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Experimental and theoretical research on a ammonia pulsating heat pipe: New full visualization of flow pattern and operating mechanism study

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ABSTRACT

This paper presents a novel study on performance of pulsating heat pipe using ammonia as working fluid. Firstly, a new full visualization experiment with high speed camera is conducted, to study the relationship between the flow patterns and thermo-hydrodynamics of the PHP. The tested PHP, consisting of 6 turns, is fully made of quartz glass tubes with 6 mm outer diameter and 2 mm inner diameter. The filling ratio for ammonia fluid is 70%. Wall temperature fluctuations of several key positions are recorded under a series charge of heat transfer rates, which are from 25 W to 520 W. In visualization results, the motion identities, flow pattern variations, breakup and coalescence between the vapor plugs and liquid slugs are illustrated and discussed. In addition, the actual velocity of the vapor is computed from the experimental measurement in this paper, which is never found in other literature but is very important for the mechanism study in theoretical model.

Furthermore, a theoretical model including the dynamical characteristics and heat transfer is investigated coupled with the thermal driving force, friction force and capillary force variations as the flow patterns changed at different transport powers, which are derived from the full visualization experiment. The theoretical results are compared with the experimental results analytically, and the operating mechanism of PHP will be discussed in detail finally.

1. Introduction

The pulsating heat pipe (PHP), also called Oscillating Heat Pipe (OHP), is considered as one of the promising technologies for a high heat transfer device on small space in electronics cooling due to its high heat transport capability, simple structure without wick, compact size and low cost of manufacturing [1–6]. PHP will have a wide engineering application in electronics cooling, furthermore, becoming an ideal candidate for space application via lower weight than conventional heat pipe [7–12].

Although simple in its construction, PHP operating mechanism seems very complicated and has been studied in theoretical and experiment by many researchers [13–35]. The experimental studies are main focused on the following issues: about the parameter effects of tube diameter, filling ratio, number of turns, inclination angle, and working fluid properties; the flow visualization to observe the oscillating motion, vapor generation, liquid nucleation boiling, coalescence of bubbles, flow direction variation, and phase volume fraction of vapor bubbles and liquid slugs; the thermal performance including temperature fluctuations and thermal resistance. While theoretical investigations attempt to analytically and numerically model the fluid dynamics and/or heat transfer related with oscillating two-phase flow, by means of many simplifying assumptions including one-dimensional models, one flow pattern such as slug flow, a straight tube neglecting the effect of bends, and no effects of surface tension and gravity. These literature are rare cared about different flow patterns corresponding to different working states of PHP and representing the different operating mechanisms, which are needed to consider at the same time in the theoretical model for better understanding the mechanism and main parameter effects of PHP.

The main objective of this paper is to investigate the relationship between the flow patterns and the thermo-hydrodynamics of PHP, thereby determining its operating mechanism at different transport powers, by means of two implements of experimental and theoretical study. Firstly, a new full visualization experiment with high speed camera is conducted, to obtain a series of more elaborate and specific characteristics of flow pattern variations at different transport powers and provide some basic and useful

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Nomenclature

A	cross area of PHP tube (m^2)	h_{fg}	latent of liquid (kJ/kg)
V	velocity of fluids in tube (m/s)	c_p	specific heat (J/(kg K))
T	temperature (K)	h	heat transfer coefficient (W/m^2 K)
L	length for PHP (m)	k	thermal conductivity (W/m K)
ρ	density of fluid (kg/m^3)	FR	filling ratio
p	pressure of fluid (Pa)	θ	inclination angle (°)
d	internal diameter of PHP tube	θ'	contact angle in interface (Radian)
d'	external diameter of PHP tube		
g	gravity acceleration (m^2/s)		
R	gas constant (J/(kg K))		

information for theoretical model. At the same time, the actual flowing velocity of the fluids in ammonia PHP that represents hydrodynamics of PHP is tested in the visual experiment, which is never found in other literature, but is very important for the mechanism study in theoretical model. Furthermore, a theoretical model including the dynamical characteristics and heat transfer is proposed, coupled with the thermal driving force, friction force and capillary force variations as the flow patterns variation which are derived from the full visualization experiment. The theoretical results are compared with the experimental results analytically to verify its validity, and finally the operating mechanism of PHP is discussed in detail. These investigations may be helpful for us to promote the knowledge of flow and heat transfer features of PHP, and extend our understanding the working mechanisms for explanation some indistinct phenomena or issues in PHP research.

2. Experimental investigation

2.1. Experimental setup

The schematic of the tested PHP constituting 6 meandering turns is shown in Fig. 1(a). The prototype is fully made of quartz glass capillary tubes with the total length of 320 mm from the top to the bottom [35]. The inner and outer diameters of the glass tube are 2 mm and 6 mm, respectively. The radius of each turn is 10 mm. The evaporator section of the PHP is heated by electrical wires which are wrapped on the outer wall surface of the tubes. The total length of heating section is 100 mm. The condenser part of the PHP is cooled by cooling water in cooler box which is circulated by a cold bath appliance. In order to achieve the full visualization of PHP, the upper cover plate of cooler box is also made of quartz glass. The inlet temperature of cooling water is maintained at 17 °C with ±1 °C accuracy. The length of cooling section is 100 mm. The motions of vapor bubbles and liquid slugs are photographed and recorded by a high speed CCD camera. Due to the limitation between photo area and high-resolution photos, two photo zones are selected as shown in Fig. 1(b), including zone I in adiabatic section and zone II in heating section. There are 8 thermocouples located as shown in Fig. 1 to measure the temperature fluctuations of the evaporator, adiabatic and condenser sections of the PHP and the inlet and outlet of cooler box. Four thermocouples T1 to T4 (accuracy ±0.5 °C) are located in different tubes to give an average value of evaporator outlet temperature. Two thermocouples T5 and T6 (accuracy ±0.5 °C) are placed in the corresponding tubes to provide an average temperature of condenser. The left two thermocouples T7 and T8 (accuracy ±0.2 °C) are used to measure the temperature variation of water in inlet and outlet of cooler box. All temperature data are recorded by a highly sensitive temperature logger (Agilent 34970A with resolution 0.1 °C) and connected to a PC for scanning the data every one second. Fig. 1(c) gives the real PHP full visualization platform, which could be adjusted the inclination angle of PHP from −90° to +90°. Fig. 1(d) shows one real experiment heating test at high input power when the whole heating wires are turned into the red color.

2.2. Working fluid selection

Up to date, it is found that the working fluids of PHP employed always are water, ethanol, methanol, acetone, R-123, etc. But for ammonia, there is rarely used. Nevertheless, ammonia has much more advantages than these working fluids [36]. It has much higher value of $(dp/dT)_{sat}$, much lower superheat required for start-up, as shown in Fig. 2, little lower dynamic viscosity and surface tension than those fluids. In addition, ammonia PHP is more easier to realize the visualization of flow patterns and its variation range with small input power and low temperature. Therefore, the ammonia is selected as the working fluid in this paper, and could be regarded as one kind of excellent fluids for PHP research and application.

2.3. Thermal response identities

The heat transport performance of the ammonia PHP with a filling ratio (FR) of 70% at different inclination angles θ of 30°, 60° and 90° are illustrated in Fig. 3. The total power transiting from evaporator to condenser is computed as 25 W to 520 W corresponding the increment of heat load. The largest uncertainty of transport power is ±46.7 W at the state of 520 W.

It could be seen that the temperatures of evaporator and condenser behave fluctuation continually from three figures. This phenomenon could be explained by the local oscillations of vapor bubbles and liquid slugs in capillary, even at the state of circulation for PHP. The ammonia PHP could easily start up even the total transport power is only 25 W, in the case of each capillary tube is contributed with 2.083 W. Of course, it is obvious that the start-up time is decreased as the inclination angle increased by comparing Fig. 3(c) with (a). After the start-up, the PHP operating trends including the temperature growth curves, and flow patterns transit are similar, no matter what the inclination angle is, as the increment of input power. Therefore, the thermal performance results at the inclination angle of 60° will be selected in the following section to assess the flow pattern identities and compare with the theoretical analysis results.

It is noted that the temperature fluctuations and levels for different measurement points in evaporator outlet placements arise obviously different as the transport power increases. And these phenomena will magnify as the inclination angle increases. Because in high power state for PHP, A large one-direction circulation is formed and the flow pattern will be changed remarkably (discussed in detail in the visualization section). When the PHP works in the large one-direction circulation, the flow direction of