparticles [22–24] have been used to investigate their effects on the performance. For example, nano fluids can improve the heat transfer performance because nanoparticles not only increase the thermal conductivity of the fluids but also improve the convective heat transfer of the fluids because of Brownian motion of nanoparticles increasing with the increasing temperature.

The MEPCM suspension is a novel latent heat fluid with high heat storage density. It is also one of the potential working fluids for PHP. Concentration and latent heat of phase change are the important factors affecting the heat transfer efficiency among all the factors, and there are different heat transfer performance with MEPCM suspension at different mass concentrations and latent heat of phase change. At present, there are just a few studies on heat transfer performance of PHP with MEPCM suspension by theory and experiments. Li et al. [25] investigated anti-dry-out ability with MEPCM suspension in a PHP by Computational Fluid Dynamics (CFD) technique and showed MEPCM suspension within a certain phase change temperature range can effectively improve the anti-dry-out ability of the PHP. They also mentioned that the appropriate phase change temperature range should be selected around the evaporation section temperature when the PHP transforms from the circulating flow state to the dry-out state. Lin et al. [26] compared heat-transport capabilities of PHP with different working fluids of FS-39E MEPCM(A microcapsule phase change material produced by Mitsubishi Paper Mills) suspension, water, Al_2O_3 nano-fluid. It was found that the heat-transport capability of PHP could be enhanced by using functional thermal fluids as working fluids under certain conditions and MEPCM suspension with mass concentration of 1% had the best performance with inclination angle of 90°. Heydarian et al. [27] found by experiments that the heat transport effect of charged with paraffin nano-encapsulated fluid became stronger, which was presented as a lower thermal resistance of the PHP and an increasing heat transfer limit.

The starting and the stable running are two main processes of the PHP. The starting power, start-up time and starting temperature are three main characters of this early stage and are related with the performance in the normal running process. This paper focused on the start-up and running performance of a PHP with MEPCM suspension at 0.5% of mass concentration as working fluid. The considered filling ratios are 35%, 50% and 70%, respectively. The heating power is from 30 W to 210 W and the inclination angle is in the range from 30° to 90°.

2. Methodology

2.1. Property of the MEPCM suspension

The PCM (phase change material) is widely used in heating, heat storage and micro-scale exchangers. Some common interactions in MEPCM suspension, like Brownian motion, are similar as the nanofluid. The MEPCM suspension used in this study is a colloidal mixture of ultra-pure water, phase change material (PCM) consisting of modified paraffin and further some surfactant to prevent the aggregation. A stirrer and an ultrasonic oscillator were used in the preparation of the working fluid.

Before the performance investigation of the PHP, some properties of the MEPCM suspension were tested. From the scanning electron microscopy (SEM) photo of the motionless MEPCM suspension, as shown in Fig. 1, the MEPCM are evenly dispersed in the basic fluid. The diameter of the MEPCM distributes in a wide range. The largest value is almost 30 μm and the minimum particle is about 1 μm.

From the detailed particle size distribution, as shown in Fig. 2, the average particle diameter is about 15 μm weighted by volume density. By differential scanning calorimetry (DSC), the variation of heat flow with temperature was obtained as shown in Fig. 3 which indicates the phase transition temperature of the MEPCM suspension. The phase change begins from 26 °C to 57 °C and the highest heat flow appears at

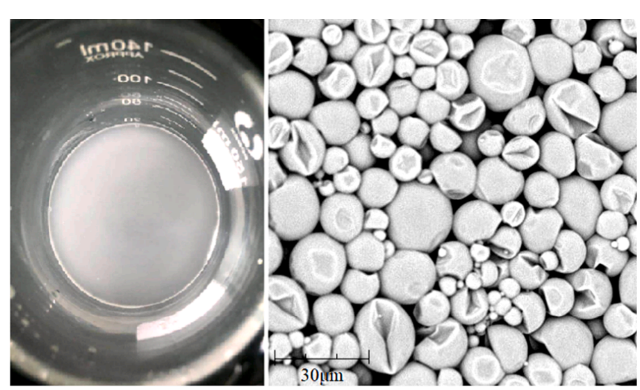

Fig. 1. Appearance and SEM photo of the motionless MEPCM suspension.

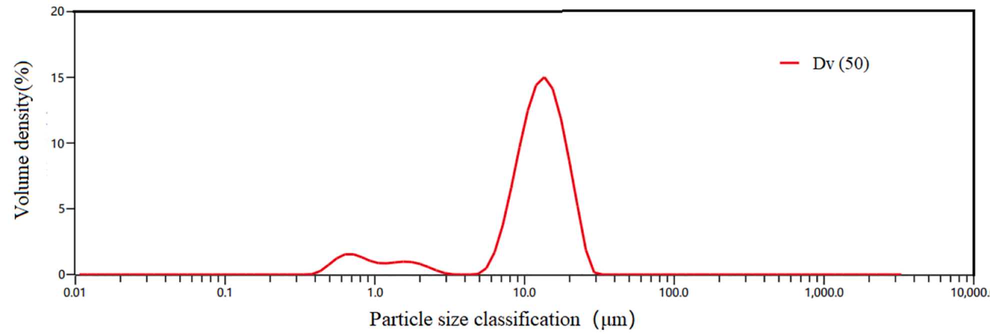

Fig. 2. Particle size distribution.

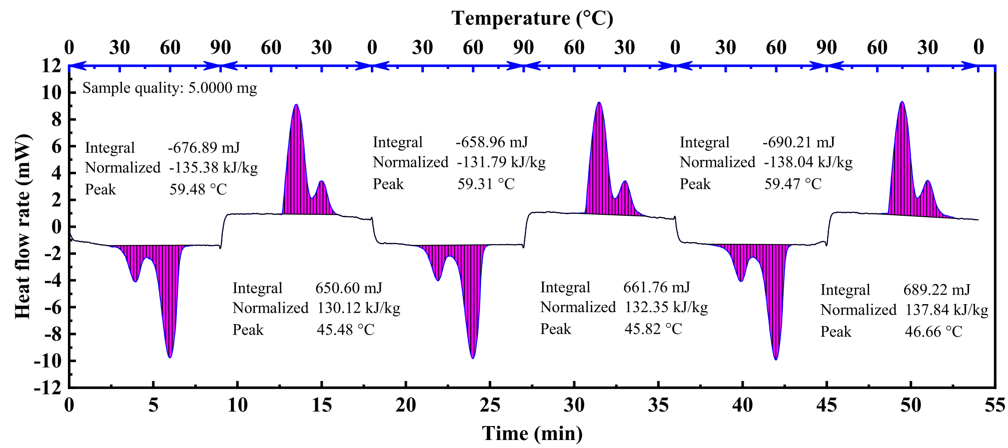

Fig. 3. Variation of heat flow rate with temperature.

53.17 °C.

The viscosity is another important property which impacts the running performance of the PHP. The viscosity is measured by HAAKE MARS40 as shown in Table 1, the viscosity of MEPCM suspension with 0.5% of the mass concentration at 30 °C is 3.09 mPa·s and the ultra-pure water at 30 °C is 0.8 mPa·s. At 70 °C, the viscosity of both the MEPCM suspension and the ultra-pure water shows a big drop. With the mass concentration of 3.0%, the viscosity of MEPCM suspension is 5.33 mPa·s at 30 °C and goes down to 2.43 mPa·s at 70 °C.

2.2. *The PHP an the experimental system*

The whole schematic diagram of the experimental system is shown in Fig. 4. It consists of a closed-loop PHP, a heating system, a cooling system, a data acquisition system and other auxiliary equipment.

The evaporating section of the PHP is wound by a Nichrome heating wire and its electricity power is supplied and adjusted by a DC power supply. With power on, the PHP can be evenly heated by the hot heating wire and the heating power can be regulated by the voltage and measured by digital power meter of Yokogawa WT310. Tap water is used to cool the pulsating heat pipe in the condensing section. Tap water fills the high-level constant pressure water tank with both height and diameter of 450 mm and flows out from the valve on the lower side, and then the cooling water flows into the cooling water tank with internal size of 162 × 17 × 90 mm after passing through the glass rotameter. The cooling water tank is fitted at the condensing section of pulsating heat pipe and is used to condense the working fluid in the condensing section. In the evaporating section and thermal insulation section, the surface of the PHP is wound by a double-layer asbestos to reduce heat loss. However, some heat still transfers from the wall of the pulsating heat pipe to the environment and it can be evaluated by the Eq. (1). The surface area of the evaporating section is 75.36 cm^2. The thickness of the double-layer asbestos is 12 mm and its thermal conductivity is 0.036 W/(m·°C). During the experiments, the environment temperature is about 25 °C. Based on these data, the heat loss fraction of the heating power is less than 8%.

Table 1
Thermophysical parameters of ultrapure water and MEPCM suspension.

Working fluid	Temperature (°C)	Specific heat (kJ/kg·°C)	Thermal diffusion coefficient (mm^2/s)	Dynamic viscosity (mPa·s)
Ultrapure water	30 70	4.2 4.187	0.15 0.16	0.8 0.41
MEPCM suspension (0.5%)	30	4.12	0.13	3.09
MEPCM suspension (3.0%)	30 70	4.19 4.25	0.12 0.14	5.33 2.43

$$Q_{\text{loss}} = \frac{\lambda \cdot A \cdot \Delta t_{\text{loss}}}{h} \tag{1}$$

The temperature data is tested by T-type thermocouples and collected by a data acquisition system of Agilent 34980A. A vacuum pump of Agilent DS202 is used to vacuumize the PHP before filling the working fluid. In the vacuumizing process, the absolute pressure in the PHP reaches a minimum value 4 × 10^2 Pa and this value can keep for more than 24 h.

The structure of the closed-loop PHP are shown in Fig. 5. The material of the tube is red copper. Its inner and outer diameter are 2 mm and 3 mm, respectively. There are five bends at the evaporating section and the electric heating wire is wound on the pipes. Five thermocouples

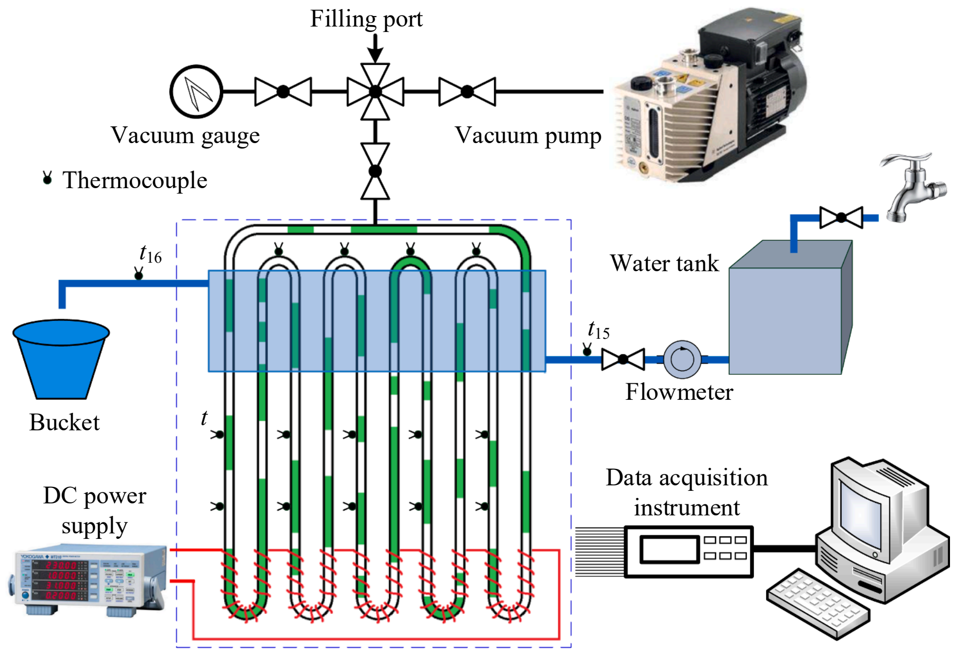

Fig. 4. Schematic diagram of the experimental system.

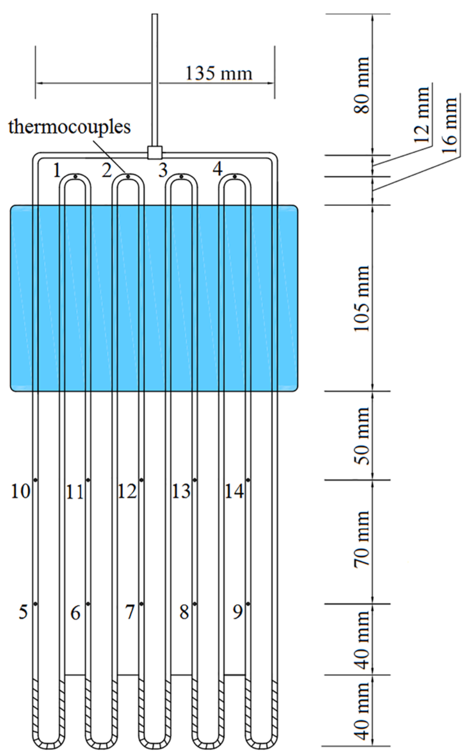

Fig. 5. Structural and thermocouple location of the PHP.

are located on the surface at the evaporating section, as well as the thermal insulation section. The evaporating section is composed of several regions at the U-bends. In order to arrange longer electric heating wires around the tube to apply higher heating power, there is no enough space to locate the thermocouples at the U-bend and the actual wall temperature at the evaporating section is not able to be measured there. Therefore, the thermocouples are located at the end of each region of the U-bend where is close to the evaporating section and the measure values (t_5-t_9) are considered to be the wall temperature at the evaporating section. At the condensing section, four thermocouples are located on the bends to test the condensing temperature.

Filling ratio, inclination angle and heating power are three most important operating parameters which impact the running performance. The filling ratio is specified by the filling volume and the whole volume of the PHP. The filling ratios of 35%, 50% and 70% are considered in the study. The PHP apparatus is fixed on a rotary platform which can adjust the inclination angle of the PHP. The inclination angle refers to the angle between the PHP plane and the horizontal plane. Three inclinations 30°, 60° and 90° were considered. As mentioned above, the heating power is regulated by changing the supplying voltage. The considered heating power is in the range from 30 W to 210 W.

2.3. Uncertainty of the measurement

The analysis of the starting and running performance depends on the measurement temperature and mass flow rate measurement. The overall thermal resistance can be calculated by the measurement value and its uncertainty is determined by the measurement accuracy. We used Agilent 34980A to measure the temperature. The 34980A offers 6½ digits of resolution with 0.004% of accuracy with DC voltage measurements, as shown in data sheet of 34980A data acquisition system. The measurement error of 34980A is very little and isn't the main factor to influence the whole uncertainty.

The mean temperature at the condensing section can be calculated by averaging the measurement values of the four thermocouples, as shown in Eq. (2). It is the similar at the evaporating section, as shown in Eq. (3).

$$\overline{t_{\rm cond}} = \frac{1}{4}\sum_{i=1}^{4} t_{{\rm cond},i} \tag{2}$$

$$\overline{t_{\rm evap}} = \frac{1}{5}\sum_{i=5}^{9} t_{{\rm evap},i} \tag{3}$$

The temperature difference between the two ends of the PHP can be expressed as,

$$\Delta t_{\rm PHP} = \overline{t_{\rm evap}} - \overline{t_{\rm cond}} \tag{4}$$

From the cooling water side, the heat flow can be calculated by,

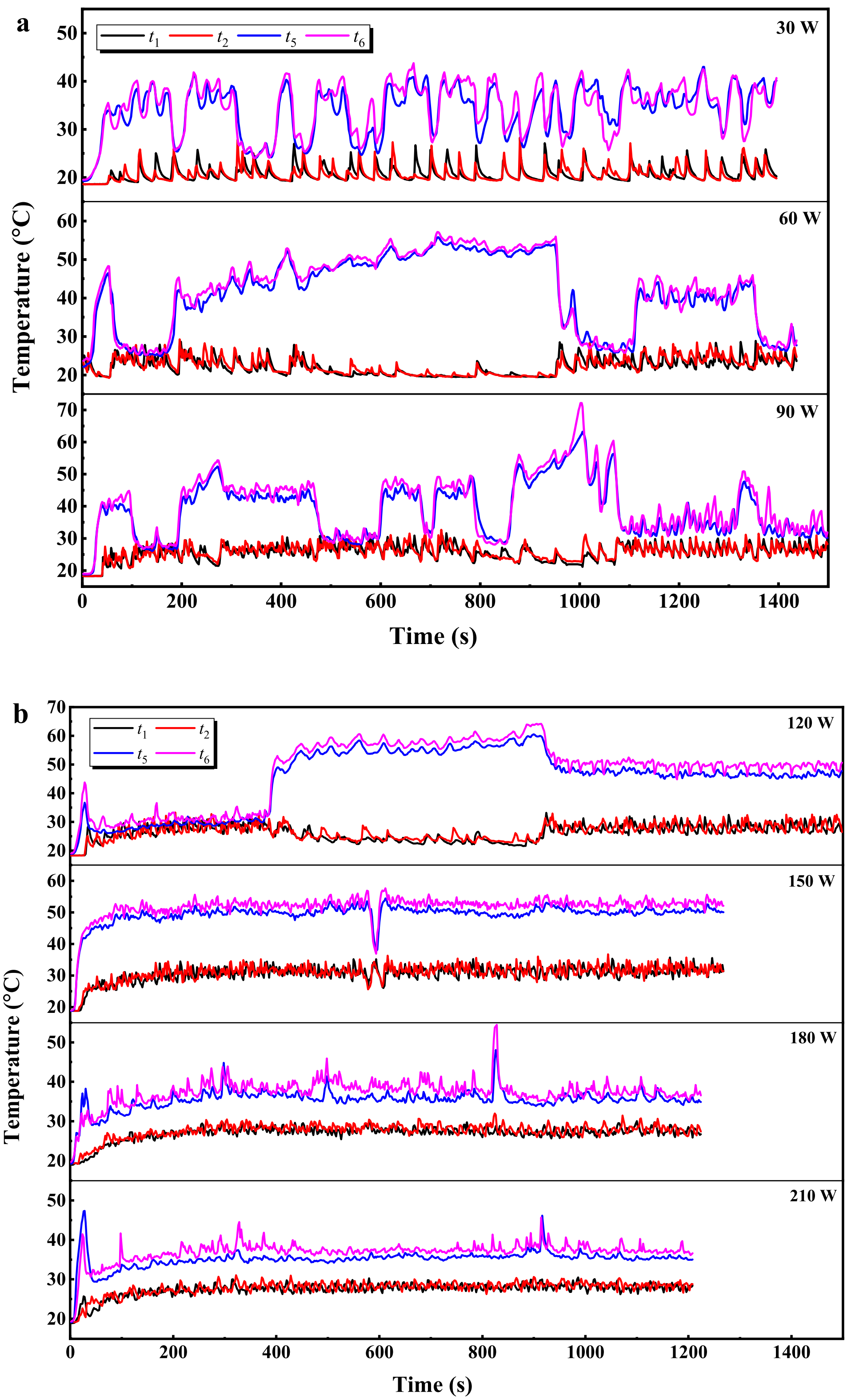

Fig. 6. Variation of wall temperature at four points at the condensing and evaporating section using 0.5% MEPCM suspension with the filling ratio of 50% and the inclination angle of 90°. (a. bad starts; b. good starts).

$$Q_{PHP} = \dot{m}_{cooling} \cdot c_p \cdot \left(t''_{cooling} - t'_{cooling} \right) \tag{5}$$

Based on the above two parameters, the thermal resistance can be expressed as,

$$R_{PHP} = \frac{\Delta t_{PHP}}{Q_{PHP}} = \frac{\overline{t_{evap}} - \overline{t_{cond}}}{\dot{m}_{cooling} \cdot c_p \cdot \left(t''_{cooling} - t'_{cooling} \right)} \tag{6}$$

Further, the relative uncertainty of the thermal resistance can be calculated by the following equation [28].

$$\begin{aligned} \frac{U_R}{R} &= \sqrt{\left(U_t \cdot \frac{\partial \ln R_{PHP}}{\partial \overline{t_{evap}}} \right)^2 + \left(U_t \cdot \frac{\partial \ln R_{PHP}}{\partial \overline{t_{cond}}} \right)^2 + \left(U_{\dot{m}} \cdot \frac{\partial \ln R_{PHP}}{\partial \dot{m}_{cooling}} \right)^2 + \left(U_t \cdot \frac{\partial \ln R_{PHP}}{\partial t''_{cooling}} \right)^2 + \left(U_t \cdot \frac{\partial \ln R_{PHP}}{\partial t'_{cooling}} \right)^2} \\ &= \sqrt{2\left(\frac{U_t}{\overline{t_{evap}} - \overline{t_{cond}}} \right)^2 + \left(\frac{U_{\dot{m}}}{\dot{m}_{cooling}} \right)^2 + 2\left(\frac{U_t}{t''_{cooling} - t'_{cooling}} \right)^2} \end{aligned} \tag{7}$$

The standard uncertainties of the thermocouple and glass rotameter are 0.5 °C and 0.28 g/s, respectively. If the heating power is specified as 210 W and a mass flow of 6.7 g/s cooling water of is heated by 6.8 °C, the temperature difference between the two sides of the PHP is 12.6 °C in a condition in the experiment. According to these data and the equation (6), the relative uncertainty of R can be obtained as 12%.

3. Results and discussion

The introduction of MEPCM influences the flow and heat transfer and of the PHP. It raises the flowing disturbance and the vaporization core of the base liquid, which is helpful for improving the heat transfer performance. On the other hand, it increases the viscosity and the flow resistance of the working fluid. In this section, the effect of working fluid, filling ratio and inclination angle on the starting and running characteristic of the PHP is discussed detailedly. In the PHP, the MEPCM suspension at mass concentration of 0.5% is used as the working fluid.

3.1. Starting characteristic with the filling ratio of 50%

The wall temperature is the most direct reflection of the starting and running state. At 90° of the inclination angle, the variation of wall temperature at four points of the condensing and evaporating section are measured and shown in Fig. 6. Fig. 6a shows three bad starts with low heating powers, 30 W, 60 W and 90 W and Fig. 6b shows good ones with low heating power of 120 W, 150 W, 180 W and 210 W.

Under the heating power of 30 W, the wall temperature at the evaporating section varies violently, with the maximum value of 43.7 °C and the minimum value of 19.3 °C. The wall temperature at the condensing section varies in the range from 18.6 °C to 28.3 °C and shows a relatively uniform pulsation. With the heating power increasing to 60 W and 90 W, generally speaking, the temperature increases slightly and violent jumps occurs for the temperature at the evaporating section. The pulsation isn't uniform during the considered period. Under 60 W of the heating power, the wall temperature at the evaporating section shows a high peak at 52 s and two plateaus in the ranges of 194–956 s and 1112–1352 s, respectively. On the plateaus, the temperature fluctuates slightly. During the other periods, the wall temperature at the evaporating section goes towards that at the condensing section. With the heating power of 90 W, there are five plateaus of the wall temperature at the evaporating section. When the heating power is low, it can't drive the working fluid smoothly in the PHP, then the working fluid is sometimes fast and sometimes slow. Additionally, an unstable running condition can easily lead to a change of the flow direction. In other words, a point at the evaporating section shows a high temperature with working fluid there coming from the evaporating bend, and suddenly it drops to a very low temperature with the direction change and working fluid coming from the condensing bend. This phenomenon causes the violent jumps of the wall temperature at the evaporating section.

With the heating power increasing to 120 W, the PHP starts successfully and runs smoothly. In the starting process, the wall temperature at the evaporating section rises rapidly, then drops suddenly and finally goes towards a stable oscillating state, which is consistent with the first starting mode discovered by Xu et al. [29]. The heating power is still a little low and the working fluid can't flow stably towards a constant direction. Because of the direction change, the wall temperature at the evaporating section fluctuates between the temperature at the evaporating section and the condensing section. In the range from 40 s to 390 s, the wall temperatures at the evaporating section are very close to that at the condensing section. A plateau locating in the range of 390–930 s is also can be observed. Finally, the PHP shows a high oscillating frequency and a stable running in the latter half of the time.

In the condition with the heating power of 150 W, 180 W and 210 W, the starting process is very successful and the running process is stable with a high oscillating frequency. The amplitude of the wall temperature is small and no plateau of the wall temperature was observed in the latter three conditions, but there are still some peaks of the wall temperatures, such as, the negative peak at 594 s under 150 W, the peak at 828 s under 180 W and the peak at 916 s under 210 W. Though the heating power increases strongly, the flow speed and the evaporating rate of the working fluid also increases fast, which causes the decrease the average wall temperature at the evaporating section from 50 °C to 36 °C. It also should be noted that the phase transition temperature of

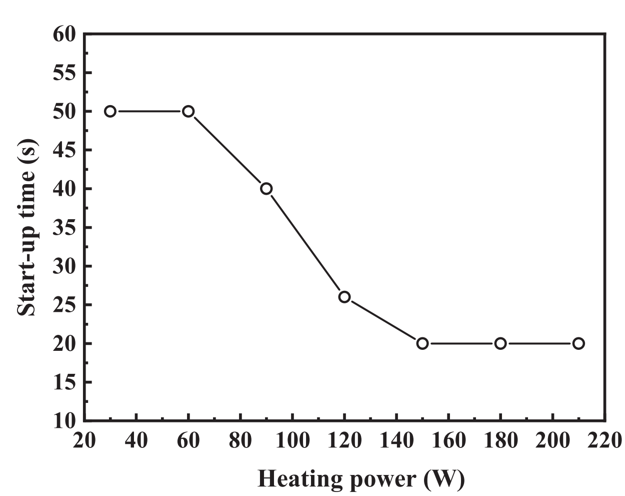

Fig. 7. Variation of start-up time with heating power using 0.5% MEPCM suspension with the filling ratio of 50% and the inclination angle of 90°.

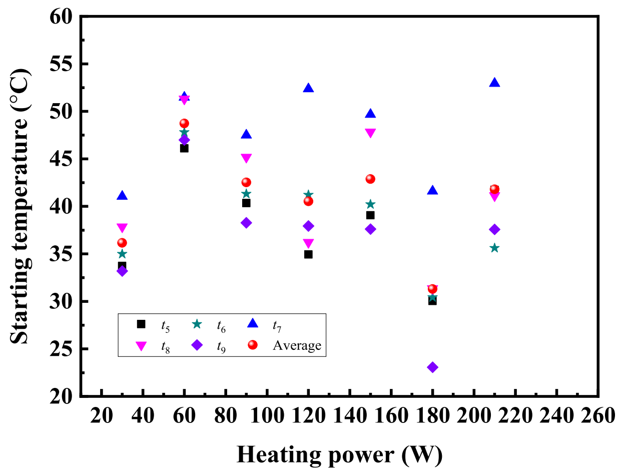

Fig. 8. Variation of starting temperature at the evaporating section with heating power using 0.5% MEPCM suspension with the filling ratio of 50% and the inclination angle of 90°.

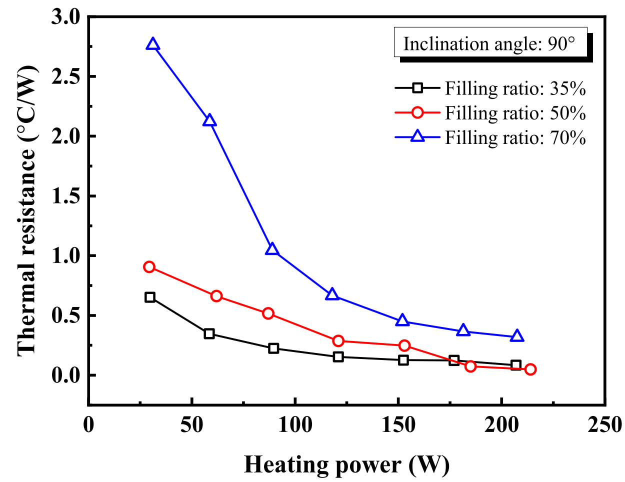

Fig. 10. Variation of thermal resistance with heating power using 0.5% MEPCM suspension with the inclination angle of 90° and the filling ratio of 35%, 50% and 70%.

the MEPCM is in the range form 26 °C to 57 °C and the latent heat of the MEPCM suspension also contributes to the low operating wall temperature at the evaporating section.

In the starting process, the heating power also influences the start-up time, the starting temperature and the stable running temperature at the evaporating section. The time when the wall temperature at the evaporating section reaches the first peak is specified as the start-up time. The starting temperature is specified as the wall temperature at the first peak of the evaporating section in the starting process and the stable running temperature is the average wall temperature of the evaporating section in the stable running process.

As shown in Fig. 7, the start-up time is 50 s with the heating power of 30 W and 60 W, then it decreases with increasing the heating power and finally it reaches 20 s under 150 W and keeps constant. At lower temperature, the working fluid has higher viscosity and the PHP can't produce enough driving power to make the working fluid runs fast. Under low running speed, the heat that the working fluid takes from the evaporating section to the condensing section is also low and the thus the heat resistance is high. Higher heating power can input more thermal energy quickly and drive the working fluid fast. When the heating power reaches to a certain level, the influence of the heating power on the starting time becomes less and less. This is the reason why the starting time reaches 20 s and keeps constant with the heating power in the range from 150 W to 210 W.

As shown in Fig. 8, the starting temperature is about 35 °C at 30 W of the heating power. With increasing the heating power, the starting process reaches to a new balance with higher wall temperature of the evaporating section. With raising the heating power, the generated driving force in the PHP can make the working fluid run faster, so more heat can be transferred from the evaporating section to the condensing section by the PHP and the starting temperature drops to about 30 °C. When the heating power reaches to 210 W, the PHP had already arrived the maximum ability of heat transfer, so the starting temperature goes up to about 40 °C.

In the stable running process, the variation of wall temperature at the evaporating section with the heating power is shown in Fig. 9. The stable running temperature varies from 45 to 50 °C firstly then drops to 35 °C with increasing heating power from 120 to 210 W. The mechanism is similar as that in the starting process.

3.2. Running performance with different filling ratio (35%, 50% and 70%)

The filling ratio and inclination angle impact on the running performance of the PHP. As shown in Fig. 10, the thermal resistance

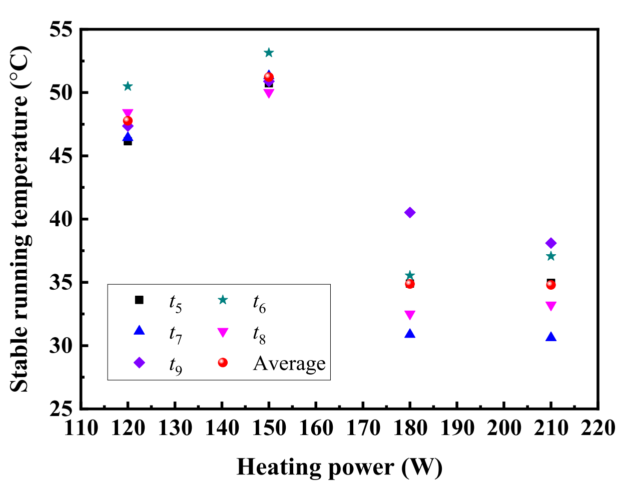

Fig. 9. Variation of stable running temperature at the evaporating section with heating power using 0.5% MEPCM suspension with the filling ratio of 50% at 90° of the inclination angle.

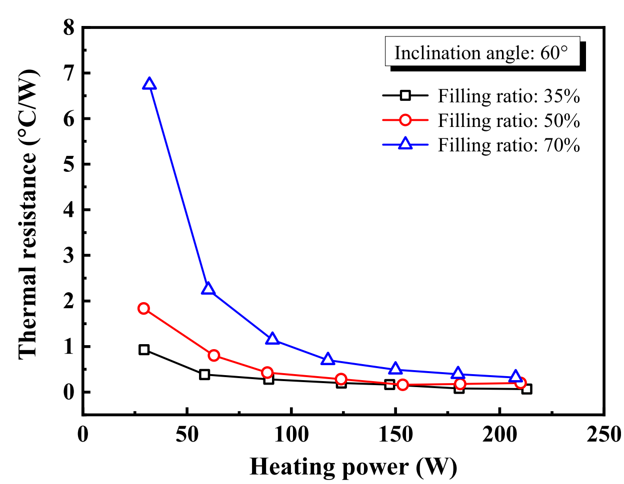

Fig. 11. Variation of thermal resistance with heating power using 0.5% MEPCM suspension with the inclination angle of 60° and the filling ratio of 35%, 50% and 70%.

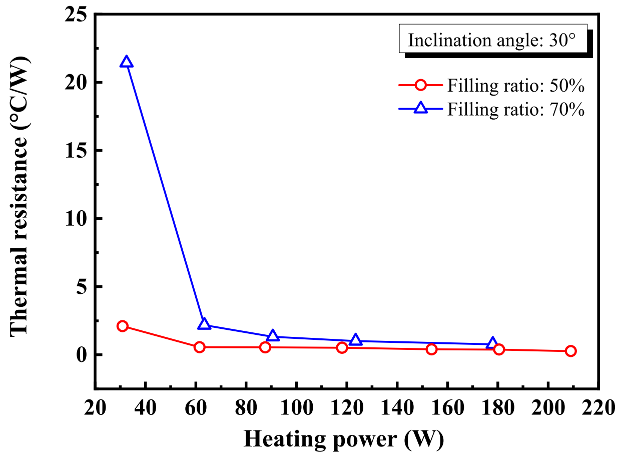

Fig. 12. Variation of thermal resistance with heating power using 0.5% MEPCM suspension with the inclination angle of 30° and the filling ratio of 50% and 70%.

decreases rapidly with raising the heating power from 30 W to 120 W and then tends to be a stable value with the heating power in the range from 120 W to 210 W. For these specified PHPs, they give better running performance and less thermal resistance with higher heating power and then they achieve their heat transfer capacity. In these optimal conditions, the heating power can produce enough motive power to drive the working fluid fast.

The heating power is the initial source of the driving power and the friction is the main flow resistance of the PHP. For the plug flow and the slug flow in the PHP, the liquid and the vapor have the similar speed, but the vapor shows lower viscosity than the vapor, so the PHP with low filling ratio shows low flow resistance.

In the following step, two other inclination angles were considered. When the inclination angle is 60°, the variation trend of the thermal resistance is similar as the condition with the inclination angle of 90°, but its value is much higher than the above condition, as shown in Fig. 11.

The similar appearance is also observed in Fig. 12. With decreasing the inclination angle to 30°, the thermal resistance climbs to a very high value, especially in conditions with low heating power. More notably, the PHP with the filling ratio of 35% can't start up and runs normally. The inclination angle impacts the effect of gravity. The component in the flow direction shows a maximum value at 90° of the inclination angle and decreases with decreasing the inclination angle. A little component of gravity in the flow direction harms the flow back of the liquid working fluid to the evaporating section. With lack of sufficient gravity effect, the PHP with filling ratio of 35% can't be driven at 30° of the inclination angle. With the filling ratio of 50% and 70%, the thermal resistance finally maintains about 0.5 °C/W and 1.3 °C/W, respectively. The observed minimum thermal resistance at the filling ratio of 50% is 0.269 °C/W with the heating power of 209 W, which shows the best heat transfer performance.

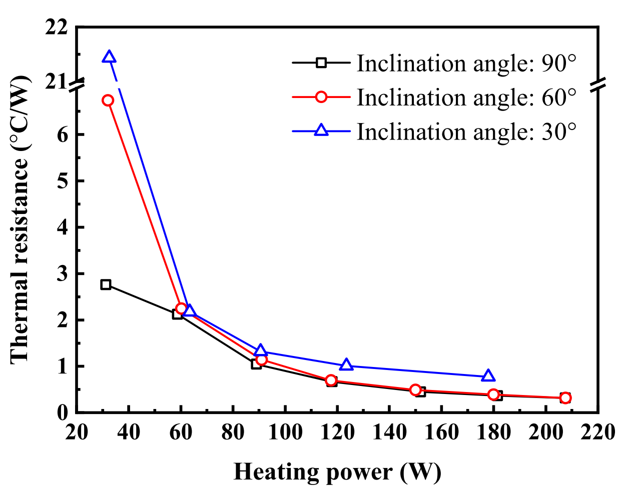

Fig. 13. Variation of thermal resistance with heating power using 0.5% MEPCM suspension with the filling ratio of 70% and the inclination angle of 30° 60° and 90°.

3.3. Running performance at different inclination angles (90°, 60° and 30°)

In the analysis of above section, it is introduced that the inclination plays a great role on the thermal resistance. In this section, the thermal resistance with the filling ratio of 70% at three inclination angles, 90°, 60° and 30° is shown in a single figure, Fig. 13. The PHP at 90° of the inclination angle shows the best heat transfer performance and the thermal resistance increases with decreasing the inclination angle. This phenomenon is more obvious in low heating power. For example, in the condition with the heating power of about 30 W, the PHP at 90° of the inclination angle gives a thermal resistance of 2.8 °C/W and it shows that value of 6.7 °C/W and 21.4 °C/W at 60° and 30°, respectively. In the conditions with heating power higher than 60 W, the difference becomes less obvious. The PHP runs normally as the heating power up to 210 W at 90° and 60° of the inclination angle. At 30°, it can't run with 210 W of the heating power and a heat transfer limit is achieved with heating power of 180 W.

The driving force provided by the PHP with small inclination angle of 30° is not enough to promote circulation of higher viscosity fluid, which leads to the weak circulation and difficulty of heat transfer to the condensation section. Therefore, it is helpful to the circulating flow of the working fluids at 90°. With the help of gravity, the liquid working fluid after condensation can flow back to evaporator as quickly as possible. But with the decreasing of inclination angles, the operating of the PHP becomes worse because of less gravitational force, which lead to increasing thermal resistance and decreasing heat transfer limit.

3.4. Running performance comparison of ultrapure water and MEPCM suspension at 90°

In order to compare the running performance of ultrapure water and MEPCM, the thermal resistance of the PHP with ultrapure water and MEPCM suspension (0.5% and 1.0% of the mass concentration) was tested and calculated with inclination angle of 90°. The heating power

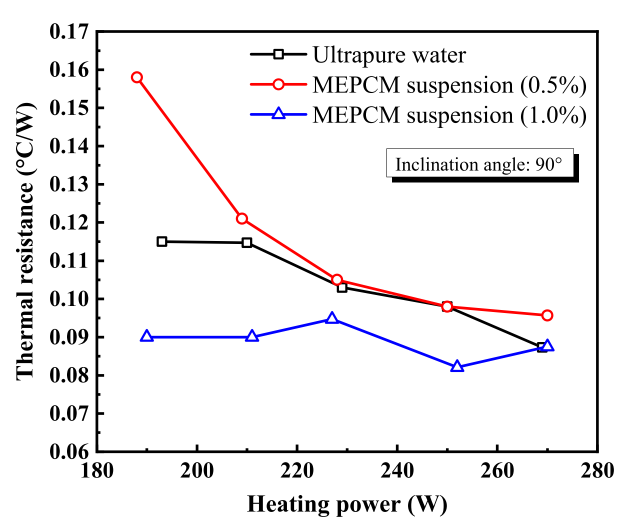

Fig. 14. Variation of thermal resistance with heating power at 90°.

was specified in a range from 180 W to 280 W and the PHP ran well in these conditions. As shown in Fig. 14, the thermal resistance of PHP with MEPCM suspension at 0.5% of the mass concentration is higher than that of PHP with ultrapure water. However, when the mass concentration increase to 1.0%, the PHP with MEPCM suspension shows better running performance than that with ultrapure water.

PCM particles show double effects on the heat transfer performance of PHP. On one hand, PCM particles can enhance the flow disturbance, increase quantity of the vaporization cores of the base liquid and meanwhile improve the phase change latent heat of the MEPCM suspension. On the other hand, the addition of PCM particles increases the viscosity and flow resistance of the working fluid, which is harmful to the well running of the PHP. Therefore, the total performance of the MEPCM suspension mainly depends on which effect plays the leading role.

4. Conclusions

The MEPCM suspension at mass concentration of 0.5% was selected as a new working fluid of the PHP. A series experiment was carried out to study the starting and running performance and analyzed the influence factor. Some conclusions were obtained and shown below.

(1). At 50% of the filling ratio, the PHP gives a poop start under low heating power in the range of 30–90 W. In conditions with higher heating power, it starts well and finally goes towards a stable oscillating state.

With increasing the heating power, the starting temperature shows a trend of rising, falling and rising again. The start-up time shows a decreasing trend and goes towards a constant value of about 20 s.

(2). In the stable running process, the thermal resistance of the PHP decreases with decreasing the filling ratio from 70% to 35%. However, because of the lack of sufficient gravity effect, the PHP with the filling ratio of 35% can't run normally at 30° of the inclination angle.

The vertically placed PHP shows best heat transfer performance and the thermal resistance increases with regulating it to horizontal.

(3). Viscosity plays a leading role during the running of PHP with 0.5% mass concentration MEPCM suspension and ultrapure water, which goes against oscillating flow of the working fluid between evaporation section and condensation section. PHP using MEPCM suspension with mass concentration of 0.5% show the worse heat transfer performance than that with ultrapure water.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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