Effect of Annealing Pretreatment on Performance of Pulsating Heat Pipe

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Keywords: Pulsating heat pipe (PHP), Annealing pretreatment, Thermal performance, Thermal resistance.

Abstract. Experimental work was carried out to clarify the thermal performance of a pulsating heat pipe (PHP) with the tube body was pretreated by a muffle furnace at 500°C for 5 hours. It is found that the annealing of the pipe body improves the wettability of the working fluid on the tube wall, thus enhance heat transfer between the tube wall and working fluid due to the increase in the liquid film area. Experimental results show that after annealing, the PHP starts to accelerate. Comparing to the original PHP, the starting time of the surface annealed PHP can be shortened by 78s at 30W while the minimum starting power is reduced from 30W to 16W and the starting temperature can be reduced by about 10°C.

Introduction

The researchers are working to develop enough source of sustainable energy for buildings. Building solar integration is one of the paths to implement green cities and buildings in the future. Solving the thermal management and energy efficiency optimization of building solar energy systems is of great significance for realizing the integration of solar buildings, and so, energy management has become a hot topic in scenario of energy and buildings. For an effective energy management system, the heat transferring system needs to be eco-friendly and should consume less energy in the process. A passive heat transfer device called Pulsating Heat pipe (PHP) was developed by Akachi [1], later in 1990s, was found that can transfer heat from one point to another and is sometimes referred to as superconductors of heat. PHP has gained a lot of attention as potential device that application in solar cell [2],[3] and as potential device of the heat management system due to its simple structure, low cost and excellent heat transfer capability [4]. Heat transfer process inside a PHP is governed mainly by the flow regimes of the working fluids, which can be further disintegrated as bubble generation, bubble growth and annular flow shown as Fig.1 (a) [5], [6]. There is a curved interface between the vapor bubble and liquid slug. Bubbles in the evaporator are produced as enough heat is supplied at this region, and then moves into the liquid column at condenser where is at a lower pressure and temperature. The liquid is heated to evaporation, and then come into supplement under about the constant wall temperature. A stable curved interface form between the vapor and liquid when they reach equilibrium and the half of vapor-liquid interface can be shown as Fig.1(b) symmetrically. The heat transfer characteristics inside the PHP with the continuous cycle of generation, growth and dissipation of bubbles in a pulsating flow path is not only related to the thermophysical properties of the working fluid, but also closely related to the interfacial properties between the working fluid and the inner wall of the pipe. Start-up time is an important performance indicator of PHP. How to shorten the start-up time is one of the key points of related research. The main ways include changing the working medium [7], [8], adjusting the heating method [9], improving the surface wetting condition [10] and the inner wall microstructure [11], [12] and other aspects. The studies on using of the surface wettability to control the interface of vapor-liquid two-phase flow and enhance the transfer process are one of the most active academic fields in recent years. The surface wettability of the inner wall surface structure of the heat pipe and the working fluid has an important influence on the starting performance of the PHP. The annealing pretreatment of the
tube body can change the wettability of the inner wall surface structure and the working fluid on the inner wall surface, and the related research on the starting performance has not been reported.

Furthermore, annealing the tubing can improve flexibility and allows PHP to be better integrated into building components to better serve the thermal management of building solar integrated systems. In this study, the influences of annealing pretreatment on the surface tension and contact angle are experimentally investigated. Comparative experiments on the thermal performance of a pulsating heat pipe (PHP) that the tube body was annealing pretreated in a muffle furnace at 500°C for 5 hours between that of the original one had been done.

**Interfacial Properties of the Tube after Pre-annealing**

**Annealing Treatment and Internal Surface Structure of the Tube**

Put the tube into the muffle furnace, heat it to 500 °C, keep it for 5 hours, stop heating, and cool the tube body to ambient temperature with the furnace. The treated tube body was taken to have a length of about 1 cm, was cut away from it. The inner wall surface structure of the copper tube was observed under a 10X magnification microscope by a 3D laser confocal microscope, the surface image of tube was collected by the software Axio-Vision. The inner wall surface of the tube before and after annealing treatment are shown in Fig. 2. Where (a) is not annealed and (b) is annealed

![Figure 2. The images of the inner wall surface.](image)

Fig. 2. shows that there are polygonal cracks and potholes on the inner surface of the original tube, but the overall is relatively smooth and the inner surface of the tube after annealing at 500 °C is rougher, with the grain is phosphorous but no breaks.

**Wettability of Working Fluid on the Inner Wall of PHP Tube**

A contact angle measuring instrument was employed to observe the spread of anhydrous ethanol (working fluid) on the inner wall of the PHP tube. The wettability of the working fluid on the inner surface of the pipe can be judged by the shape change of the droplet with the amount of drip to be controlled by a micro-injector to 3 μL. The results of the comparison experiment before and after annealing treatment of tube body are shown in Fig. 3. The results show that the contact angle of the working fluid in the inner wall of the tube is reduced from 23° to 15° after the tube to be annealing
treatment. It shows that the wettability of the working fluid on the inner surface of the PHP tube is improved.

![Figure 3](image)

Figure 3. The contact angle of the working fluid in the inner wall of the tube.

**Experimental System and Uncertainty**

Fig. 4 illustrates the schematic diagram of the PHP experimental system. The facility consists of a PHP unite, a water tank cooling bath, an electric wire heating unite adjusted by RCN-604 DC power supply, measurement and data acquisition device. A copper tube with external diameter of 4 mm and inner diameter about 2 mm was employed to make the PHP with 10 elbows. The PHP unite consists of evaporation section, adiabatic section and condensation section, and the length of each section is 100 mm. The condensation section was directly attached to a cooling lock which was cooled by a constant temperature cooling bath. Nickel chrome electric wire was wound around the evaporation section that wrapped in thermal insulation adhesive plaster.

![Figure 4](image)

Figure 4. Schematic of experimental system.

The test system including the PHP, cooling block, and heater were well insulated by glass wool. The OMEGA K-type thermocouples with accuracy ±0.1°C that to be installed at different positions of PHP to measure the tube temperature at different heat loads as shown in Fig. 4. The system should be kept at the temperature of 20 ± 0.5°C by using the cooling media.

The thermal resistance of PHP can be calculated by formula (1):

$$ R = \frac{(T_e - T_c)}{Q} $$

(1)

where the evaporation temperature Te and the condensation temperature Tc are based on the average temperature of several thermocouples placed on the evaporation and condensation sections shown as in Fig. 4, and so:

$$ T_c = T_1 + T_2 + T_3 + T_4 $$

(2)

$$ T_e = T_5 + T_6 + T_7 + T_8 + T_9 $$

(3)

Q is the input power that can be calculated by formula (4):

$$ Q = U \cdot I $$

(4)
where \( U \) and \( I \) are the electric voltage and current of heating system, respectively.

The uncertainties of the measurement parameters are analyzed by the error propagation method. The relative uncertainty of the thermal resistance is calculated as follows:

\[
\frac{\delta R}{R} = \sqrt{\left( \frac{\delta T_e}{T_e - T_C} \right)^2 + \left( \frac{\delta T_C}{T_e - T_C} \right)^2 + \left( \frac{\delta Q}{Q} \right)^2}
\]  

(5)

Then, the relative uncertainty of thermal resistance of the Experimental system was less than 7%.

Result and Discussion

Influence of input power on the startup and thermal performance of the PHP are analyzed and discussed. The thermal performance of a closed loop PHP, using vertical bottom heat mode and Anhydrous Ethanol of analytical grade as working fluid, with a liquid filling rate of 50%, were tested. The pulsating curve of the temperatures was stable and lasted for 30 min, then the temperature data were recorded. Moreover, the measurement of thermal resistances was repeated for three times under the same conditions.

Influence of Input Power on Startup Time

The period in which the evaporation temperature appeared significantly decreased was defined as the startup time of a PHP [12].

Fig. 5 shows the startup time of PHP with different input powers. It is observed that the startup time of the PHP decreases as increasing input power and the startup time of the annealed PHP is lower than that of the original at the same heating power. Experiments show that after annealing the tube, PHP becomes easier to start. The surface tension of the working fluids on the tube wall would be reduced by way of annealing the tube of a PHP, and so the wettability of refrigerant on inner wall of the PHP would be improved. With the improvement of wettability, bubbles on the inner wall of tube are easier to form and peel off.

Comparing to the original PHP, the starting time of the surface annealed PHP is shortened by 78s at 30W.

![Figure 5. Startup time at different input powers.](image)

Thermal Resistance at Different Input Powers

Thermal resistance of the PHP with pre-annealing and that of the original shown as Fig. 6.
Fig. 6 shows the thermal resistances of PHP with different input powers. It is displayed that the thermal resistance of PHP that the tube had been pretreated by annealing decreases as increasing input power, and the trend is like the original PHP.

After pretreated by annealing, the surface tension of the working fluids on the tube wall is reduced, and the wettability is improved, and so has better behavior on heat transfer. The boiling heat transfer in the evaporation section becomes violent at higher input power, which leads to a larger pressure difference between evaporation and condensation sections. Therefore, there is a faster operation velocity and in the PHP. Comparing to the original PHP, the minimum starting power is reduced 16W and the starting temperature can be reduced by about 10°C.

Acknowledgement

This research was financially supported by the National Science Foundation of China (Grant No.51506004), Foundation of Advanced Innovation Center for Future Urban Design, Beijing University Of Civil Engineering And Architecture (Grant No. UDC2018031121)

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