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Influence of Cooling Water Flow Rate on Start and Heat Transfer Performance of Pulsating Heat Pipe at Different Inclination Angles

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Abstract: Pulsating heat pipe (PHP) is an efficient heat transfer technology applied in the fields of heat dissipation and energy utilization. There are many factors affecting the heat transfer of PHP, including working fluid, filling ratio, inclination angle, etc. The cooling capacity of the cooling water system at the condensing section to the working fluid is also an important factor affecting the starting and operating of PHP. The research on PHP at different cooling water flow rates is of great significance for enhancing the operating performance. An experimental investigation of starting and running performance is carried out on a closed loop PHP with ultrapure water under different inclination angles of 90°, 60° and 30°. The starting and heat transfer performance of PHP with a filling ratio of 50% is obtained by adjusting the heat input in the range of 30–210 W at different cooling water flow rates of 6.7 g/s, 9.7 g/s and 13.9 g/s. The temperature and heat transfer resistance are used for analyzing the heat transfer performance. The results show that the starting mode, initial pulsating temperature and different heat transfer effects are brought about by different cooling water flow rates. It is observed that the cooling water flow rate has no obvious influence on the starting mode of PHP and that the starting mode of PHP is temperature progressive, starting with the increase in cooling water flow rates at a heating input of about 30 W. The influence of cooling water flow rates on the heat transfer performance of PHP is affected in a different way by inclination angles. The heat transfer performance of PHP with an inclination angle of 90° is similar at 6.7 g/s, 9.7 g/s and 13.9 g/s but, under the condition of 60° and 30°, the heat transfer resistance drops within a certain range effectively with an increasing cooling water flow rate from 6.7 g/s to 9.7 g/s and the heat transfer performance does not change significantly with the cooling water flow rate increasing to 13.9 g/s. Thus, there is an optimal value for the cooling water flow rate during the operating of PHP. The inclination angle also has an important effect on the temperature pulsating, and the temperature of PHP affected by gravity is stable with an inclination angle of 90°. However, the reduced influence of gravity on the backflow of the working fluid drops when the inclination angle decreases from 90° to 30°, and the wall temperature increases due to local overheating when the high heat input occurs.

Keywords: pulsating heat pipe; cooling water flow rate; start; inclination angle; heat transfer performance

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1. Introduction

Pulsating heat pipe (PHP) proposed by Akachi is a heat exchange technology with great heat transfer potential applied in the heat dissipation and energy utilization fields [1] that is processed by bending a capillary tube or a flat plate. PHP includes an evaporation section, an adiabatic section and a condensation section. The working fluid circulates in the PHP under the pressure difference between the evaporation section and the condensation section. It can be divided into open PHP and closed PHP according to the structure. Because of the pressure difference between the evaporation section and the condensation section, the working fluid spontaneously oscillates and flows for heat transfer in the PHP [2]. Because of the significant advantages of PHP in volume and heat transfer efficiency, it is currently applied in lots of fields such as heat dissipation of electronic equipment, heating ventilation and air conditioning and thermoelectric power generation with the biomass energy-based system [3–7].

It has been found that the working fluid flow pattern has experienced some flow patterns such as bubble flow, plug flow and annular flow under different heat inputs during the visualization experiments [8,9]. Many factors influence the start-up and heat transfer performance of PHP, including pipe diameter [10], heating power [11], liquid filling ratio [12], inclination angle [13] and working fluid [14,15]. Scholars pay more attention to the running law and mechanism of PHP analyses by theoretical calculation and heat transfer experiments.

The cooling capacity of the condensation section of PHP is also very important among many factors and has attracted the attention of many scholars in recent years. Naik et al. [16] put forward a simplified theoretical model of PHP used in the vapor compression refrigeration system. It was found that the performance of the system was improved at a higher temperature of the evaporation section and a lower temperature of the condensation section. Xu et al. [17] reported that water cooling had a better effect than natural cooling and that the performance of PHP could be further improved by reducing the cooling temperature. Ahmad et al. [18] used the method of natural convection and forced convection at the condensation section. It was found that forced convection not only made PHP running under the conditions of a higher heat input but also improved the heat transfer limit. Zou et al. [19] adopted natural cooling and forced cooling with a wind speed of 4 m/s and found that the temperature of the evaporation and condensation sections were lower and stabilized by forced cooling, which could effectively reduce the thermal resistance and improve the heat transfer performance of PHP. Shi et al. [20] found that the heat transfer limit could be improved by increasing the cooling water flow rate by experiments using multi-channel parallel loop plate PHP. Zhang et al. [21] experimented with the PHP of varied diameters by cooling water flow rates of 0.1, 0.3 and 0.5 m^3/h at the inclination angle of 90°. It was found that the heat transfer resistance could not effectively reduce with an increasing cooling water flow rate, but the heat transfer limit could increase with an increasing flow rate. Luo [22] measured the heat release with a phase change heat storage PHP at different initial temperature and cooling water flow rates; the heat release time could be reduced by lowering the initial temperature and by appropriately increasing the water flow rate. Zhao [23] studied the influence of the cooling water flow rate and temperature on the heat transfer performance of plate PHP at the inclination angle of 90°. It was found that the condensation temperature decreased with the increase in the cooling water flow rate, resulting in a thermal resistance increase. Additionally, the heat transfer resistance decreased with increasing the cooling water temperature at low heating inputs, while the influence of the cooling water temperature weakened at the high heating inputs.

This paper focuses on the influence of the cooling water flow rate on the heat transfer performance with different inclination angles, which can accumulate basic heat transfer data and optimize the heat transfer performance; it is helpful in improving the basic theory of PHP. Multi-loop PHP charged with ultrapure water is used in the experiments. Taking wall temperature pulsating and heat transfer resistance as the evaluation parameter, the start-up performance of PHP at the inclination angle of 90° and the heat transfer performance under different inclination angles of 90°, 60° and 30° brought about by the cooling water flow rate were investigated in this paper.

2. Methodology

2.1. Experimental System

The experimental system is shown in Figure 1. It includes a PHP with multi-loop, a heating module, a cooling water system, a data acquisition system and the other equipment. Nichrome heating wire is used in the evaporating section and a voltage regulator is used to adjust the power. The working fluid is condensed by cooling water in the condensing section. Double-layer asbestos is adopted in the evaporating section and the thermal insulation section in order to decrease heat loss. However, some heat still dissipated from the surface of PHP to the surroundings and the obtained heat losing rate of the heating inputs is less than 8% [24]. The temperature data are measured by T-type thermocouples and stored by a data acquisition instrument: Agilent 34980A. The system is first vacuumized and then filled with the working fluid.

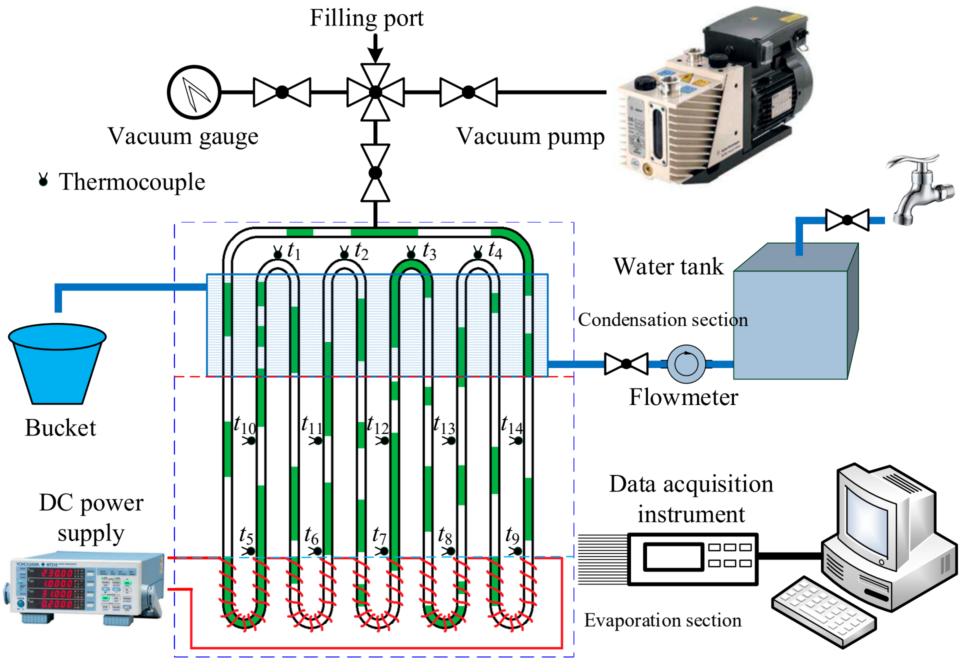

Figure 1. Schematic diagram of the experimental system.

The photo of PHP is shown in Figure 2. The structure is shown in Figure 3. Five bends are designed in the evaporating section of PHP. Thermocouples are arranged in position in the evaporating section, the thermal insulation section and the condensing section.

Ultrapure water was used in this paper and the thermophysical parameters are shown in Table 1. Viscosity is one of the important parameters as a factor affecting the operating performance; the viscosity of the working fluid decreases with the e in temperature, which is beneficial to the heat transfer of PHP. Parameters such as viscosity are shown in Table 2; the viscosity of the ultrapure water under the condition of 30 °C is 0.8 mPa·s, but shows a big drop to 0.41 mPa·s when the temperature increases to 70 °C.

The cooling water flow rate, the heating input and the inclination angle are the three most important running parameters that impact the heat transfer performance. The cooling water flow rates of 6.7 g/s, 9.7 g/s and 13.9 g/s are measured and adjusted by a flowmeter. The filling ratios of 50% and the three inclinations of 30°, 60° and 90° are used in the investigation. A rotary platform is used to fix and adjust the inclination angle of the PHP. The heating input is varied from 30 W to 210 W by regulating the supplying voltage.

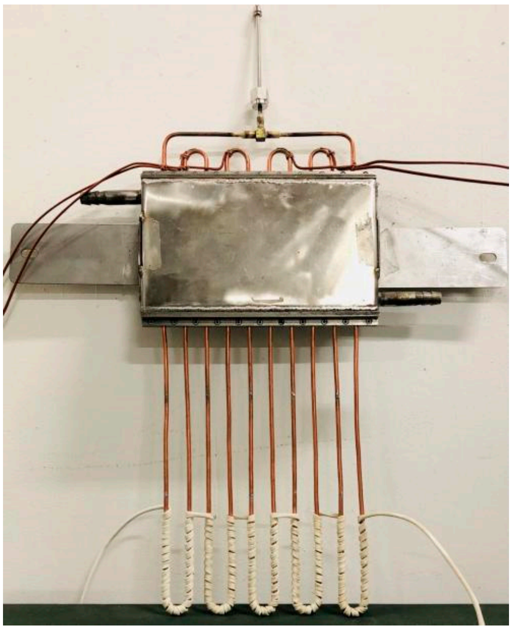

Figure 2. The photo of pulsating heat pipe.

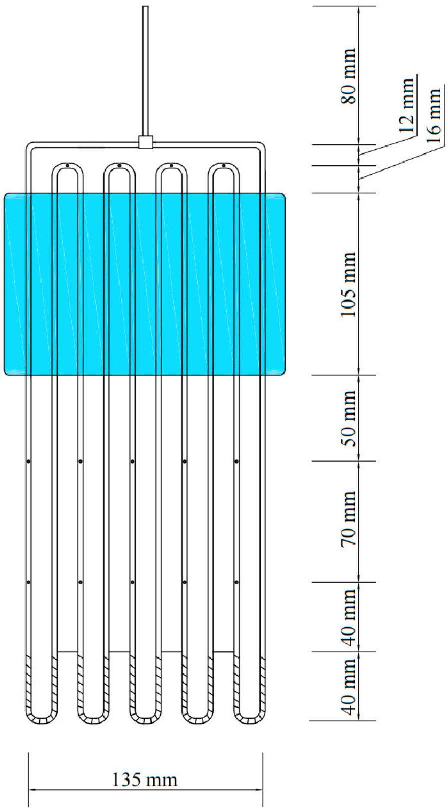

Figure 3. Structural and thermocouple distribution of PHP.

Table 1. Thermophysical parameters of ultrapure water at 101,325 Pa.

Working Fluid	Tsat (°C)	ρl (kg/m^3)	ρv (kg/m^3)	Hfg (kJ/kg)	σ (N/m)
Ultrapure water	100	958	0.6	2256.7	0.0589

Table 2. Some parameters of ultrapure water at 30 °C and 70 °C.

Working Fluid	Temperature (°C)	Specific Heat (kJ/kg·°C)	Thermal Diffusion Coefficient (mm^2/s)	Dynamic Viscosity (mPa·s)
Ultrapure water	30	4.2	0.15	0.8
	70	4.187	0.16	0.41

2.2. Data Processing

The wall temperature and heat transfer resistance are used to analyze the starting and operating performance. The mean temperature at the condensation section and the evaporation section can be obtained by averaging the measurement values as expressed in Equations (1) and (2).

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

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

The temperature difference can be calculated as

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

Because of a negligible amount of heat leakage from the PHP walls to the surroundings [25], the amount of heat exchanged between the evaporation and condensation sections can be calculated from the energy gained by the cooling water.

$$Q_{\text{PHP}} = \dot{m}_{\text{cooling}} \cdot c_{\text{p}} \cdot \left(t''_{\text{cooling}} - t'_{\text{cooling}}\right) \tag{4}$$

The thermal resistance can be calculated as

$$R_{\text{PHP}} = \frac{\Delta t_{\text{PHP}}}{Q_{\text{PHP}}} = \frac{\overline{t_{\text{evap}}} - \overline{t_{\text{cond}}}}{\dot{m}_{\text{cooling}} \cdot c_{\text{p}} \cdot \left(t''_{\text{cooling}} - t'_{\text{cooling}}\right)} \tag{5}$$

Then, the relative uncertainty of the thermal resistance can be expressed as the following equation [26].

$$\begin{aligned} \frac{U_R}{R} &= \sqrt{\left(U_t \cdot \frac{\partial \ln R_{\text{PHP}}}{\partial t_{\text{evap}}}\right)^2 + \left(U_t \cdot \frac{\partial \ln R_{\text{PHP}}}{\partial t_{\text{cond}}}\right)^2 + \left(U_{\dot{m}} \cdot \frac{\partial \ln R_{\text{PHP}}}{\partial \dot{m}_{\text{cooling}}}\right)^2 + \left(U_t \cdot \frac{\partial \ln R_{\text{PHP}}}{\partial t''_{\text{cooling}}}\right)^2 + \left(U_t \cdot \frac{\partial \ln R_{\text{PHP}}}{\partial t'_{\text{cooling}}}\right)^2} \\ &= \sqrt{2\left(\frac{U_t}{\overline{t_{\text{evap}}} - \overline{t_{\text{cond}}}}\right)^2 + \left(\frac{U_{\dot{m}}}{\dot{m}_{\text{cooling}}}\right)^2 + 2\left(\frac{U_t}{t''_{\text{cooling}} - t'_{\text{cooling}}}\right)^2} \end{aligned} \tag{6}$$

One of the experimental conditions is selected to calculate the uncertainty. The running condition of the pulsating heat pipe with an inclination angle of 30° and a heating power of 149 W is analyzed in this paper. The uncertainties of the glass rotameter and the calibrated thermocouple are 0.28 g/s and 0.2 °C, respectively. The cooling water is heated by 3.6 °C with a mass flow of 9.7 g/s and the temperature difference between the evaporation section and condensation section of the PHP is 16 °C. As mentioned above, the relative uncertainty of R is obtained as 9.46%. The uncertainty decreases slightly with the increase in the heating power.

3. Results and Discussion

3.1. Start-Up Performance at Inclination Angle of 90° and Different Flow Rates

Two starting modes were proposed based on the start-up characteristics of PHP. Xu [27] studied the influence of heating inputs on the heat transfer performance of typical multi-loop PHP by experiments. It was found that the temperature at the evaporation section experienced a start-up mode of rapid rise–steep drop–stable pulsation at low heating inputs, while it was the mode of slow rise–slow drop–stable pulsation at high heating inputs, I, II, III mean temperature rising area, stable operating transition area and stable operating area, respectively. T_e is the mean average temperature in the evaporation section, T_7 and T_8 are both temperatures in the adiabat section. Liu et al. [28] summarized two ways of the temperature rising mode and the temperature progressive mode, which is realized by the slow rising of temperature and then directly entering the stable pulsating, as shown in Figure 4.

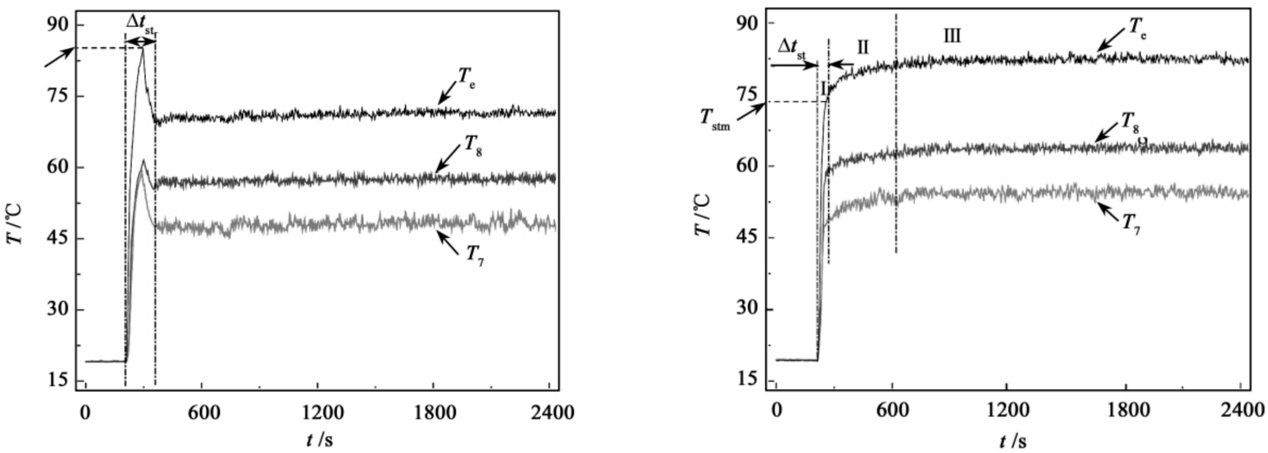

Figure 4. Temperature rising mode and temperature progressive mode [26].

Figures 5–7 show the wall temperature pulsation in the evaporation section of PHP at 90° with different cooling water flow rates of 6.7 g/s, 9.7 g/s and 13.9 g/s, respectively. The initial pulsating temperatures of PHP at the three cooling water flow rates from 6.7 g/s to 13.9 g/s are, respectively, 41.7 °C, 34 °C and 34.6 °C. The experimental results show that the beginning pulsating temperature is affected by the cooling water flow rate, but the effect on the starting mode of the PHP brought by the flow rate is not obvious. The temperature progressive start mode is shown at different cooling water flow rates.

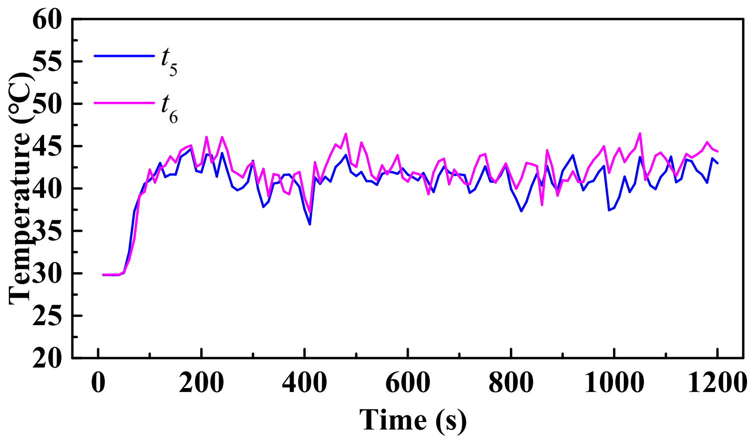

Figure 5. Start-up temperature variation at flow rate of 6.7 g/s.

The condensation and heat dissipation process of the working fluid during starting is affected by the flow rates of the cooling water. Bubbles and higher pressure in the evaporation section are generated by the continuous energy absorption. Due to the pressure difference between the evaporation section and the condensation section, the working fluid flow to the condensation section releases heat from the evaporation section. If the heat absorbed by the liquid working fluid is not enough to make the working fluid flow, the temperature at the evaporation section will show a rising trend, the liquid working fluid will flow to the condensation section rapidly and the temperature will drop to a stable pulsating stage with enough accumulated energy to promote the operation of the working fluid.

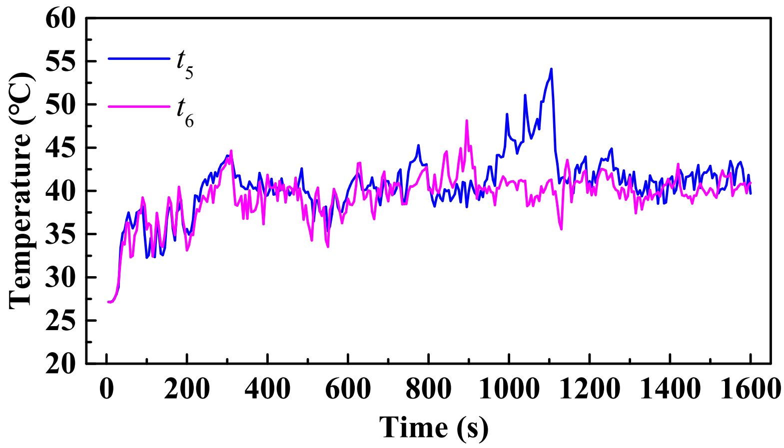

Figure 6. Start-up temperature variation at flow rate of 9.7 g/s.

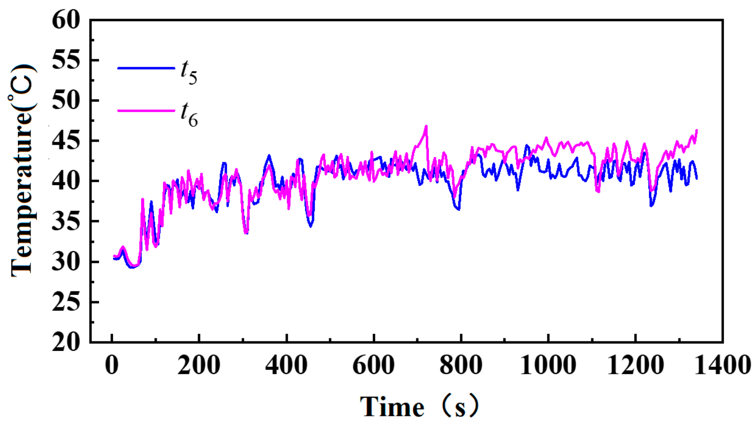

Figure 7. Start-up temperature variation at flow rate of 13.9 g/s.

Condensation and heat release cannot be completed quickly in the condensation section with the lower cooling water flow rate of 6.7 g/s, which will affect the circulating pressure difference of the two sections and the circulating operation of the working fluid. It is necessary to accumulate energy and increase the pressure difference, which results in a higher beginning pulsating temperature with the lower cooling water flow rate of 6.7 g/s. With the increase in the cooling water flow rate, the heat carried by the working fluid can dissipate to the cooling water faster and the pressure difference that drives the circulation of the working fluid can be generated quickly. At the same time, the higher cooling water flow rate is helpful to the temperature drop in the condensation section, which can also increase the temperature difference and the pressure difference between the two sections. Therefore, it is easier for PHP to start and to generate a lower beginning pulsating temperature with a higher flowing rate. Then, the liquid working fluid flowing back to the evaporation section continues to absorb heat and mainly promotes a consistent thermodynamic state between the liquid working fluid flowing back and the original working fluid in the evaporation section [24].

3.2. Heat Transfer Performance at Inclination Angle of 90° and Different Flow Rates

Figure 8 shows the variation of thermal resistance with increasing heating inputs at different cooling water flow rates. Figures 9–11 show the wall temperature pulsation at different flow rates. The increase in the cooling water flow has no obvious effect on the temperature fluctuation of PHP.

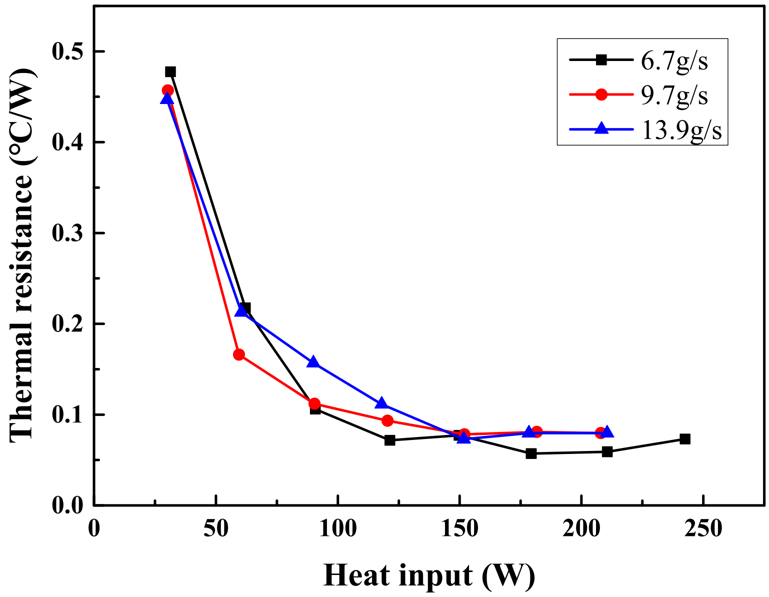

Figure 8. Variation of thermal resistance at 90°.

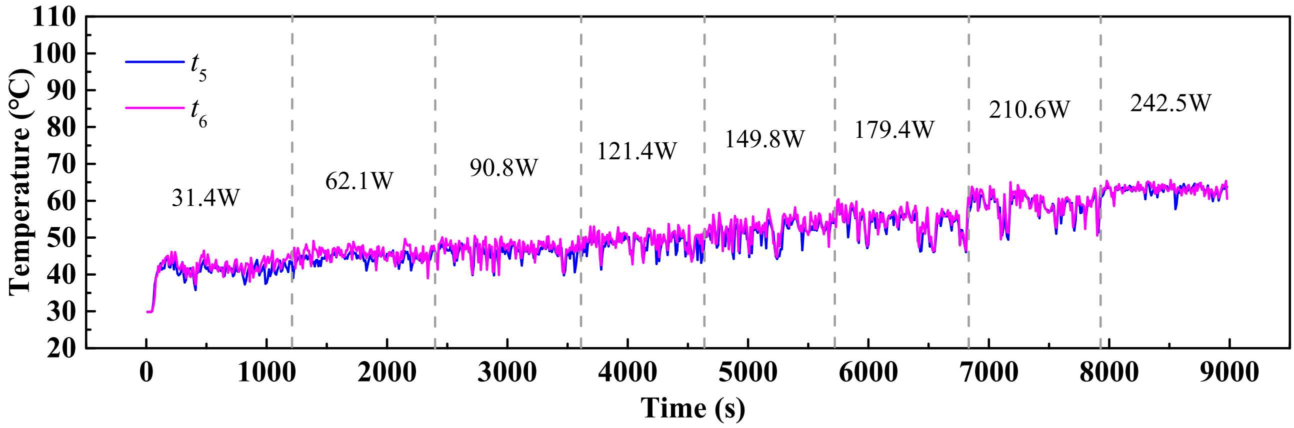

Figure 9. Variation of wall temperature at cooling water flow rate of 6.7 g/s.

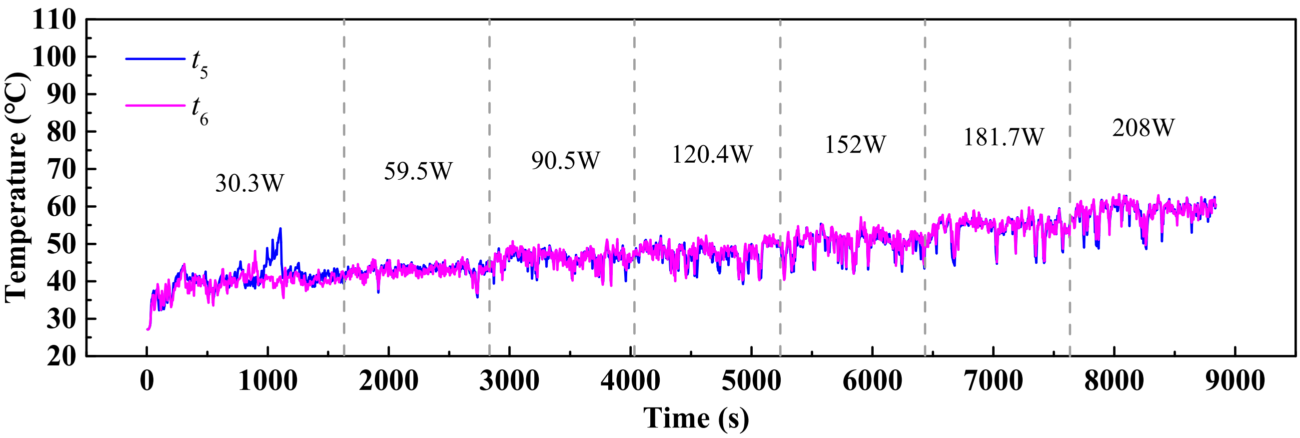

Figure 10. Variation of wall temperature at cooling water flow rate of 9.7 g/s.

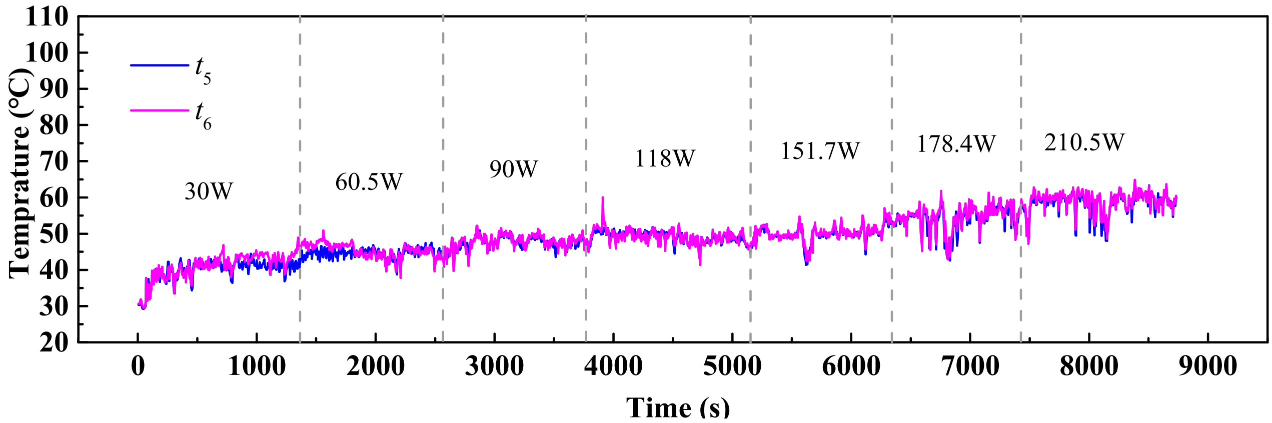

Figure 11. Variation of wall temperature at cooling water flow rate of 13.9 g/s.

It can be seen from the figures that the cooling water flow rate has some influence on the pulsating amplitude and the frequency of the wall temperature of PHP and that the pulsating trend is basically the same at different cooling water flow rates. The heat is transferred in the PHP system through heat conduction and convection from the evaporation section to the condensation section. The thermal resistance of the PHP decreases rapidly in the heating input range of 30–90 W with the inclination angle of 90°; the variation of the thermal resistance tends to be gentle with heating inputs more than 90 W. There is little difference in the thermal resistance of PHP at three different cooling water flow rates, with the heat inputs increasing more than 90 W. The heat transfer effect of PHP is also the best at 9.7 g/s, with the heating inputs less than 90 W. The lowest thermal resistance is obtained at 6.7 g/s, with heating inputs greater than 90 W. The thermal resistance at 9.7 g/s and 13.9 g/s even tends to be the same by gradually increasing the heating inputs.

The main reason for the above phenomenon is that less circulation power of PHP is generated with heating inputs less than 90 W, which is not conducive to heat transfer; however, increasing flow rate is helpful to allow the heat to be quickly taken away by the cooling water and to increase the pressure difference between the two sections. Thus, the PHP shows a better heat transfer effect at 9.7 g/s. However, sufficient circulating power can be generated at a small cooling water flow rate of 6.7 g/s to achieve a better running effect by increasing the heating input more than 90 W. It is better for the cooling water flow rate of 6.7 g/s to meet the heat dissipation requirements during running. There is less influence on the heat dissipation and condensation process of the working fluid with the increase in heat inputs. However, the condensation section temperature drops with an increase in the cooling water flow rate and it will bring the increase in heat transfer temperature difference between the two sections and the thermal resistance of the PHP.

3.3. Heat Transfer Performance at Inclination Angle of 30° and 60° and Different Flow Rates

Figures 12–14 show the wall temperature pulsating at 30° with the various cooling water flow rates. It can be found that the operating stability of the PHP is poorer with the decreasing inclination angle. The wall temperature of the evaporator at 6.7 g/s is higher than those of the other two flow rates of 9.7 g/s and 13.9 g/s and it reaches as high as 110 °C when the heat input is 208.5 W.

The variation in temperature difference in the evaporation section and the condensation section with heat inputs at 30° can be seen in Figure 15. The temperature difference at 9.7 g/s is the lowest compared with those of the other two flow rates; this indicates the higher heat transfer performance. With the cooling water flow rate increasing as high as 13.9 g/s, the temperature in the condensation section decreases rapidly and maintains a relatively low cooling temperature, which leads to a higher heat transfer temperature difference. However, with the cooling water flow rate dropping as low as 6.7 g/s, the temperature difference increases quickly with the increasing heat input lower than 120 W, becomes flat from 120 W to 180 W, and finally rises rapidly again together and drying out at 208.5 W. There is a similar variation trend for the temperature difference with the increasing heat input at 9.7 g/s and 13.9 g/s, which indicates a flat and then dropping trend with the heat input greater than 150 W. Therefore, the optimal heat transfer performance of the PHP can only be obtained by the cooling water flow rate that matches the operating condition.

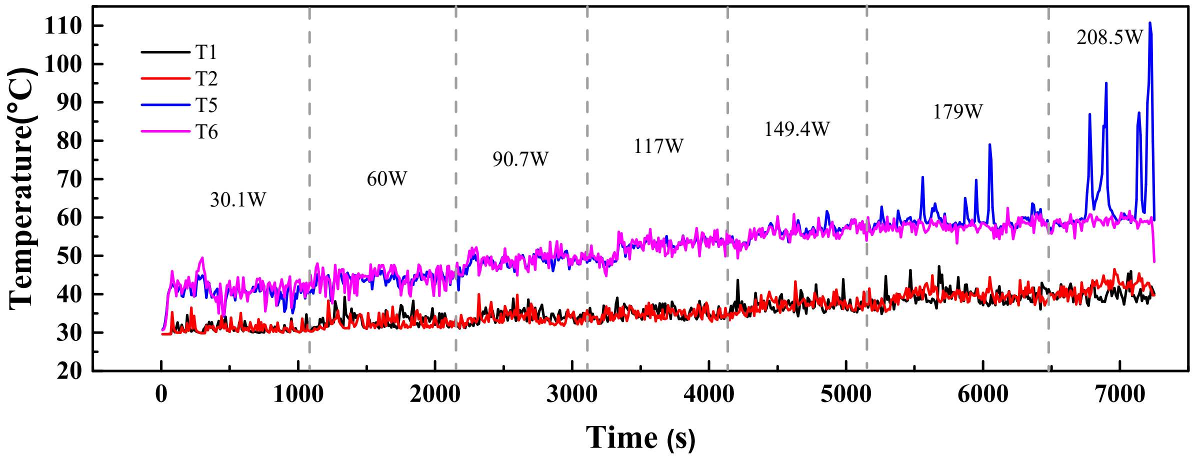

Figure 12. The wall temperature pulsating at 30° (6.7 g/s).

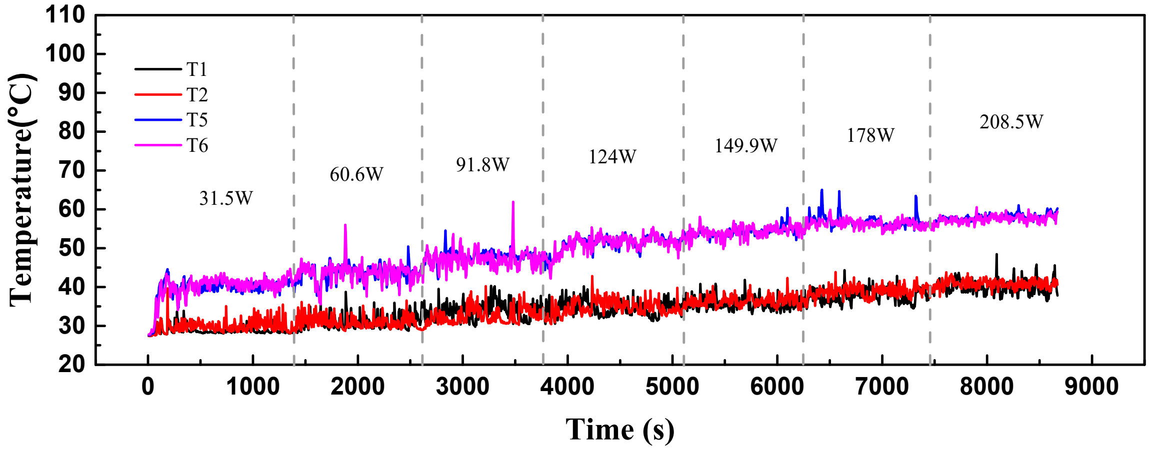

Figure 13. The wall temperature pulsating at 30° (9.7 g/s).

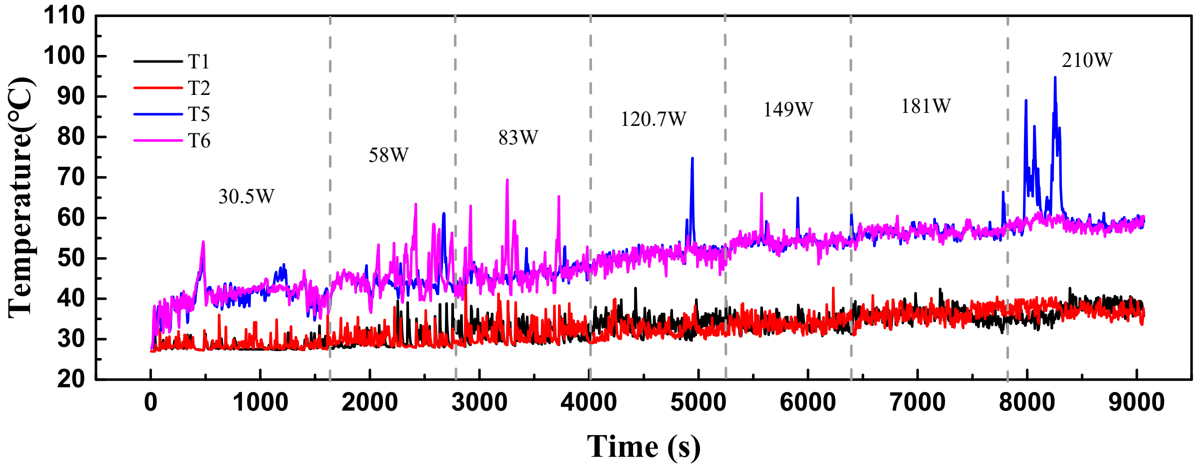

Figure 14. The wall temperature pulsating at 30° (13.9 g/s).

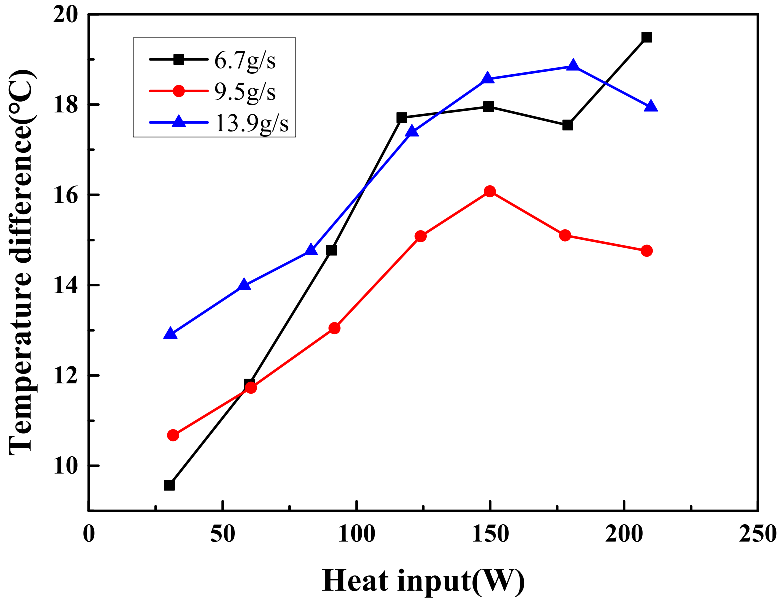

Figure 15. Variation of temperature difference with heat input at inclination angle of 30°.

Figures 16 and 17, respectively, show the variation of thermal resistance of PHP with different heating inputs at different cooling water flow rates and inclination angles of 60° and 30°.

Thermal resistance drops with increasing heating inputs under the inclination angle of 30°, and the thermal resistance of the PHP with a cooling water flow rate of 6.7 g/s is higher than that of the other two flow rates. The cooling effect at 9.7 g/s is basically the same as that at 13.9 g/s. The variation of the thermal resistance at 60° is shown in Figure 17. Thermal resistance decreases rapidly in the range of 30 W–90 W at the inclination angle of 60° and the variation gradually flattens and tends to be stable after heating inputs greater than 90 W. The best overall performance is obtained with a cooling water flow rate of 13.9 g/s with heat inputs less than 90 W, followed by 9.7 g/s and 6.7 g/s. The thermal resistances at the cooling water flow rates of 9.7 g/s and 13.9 g/s gradually decrease and are basically consistent with each other with heat inputs greater than 90 W.

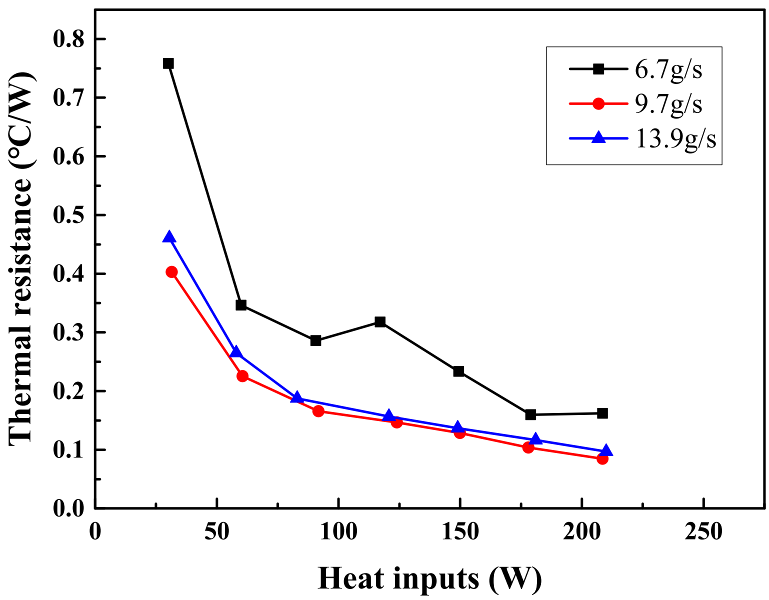

Figure 16. Variation of thermal resistance at 30°.

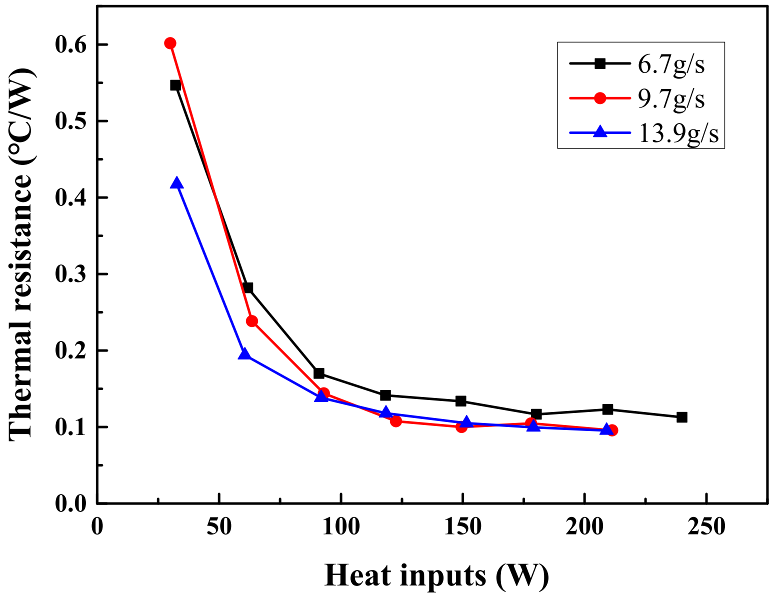

Figure 17. Variation of thermal resistance at 60°.

Generally speaking, the cooling effect is the worst at 6.7 g/s at the inclination angles of 60° and 30° and the heat transfer performance of the PHP is improved when the cooling water flow increases to 9.7 g/s, but the heat transfer performance is not significantly improved with a flow rate continuously increasing to 13.9 g/s. In other words, it is not a case of the greater the cooling water flow rate the better the heat transfer performance, but that there is an optimal value for the best heat transfer performance.

The main reason is that the weakening of gravity leads to the smaller working fluid circulation power with a decreasing inclination angle, but the speed of the working fluid condensing at the condensation section and flowing back to the evaporation section improves when increasing the cooling water flow rate. At the same time, it also increases the pressure difference between the evaporation section and the condensation section and it is beneficial to the circulating flow of the working fluid. Therefore, compared with the running condition at a small cooling water flow rate of 6.7 g/s, the better heat transfer performance is obtained with a cooling water flow rate of 9.7 g/s. However, the temperature of the working fluid at the condensation section drops with the continuous increase in the cooling water flow rate and brings a higher heat transfer temperature difference between the two sections and the heat transfer resistance. That is to say, increasing the cooling water flow rate within a certain range is helpful for improving the heat transfer effect. The greatest heat transfer performance of PHP can be obtained only on the condition that the heat transfer rate from the evaporation section to the condensation section is consistent with the heat releasing rate from the condensation section to the cooling water. Moreover, it is very important for the cooling water flow rate to match the running conditions.

4. Conclusions

The three different cooling water flow rates of 6.7 g/s, 9.7 g/s and 13.9 g/s and the different inclination angles were used as the main influencing factors of the PHP. A series of experiments were carried out to study the starting and running performance and the influence factors were analyzed. Some conclusions were obtained and are shown below.

(1) The influence of the cooling water flow rate on the starting mode of PHP is not obvious; the temperature progressive starting mode is shown under different cooling water flow rates. The beginning pulsating temperature in the evaporation section drops within a certain range when increasing the cooling water flow rate from 6.7 g/s to 9.7 g/s, but the influence is weakened with a continuous cooling water flow rate increasing from 9.7 g/s to 13.9 g/s.

(2) The influence of cooling water flow rates on the heat transfer performance of PHP is different with different inclination angles. The heat transfer performance of PHP with an inclination angle of 90° is similar under the conditions of different cooling water flow rates of 6.7 g/s, 9.7 g/s and 13.9 g/s, but the heat transfer resistance of PHP under the condition of 60° and 30° drops within a certain range effectively when increasing the cooling water flow rate from 6.7 g/s to 9.7 g/s and the heat transfer performance does not change significantly with the cooling water flow rate increasing to 13.9 g/s. Thus, there is an optimal value for the cooling water flow rate during the operating of PHP.

(3) The inclination angle has an important effect on the heat transfer of the PHP. The working fluid wall temperature pulsation of PHP affected by gravity is stable with an inclination angle of 90°. However, the acceleration of gravity on the backflow of the working fluid drops with the inclination angle decreasing from 90° to 30°, affecting the operation performance of the PHP. The wall temperature appears locally overheating when the high heat input occurs. Increasing the cooling water flow at a small inclination angle of 30° can alleviate the local overheating in the evaporation section of the PHP; at the same time, it can increase the heat transfer limit within a certain range. However, the effect of an increasing cooling water flow rate will drop with the continuous increase in heat inputs in the evaporation section.

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Nomenclature

c	specific heat capacity (J/kg·°C)
i	number of thermocouples
U	uncertainty
$\dot{m}$	the mass flow rate of cooling water (kg/s)
Q	quantity of heat transfer (W)
R	thermal resistance (°C/W)
Δt	temperature drop: evaporator–condenser (°C)
t	temperature (°C)
abbreviation	
PHP	pulsating heat pipe
subscript	
cond	condenser
evap	evaporator
cooling	cooling water
p	isobaric
superscript	
′	inlet
″	outlet

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