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Experimental Investigation of Oscillating Motions in a Flat Plate Pulsating Heat Pipe

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An experimental study was conducted to evaluate the motion of vapor bubbles and liquid plugs within a flat plate pulsating heat pipe to determine the effects of working fluids (water, ethanol, Flutec PP2, and Flourinert), power input, filling ratio, and angle of orientation on the pulsating fluid flow. Experimental investigations quantify the position and velocity of the liquid–vapor interface for various conditions. Through the use of a Photron high speed camera, precise locations of the liquid–vapor interface were tracked and analyzed. Experimental data show that both the macromovement and oscillating motion of vapor bubbles and liquid plugs exist for a functional pulsating heat pipe. The amplitude of these oscillations was increased as more power was inputted into the pulsating heat pipe. The pulsating heat pipe investigated here would not function when charged with 50% high performance liquid chromatography grade water and positioned horizontally. On the other hand, the experimental results show that when the heat pipe was charged with ethanol, it created the largest amplitudes and velocities. The oscillating motion of vapor bubbles and liquid plugs including the macromovement is very sensitive to the tilted angle, and large increases in amplitude were observed when the angle was increased (bottom heating mode) from horizontal.

Nomenclature

Bo	=	bond number
D	=	diameter (m)
e	=	error
g	=	gravity, m/s^2
ρ	=	density, kg/m^3
σ	=	surface tension, N/m
Δt	=	time interval, s

Subscripts

crit	=	critical
l	=	liquid
max	=	maximum
pos	=	position
v	=	vapor, velocity

Introduction

AS the computer industry continues to make rapid advances in processor speed, thermal management plays a more and more important role. Computers have presently reached processor speeds exceeding 3.4 GHz. A further increase in speed is limited by the ability to dissipate the heat generated by these chips. Insufficient rejection of heat will result in computer failure. As the conventional heat sinks with the forced convection of heat rejection meet their limit, the cooling devices with the phase-change heat transfer have been widely used and present the next generation of electronics cooling.

The pulsating heat pipe (PHP) is a relatively new idea in the field of thermal management. The concept was first proposed by Akachi in 1987 [1]. Pulsating heat pipes are small capillary tubes or grooves arranged with multiple U-bends in the evaporator and condenser regions. The grooves or tubes may be arranged in a closed or open loop. Over the last several years, extensive investigations on the PHP have been conducted [2–13]. Experimental results have shown that the closed looped PHP has better heat transport capabilities. In an unlooped PHP, the working fluid is unable to circulate and heat is transferred by driving force due to the oscillation [2]. On the other hand, the closed looped PHP uses oscillating motion along with circulation motions of liquid and vapor slugs.

Once constructed, the channel is charged with an appropriate working fluid and sealed. Assuming the channel has been constructed small enough; the working fluid will maintain distinct liquid and vapor slugs due to the surface tension of working fluid. As heat is applied to the PHP, temperature gradients are created. These temperature gradients result in corresponding pressure gradients that are the driving force for the pulsating motion. Vapor expansion in the evaporator coupled with vapor contraction in the condenser creates pressure perturbations that cause the oscillatory motion seen experimentally in these devices. The motion of these slugs depends on many parameters such as the working fluid, PHP dimensions, heating and cooling processes, operating temperature, charge ratio, operational mode, surface condition, and gravity. To determine the primary factors affecting the oscillating motion occurring in a PHP, a miniature flat-plat PHP was fabricated and studied experimentally in this current investigation.

Heat Pipe Design

Among those parameters that affect a pulsating heat pipe's performance, the three most important parameters when designing a PHP are the channel diameter, number of turns, and length of channels. The maximum diameter of the channel is determined by the critical Bond number. As the Bond number exceeds this experimentally determined value, gravitation forces on the liquid begin to dominate surface tension forces. Once this occurs, the liquid will no longer form distinct plugs in the channel and pool in the bottom of the channel as gravity dominates.

The Bond number is a function of liquid and vapor densities and surface tension, and is given as

$$Bo = \frac{D^2 g(\rho_l - \rho_v)}{\sigma} \tag{1}$$

The maximum diameter allowed to create distinct slugs is determined by applying a critical Bond number determined experimentally and is defined as

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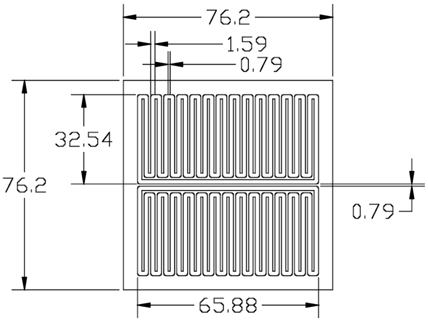

Fig. 1 Schematic of the flat-plate PHP (dimension: mm).

$$D_{\max} = \sqrt{\frac{Bo_{\text{crit}}\sigma}{g(\rho_l - \rho_v)}} \tag{2}$$

Shafii et al. [2] use a critical Bond number of 1.84 whereas Khandekar et al. [3] use the value of 2. This value is highly debatable and further research needs to be done to determine its value for various fluids.

The pulsating heat pipe was designed to function with a wide variety of fluids such as water, ethanol, Flutec PP2, and Flourinert. To maintain distinct liquid plugs and vapor slugs, Eq. (2) was applied to the fluid properties of Flutec PP2 over a specific operating range because Flutec PP2 has the highest density among these working fluids. Using a critical Bond number of 2, a maximum channel diameter was determined to be roughly 1.5 mm. The actual size used was 1.5875 mm because $\frac{1}{16}$-in. end mills are readily available.

The other defining dimensions of the pulsating heat pipe were determined based on a size constraint. The 1.5875×1.5875 mm square cross section groove, as shown in Fig. 1, was to be machined into a flat copper plate with a thickness of 2.54 mm and a width and length of 76.2 mm. The goal was to create two separately functioning closed loops with the maximum number of turns in each based on the size constraint. Two separate closed loops were desired to decrease the lengths of each channel resulting in reduced pressure drops from the evaporator to the condenser. Khandekar et al. [4] states that by increasing the number of turns, the probability of preventing a large agglomeration of vapor in the evaporator reduces. By leaving a 0.79 mm wall between each adjacent channel, the maximum number of turns in each of the two closed loops was determined to be 14. The length of each channel was likewise constrained to the 76.2 mm length of the copper plate. Also, because there are two loops, the length of each channel had to be less than half the total length of the copper plate. The depth of each channel is 1.5875 mm, which created a square channel that produced a lower wall thickness of 1.0 mm.

Heat Pipe Manufacturing

The pulsating heat pipe was manufactured in a flat plate of copper using a vertical milling machine. A carbide end mill with a 1.5785 mm diameter was used to create the groove to the given dimensions. Once machined, the copper plate was surface treated using a 50–50% solution of Duraclean and water. This removes all oxidation and oils from the grooves. A Lexan cover was fabricated to seal the channels and allow visual data to be collected. Using a high temperature silicone sealant the Lexan cover was fastened to the copper plate. Copper tubes for each closed loop were placed in the cover to allow for charging of the working fluid.

To charge the heat pipe, a vacuum pump was connected to both charging tubes to evacuate the heat pipe channels. Surgical clamps were then used to clamp the hose attached to the heat pipe to prevent any leakage and then the appropriate working fluid was backfilled in the heat pipe. This process was repeated several times to ensure all air bubbles were removed from the channels. The desired filling ratio was attained by calculating the mass of the fluid required to fill up a certain percentage of the total volume. The mass is calculated by multiplying the desired filling ratio with the known volume of the PHP and then multiplying by the density of the working fluid at room temperature as defined by

$$m = \phi V_{\text{PHP}}\rho_l \tag{3}$$

Once calculated, the filling ratio can be verified by weighing the heat pipe before and after charging. When the desired weight is reached both charging tubes were sealed by crimping the tubes then soldering over the ends to ensure there was no leakage. Figure 2 shows a charged and sealed PHP for a filling ratio of 80%.

Fig. 2 Photography of charged pulsating heat pipe.

Experimental Setup and Procedure

To test the heat pipe, an experimental setup shown in Fig. 3 was constructed consisting of a test section, a data acquisition system, a high speed camera, a cooling bath, and a power supply and measurement unit. A test section consisted of the PHP, cooling blocks, a heater, and supporter. The test section supporter was machined from an aluminum block and designed to allow for various setups. The two cooling blocks could easily be moved to either increase or decrease the size of the condenser region. A heater could easily be removed and replaced by one of a different size. The design also kept the area above the PHP clear for an unobstructed view of the fluid motion. The pulsating heat pipe was positioned on top of the two cooling blocks and was held firm by multiple screws. The heater was placed directly in the center of the PHP and could be raised or lowered by screws from beneath. This allowed for adequate contact between the heater and PHP base. The heater was also surrounded by insulation to ensure the heat flux was directed into the PHP. A Julabo cooling bath was connected to the two aluminum cooling blocks to maintain a constant condenser temperature. A Staco dc power supply was connected to the heater, which was in turn connected to a digital multimeter. This was to precisely determine the heat input to the PHP. Multiple type T thermocouples were placed in the evaporator, condenser, and adiabatic regions to monitor the temperature throughout the PHP. An Iotech data acquisition system was calibrated and used to obtain voltage readings from the thermocouples. The data acquisition system was connected to a computer to directly convert the voltage readings and display the temperature. The Photron high speed camera, which can record up to 10,000 frames per second, was connected to the computer to collect

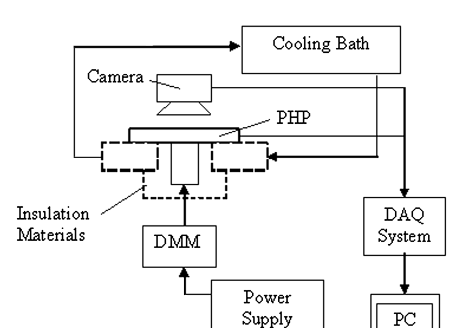

Fig. 3 Schematic of experimental setup.

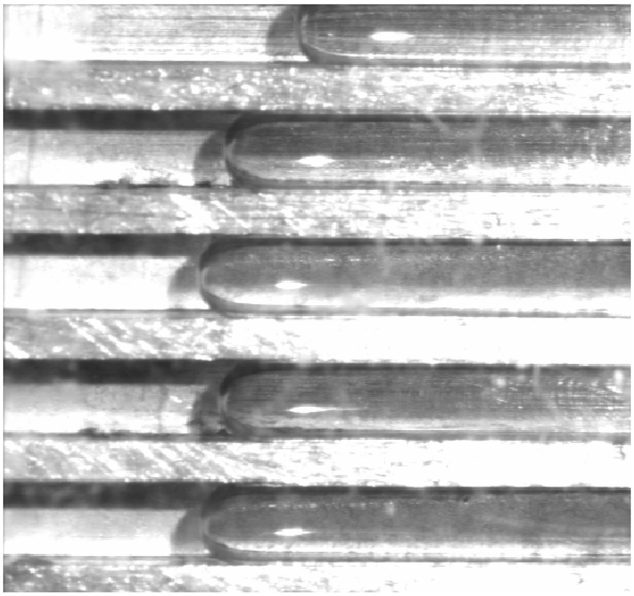

Fig. 4 Photography of liquid and vapor slugs recorded by the high speed camera.

visual data. Using the tracking software, the recorded images can be used to determine the slug position and velocity of working fluid in the PHP.

The PHP was placed in the test section so that there was 15 mm of condenser length in each of the two closed loops. A long copper heater block was fashioned with the dimensions 50.8 × 15 mm to span the middle of the PHP. The voltage to the heater was varied to obtain the desired power output. The cooling blocks were set to a constant temperature of 20°C. The PHP was allowed to reach steady state and video recordings were taken of the pulsating motions using a Photron high speed camera. The camera recording speed was set to take 60 frames per second. The video recording, as shown in Fig. 4, was then analyzed to determine slug position and velocity with the auto tracking software produced by Photron motion tools. The manufacturer states that the repeatability of the software to track a point of interest is roughly 0.2 pixels for a clear contrasted image. For a given zoom the image needs to be calibrated with a known dimension. All distances were scaled relative to the known channel width of 1.5875 mm. Once adjusted for the proper length scale, the software can calculate the number of pixels per unit length and display it on the exported Excel file. By knowing the number of pixels per millimeter, the measurement errors can be determined based on repeatability. The measurement error of position is calculated as follows:

$$e_{\mathrm{pos}} = \frac{0.2}{\#_{\mathrm{pixels/mm}}} \tag{4}$$

where 0.2 is the repeatability and # is the number of pixels per mm. And the measurement error of velocity can be found as

$$e_v = \frac{e_{\mathrm{pos}}}{\Delta t} \tag{5}$$

Using Eqs. (4) and (5), the measurement errors of positions and velocities were determined for each image and the error bars are shown on each plot hereafter. The uncertainty associated with the filling ratio was determined through manufacturing tolerances and bias corresponding to the scale used. The maximum uncertainty for the charging percentage was calculated to be ±0.297%. The maximum uncertainty for heat input was calculated to be ±1.54 W at 160 W based on the error corresponding to the voltage and resistance measurements from a Fluke 45 dual display multimeter.

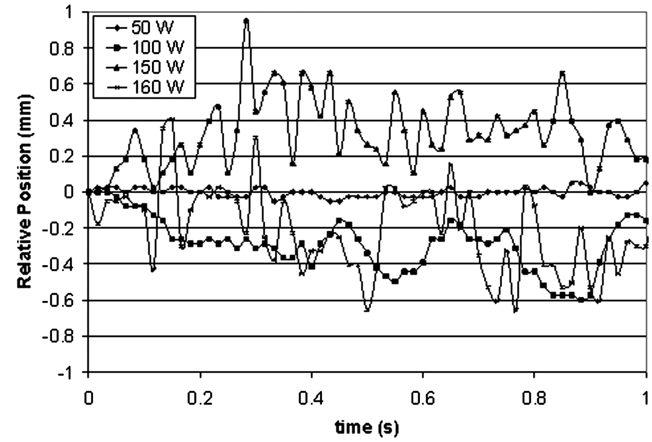

Fig. 5 Slug position measurement (filling ratio = 50%; working fluid = ethanol).

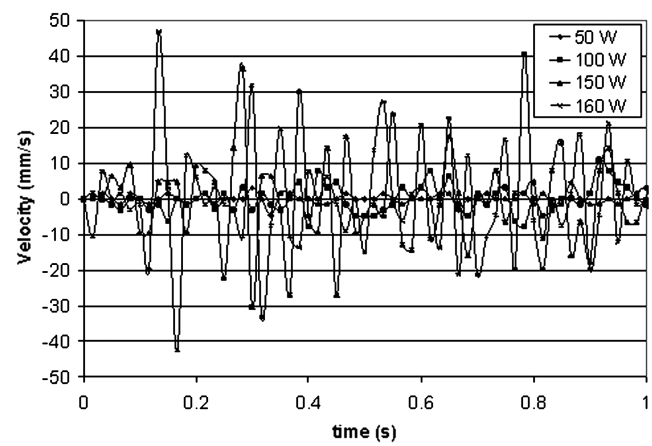

Fig. 6 Slug velocity measurement (filling ratio = 50%; working fluid = ethanol).

Experimental Results and Discussion

Heat Input Effect on Slug Motion

Using the experimental setup described above, the heat pipe shown in Figs. 1 and 2 was tested to determine the effects of power input, type of working fluid, and orientation relative to gravity. Figures 5 and 6 show the experimental results of the slug position and velocity with respect to time for a 50% filling ratio of ethanol. The heat pipe was oriented in a horizontal position and the heat input was varied from 50 to 160 W. As shown in Figs. 5–13, there is not a consistent amplitude or frequency, which makes it difficult to quantify each motion. For this investigation, the maximum displacement over the 1 s span was determined to gauge the effect of varying heat input. The maximum displacements of the liquid/vapor interface for heat inputs of 50, 100, 150, and 160 W are 0.1, 0.59, 0.95, and 1.05 mm, respectively. The maximum velocity of the slugs/plugs as the heat input is increased is 5, 11, 38, and 43 mm/s. Other investigators [14,15] have seen this increase in motion with increased heat input for similar flat-plate PHPs . This increase in pulsation amplitude and velocity is expected for an increase in heat input because higher heat inputs create larger temperature gradients that drive the pulsating motion. Furthermore, as the pulsating motions are amplified due to increased heat input, the temperature gradients may be reduced resulting in decreased motion.

Fluid Effect on Slug Motion

The different properties of dissimilar working fluids cause drastic effects on the motion of the interfaces. The heat pipe charged with high performance liquid chromatography (HPLC) grade water at a filling ratio of 50% was first tested horizontally and experimental

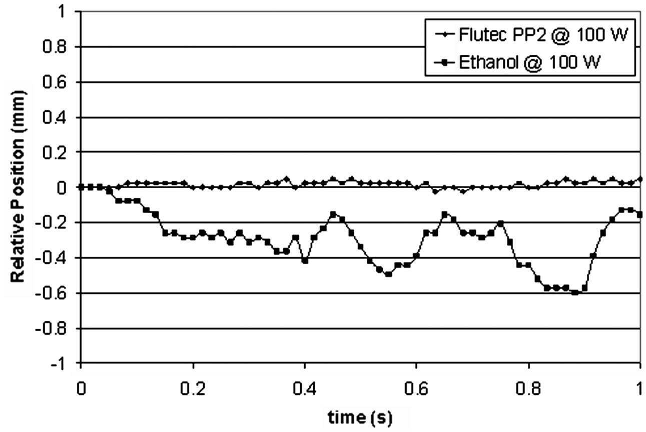

Fig. 7 Slug position measurement (filling ratio = 50%; working fluids = Flutec PP2 and ethanol; power input = 100 W).

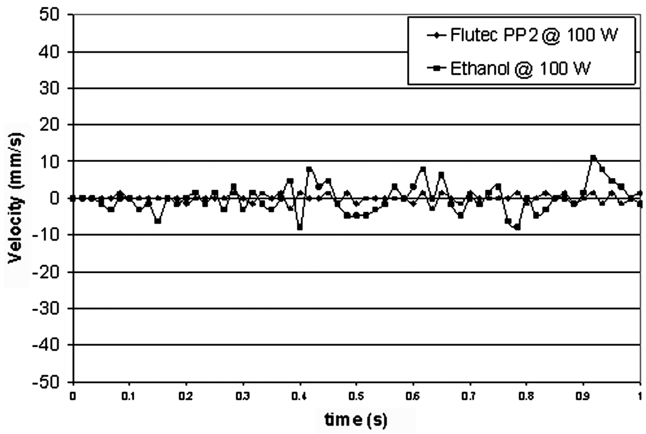

Fig. 8 Slug velocity measurement (filling ratio = 50%; working fluids = Flutec PP2 and ethanol; power input = 100 W).

data show that no oscillating motions were observed and the heat pipe would not function. Figures 7 and 8 show the slug/plug positions and velocities for a 50% filling ratio of Flutec PP2 and ethanol at a heat input of 100 W. For a heat input of 100 W, the maximum displacement is 0.07 and 0.59 mm for Flutec PP2 and ethanol, respectively. Similarly, the maximum velocity is larger for ethanol (11 mm/s) than for Flutec PP2 (1.4 mm/s). As the heat input is increased to 160 W, the discrepancies between the two fluids remain as shown in Figs. 9 and 10. For this condition, the maximum displacement of the interface is 0.24 and 1.05 mm for Flutec PP2 and ethanol, respectively. The maximum velocity for Flutec PP2 and ethanol at 160 W was determined to be 5.7 and 43 mm/s, respectively. The large difference in fluid motion for the two fluids given similar operating conditions is due to the properties of each fluid. At a given temperature, the liquid and vapor densities of Flutec PP2 far exceed those of ethanol. The increase in density significantly raises the mass of each liquid plug and vapor slug which requires a larger driving force to move. Also, the liquid and vapor viscosity of Flutec PP2 is much higher than ethanol, resulting in impeded motion.

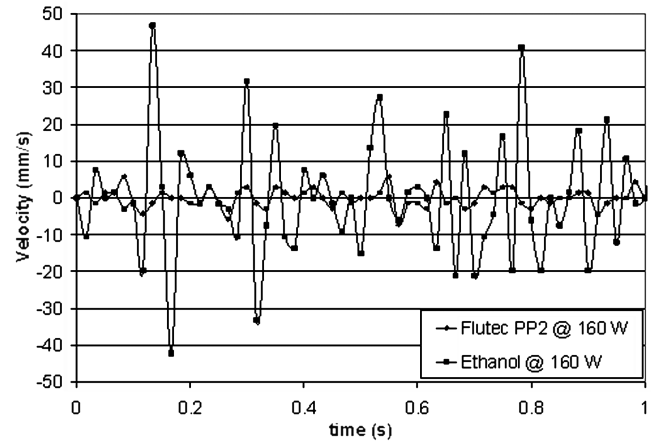

Fig. 10 Slug velocity measurement (filling ratio = 50%; working fluids = Flutec PP2 and ethanol; power input = 160 W).

Orientation Effect on Slug Motion

The orientation of the PHP with respect to gravity showed remarkable changes in fluid motion. Previous work shows that when a functional PHP was changed a position from the horizontal to vertical (90 deg), the oscillating motion and heat transfer performance of the heat pipe are different. In the current investigation, slight increases in angle from the horizontal resulted in large increases in displacement and velocity for bottom heating mode. Cao et al. [16] show an increase in orientation angle will reduce the thermal resistance of the overall PHP. This can be attributed to the increase in motion of the fluid. The PHP was charged to an 80% filling ratio with Flourinert, the power input was set to 125 W, and oriented at angles of 0, 2, and 5 deg from the horizontal. Figure 11 showed maximum displacements of 0.2, 1.3, and 4.5 mm for angles of 0, 2, and 5 deg, respectively. The maximum velocity of the liquid/vapor interface increased dramatically from 9 to 9.21 to 45.4 mm/s for increasing angles as shown in Fig. 12.

Macromovement Phenomenon

During the described experiments, the macromovement (bulk movement) phenomenon (circulation) of the liquid plugs and vapor

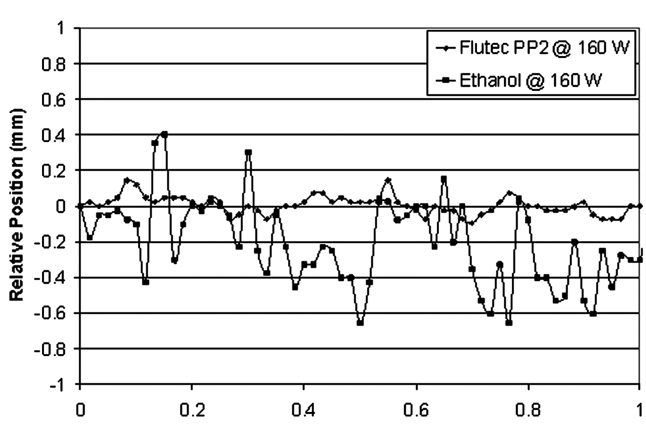

Fig. 9 Slug position measurement (filling ratio = 50%; working fluids = Flutec PP2 and ethanol; power input = 160 W).

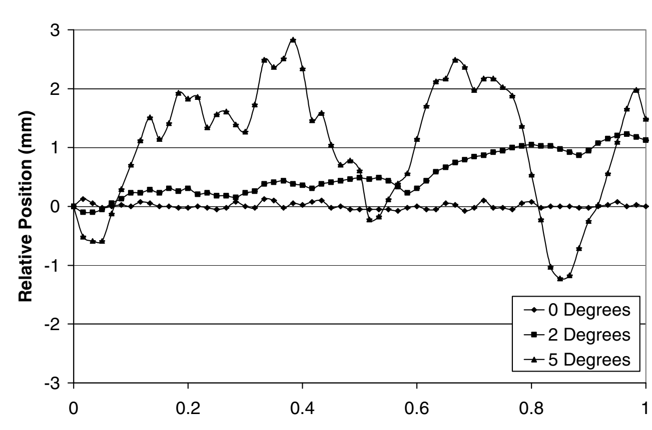

Fig. 11 Slug position measurement (filling ratio = 80%; working fluid = Flourinert power input = 125 W).

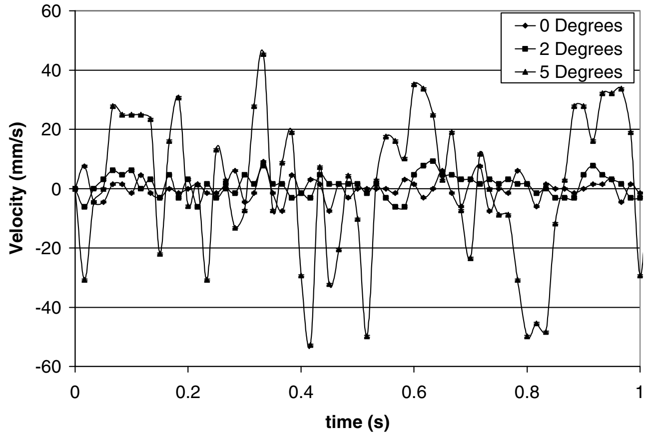

Fig. 12 Slug velocity measurement (filling ratio = 80%; working fluid = Flourinert power input = 125 W).

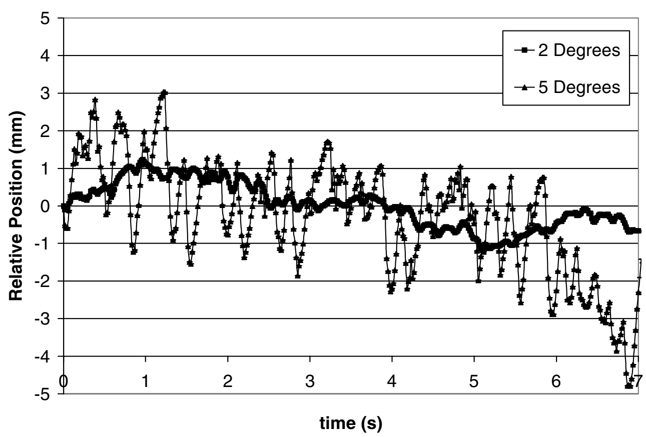

Fig. 13 Slug position measurement showing macromovement (filling ratio = 50%; working fluid = Flourinert power input= 125 W).

slugs was encountered for a functional PHP in addition to the oscillating motion. And as the input power increased, both the macromovement and oscillating motion became stronger. Obviously, the macromovement will aid in the overall performance of the pulsating heat pipe. And it was found that the macromovement is very sensitive to the tilted angle. Figure 13 shows the slug positions for the two angled cases (2 and 5 deg) over an extended period of time. As shown, when the angle increased from 2 to 5 deg, the macromotion became stronger. Other investigators [4] state the macromotion in PHPs tends to circulate through the channel in a given direction with occasional reversal at high heat fluxes. Complete circulation of the liquid slugs was not seen in the specified PHP due to an inadequate driving force. The bulk motion seen in the given PHP complicates the current problem of adequately modeling the pulsating motion and further understanding of this bulk motion needs to be investigated.

Conclusions

1) An experimental system was established to measure the oscillating motions of vapor bubbles and liquid plugs occurring in a PHP with noncircular channels including displacement, velocity, and frequency. The measurements show that when power input increases, the displacement, velocity, and frequency all increase. However, the oscillating motions were very irregular.

2) Working fluid significantly affects the oscillating motion occurring in the PHP. When the heat pipe was charged with HPLC water, no oscillating motions were observed and the heat pipe would not function. The experimental results show that when the heat pipe was charged with ethanol, it created the largest amplitudes and velocities.

3) Both oscillating motion and macromovement (circulation) exist in a functional PHP. When the input power increases, both movements become stronger. Slight increases in angle resulted in greatly increased amplitudes of positions and velocities of vapor bubbles and liquid plugs in a PHP.

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