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Experimental research on heat transfer of pulsating heat pipe

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Experimental research was conducted to understand heat transfer characteristic of pulsating heat pipe in this paper, and the PHP is made of high quality glass capillary tube. Under different fill ratio, heat transfer rate and many other influence factors, the flow patterns were observed in the start-up, transition and stable stage. The effects of heating position on heat transfer were discussed. The experimental results indicate that no annular flow appears in top heating condition. Under different fill ratios and heat transfer rate, the flow pattern in PHP is transferred from bulk flow to semi-annular flow and annular flow, and the performance of heat transfer is improved for down heating case. The experimental results indicate that the total heat resistant of PHP is increased with fill ratio, and heat transfer rate achieves optimum at filling rate 50%. But for pulsating heat pipe with changing diameters the thermal resistance is higher than that with uniform diameters.

Keywords: pulsating heat pipe, influence factors, performance of heat transfer

Introduction

The complexity of microchip has been increasing at a rate of a factor of 2 per year over the past several decades as previously predicted by More. The number of transistors on a chip has increased to as many as 500 billion transistors packed on a single chip. The further miniaturization of electronic devices is leading to greater chip packing densities and thus higher chip power densities. The new challenge in the field is on removal of large quantities of heat quickly and efficiently from chip in order to keep chip temperature within an operational range. Therefore, a new cooling device is needed to meet the technological advancement.

Pulsating heat pipe (PHP) was first proposed by Akachi [1]. In recent years, many experimental studies were conducted to understand the mechanism of the PHP. Charoensawan et al.[2]，Khandekar et al.[3,4], Rittidech et al.[5], and Tong et al.[6] had discussed the effects of many parameters on thermal performance, such as internal diameter, number of turns, working fluid and inclination angle (from vertical bottom heat mode to horizontal orientation mode) of the device. Wook et al. [7] had conducted flow visualization for the closed-loop PHP made from brass plate. The heat pipe consisted of only four meandering channels machined on the plate. The channels were covered by an acrylic plate, and were partially filled with ethanol. It was reported that circulation of working fluid was not observed but most active oscillation was observed when the FR is from 0.4 to 0.6 at 90^o inclination angle. Gi et al.[8] also conducted flow visualization for closed-loop PHP made from Teflon tube of 2 mm internal diameter and partially filled with R142b. The PHP consisted of 10 meandering turns and it is 400 mm from the evaporator to condenser. The evaporator was heated by a hot bath and the condenser was cooled by a cold bath. It was concluded that the best thermal performance for the PHP is achieved when the FR is from 0.5 to 0.6.

In this paper, the visualization of flow in PHP and the performance of pulsation heat pipe were investigated for the variation of heat input, filling ratio, inner diameter

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and heat mode of the device. It is the foundation of the systematic study of the PHP.

Experimental System

Fig.1 and Fig.2 show the schematic of experimental setup comprising five parts: pulsating heat pipe, a vacuum/charging system, the power supply unit, cooling system and data acquisition system.

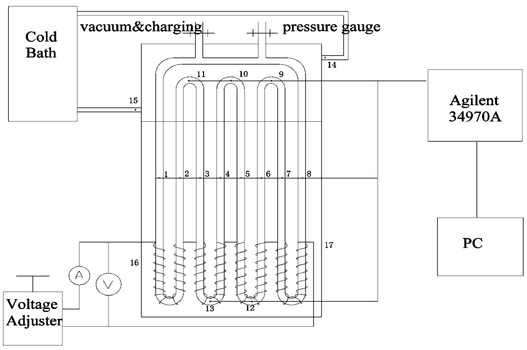


Fig.1 The heating mode from bottom

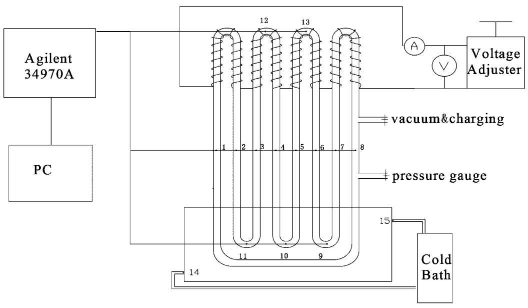


Fig.2 The heating mode from top section

The PHP is made of high quality glass capillary tube with the total height 250 mm and the width 204 mm composed of 8 parallel tubes forms four turns. The outer diameter of the even inner diameter pipe is 6 mm and the inner diameter is 1.6 mm.

PHP have three parts: evaporator section, cooling section and adiabatic section. The height of evaporator section is 60 mm and the height of cooling section is 76 mm in this study. The uneven inner diameter pipe is also composed of 8 tubes with inner diameter 1.6 mm and 1 mm alternate for this research. Other geometrical parameters are the same to even inner diameter pipe.

In the evaporator section, the thermal load was provided by thermic wire, which was wrapped on the outer surface of the PHP. In order to minimize the heat dissipated to the environment in the evaporator section, the high quality thermal insulation material was wrapped. The condenser was cooled by a cold bath. For temperature measurements, Agilent 34970A data acquirement was employed, coupled with K type thermocouples. There are eight thermocouples with the diameter of 0.5 mm sticked on the outer surface of the PHP.

The top horizontal capillary tube has two ports for vacuum and charging the PHP. It was vacuumed to 5 kpa and then partially filled with ethanol. The fill ratio is defined as the net liquid volume divided by the total inside volume of the PHP.

PHP working principle and the influencing parameters

If the diameter of a capillary tube is small enough such that $d_{max} \leqslant 2(\sigma / \rho g)^{0.5}$, the vapor plug and liquid slug distributed inside the capillary tube can be formed for vacuum capillary tube when liquid is charged. The liquid film between the vapor plug and the inner wall will evaporate in the evaporator, in result of the pressure of the vapor increased, pushing the vapor plug and liquid slug to the condenser region, and the vapor which reaches the condenser section will condense and shrink. The heat received in the evaporator is dissipated to the condenser region.

The heat received in the evaporator is the energy source that provides the driving force to cause fluid flow. Fluid motion begins when the liquid slug, which is adjacent to the plug in the evaporator region, is pushed due to the high pressure of the plug, and the motion is enhanced when the vapor shrink in the condenser region.

From the working principle of the PHP, the oscillation in the PHP relies on three driving forces: gravity force, surface tension, and oscillating force, which comes from the pressure fluctuating between the evaporator and condenser. These forces are influenced by many factors. The gravity force is influenced by the inclination angle of the device, the physical features such as channel size and shape can have a significant effect on the surface tension, and the heat flux has great effect on the oscillating force.

For the two-phase flow pattern existing in the PHP, the liquid along the tube blocks the motion of the vapor. So, it's also a parameter which has effect on the thermal operation of the PHP, and this is embodied by the fill ratio.

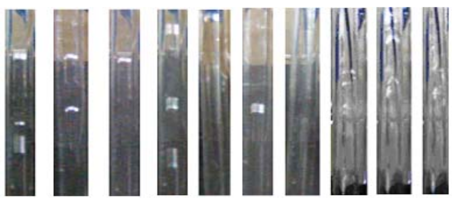
It has been indicated by earlier studies [6][9] that there are a large number of parameters influencing the operation of the PHP. These can be summarized as: (a) geometrical parameters, i.e., diameter of tube, cross section shape of tube, length of evaporator/condenser section, overall length of the device, number of turns, (b) operational parameters, i.e., global orientation, orientation, use of flow control check valve in the circuit and (c) physical parameters i.e., thermo-physical properties of working fluid and its fill ratio. It is noted that most of the works [2,5] were focused on the experimental study. The objective of this work is to analyze the influence of three primary parameters: heat input, fill ratio, and the proportion of the non-condensable gas of the device. Also the visualization was given in this paper.

Visualization of the flow in PHP

The flow in PHP is a complex phenomenon and it is influenced by many factors, for instance, heating rate, liquid fraction, diameter of tube, cross section shape of tube and inclined angle. Three flow patterns were observed in the experiments: slug flow, mix flow and circular flow, see Fig.3.

The flow patterns of the working fluid in the heat pipe are different, when the fill ratio is changed from 0 to 100%.

When the fill ratio is low, the mass of the fluid in the pipe is small, the number of the liquid slug is less, and the length of the slug is short. When the vapor in the evaporator flow in the direction of the tube to the condenser region, the flow resistance of the vapor in every tube is low, meanwhile, the liquid which comes from the condensate of the vapor could flow down along the wall of the tube, so there is no single-phase oscillating flow in tubes. The restoring force of the evaporator depends on the gravity force and surface tension, and the device is performed as an intermittent operation with partial or total dry-out commencing in the evaporator section. In addition, the heat, which carried by the working fluid, is less, therefore, the heat transfer characteristic of the PHP is poor.



Slug flow mix flow circular flow

Fig.3 The flow pattern

Discussion on heat transfer

The overall thermal resistance could be used to estimate the performance of the PHP, and it is defined as:

$$R = (T_e - T_c)/Q$$

Here, R is overall thermal resistance, T_e, T_c are temperature of the evaporator and condenser respectively, and Q is heat input.

The overall thermal resistance consists of two parts: conduct thermal resistance and the operation resistance. They are parallel connected,

$$\frac{1}{R} = \frac{1}{R_{PH}} + \frac{1}{R_{Glass}}$$

The conduction contribution of the glass is ignored for the internal diameter of the channel is very small and the thermal conductivity of the glass is small. The overall heat resistance of the device could reflect the operation resistance.

The effects of heat input

The heat input in the evaporator is the energy source of the fluid. When heat is added to the evaporator, the pressure and temperature of the vapor in the evaporator are increased, and it is the driving force of fluid flow.

Fig.4 illustrates the effect of heat input on the overall thermal resistance. As shown, the overall thermal resistance is decreased significantly when the heat input is increased.

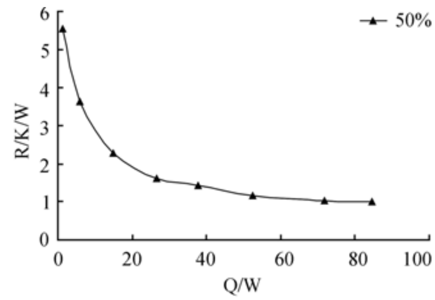


Fig. 4 The typical variation of thermal resistance with heat input power

When heat is added to the evaporator, the pressure and the temperature of the vapor are increased, and the force on the adjacent slug is increased, which causes motion of the fluid. The mass of the liquid slug vaporized becomes the mass influx for the adjacent plug. As a result, the density of the plug increases and consequently, a pressure rise is expected, and the heat carried by the vapor is increased, so the overall thermal resistance is decreased.

The effects of fill ratio

Fill ratio also has a significant influence on the characteristic of heat transfer. The effects of fill ratio are introduced as follows.

Thermal resistance increases as increasing of fill ratio

Fig. 5 shows the effects of fill ratio on the overall thermal resistance. The overall thermal resistance increases with the fill ratio.

When the fill ratio is low, vapor plug is more than liquid slug. As a result, the driving force is larger. On the contrary, the mass of fluid is small, and the heat carried by the fluid is less, so the temperature difference between the evaporator and condenser is small, and the overall thermal resistance of the device is small, too. On the other hand, the flow friction between the fluid and the wall is increased as increasing of the fill ratio. The driving force for the oscillation and transportation of the heat from the evaporator to the condenser is decreased. The overall thermal resistance is increased in the result of the increasing of the temperature difference.

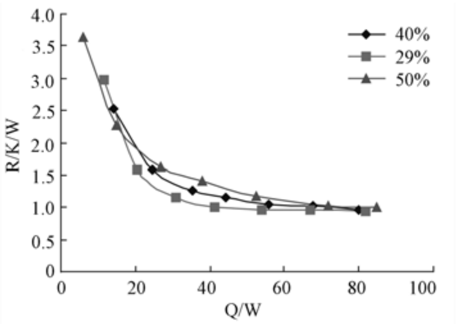


Fig. 5 The typical variation of thermal resistance with heat input at different fill ratios

Optimum fill ratio

The heat transfer rates at different fill ratio of working fluid were shown in Fig. 6. The heat transfer rate increases with the fill ratio, and it reaches the maximum heat transfer rate at the fill ratio 45% to 55%. The heat transfer performance decreases as fill ratio increases when the fill ratio is over 55%. So PHP will perform better at 50% fill ratio in this case. When the fill ratio is high enough, there are only few bubbles in tubes, and the effective oscillation can't be achieved.

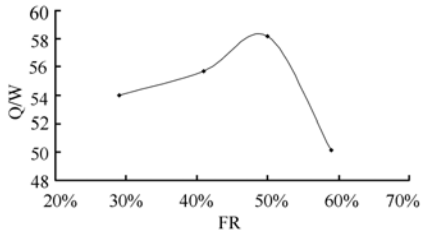


Fig. 6 The variation for heat transfer rate with different fill ratio

When PHP is fully filled with the working fluid (FR=100%), the oscillation of the plug and slug can't formed. In this case the heat transfer of the PHP is only by conduction, and the overall thermal resistance is high.

In fact, there exists an optimum fill ratio. More the bubbles (lower fill ratio), more is the degree of freedom but simultaneously there is less liquid mass for sensible heat transfer. Less bubbles (higher fill ratio) cause less perturbations and the bubble pumping action is reduced thereby lowering the performance. Under the optimum fill ratio, the device acts in a true pulsating mode, and the working fluid in the tubes is enough for the flow motion, so there also have enough vapor to supply the driving force of the fluid motion.

Heating Mode

The overall thermal resistance increases with increasing of the filling ratio. The influence of the filling ratio on the overall thermal resistance for bottom and top heating were showed in Fig.7. The thermal resistance is higher for bottom heating mode than top heating mode. In the case of bottom heating mode, working fluid turns back to evaporator section easily with respect to gravity so dry-out can't occur. On the contrary, for top heating mode it is hard for working fluid to flow back to evaporator section to form steady circulation and results in bad heat transfer performance of the PHP, so the thermal resistance increases. Gravity has a significant influence on the characteristic of heat transfer. For bottom heating mode working fluid flows back to evaporator section due to gravity so dry-out can not occur. Gravity is an important factor inducing pressure perturbation which makes working fluid start to flow.

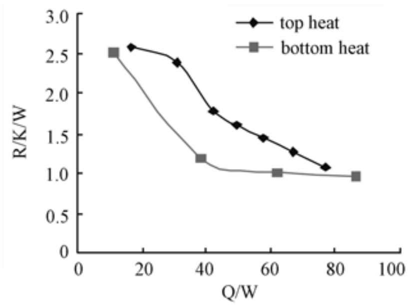


Fig.7 Thermal resistance of PHP for different heating mode

Fig.8 indicates that the thermal resistance of the uneven inner diameter pipe is higher than that of even inner diameter pipe in the case of 50% filling ratio. The surface tension becomes larger and makes the working fluid hard to flow back to evaporator section in the small inner diameter channels. Otherwise, the joint section is not very smooth and leads to larger flow resistance.

Conclusions

1. The thermal resistance is decreased as increasing of the heat input;

2. The thermal resistance is increased as increasing of the fill ratio;

3. There is an optimum fill ratio for PHP operation. When the fill ratio is 50%, the operation of the PHP is

better than other mode;

4. Thermal resistance of PHP for bottom heating mode is higher than top heating mode under the same condition;

5. Thermal resistance of uneven inner diameter PHP is higher than even inner diameter pipe under the same condition.

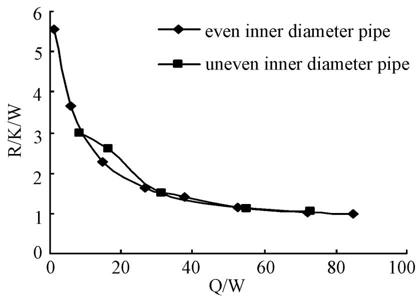


Fig.8 Thermal resistance for heat transfer rate at different pipes

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