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ORIGINAL ARTICLE

Full visualization and startup performance of an ammonia pulsating heat pipe

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Abstract In this paper, a novel study on full visualization and startup performances of pulsating heat pipe using ammonia as working fluid are experimented. The tested pulsating heat pipe, consisting of 6 turns, is fully made of quartz glass tubes with 6 mm outer diameter and 2 mm inner diameter. The filling ratio is 70%. Wall temperature fluctuations of several key positions are recorded under a series charge of heat inputs. The visualization investigation is conducted to observe the oscillations and circulation flows with the advantage of high quality digital video camera, by which the unique thermodynamic behaviors are able to recognize and analyze more easily. The experimental results show that the startup power required by the ammonia Pulsating Heat Pipe (PHP) is very small, owing to particular identities of ammonia. It is observed that there are also some unevenly distributions in slug-train during initial and operating state. Phenomena such as circulation flows and local oscillations coupling breaking up of bubbles and formation of slugs are observed.

1. Introduction

With the rapid development in electronic industry, including dramatic increase in chip density and power density, as well as continuous decrease in the physical dimensions of electronic packages, the thermal management has become, and will continue to be one of the most critical technologies in the electronic product development [1]. The Pulsating Heat Pipe (PHP), is considered as one of the promising technologies for a high heat transfer device on small space, due to its potential high heat transport

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capability, simple structure with no wick, and low cost of manufacturing. Although simple in its construction, PHP seems very complicated when we try to understand its operation for phase change and interactions between the vapor plugs and liquid slugs. The PHP has been studied experimentally by many investigators [2–10], focused on either visual observation of flow patterns or various operation parameters related with thermo-hydrodynamics of PHP.

Gi and Sato [2] performed the flow visualization of a R142b PHP with an 8 mm camera to record the flow, but little information of detail description of flow pattern was observed. Tong and Wong [4] firstly visualized the flow patterns of a closed loop glass PHP filled 60% with methanol. It was found that large amplitude oscillations from evaporator to the condenser during the start-up period, however, at steady operating state, the working fluid circulated, coupled with complex processes such as nucleation boiling, coalescence of bubbles. The direction of circulation was consistent once circulation was attained, but it could be different for the same experimental run. Qu and Ma [9] also conducted an experimental investigation on a glass PHP with water, and two kinds of vapor bubbles, i.e. small round (globe) bubbles and long column (Taylor) bubbles, were formed and circulated in the whole PHP. It can be concluded that the startup of PHP and steady circulation were primarily due to the boiling heat transfer associating with the temperature difference and pressure difference between heating section and cooling section. Charoensawan and Khandekar [6] studied the parameter effect to thermal performance of the copper PHP, including the variation of internal diameter, number of turns, working fluid and inclination angle. The working fluids employed were water, ethanol and R-123. The results indicated a strong influence of gravity on the performance, that the highest heat flux of PHP in horizontal mode decreasing obviously comparing vertical mode if the turns were less than a certain number. Besides, thermo-physical properties of working fluids affected the performance strongly. Khandekar and Dollinger [5] indicated that the operating mechanism of PHP was not well understood and the present state of the art could not predict required design parameters for a given task. And they summarized the choice of working fluids which had high value of $(\mathrm{d}P/\mathrm{d}T)_{sat}$, low dynamic viscosity, low latent heat, low surface tension.

It is found that the working fluids of PHP employed as mentioned earlier, usually are water, ethanol, methanol, R-123 and so on. But for ammonia, there is rarely used, especially in the whole glass PHP. Nevertheless, ammonia has much more advantages than these working fluids. It has much higher value of $(\mathrm{d}P/\mathrm{d}T)_{sat}$, little lower dynamic viscosity and surface tension than those fluids, and much lower latent heat than water, so we infer that ammonia could be regarded as one kind of excellent fluid for PHP.

In the present work, a novel study on full visualization and startup performance of glass PHP using ammonia as working fluid is experimented. In order to better understand the operation of ammonia PHP, a full visualization of evaporator section, adiabatic section and condenser section is firstly conducted. Then, a detail discussion of startup and operation to ammonia PHP affected by inclination angle is presented.

2. Experimental setup and procedure

2.1. *Experimental setup*

The schematic of the tested PHP constituting 6 meandering turns is as shown in Figure 1. The prototype is fully made of quartz glass capillary tubes with inner and outer diameters are 2 mm and 6 mm, respectively. The liquid slugs and vapor bubbles are generated for PHP operation as the Bond number is less than 2 in such tubes. The evaporator section of the PHP is heated by the 0.2 mm electrical wires of 4.86 Ω/m resistance adjusted by variation of input power. The heat wires are wrapped at intervals of 1.5 mm on the outer wall surface of the PHP. The length of heating section is 100 mm in the whole PHP with 320 mm length. The condenser part of the PHP is cooled by cooling water in cooler box which is circulated by a cold bath appliance. The length of cooling section is 120 mm. The motions of vapor bubbles and liquid slugs are photographed and recorded by a high speed CCD. There are 9 thermocouples located as shown in Figure 1 to measure the temperature fluctuations of the evaporator, adiabatic and condenser sections of the PHP and the inlet and outlet of cooler box. All temperature data are recorded by the highly sensitive temperature logger (Agilent 34970 A with $\pm 1\ ^{\circ}$C accuracy) and connected to a PC for scanning the data every one second.

For full visualization of glass tubes, the cooler box is also made of transparent glass, and four CCD installations are arranged as shown in Figure 2. The whole PHP system including a glass PHP, heat wires, a cooler box, and CCD recorder is fixed on one (500 × 600) mm aluminum plate. When the experiment is conducted, as one of important

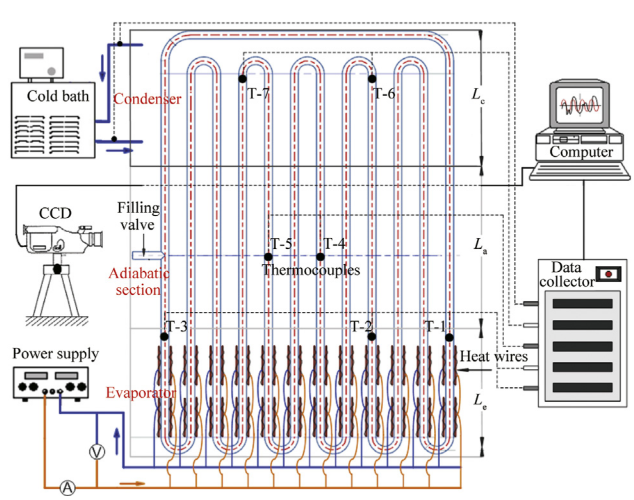

Figure 1 Schematic program of experimental setup.

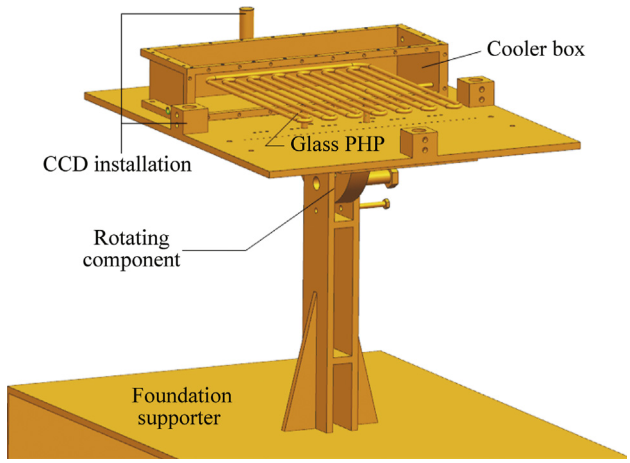

Figure 2 Assembly illustration of experimental setup.

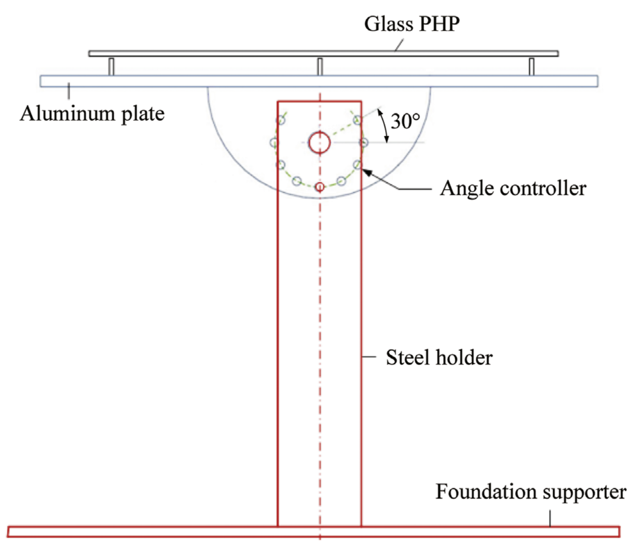

Figure 3 Inclination angle variations for PHP.

factors, operation orientation angles of the PHP should be taken into consideration. Therefore, a rotating component is used as given in Figure 2, and an angle controller bolt is coupled to realize the variation of inclination angle from −90 degree to +90 degree by a step of 30 degree for the PHP system, as seen in Figure 3.

2.2. *Experimental procedure*

The experimental procedure is as follows:

Firstly, the PHP should clean using the deionized water injected by a micro pump, and other components also should clean with some alcohol using ultrasonic waves. The cleaning is absolutely indispensable, which can remove any surface impurities. These impurities if not removed, could disturb the pattern in later stages of the fabrication process. The PHP are then put in a constant temperature oven for the dehydration bake about 20 minutes at 120 °C to ensure the water or alcohol drying out completely. For filling the working fluid into the PHP, it's the most difficult and suffering thing. Since the

Table 1 Ammonia PHP experimental program.

Case	Inclination angles/Deg	Input voltage/V				
I	60	5	10	20	30	40
II	0	/	10	20	30	40
III	−30	/	/	20	30	40

saturation pressure of ammonia at 30 °C reaches in 12 bars, clearly the pressure is too high to have sealing easily, especially for a silicon glass tube with smooth outer surface. However, the difficulty is solved well, and the vacuum of PHP is 10^{-4} Pa, charging the ammonia with 70%.

The experiment program is designed as illustrated in Table 1. There are two variable parameters, which are the input voltage and inclination angle. In experiment, the input voltage is used to adjust the input power to temperature of heating.

3. Results and discussions

3.1. *Start up*

The startup of the ammonia PHP is quite different from the normal liquid working fluid, owing to the particular identities of the ammonia fluid. In the experiment, the ambient atmosphere temperature is 29 °C. At this temperature, ammonia becomes gas already in a standard atmosphere pressure. But in capillary, there are liquid slug and gas plug occurred at the same time, therefore, the ammonia should be almost in a saturation state. As the liquid ammonia changes to gas, there is no need to accumulate enough power for phase changes. On the other hand, for saturated ammonia, there will a large variation in pressure, when there will a few changes in its temperature. So the ammonia PHP is very sensitive to the variation of temperature compared with the normal working fluid. It is observed that there is no nucleation boiling at the whole period of operations. Once the temperature satisfies the condition that the latent heat of the ammonia is overcome and the pressure is in excess of the surface tension, the liquid slug will transform to the gas slug quickly along the liquid film and liquid-gas interface, and shift the positions as soon as possible.

According to the experiment program, the influence of the inclination angles of the PHP is investigated. Case I is the inclination angle of 60 degree, which means the bottom heating operation mode. In this mode, as we all know, the PHP performs the best behaviors. Similarly, the ammonia PHP has good startup with 60 degree of inclination angle. When the temperature in evaporator exceeds 4 centigrade than in condenser, the PHP starts the oscillations, as shown in Figure 4. Obviously, at bottom heating mode the startup is very easy in a short time.

Case II is the inclination angle of 0 degree, which means the horizontal operation mode. In this case, the effect of gravity is becoming impaired. Consequently, the liquid slug in condenser is not easy to return back to the evaporator.

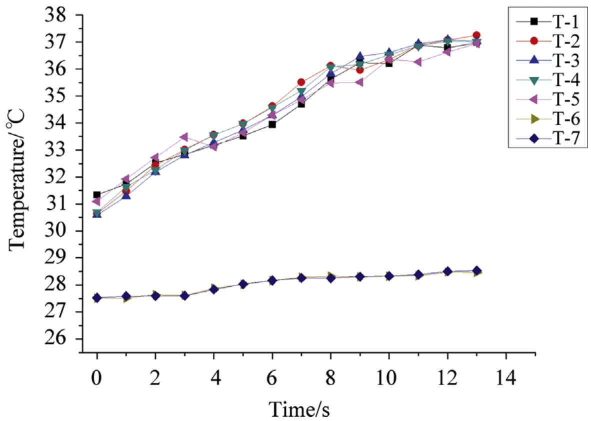

Figure 4 Startup of ammonia PHP in 60 degree inclination angle.

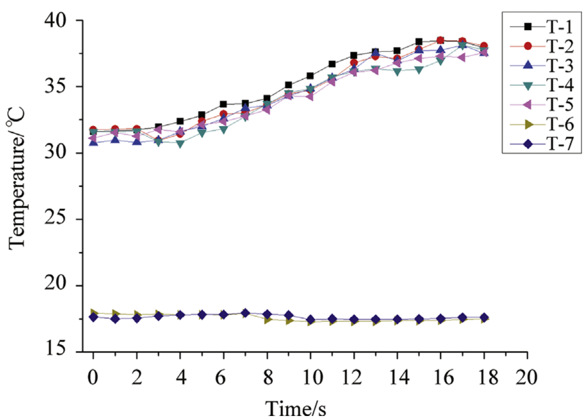

Figure 5 Startup of ammonia PHP in 0 degree inclination angle.

But for ammonia PHP, due to its higher value of $(\mathrm{d}P/\mathrm{d}T)_{sat}$, little lower dynamic viscosity and surface tension than normal working fluids, the startup performance behaves more conveniently and quickly, as shown in Figure 5.

Case III is the top heat operation mode with inclination angle of −30 degree. Unfortunately, the ammonia PHP is not started in this case. Clearly, the PHP operates in a state of anti-gravity. All the long liquid slugs almost stay at condenser but hard to shift to the heating section. At this time, the driving force should be enough bigger to overcome the joint interactions of gravity force, surface tension and friction force.

3.2. Bottom heating mode

In the bottom heat mode, during a period of oscillations about the liquid slugs and vapor plugs after startup, a circulation flow will be occurred in the PHP. As the temperature increases continuously in the evaporator, single direction flow will be sustained, and the flow velocity will increase at the same time. Figure 6 shows the circulation flow in the long capillary of condenser. It is found that two kinds of vapor bubbles, i.e., small round (globe) bubbles and long column (Taylor) bubbles, are formed and circulated in the whole PHP. The globe bubbles are easily generated and grew faster in the liquid plugs from the heating section. In Figure 6,

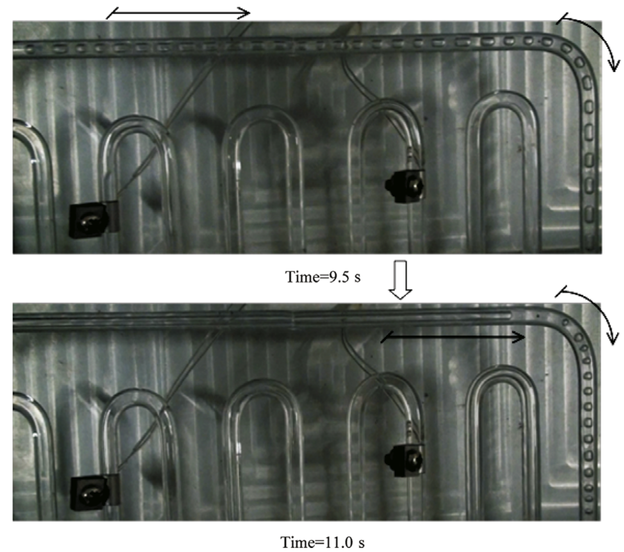

Figure 6 circulation flows in bottom heating mode.

the direction of the circulation flow is the clockwise, however, sometimes may change into anti direction suddenly.

3.3. Horizontal operation mode

When the ammonia PHP works in a horizontal operation mode, firstly its startup seems a little slower, and oscillation phenomenon continued for much more times. But ammonia PHP has good thermal performance in this mode. Figure 7 illustrates the gas plug oscillation in a capillary at different time. Figure 8 shows expansion of bubbles in one U-bend of the heating section. The vapor bubbles at first move downward and get into the heating section, but a few seconds later, the direction changes to upward. These motions continue and alternatively change, leading to the heat transfer from one end of the capillary to another end. The same phenomenon takes place at the U-bend of the heating section as shown in Figure 8. A long vapor bubble enters into the U-bend by the inertia in anti-clockwise direction. Due to the pressure increased in the heating section of right capillary, the vapor is pushed back in clockwise direction, and broken into many small bubbles finally.

4. Conclusions

A novel study on full visualization and startup performances of glass PHP using ammonia as working fluid are experimental investigated. It is found that the ammonia PHP is quite easy to startup and unevenly distributed in slug-train during initial and operating state.

(1) Due to particular identities of the ammonia working fluid, the startup power of the ammonia PHP required is very small. When in bottom heating mode, the PHP can start when the temperature of evaporator is only 4 centigrade higher than condenser.

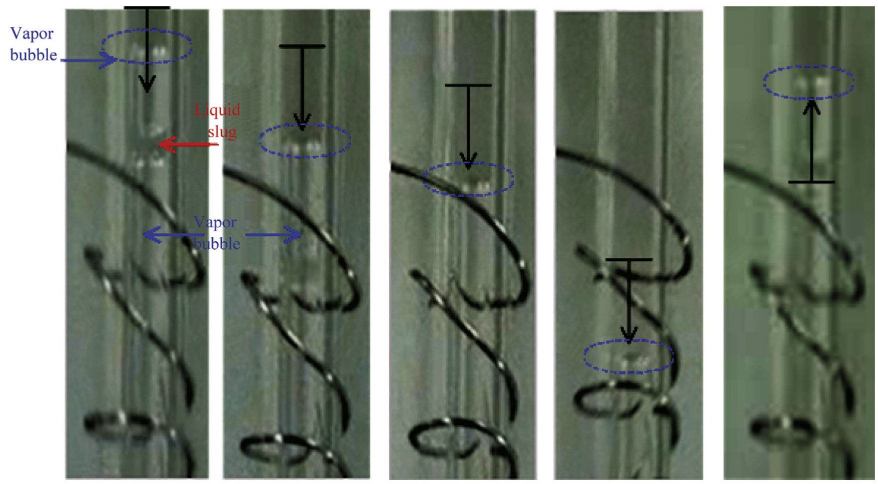

Figure 7 gas plugs oscillation in horizontal operation mode.

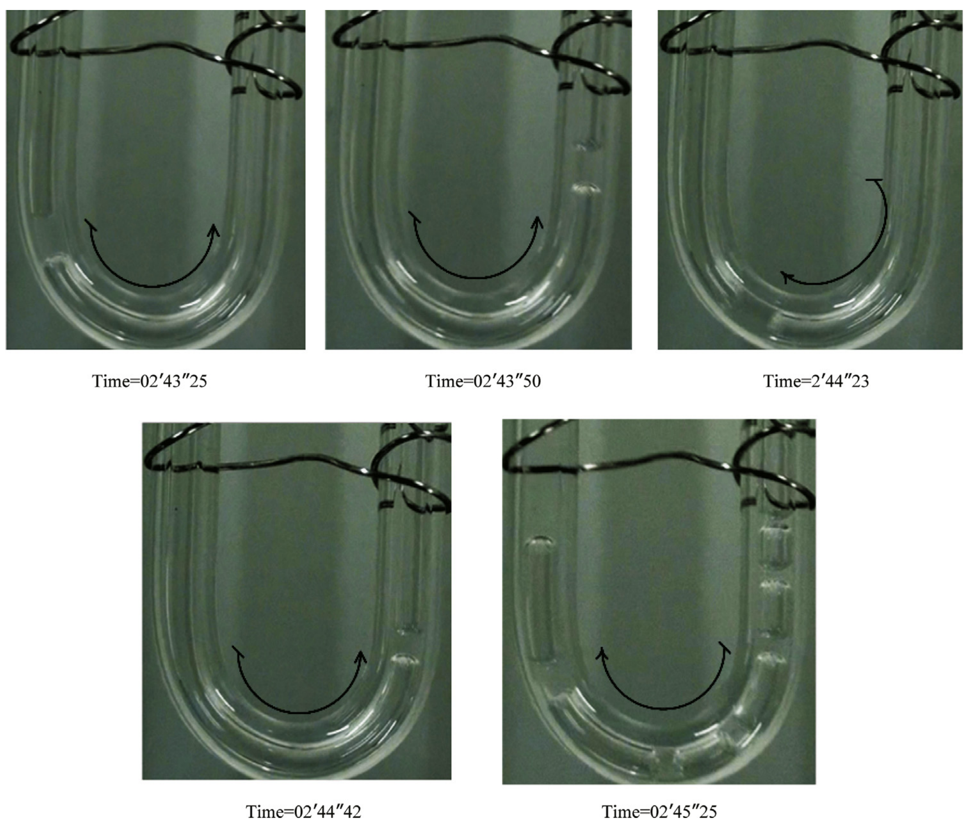

Figure 8 Expansion of bubbles in horizontal operation mode.

(2) The full visualization shows that the oscillation is continuous due to interplay between the driving and restoring forces so that heat transfers from the evaporator to condenser.

Acknowledgements

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