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Testing and Modeling of the Dynamic Response Characteristics of Pulsating Heat Pipes during the Start-up Process

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Abstract: Pulsating heat pipes (PHPs) are two-phase heat transfer heat pipes with high heat transfer capability and simple structure. Heating power is an important factor that affects the start-up response characteristics of PHPs. The operational characteristics during the start-up and stable operating stages were studied through experiments, and the corresponding dynamic response model under a specified heating power was established based on experimental data and flow pattern in the tube. The starting time, starting temperature, and dynamic response characteristic parameters at a certain heating power were calculated by the dynamic response model. The response characteristics of working fluid during the stable operation of PHPs were deduced based on the dynamic response curve of PHPs during the non-operational and stable operation stages. The response characteristics of PHPs for the step effect (given heating power) were quantitatively described by amplification factor K and time constant τ, thereby presenting the basis for the study on heat and mass transfer mechanisms of PHPs from non-operational to steady operation stage. Results showed that the minimum thermal resistance and the minimum time constant of the PHP are approximately 0.28 °C/W and 75, respectively, obtained at a heating power of 160 W. Moreover, these results indicated that the dynamic response of PHPs demonstrates a favourable performance and rapidly reaches another stable working state when their heat transfer performance is stable. However, the dynamic response time constant of pure fluids decreases when the quantity of the liquid working fluid in the PHP decreases with the increase in heating power.

Keywords: pulsating heat pipe, heating power, dynamic response characteristic, time constant, amplification factor

1. Introduction

Pulsating heat pipes (PHPs) were first proposed by Akachi [1-2] in the early 90s as a kind of electronic device cooling element with high efficiency; these devices exhibit the advantages of simple structure, low cost, and high heat transfer capability and have attracted considerable attention. PHPs are considered as an effective means of solving the challenge of high heat fluxes. Hua et al. [3] experimentally studied the effect of cross section shape

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Nomenclature

A	Constant coefficient	**Subscripts**	
B	Constant coefficient	A	Adiabatic section
c	heat capacity, J/(kg·°C)	C	Condensation section
m	Mass, kg	Cu	Copper plate
P	Heating Power, W	E	Evaporation section
Q	Energy, W	F	Working fluid
T	Temperature, °C	G	Glass
t	Time, s	in	Inlet
Greek letters		M	Stainless steel clip
τ	Time constant	out	Outlet
		W	Cooling water

on the startup characteristics and heat transfer performance of a PHP, and their results showed that the start-up heating power of the PHP with rectangular channels was 1.5612 times greater than that of the heating power of the PHP with circular channels. Dang et al. [4] proposed a rack cooling system with a PHP and an inner tube in the data center of a CPU and investigated the heat transfer performance numerically. The results showed that the CPU temperature increased with the rack heating power, and was no more than 60°C in the rack cooling system with a load of 1380 W.

Sensible heat transfer is the main heat transfer approach of PHP, while latent heat provides oscillation power that is different from traditional heat pipes. The working stages of PHPs are divided into non-operational, transition, and stable operation stages. The non-operational and transition stages are called the start-up stage. The start-up stage determines whether PHPs are fast and reliable to reach the stable operation stage.

Currently, many studies have focused on the start-up and running stages of PHPs. Zhu et al. [5] studied the performance of a closed-loop PHP using water–acetone mixture as working medium with different filling ratios and heat inputs. The results showed that the water–acetone mixture with mixing ratios of 13:1, 1:1, 1:4, and 1:13 improved the start-up performance compared with pure water. Li et al. [6] found that the start-up capability of PHPs depended on their tilt angle. The required heat input to initiate the oscillatory motion was decreased by increasing the tilt angle. The results [7] showed that the heating power and filling ratio are important factors for starting up a plate-type PHP. Different start-up powers are required with various filling ratios, and it is easier to heat the heat pipe at the bottom than that on the top. Wang et al. [8] conducted experimental research on the start-up characteristics of a PHP. Their results showed that the start-up time of the PHP gradually decreased with the increase of the heat load inputs. The start-up time of the PHP using methanol solution was longer than that of methanol, but shorter than that of water with 50% filling ratio. Yang et al. [9] investigated the effect of working fluid ratio and their thermophysical properties on the start-up characteristics of a PHP. The results showed that PHPs with water did not produce constant pulsating two-phase flows, thereby resulting in a high thermal resistance, while the 80% filling ratio of a vertically oriented PHP with methanol showed a pulsating two-phase flow at an input power of 6 W. Zou et al. [10] analyzed the starting characteristics and performance of PHPs under forced convection. It is indicated that the PHPs have two kinds of start-up modes: the intermittent and apparent temperature overshoot process at lower heating power, and the smooth continual start-up process incorporating with a steady operation at higher heating power. Liu et al. [11] found that the optimum liquid filling ratios for start-up were approximately 41%, 52%, and 35%–41% for water, ethanol, and methanol, respectively. Stability is improved when the dip angle increases from 0° to 90°. Xue et al. [12] conducted an experimental study on the visual start-up and heat transfer performance of a PHP using ammonia as the working fluid. The results showed that the ammonia PHP can start smoothly at any inclination. The overall thermal resistance was as low as 0.02 °C/W at a stable operation condition. Tong et al. [13] and Katsuhiko et al. [14] found that a clear sound was heard when heating power was loaded at the evaporator section. A minimum heat load oscillated the working fluid inside PHPs and acted as a PHP. At the same time, a lot of research has been conducted on the heat transfer performance of PHPs. Han et al. [15] pointed out that the heat transfer performance of PHPs is affected by many parameters, such as the inner diameter and cross-sectional shape. Kwon and Kim [16] conducted a series of experiments to investigate the effect of double-diameter tubes on the flow and heat transfer characteristics of a single-lap PHP. Their results showed that the circular flow promoted by the double-diameter tube reduced the thermal resistance of PHPs by 45% and had an optimum range of diameter differences to maximize the thermal performance enhancement. Sarangi et al. [17] discovered that heat load initiation is unrelated to the filling ratio, but the maximum heat load depends on the filling ratio. The working fluid for a given PHP and working temperature determines the optimal filling ratio for the maximum heat load. Vadim et al. [18] investigated the onset of pulsation in a PHP along with the heat conduction of the pipe. Their results showed that the activation threshold was determined by the temperature gradient along the tube. The activation threshold also depended on other system parameters, such as condenser temperature or adiabatic section length. Wang et al. [19] studied the effect of different refrigerants on heat transfer performance of a PHP. The results showed that when the heating power was within the range of 10W-100W, the starting time of the PHP with R134a as the refrigerant was less than 4 min, which decreased with the heating power. The thermal resistance of PHP with a filling ratio of 20.55% was obviously greater than that of other filling ratios. Li et al. [20] experimentally studied the thermal performance of PHPs and found that the thermal resistance of the PHPs decreased with the increase of the heating power.

For a given heating power, the working fluid in PHP is heated from a sub-cold state to a bubble flow and a steady working state with agitated or plug flows. This process is dynamic and unsteady. Meanwhile, the heat transfer performance of PHPs depends on the flow patterns. The starting power for the concerned electronic device is frequently large, and PHPs start with a high thermal resistance, which leads to an unstable operating state. To the best of our knowledge, far less has been done to investigate this unsteady process. It is necessary to perform the study on the dynamic response of PHPs under different powers and the construction of the dynamic response model. Thus, the response curve and function relation expression are used to analyze the operation characteristics of PHPs.

In the present study, the temperature rise curves of PHPs at different positions under a given heating power are experimentally tested. Then, the corresponding dynamic response model is established based on its maintenance structure and working fluid property. Finally, the dynamic response model of PHPs is obtained by using the model to predict the starting temperature and time under different heating powers. Simultaneously, the dynamic response of the working fluid inside PHPs is obtained at a stable operation stage. This study is crucial to investigate the PHP operation.

2. Experimental apparatus and method

HFE7100 (a product of 3M®) was used as the working fluid for its safety and chemical inertness. The basic working conditions for this experimental study were as follows: the filling ratio of the PHP is 50%, the tilt angle is 60°, and the flow rate of cooling water is fixed at 60L/h.

Fig. 1 illustrates the experimental system for visual and thermal performance study, which consisted of a PHP sample, the main part of PHP, the heating and cooling systems, the evacuation and liquid filling systems, and the data acquisition (DAQ) equipment. Fig. 2 shows the exploded view of the PHP test cell, which had a closed loop pattern. The main body of a PHP cell was made up of a copper plate, and a rectangular groove (2 mm × 2 mm) was formed on the copper plate (58 mm × 163 mm), as demonstrated in Fig. 3. The copper plate had 14 parallel distribution channels with a spacing of 1 mm. The channels were connected to a loop. The top part of the copper plate was sealed with quartz glass to form the working fluid channel. Meanwhile, the upper part of the copper hole was connected to the valve to vacuum and fill the working fluid from the top of the channel. A heating rod driven by a direct current (DC) power supply (M8852, voltage accuracy: ±0.1 V, current accuracy: ±0.01 A) was connected to the heat-conducting copper plate to heat the lower part of PHPs. The maximum heating power of DC was 600 W, which could achieve a heat flux density of approximately 30 W/cm^2. The upper part of the condensation section was affixed to the heat exchanger for cooling, and cooling water was provided by the thermostat with a flow rate of 60 L/h controlled by a rotor flowmeter (accuracy of 2.5%). Then, the components were fixed with two stainless steel plates, and the last specimen was insulated using insulation cotton and covered with a plastic housing, except for the glass window.

Agilent 34972A was used as the DAQ device for collecting instantaneous temperatures of each measuring point with a sampling frequency of 10 Hz. The T-type thermocouples (OMEGA®) with an accuracy of ±0.1°C were used as the temperature sensors. The measuring points of the thermocouple are exhibited in Fig. 3. Both the condensation and evaporation sections had four temperature measuring points T_1–T_4 and T_7–T_{10}, respectively, as shown in Fig. 3. The adiabatic section had two measuring points T_5 and T_6. The inlet and outlet of cooling water had one temperature measuring point. Phantom® V211 high-speed video camera was used to record the flow pattern changes in the working fluid, and the sampling frequency was 500 Hz.

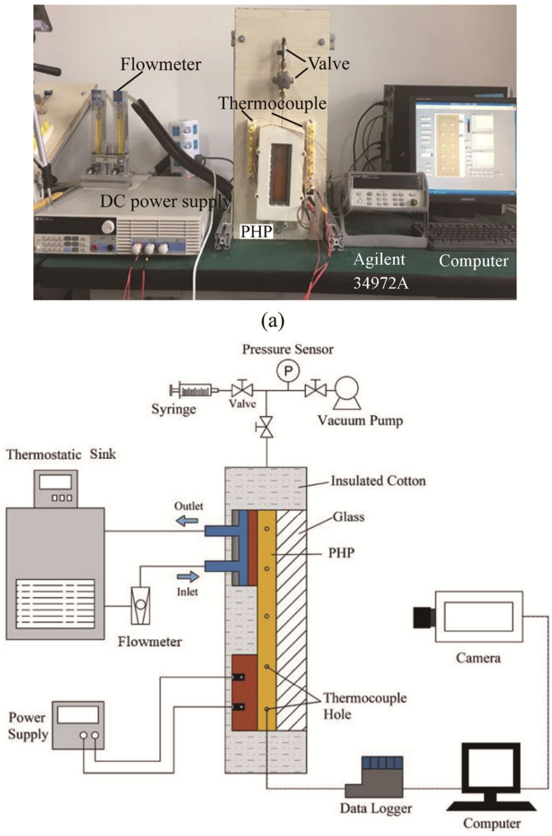
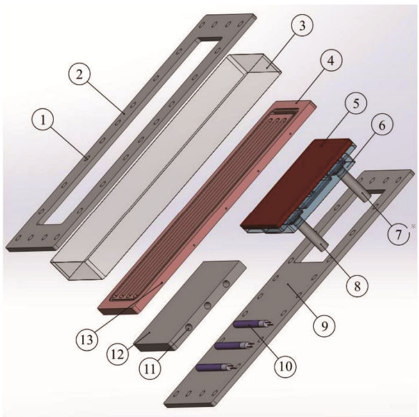


Fig. 1 Experimental rig: (a) actual photos and (b) schematic figure



① Screw holes, ② Stainless steel splint, ③ Quartz glass, ④ Pulsating heat pipe, ⑤ Condenser heat transfer-enhanced copper section, ⑥ Cooling sink, ⑦ Cooling water outlet pipe, ⑧ Cooling water inlet pipe, ⑨ Stainless steel under splint, ⑩ Electric heating rods, ⑪ Electric heating rod slot, ⑫ Evaporation section of copper, ⑬ Thermocouple hole

Fig. 2 Exploded view of the closed-loop PHP test cell

The main experimental procedures are expressed as follows:

1) Ensure that the PHP is vacuumed before filling the working fluid.

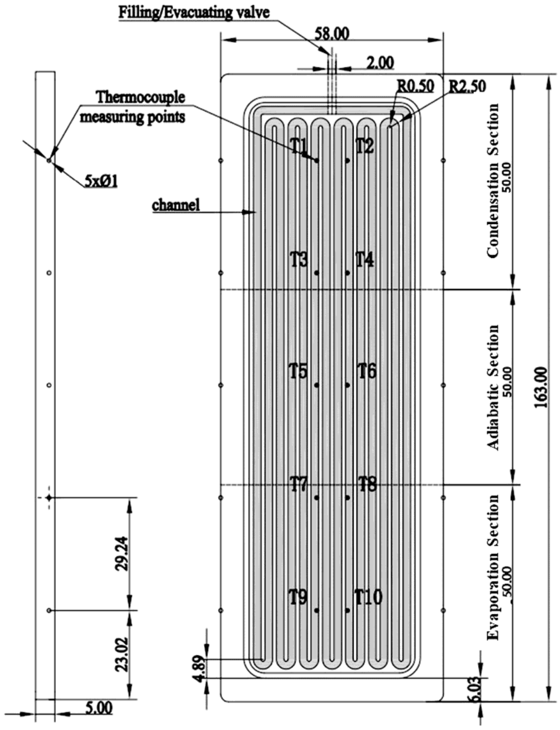


Fig. 3 Locations of thermocouples

2) Fill 50% of the HFE-7100 as the working fluid and close the filling valve.

3) Maintain a thermostat temperature of 17°C, keep the cooling water flow at 60 L/h, and adjust the tilt angle of the PHP to 60°.

4) Start the DAQ system for temperature and cooling water flow.

5) Start the DC power supply, and adjust the heating power to 20 W.

6) Use a high-speed camera to record the characteristics of flow patterns, and simultaneously record the evaporator temperature and cooling water flow using DAQ.

7) Adjust the heating powers to 30, 50, 70, 90, 110, 130, 150, 160, 170, 180, 190, 200, and 210 W.

8) Repeat the experiments in step 4–6.

9) Turn off the DC and cooling water systems.

3. Experimental results of the dynamic response characteristics of PHPs

Heating power used for heating the working fluid is the main factor that affects the PHP start-up process and is also the driving force of the PHP. The working fluid cannot boil if the heating power is low (P=20W, non-operational), while PHPs will be dried out when the heating power is high. The temperature for each PHP section, the flow pattern of the working fluid, and the change in thermal resistance correspond to the time at different heating powers. In the visualization experiments, small bubbles appear, and bubble frequency increases when the temperature of the evaporator section of PHPs reaches a certain value; this process is called bubble flow formation. Bubbles enlarge when the temperature increases and form a slug flow. Then, the flow intensifies and gradually changes to a steady slug or agitated flow.

The tube working fluid experiences a steady slug or agitated flow in the sub-cold state. The states are artificially divided into three stages, namely, non-operational (no bubble generation), transition (from bubble generation to steady flow pattern formation; this stage is also called transition section), and stable operation stages (stable temperature and thermal resistance to form a periodic change). Flow patterns from the non-startup stage to the stable operation stage of PHP are shown in Fig.4. By visualizing the image, we can see that the flow pattern of the working fluid changes: no bubble generation (Fig. 4(a)) - obvious bubble generation (Fig. 4(b)) - significant oscillation (Fig. 4(d)) - accelerating oscillation (Fig. 4(e)) - full ocillation (Fig. 4(f)).

The non-operational, transition, and stable operation stages are also confirmed by the variation profiles of the average temperature at the evaporator section and the thermal resistance, as displayed in Figs. 5 and 6. The evaporator temperature and thermal resistance increase rapidly when the heating power is more than 170 W. This condition indicates the occurrence of local dry-out in the evaporator section.

The temperature change curves at the evaporator, adiabatic and condensation sections of the PHP reflect the dynamic response characteristics of the pulsating heat; that is, the temperature curves of the PHP are the actual "transition curve" at different given heating powers.

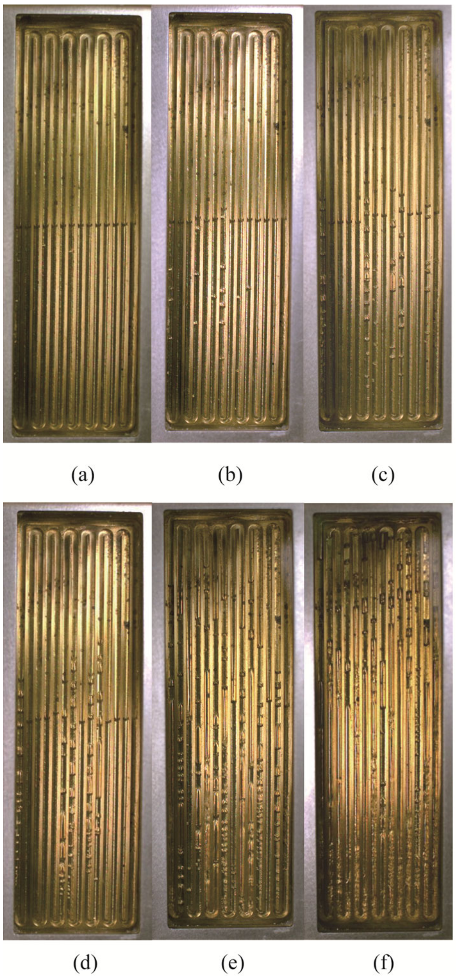


Fig. 4 Flow pattern of the working fluid (P = 130 W)

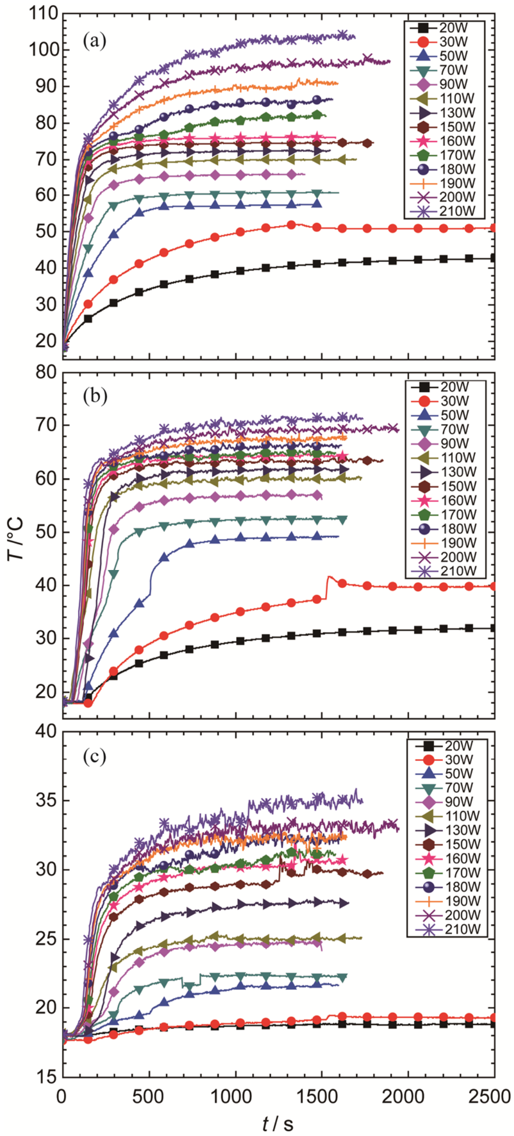


Fig. 5 Temperature change curves at the evaporator (a), adiabatic (b) and condensation (c) sections of the PHP

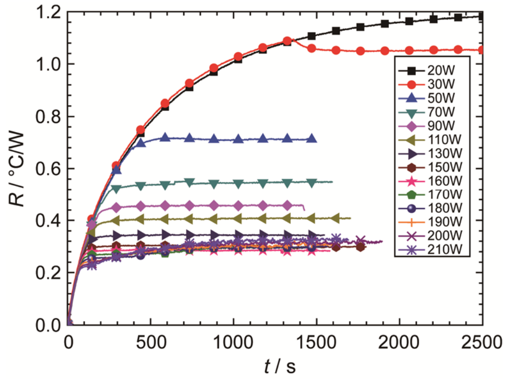


Fig. 6 Change curve for the thermal resistance of the PHP with time

4. Modeling and Parameter Analysis of the Dynamic Response Characteristics of PHPs

4.1 Dynamic response modeling of PHPs

A PHP is composed of working fluid and maintenance structure. The maintenance structure consists of a copper plate with channels, glass, stainless steel clip, insulation, and protective shell. Therefore, the dynamic response characteristics of a PHP are determined by the working fluid and maintenance structure.

For a simple maintenance structure, a portion of added heat at a given heating power is converted to the intrinsic energy of the maintenance structure, resulting in the temperature rise in the structure. A portion is transferred to the condensation section by heat transfer that is consumed by cooling water, and a portion dissipates to the environment. A steady state is reached when the heat input is equal to the heat transferred to cooling water and heat leakage. The working fluid experiences gasification and pulsation at a given heat input power, and heat is transferred to the condensation section. The heat transfer capacity of the working fluid is also different in the case of different flow patterns. The dynamic characteristics of the PHP become complicated when the phase change in the working fluid at a given heating power is considered.

The operating characteristics of the evaporation section represent the characteristics of the entire PHP because heating power is directly loaded in the evaporation section. The temperature of the evaporation section directly expresses the working characteristics of the PHP. Therefore, the temperature of the evaporation section temperature in a PHP is used to express its dynamic characteristics. The dynamic response model for the evaporative section of a PHP is established (temperature rise model).

$$\left(m_{\mathrm{E\_G}}c_{\mathrm{G}}+m_{\mathrm{E\_Cu}}c_{\mathrm{Cu}}+m_{\mathrm{E\_M}}c_{\mathrm{M}}\right)\frac{dT_{\mathrm{E}}}{dt} = Q_{\mathrm{E\_in}}-Q_{\mathrm{E\_out}} \tag{1}$$

where $Q_{\mathrm{E\_in}}$ is the heating power, and $Q_{\mathrm{E\_out}}$ is the heat that is transferred to the adiabatic section.

The dynamic model for the adiabatic section can be set as

$$\left(m_{\mathrm{A\_G}}c_{\mathrm{G}}+m_{\mathrm{A\_Cu}}c_{\mathrm{Cu}}+m_{\mathrm{A\_M}}c_{\mathrm{M}}\right)\frac{dT_{\mathrm{A}}}{dt} = Q_{\mathrm{A\_in}}-Q_{\mathrm{A\_out}} \tag{2}$$

The condensation model is expressed as

$$\left(m_{\mathrm{C\_G}}c_{\mathrm{G}}+m_{\mathrm{C\_Cu}}c_{\mathrm{Cu}}+m_{\mathrm{C\_M}}c_{\mathrm{M}}\right)\frac{dT_{\mathrm{C}}}{dt} = Q_{\mathrm{C\_in}}-Q_{\mathrm{C\_out}} \tag{3}$$

where $Q_{\mathrm{E\_out}}$ is equal to $Q_{\mathrm{A\_in}}$, and $Q_{\mathrm{A\_out}}$ is equal to $Q_{\mathrm{C\_in}}$.

The heat transferred to the cooling water is $Q_{\mathrm{C\_out}}$.

$$Q_{\mathrm{C\_out}} = m_{\mathrm{W}}c\left(T_{\mathrm{W\_out}}-T_{\mathrm{W\_int}}\right) \tag{4}$$

where $T_{\mathrm{W\_int}}$ is the cooling water inlet temperature, which is 17°C, and $T_{\mathrm{W\_out}}$ is the cooling water outlet temperature, which is measured experimentally.

The above equations are used to solve the dynamic response model for the evaporation section of a PHP.

$$T_{\mathrm{E}} = \mathrm{A}e^{-\frac{t}{\tau}}+\mathrm{B} \tag{5}$$

where

$$\mathrm{A} = -\frac{\tau}{m_{E\_G}c_G+m_{E\_Cu}c_{Cu}+m_{E\_M}c_M} \tag{6}$$

B is the stable operation temperature of a PHP, and τ is the time constant. The dynamic response equation of the PHP under a given heating power is expressed as a function of the average temperature and time in the evaporation section, as expressed in Equation (5).

The experimental data in Section 3 are used to solve the dynamic equation. The running states of the working fluid in the PHP are divided into three cases as follows:

1) The working fluid does not boil if the heating power is minimal. The heating power input is converted into the sensible heat of the working fluid, and the temperature of the working fluid is increased. The PHP containing a working fluid is considered to have a typical first-order dynamic response.

2) The dynamic response for the working fluid is divided into three stages, namely, non-operational (no boiling), transition (bubble formation to steady flow pattern), and stable operation stages (steady flow pattern). When the heating power is sufficiently large, and PHP is not dried out as described previously. The heating power input is converted into the sensible heat of the working fluid, raising its temperature at the non-operational stage. In the transition stage, the working fluid undergoes a complex flow pattern change from a bubble flow to a steady state of a slug or an agitated flow. The working fluid flow during the stable operation stage is stable, and the temperature is periodically changed or stabilized.

3) The PHP dries when the heating power is large. The

working fluid has experienced the non-operational, transition, and dry-out stages. The unstable dry-out stage is gradually formed.

Therefore, the solution to the dynamic response equation for the PHP is concretely attributed to two types:

No bubbles are generated when the heating power is minimal, and heat is transferred through thermal conductivity. The response is a first-order dynamic response.

Bubbles are generated when the heating power is sufficiently large. The entire dynamic response process is divided into three stages as follows:

1) The non-operational stage is a first-order dynamic response.

2) The transition stage is a complex stage that experiences a first-order response to the second-order response transition. The transition stage is considered a first-order dynamic response to simplify the problem.

3) The working fluid in the stable operation stage under different heating power inputs dynamically adjusts the heat transfer capacity to adapt to heating power, and the temperature changes periodically. This process is a second-order dynamic response. For the PHP used in this study, temperature fluctuations in the stable operating state are less than 0.5°C. Therefore, this process is simplified as a zero-order dynamic response; that is, each heating power corresponds to a temperature.

The dynamic response equation for the PHP under a given heating power is solved based on the experimental result and is summarized in Table 1.

In Equation (5), coefficients A, B, and τ are the functions of the heating power. Thus, the dynamic response function of the PHP at a given heating power is obtained as follows.

Non-operational stage:

$$T_{\mathrm{E}} = \mathrm{A}e^{-\frac{t}{\tau}} + \mathrm{B} = \left(-0.36P-20.95\right)e^{-\frac{t}{865.07e^{-\frac{P}{27.6}}+106.84}} + 0.35P + 40.69 \tag{7}$$

Transition stage:

$$T_{\mathrm{E}} = \mathrm{A}e^{-\frac{t}{\tau}} + \mathrm{B} = (900e^{-\frac{P}{19.33}} - 34.53)e^{-\frac{t}{1.76e^{\frac{P}{41.5}}+85.51}} + 5.89e^{\frac{P}{94.64}} + 47.07 \tag{8}$$

Stable operation stage:

$$T_{\mathrm{E}} = 6.92e^{\frac{P}{100.82}} + 45.8 \tag{9}$$

4.2 Model validation

The dynamic response curves of PHP under heating powers of 180 and 200 W are simulated by the established model and compared with the experimental data. Fig. 7 indicates that the simulation results agree well with the experimental results. Therefore, the established model can be used to predict and analyze the operation of a PHP.

The dynamic response equations transform the dynamic response relationship between the average evaporation temperature and time to the relation between the average evaporation temperature and heating power. At a given heating power, we solve the equations for the non-operational and transition stages as well as the intersection point of these two curves. The intersection point is the starting point of the PHP; the abscissa of the intersection point is the starting time, and the ordinate is the average evaporation temperature of start-up time. The intersection point of transition and stable operation stages is solved using the model equations. This intersection point is the stable operating point of the PHP; the inter-

Table 1 Dynamic response equation for the PHP under a given heating power

Response model	Non-operational stage $T_{\mathrm{E}} = \mathrm{A}_1e^{-\frac{t}{\tau}} + \mathrm{B}_1$			Transition stage $T_{\mathrm{E}} = \mathrm{A}_2e^{-\frac{t}{\tau}} + \mathrm{B}_2$			Stable operation stage T_E = constant
Power/W	A_1	B_1	τ	A_2	B_2	τ	B_3
20	−22.44	42.75	529.02	-	-	-	-
30	−32.05	51.78	393.46	−221.61	50.75	68.09	50.98
50	−43.65	62.50	247.25	−120.2	57.25	109.02	57.44
70	−50.40	68.08	180.40	−40.92	60.55	122.88	60.79
90	−54.28	72.06	137.95	−20.44	65.75	148.61	65.90
110	−62.20	79.93	132.16	−51.76	69.41	90.58	69.90
130	−65.73	82.50	111.21	−39.99	72.00	93.17	72.39
150	−69.50	87.25	101.14	−43.76	74.28	81.15	74.59
170	−73.34	90.24	93.08	−20.50	80.83	273.39	81.80
190	−106.17	122.68	131.32	−33.40	89.81	250.50	90.93
210	−81.61	98.32	182.28	−42.92	103.52	349.95	103.20

section coordinates are the time required for stable operation, and the ordinate is the average evaporation temperature for the stable operation stage.

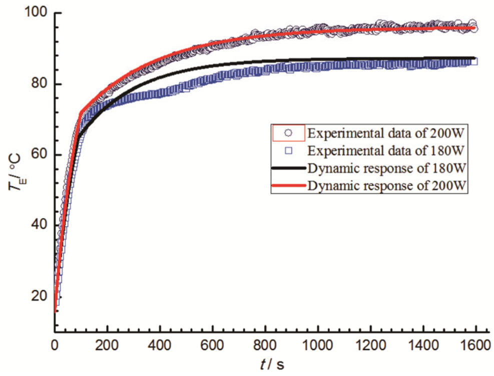


Fig. 7 Dynamic model validation

4.3 Dynamic characteristics analysis

Dynamic response characteristics are typically expressed in terms of time constant τ and amplification factor K. Time constant τ is the time required to change the controlled parameter to a new steady-state value at a constant speed at the initial maximum change rate after the subject is disturbed. It can also be defined as the time when the controlled parameter changes to 0.632 times the new steady-state value. Time constant τ reflects the length of the object's self-balancing process, which reflects its dynamic characteristic. This characteristic is related to the inertia of the object. Constant τ in the first-order step response is the time constant at this power. Magnification factor K indicates that the object is disturbed, and the performance of the new balance is achieved. Magnification factor K is equal to the ratio of the difference between the new and old steady-state values and the amplitude of the interference. This factor characterizes the static property, which is independent of the changing process of the parameter, is related to the initial and final values of the process. The self-balancing capability is unfavorable when the K value is small. The self-balancing capability is robust when K value is high.

In Fig. 8, time constant τ and amplification factor K decrease firstly and then increase with the heating power with the lowest value obtained at a heating power of 160W. In Fig. 6, thermal resistance decreases firstly and then increases with the increase of the heating power with the lowest value obtained at 160 W. On the basis of the visualization experiment, local dry-out occurs when the heating power is more than 160 W. The evaporation temperature and thermal resistance increase when the dry-out occurred. However, dry-out is a gradual process, and the PHP does not burn immediately. Due to the increase of the average evaporation temperature, 63.2% of the new steady-state value increases, thereby increasing the time of the corresponding x-axis; that is, the time constant increases. At the same time, due to the increase of the new steady-state value, amplification factor K increases. Thus, time constant τ and amplification factor K are increased with heating power. In addition, the significant heating power is 160 W, and the thermal resistance and dynamic response time of the PHP are low.

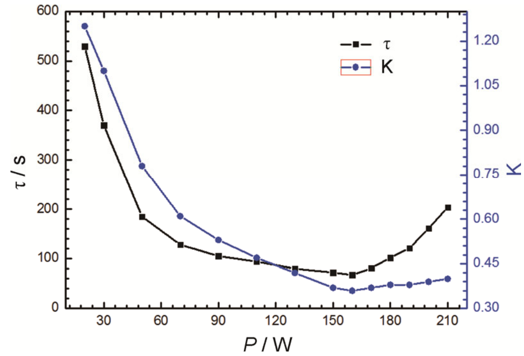


Fig. 8 Time constant τ and amplification factor K of the PHP

4.4 Dynamic response characteristics of the working fluid

The dynamic response characteristics of a PHP at a given heating power are complicated, and the dynamic response characteristics of the working fluid are difficult to analyze considering the complex heat and mass transfer processes of the working fluid in the tube. The dynamic response model for the working fluid is established based on the operational characteristics of the PHP. It can be used to analyze the effect of the working fluid on the dynamic response of a PHP.

The dynamic response characteristics of a PHP is composed of the maintenance structure and working fluid in the stable operating stage, and the working fluid has a significant influence on the dynamic response. The dynamic response model of the PHP is established as a whole in Section 4.2. The corresponding model for the maintenance structure remains a first-order step model, regardless of the condition of the working fluid. Currently, the dynamic response characteristics of the working fluid are obtained by reducing the operational characteristics of the PHP at the stable operation stage and operational characteristics of the maintenance structure. This process is nearly equal to Equation (9) minus Equation 7.

$$\begin{aligned} T_{\mathrm{E\_F}} &= \mathrm{A_F} \mathrm{e}^{-\frac{t}{\tau}} + \mathrm{B_F} \\ &= (-0.2P - 2.1)\,\mathrm{e}^{-\frac{t}{1244.03\mathrm{e}^{-\frac{P}{26.32}} + 132.83}} \\ &+ 0.07\mathrm{e}^{\frac{P}{31.31}} + 4.85 \end{aligned} \tag{10}$$

The dynamic response time constant τ of pure fluid is a function of the heating power and is compared with the experimental data, as shown in Fig. 9. In Fig. 9, the dynamic response time constant τ of pure fluid is decreased by increasing the heating power, and the decrease rate gradually slows down. This condition is because considerable working fluids become vapor when the heating power is increased, and the dynamic response of the working fluid accelerates.

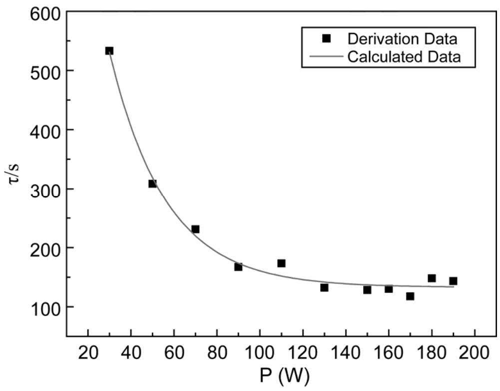


Fig. 9 Dynamic response time constant τ of pure fluid

5. Conclusions

The operational characteristics of the start-up and stable operation stages of PHPs were experimentally studied, and the corresponding dynamic response model under a given heating power was established. Major conclusions could be drawn as follows:

(1) The dynamic response of PHPs is classified to two types: the non-operational and transition stages are a first-order dynamic response, and the stable operation stage is a zero-order dynamic response.

(2) The starting time, starting temperature, and dynamic response characteristic parameters at a certain heating power are calculated by the dynamic response model. Time constant τ and amplification factor K are decreased firstly and then increased with heating power. The thermal resistance and dynamic response time of the PHP reach their minimum value when the heating power is 160 W.

(3) The dynamic response time constant τ of pure fluid is decreased with the increase of the heating power, and the decrease rate gradually slows down.

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