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Experimental Investigation of the Operating Characteristics of a Pulsating Heat Pipe with Ultra-Pure Water and Micro Encapsulated Phase Change Material Suspension

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Abstract: The specific heat capacity of working fluid is an important influence factor on heat transfer characteristic of the pulsating heat pipe (PHP). Due to the relatively large specific heat capacity of micro encapsulated phase change material (MEPCM) suspension, a heat transfer performance experimental facility of the PHP was established. The heat transfer characteristic with MEPCM suspension of different mass concentrations (0.5% and 1.0%) and ultra-pure water were compared experimentally. It was found that when the PHP uses MEPCM suspension as its working fluid, operating stability is impoverished under lower heating power and the operating stability is better under higher heating power. At the inclination angle of 90°, the temperature at heating side decreases compared to ultra-pure water and the temperature at heating side decreases with the raising of MEPCM suspension mass concentration. The heat transfer characteristic of the PHP is positively correlated with the inclination angle and the 90° is optimum. The unfavorable effect of the inclination angle decreases with heating power increasing. When the inclination angle is 90°, the PHP with MEPCM suspension at 1.0% of mass concentration has the lowest thermal transfer resistance and followed by ultra-pure water and MEPCM suspension at 0.5% of mass concentration has the highest thermal transfer resistance. When the inclination angles are 60° and 30°, the effect of gravity on the flow direction is reduced to 86.6% and 50% of that on the inclination angle of 90°, respectively, and the promoting effect of gravity on the working fluid is further weakened as the inclination angle further decreases. Due to the high viscosity of MEPCM suspension, the PHP with ultra-pure water has the lowest heat transfer resistance. When the inclination angles is 60°, the thermal resistance with MEPCM suspension at 0.5% of the mass concentration is lower than that at 1.0% at the heating power below 230 W. The thermal resistance of MEPCM suspension tends to be similar for heating power of 230–250 W. At the heating power above 270 W, the thermal resistance with MEPCM suspension at 1.0% of the mass concentration is lower than that at 0.5%.

Keywords: pulsating heat pipe (PHP); micro encapsulated phase change material (MEPCM); heat transfer characteristic; inclination angle

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Nomenclature

I	current/A	MEPCM	micro encapsulated phase change material
i	number of thermocouple	PHP	pulsating heat pipe
Q	quantity of heat transfer/W	PCM	phase change material
R	thermal resistance/°C·W^{-1}	SEM	scanning electron microscopy
t	temperature/°C	**Subscripts**	
U	voltage/V	cond	condenser
u	uncertainty	evap	evaporator
Abbreviations			
DSC	differential scanning calorimetry		

1. Introduction

In the 1990s, a heat pipe, named PHP, was proposed with its new type by Akachi [1], which consists of capillary tubes bent into a snake-like structure. The PHP has quite a few advantages such as its simpler structural form, excellent heat transfer characteristic, and being driven without external force. The PHP can achieve heat dissipation for high heat flow density of electronic components. It can be widely used as a heat transfer element with high efficiency in heat dissipation and energy storage fields such as electronic equipment heat dissipation [2, 3], solar collectors [4–6] and waste heat recovery [7]. The running and heat transfer characteristic of the PHP are affected by many factors, such as the type of the working fluid [8], structure [9–11], the operating parameters [12–16], etc. The commonly used working fluids are the mixed working fluid [17–19], surfactants [20], nanofluids [21–25], refrigerants, etc. The studies for working fluids mainly emphasize thermal properties parameters such as thermal conductivity, surface tension [26], latent heat, phase change temperature, viscosity and specific heat capacity. Lower viscosity and higher thermal conductivity and specific heat capacity are favorable to enhance heat transfer characteristic of the PHP. Lower boiling points are favorable to start-up of the PHP. The differences in thermal property parameters of the working fluid have a great impact on the heat transfer characteristic of the PHP. Xu et al. [27] charged liquid helium into the PHP. Throughout their investigations, the critical heat flux and effective thermal conductivity increased with the inclination angle increasing. Han et al. [28] charged a binary mixture of methanol and deionized water, acetone and ethanol into the PHP. It was concluded that the anti-dry-out property of mixed working fluid is better at the minor filling rate and the heat transfer characteristic of deionized water is better than that of mixture at the large filling rates. Gandomkar et al. [29] measured the contact angle of cetrimonium bromide (C-Tab) surfactant with different concentrations of the PHP and analyzed the effect of C-Tab mass concentration on the heat transfer characteristic. The result can be obtained that the maximum heat flux and thermal resistance of the PHP decreased with increasing concentration. Wang et al. [30] investigated the PHP charged with R134a, R404A and R600a. The results represent that the thermal resistance with R134a was small. The operating temperature with R404A was lower. Zhou et al. [31] investigated the PHP by experimental method. The results indicated that the start-up time and temperature with a low concentration of graphene oxide nanofluid could be reduced at lower filling rates of 20% and 50%. While the heat transfer performance with graphene oxide nanofluid deteriorated similarly at high filling rates of 80%.

The MEPCM suspension is a potential heat functional thermal fluid. The core of the microcapsule is a PCM (Phase Change Material) and the wall material is a flexible polymer compound. The heat absorption and exothermic process of the MEPCM is carried out in isolation from the outside world. The external environment has little influence on it [32], which avoids a series of issue that frequently occurs in the work of phase change materials, such as corrosion, leakage, etc. The addition of MEPCM to the working fluid can realize the dual-phase change of the working fluid and MEPCM suspension can enhance the heat transfer effect. MEPCM can also significantly strengthen the convective heat transfer characteristic of the working fluid [33] and it can reduce the size of heat transfer equipment. At the same time, PCM can improve the energy efficiency, which has been used in many fields such as energy storage [34–36] and enhanced heat transfer [37]. MEPCM has potential to improve the heat transfer characteristic of PHP. The main factors affecting the heat transfer characteristic of MEPCM suspension are the mass concentration, the thermal conductivity and specific heat capacity. There are few theoretical and experimental investigations on running characteristic of the PHP with MEPCM suspension. Lin et al. [38] compared the heat transfer characteristic of the PHP with water and nanofluids of different mass fractions and MEPCM suspensions. Their results indicated that heat transfer capacity with MEPCM suspension at mass concentration of 1.0% was optimal when heated at the vertical bottom and was poor when heated at the horizontal side. Wang et al. [39] charged MEPCM suspension and ethanol and water into the PHP. It was concluded that MEPCM suspension has a greater operating range than ethanol and water. The thermal properties of MEPCM suspension work best at high heating power. Li et al. [40] concluded that the initiation time is prolonged and the thermal resistance is slightly increased after adding MEPCM suspension consisting of melamine resin shell and n-hexadecane core to PHP. The anti-dry-out property is improved when it is in a suitable temperature range. The performance of MEPCM is greatly affected by the types of core material and wall materials, particle size, wall thickness and other factors. Paraffin hydrocarbons have many advantages such as large latent heat, phase change temperature nearby to room temperature, non-toxic, low price, good thermal stability, no subcooling phenomenon, etc. The working fluid in this study is a new MEPCM suspension with modified paraffin whose wall material is polymer and silica. MEPCM suspension has potential to improve the heat transfer performances of the PHP. At present, there are few theoretical and experimental studies on the heat transfer performance of the PHP with MEPCM suspension. To further improve the heat transfer performance of the PHP with MEPCM suspension, an experimental system was built. This study emphasizes the wall temperature and heat transfer temperature difference and thermal resistance with 50% of filling ratio. The PHP charged with MEPCM suspension at 0.5%, 1.0% of mass concentration and ultra-pure water as working fluids, at 30°, 60° and 90° inclination angles and different heating powers were obtained. A combination of theoretical and experimental analysis was created and the running and heat transfer characteristic were investigated on the PHP under different working conditions, taking the wall temperature, heat transfer temperature difference and thermal resistance as the analysis parameters.

2. Methodology

2.1 Testing of the MEPCM suspension

A special colloidal mixture, named MEPCM suspension, has excellent performance for being heat carrying and transferring fluid. The PCM is its key material whose composition of is modified paraffin and polymers and silica. The other two components of the MEPCM suspension are the surfactant and the ultra-pure water. Brownian motion exists in this type fluid as similar as nanofluids. However, aggregation is a common phenomenon, which causes that some surfactant is needed for a good mix. In the mixing process, an ultrasonic oscillator and a stirrer are needed.

Before investigating the running of the MEPCM suspension PHP, the structure of the MEPCM and the heat capacity of the MEPCM suspension are tested. A scanning electron microscopy (SEM) is used to obtain the appearance of the MEPCM, as shown in Fig. 1. The diameter of the biggest particle is nearly 30 μm while that of the smallest is about 1 μm. The uniform distribution of the MEPCM in the basic fluid also can be seen in this figure.

From Fig. 2, it is observed that the average particle diameter of MEPCM is about 15 μm. The differential volume distribution at that value of the particle diameter is around 15%. The phase transition temperature and the latent heat capacity are two other important thermophysical parameters which can be deduced in

Fig. 1 Appearance of the MEPCM and its suspension [41]

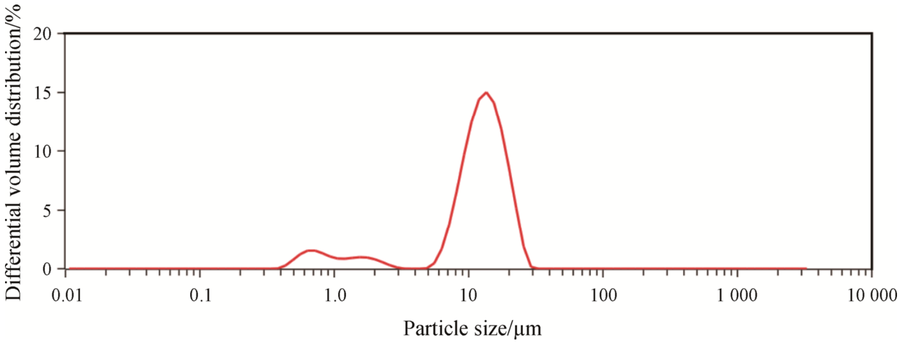


Fig. 2 The distribution of particle size [41]

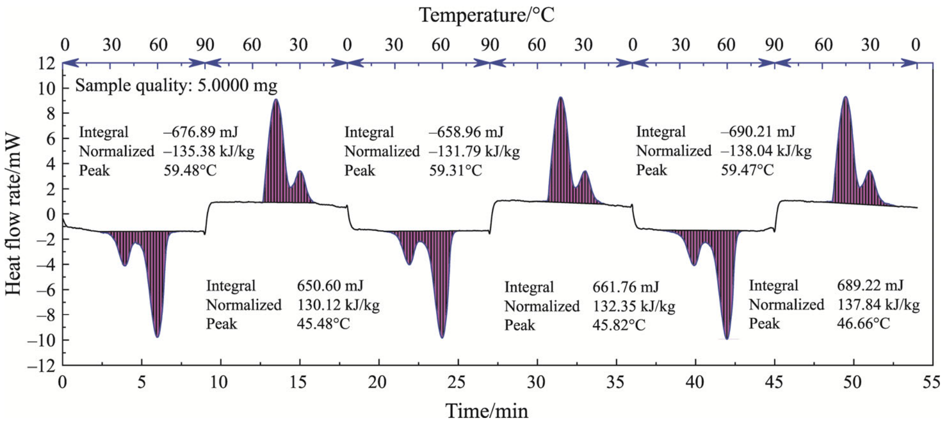


Fig. 3 Heat flow rate at different temperature [41]

Table 1 Thermophysical properties of the working fluids [41]

Working fluid	Temperature/°C	Specific heat/ $kJ \cdot kg^{-1} \cdot °C^{-1}$	Thermal diffusion coefficient/ $mm^2 \cdot s^{-1}$	Dynamic viscosity/ mPa·s
MEPCM suspension (0.5%)	30	4.12	0.13	3.09
MEPCM suspension (3.0%)	30	4.19	0.12	5.33
	70	4.25	0.14	2.43
Ultrapure water	30	4.2	0.15	0.8
	70	4.187	0.16	0.41

Fig. 3. The value of heat flow rate at different temperature is tested by differential scanning calorimetry (DSC) which can be used to obtain the relationship between temperature and heat flow related to thermal transition in materials.

The thermophysical parameters of the working fluid are important factors affecting the heat transfer characteristic of the PHP. As shown in Table 1, the thermophysical parameters of MEPCM suspensions and ultrapure water were tested at 30°C and 70°C, respectively. There are little differences of the values of the specific heat and the thermal diffusion coefficient between the MEPCM suspensions and ultrapure water. The main difference occurs in testing the dynamic viscosity. At the same temperature, the dynamic viscosity of the MEPCM suspension is much higher than that of the ultrapure water. The higher the MEPCM suspension concentration is, the higher the dynamic viscosity is. The dynamic viscosity of both MEPCM suspension and the ultrapure water decreases with increasing the temperature.

2.2 The PHP and the experimental system

As shown in Fig. 4, the experimental system is formed by five major parts, including a PHP device, a heating system, a cooling system, a data acquisition system and a vacuum pumping system. The Nichrome heating wire is uniformly wound around the heating side and supplies heating power to the PHP. By adjusting the voltage, the heating power can be regulated to the specified value. The actual value can be tested by a digital power meter (model Yokogawa WT310). A small cooling water tank (162 mm×17 mm×90 mm) is installed at the cooling side of the PHP. A high-level water tank is used to supply cooling water with stable flowing speed. The flow rate is measured by a glass rotameter. In order to reduce the heat loss, the evaporating and thermal insulating section were covered by a double-layer of asbestos cloth insulation material and the small cooling water tank was covered by a layer of rubber-plastic insulation material. The T-type thermocouples fixed on the surface of the purple copper tube wall are used to test the temperature. A data acquisition machine with an acquisition interval of two seconds (Agilent 34980A), is used to collect the temperature data and transfer them to the computer. A rotary vane vacuum pump (Agilent DS202) is used to supply the vacuum of the PHP before filling working fluid, and the ultimate pressure of the vacuum pump is 10^{-2} Pa. The vacuum pumping time is about 2 minutes, and the PHP system can maintain the vacuum for 24 hours.

The detailed dimensions of the PHP are shown in Fig. 5. The PHP is made of pure copper tube. The inner diameter of the pipe is 2 mm and its wall thickness is 0.5 mm. The cooling side is located at the top of the PHP and the cooling water tank is fixed near the four U-bends. The heating side is located at the bottom of the PHP and the Nichrome heating wire is evenly wound on the five

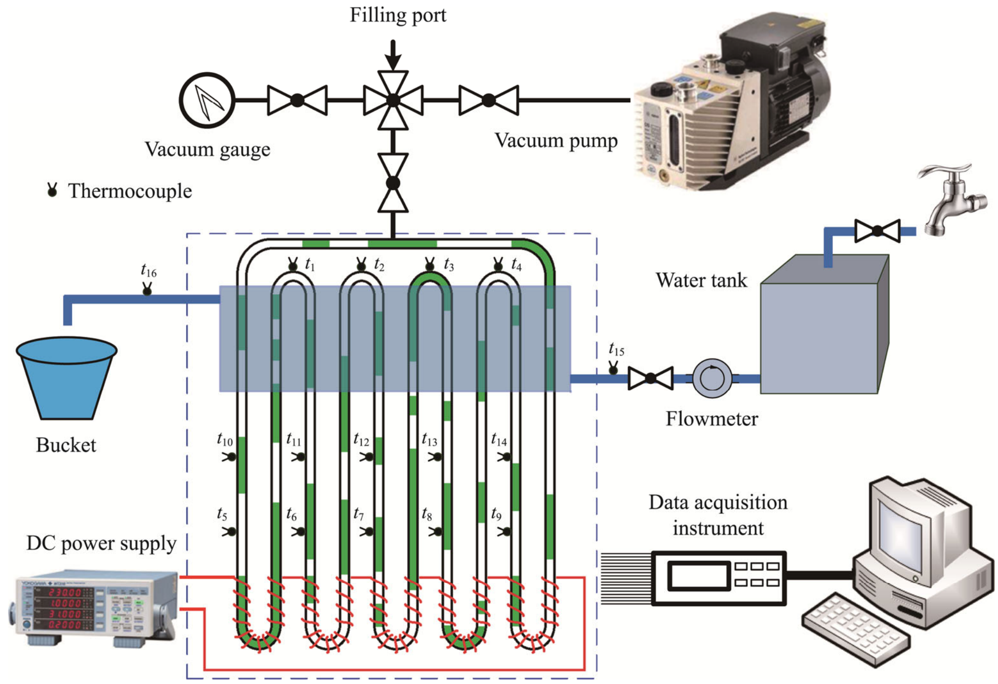


Fig. 4 Composition of the experimental system [41]

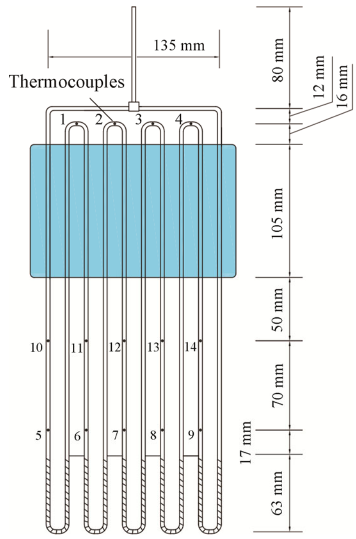


Fig. 5 Main structure of the PHP [41]

U-bends. The thermocouples (t_1 to t_4) on the U-bends are used to measure the temperature of the cooling side. Thermocouples (t_5 to t_9) far away from the U-bends are used to measure the temperature of the heating side. If these thermocouples are fixed on the U-bends at the heating section, they will occupy some space of the electric heating wire. Additionally, the hot heating wire also influences the testing value of the thermocouples.

The effect on the performance of the PHP with different working fluids is investigated when the heating power varies from 150 W to 270 W. The heating power is regulated by changing the voltage of the inputting electricity. With adjusting the inclination angle of the experimental platform, the inclination angles of the PHP are specified as 30°, 60° and 90°, respectively.

2.3 Calculation method

The wall temperature, heating power and thermal resistance are three important parameters for analyzing the characteristic of the PHP. The values of the wall temperature are tested and collected by the thermocouples and an acquisition instrument (Agilent 34980A). The accuracy of the thermocouples is 0.5°C. The accuracy of the acquisition instrument is 0.004% and the resolution ratio is 6½ digits. The average temperature at the cooling side can be calculated from the measured values of the four thermocouples fixed on the wall surface, as shown in Eq. (1). The average temperature at the heating side can be calculated from the measured values of the five thermocouples located on surface of this side, as shown in Eq. (2). The heating power can be calculated from the voltage and current, as shown in Eq. (4). The voltage and current data are measured directly by a digital power meter (model Yokogawa WT310). As shown in Eq. (5), the overall thermal resistance of the PHP can be calculated from the average temperature difference between the cooling side and the heating side and the value of heating power.

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

$$\overline{t_{\mathrm{evap}}} = \frac{1}{5}\sum_{i=5}^{9} t_{\mathrm{evap},i} \tag{2}$$

The temperature difference is defined as,

$$\Delta t_{\mathrm{PHP}} = \overline{t_{\mathrm{evap}}} - \overline{t_{\mathrm{cond}}} \tag{3}$$

The heating power is defined as,

$$Q_{\mathrm{PHP}} = U \cdot I \tag{4}$$

The thermal resistance is defined by the above two parameters as,

$$R_{\mathrm{PHP}} = \frac{\Delta t_{\mathrm{PHP}}}{Q_{\mathrm{PHP}}} \tag{5}$$

Further, the relative uncertainty of the thermal resistance can be calculated by the following equation [42].

The uncertainty of voltage and current can be expressed as,

$$u(U) = 0.1\%U + 0.05\%U_{\mathrm{range}} \tag{6}$$

$$u(I) = 0.1\%I + 0.05\%I_{\mathrm{range}} \tag{7}$$

$$\frac{u(Q_{\mathrm{PHP}})}{Q_{\mathrm{PHP}}} = \sqrt{\left(\frac{u(U)}{U}\right)^2 + \left(\frac{u(I)}{I}\right)^2} \tag{8}$$

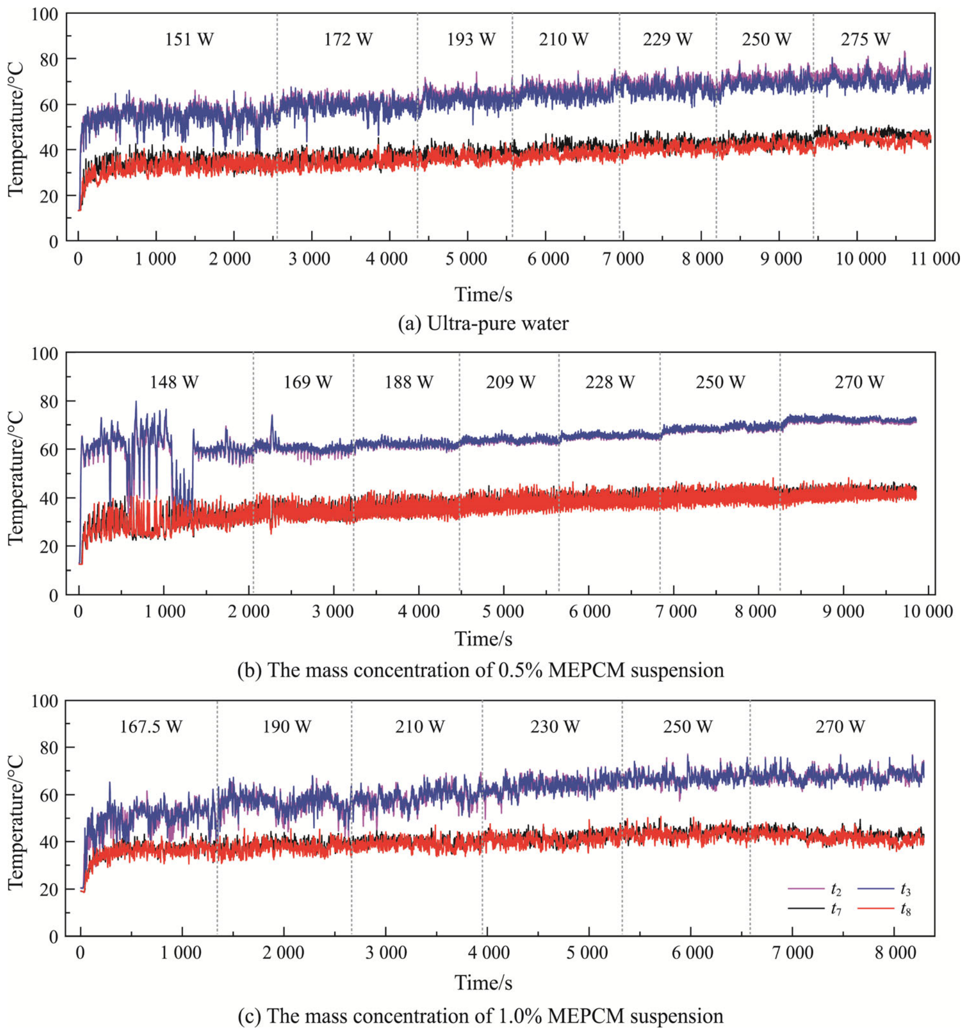
$$\frac{u(R_{\mathrm{PHP}})}{R_{\mathrm{PHP}}} = \sqrt{\left(\frac{u\left(\overline{t_{\mathrm{evap}}}\right)}{\Delta t_{\mathrm{PHP}}}\right)^2 + \left(\frac{u\left(\overline{t_{\mathrm{cond}}}\right)}{\Delta t_{\mathrm{PHP}}}\right)^2 + \left(\frac{u(Q_{\mathrm{PHP}})}{Q_{\mathrm{PHP}}}\right)^2} = \sqrt{2\left(\frac{u(T)}{\Delta t_{\mathrm{PHP}}}\right)^2 + \left(\frac{u(Q_{\mathrm{PHP}})}{Q_{\mathrm{PHP}}}\right)^2} \tag{9}$$

According to Eqs. (8)–(9), the relative uncertainty of R can be obtained and shown in Figs. 7, 8, 11 and 12.

3. Results and Discussion

3.1 Heat transfer performance at 90° of inclination angle

The wall temperature is an external expression of the PHP start-up and operation. As shown in Fig. 6, the wall temperature at the heating side with each working fluid



(a) Ultra-pure water

(b) The mass concentration of 0.5% MEPCM suspension

(c) The mass concentration of 1.0% MEPCM suspension

Fig. 6 Wall temperature variation vs. time for PHP at 90° of inclination angle varies violently under low heating power. The wall temperature oscillation range at cooling side and heating side is close. The intensity of temperature oscillation of the PHP with MEPCM suspension at the heating side is aggravated. The reason is that the driving force is weak with low heating power and the resistance dominates. Unstable operating conditions can easily lead to flow direction changes, so a good and stable working process cannot be formed. MEPCM suspension viscosity increases compared to ultra-pure water, so the resistance increases significantly. Greater driving force is required to make high viscosity fluids work. So the PHP with MEPCM suspension at 1.0% of the mass concentration cannot start under the heating power of 150 W. Rising to 190 W wall temperature at heating side still cannot have good stability. As the heating power increases, the wall temperature fluctuation at the heating side with each working fluid decreases and the operation process tends to be stable. MEPCM suspension is more beneficial to enhance the temperature stability at the heating side. Under the heating power of 270 W, the average temperature at the heating side is just 68°C of the PHP with MEPCM suspension at 1.0% of the mass concentration. It is 3.5°C lower than that of the same working condition of the PHP with ultra-pure water. The driving force is larger at the higher heating power. Driving force is more dominant than resistance, which can make the working fluid form a fast and stable unidirectional flow. MEPCM have the advantage of good continuity. The phase-change of MEPCM can fully play a role in enhancing the stability of working temperature. A large number of microcapsule particles absorb a lot of heat in the form of latent heat of phase change, so the PHP has a low temperature at the heating side.

Fig. 7 reveals that the heat transfer temperature difference shows a slow-growth trend as the heating power increases. It is closer of the PHP with ultra-pure water and MEPCM suspension at 0.5% of the mass concentration. It is the lowest with MEPCM suspension at 1.0% of the mass concentration. The heat transfer temperature difference of these three fluids eventually tends to be the same. Fig. 8 shows under the heating power of 190–270 W, the change of thermal resistance of each working fluid tends to level off as the heating power increases. The heat transfer thermal resistance is the lowest with MEPCM suspension at 1.0% of the mass concentration and its variation with heating power is very small. The thermal resistance with MEPCM suspension at 0.5% of the mass concentration is maximum. Finally, the three kinds of fluids tend to be the same. The MEPCM suspension has a dual effect on the heat transfer characteristic of the PHP. On the one hand, MEPCM suspension can enhance the vaporization core and the flow perturbation of the base fluid, which is beneficial to improve the heat transfer characteristic. On the other hand, it can be obtained through Table 1 that at a temperature of 30°C, the dynamic viscosity of MEPCM suspension at 0.5% of the mass concentration is 3.09 mPa·s, and that of ultrapure water is 0.8 mPa·s. The viscosity of MEPCM suspension with 0.5% mass concentration is 3.86 times that of ultrapure water. So increasing of the viscosity of MEPCM suspension can increase the resistance to the flow of the working fluid and it can lead to a reduction of heat transfer characteristic. Therefore, whether the heat transfer characteristic of the PHP with MEPCM suspension is improved mainly depends on whether the fluid promotion plays a dominant role. When the mass concentration of MEPCM suspension is 0.5%, the phase transition disturbance is weak and the viscosity is large. It hinders the oscillatory flow of the working fluid at the heating side and cooling side, resulting in weaker working material reflux, increased heat transfer temperature difference, larger thermal resistance and lower heat transfer performance. When the mass concentration of MEPCM suspension increases to 1.0%,

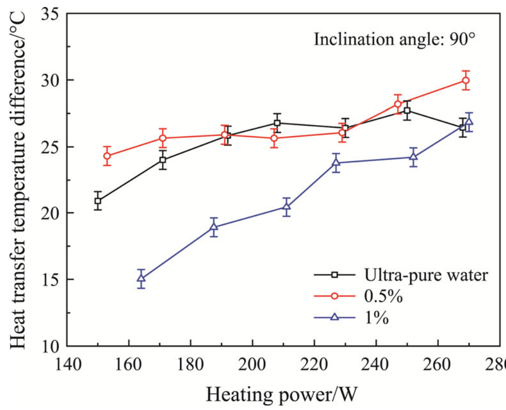


Fig. 7 Heat transfer temperature difference variation vs. heating power at 90° of inclination angle

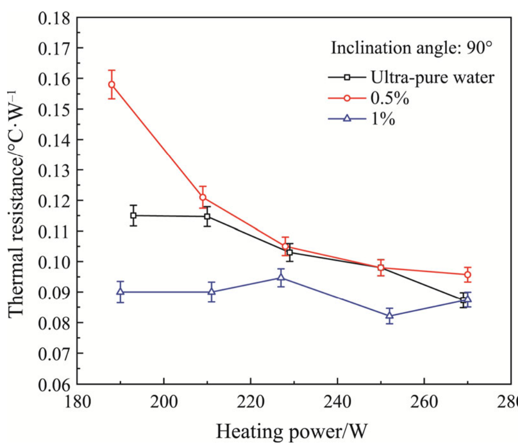


Fig. 8 Thermal resistance variation vs. heating power at 90° of inclination angle

it absorbs and releases a large amount of latent heat at the heating side and the cooling side. The effect of phase change is greater than the viscosity. The phase change can keep the temperature at the heating side on a lower range of heat transfer. It can reduce the heat transfer temperature difference and significantly reduce the thermal resistance, which improves the heat transfer characteristic of the PHP.

3.2 Heat transfer performance at 60° and 30° of inclination angle

Figs. 9 and 10 show that as the inclination angle decreases, the wall temperature pulsation of each working fluid increases, while the stability gradually decreases. The wall temperature shows a rising trend at the heating side and it shows a decreasing trend of PHP with MEPCM suspension at the cooling side. When the inclination angle is 60° and PHP is in stable operation, the average temperature at the heating side is approximately equal for each mass concentration of MEPCM suspension and slightly higher than that of ultra-pure water. The cooling side of ultra-pure water has the highest average temperature. At the inclination angle of 30°, the wall temperature at the evaporating and cooling side increased with the rising mass concentration of MEPCM suspension. And the increasing range of wall temperature at the cooling side shows a negative correlation with the mass concentration of MEPCM suspension.

The reduction of inclination angle leads to a reduction in the promotion of gravity and the viscosity plays a major role in affecting the heat exchange of the fluid flow. Viscosity increase with MEPCM suspension leads to fluid flow resistance increase and driving power is reduced. The heat cannot be transferred promptly at the cooling side, so the temperature rises at the heating side and the temperature drops at the cooling side. Flow resistance increases significantly with increasing mass concentration of the MEPCM suspension. Therefore, the wall temperature of PHP at the heating side with

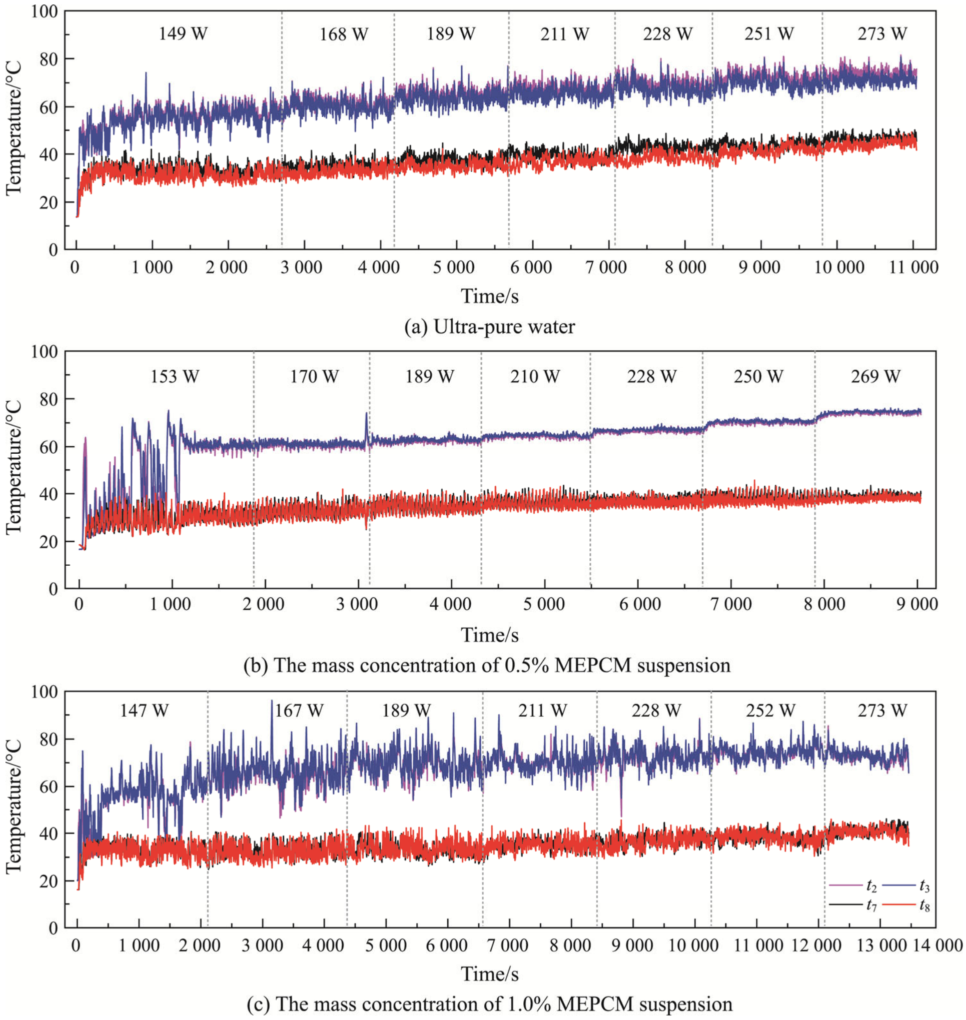


Fig. 9 Wall temperature variation vs. time for PHP at 60° of inclination angle

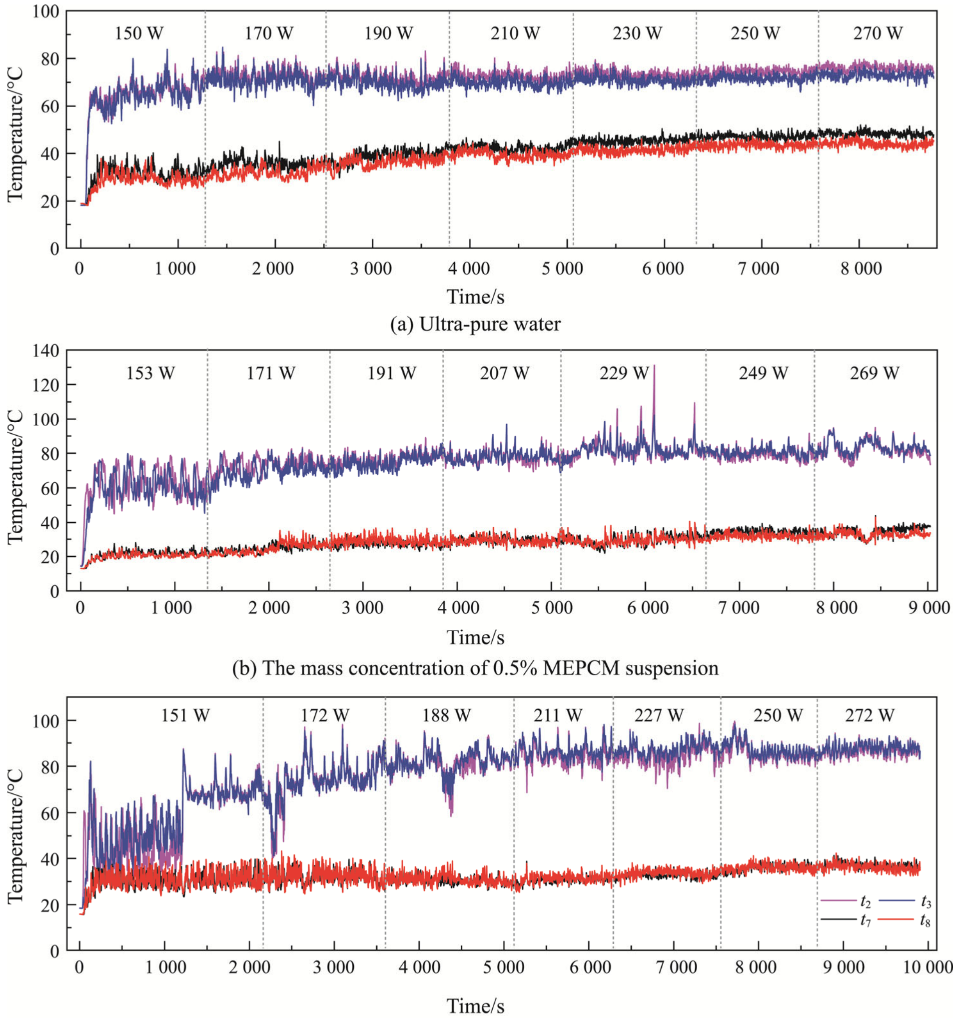


Fig. 10 Wall temperature variation vs. time for PHP at 30° of inclination angle

MEPCM suspension at mass concentration of 1.0% is higher than that at mass concentration of 0.5%. The temperature is the lowest at the heating side with ultra-pure water.

Figs. 11 and 12 show that as the inclination angle decreases, the heat transfer performance of each working fluid decreases. The unfavorable effect of the inclination angle decreases as the heating power increase. Each working fluid shows better heat transfer performance with high heating power. At the inclination angle of 60°, the heat transfer thermal resistance with ultra-pure water is the smallest. At the heating power below 230 W, the thermal resistance with MEPCM suspension at 0.5% of the mass concentration is lower than that at 1.0%. The thermal resistance of MEPCM suspension tends to be similar for heating power of 230–250 W. At the heating power above 270 W, the thermal resistance with MEPCM suspension at 1.0% of the mass concentration is lower than that with the mass concentration of 0.5%. The main

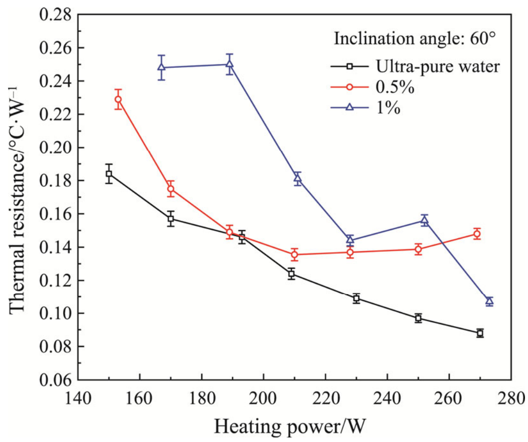


Fig. 11 Thermal resistance variation vs. heating power at 60° of inclination angle

factors affecting the operation of working fluid of the PHP are dynamic viscosity and gravity, etc. Dynamic viscosity has a weakening effect on the operation of the

PHP, and gravity has an enhancing effect on the operation of the PHP. The inclination angle mainly affects the promotion of gravity. As the inclination angle decreases, the driving force is reduced. There's not enough energy to drive the high viscosity fluid. The dynamic viscosity of MEPCM suspension is much larger than that of ultrapure water; therefore, the running characteristic of the PHP with ultra-pure water is the best. However, with increasing the heating power, enough power is generated to drive the working fluid quickly and the unfavorable effect of the inclination angle decreases. The thermal resistance of high mass concentration MEPCM suspension is weakened due to driving power dominating. Therefore, the heat transfer characteristic of the PHP with the mass concentration of 1.0% working fluid show better than that with 0.5% at the heating power above 250 W. Fig. 12 shows that the thermal resistance with MEPCM suspension is significantly higher compared to ultrapure water at the inclination angle of 30°. When the inclination angle is 60° and 30°, the effect of gravity on the flow direction is reduced to 86.6% and 50% of that on the inclination angle of 90°, respectively. The promoting effect of gravity on the working fluid is further weakened as the inclination angle further decreases. At the same time, it is affected by the flow resistance caused by viscosity. MEPCM suspension significantly deteriorates the heat transfer characteristic of the PHP and different concentrations of MEPCM tend to be consistent.

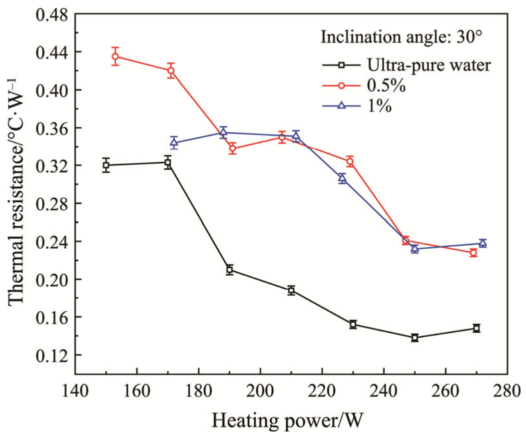


Fig. 12 Thermal resistance variation vs. heating power at 30° of inclination angle

As can be seen, the optimal operating conditions for different mass concentrations of MEPCM suspensions are different. The heating power, the latent heat transfer and viscosity of the working fluid should be comprehensively taken into account. The input heat is required to generate enough driving force to overcome the flow resistance and MEPCM are required to participate in phase change heat transfer as much as possible to make the fluid run fast and stable operation.

4. Conclusions

The working fluid, the heating power and the inclination angle are three important parameters which affect the running characteristic of the PHP. An experimental platform has been set up to characterize the performance of PHPs. The MEPCM suspension at mass concentrations of 0.5% and 1.0% and ultra-pure water were used as working fluids. The influence of different working fluids of the PHP on the start-up and heat transfer characteristic was discussed by analyzing the operating temperature curve, heat exchange temperature difference and thermal resistance at different heating power and inclination angle. The operation and heat transfer performance of the PHP are summarized and analyzed.

(1) The wall temperature pulsation of the PHP with MEPCM suspension is larger under lower heating power at the inclination angle of 90°. The MEPCM suspension can increase the operating stability of the PHP and reduce the temperature at the heating side as heating power increases. The mass concentration of MEPCM suspension has an important influence at the heating side temperature and the heating side temperature shows a decreasing trend when the mass concentration increases from 0.5% to 1.0%.

(2) The optimal operating conditions of MEPCM suspension with different mass concentration is different. The PHP with a high mass concentration of MEPCM suspension has the optimal heat transfer characteristic at larger inclination angles and higher heating power. Heat transfer performance decreases with decreasing inclination angle and is optimal at 90°. The unfavorable effect of the inclination angle decreases as the heating power increases. At 90° of inclination angle, the heat transfer thermal resistance with MEPCM suspension at 1.0% of the mass concentration was the lowest and the heat transfer characteristic was the worst at 0.5% of the mass concentration. The heat transfer characteristic of the ultra-pure water is optimal at the inclination angles of 60° and 30°. When the inclination angle is 60° and the heating power is below 230 W, the thermal resistance of MEPCM suspension with a mass concentration of 0.5% is lower than that with a mass concentration of 1.0% and thermal resistance tends to be close under 230–250 W and it is contrary to the case at low heating power when the heating power is above 270 W.

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Conflict of Interest

On behalf of all authors, the corresponding author states that there is no conflict of interest.

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