THEORETICAL AND EXPERIMENTAL INVESTIGATION OF OSCILLATING HEAT PIPES

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Master of Science

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by

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The undersigned, appointed by the Dean of the Graduate School, have examined the

thesis entitled

**THEORETICAL AND EXPERIMENTAL INVESTIGATION OF
OSCILLATING HEAT PIPES**

Presented by Shibin Liang

A candidate for the degree of Master of Science

And hereby certify that in their opinion it is worthy of acceptance.

_____   Hongbin Ma

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_____   Gary Solbrekken

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NOMENCLATURE

A	cross sectional tube area, m^2
B_s	isentropic bulk modulus, N/m^2
B_T	isothermal bulk modulus, N/m^2
C_f	friction factor
C_{pl}	liquid specific heat, J/kg K
D (d)	tube diameter (I.D), m
g	gravity acceleration, m/s^2
h	heat transfer coefficient, W/Km^2
K	gas spring constant
L	length, m
m	mass, kg
p	pressure, N/m^2
q'' or q	wall heat flux, W/m^2
Re	Reynolds number
r	capillary radius, m
s	perimeter, m
T	temperature, K or ˚C
t	time, s
u	liquid plug velocity, m/s
V	bubble volume, m^3

z	distance along the tube (channel), m
Δh	length of liquid plugs between evaporator and condenser, m

Greek

α	contact angle, °
θ	tilt angle, °
σ	surface tension, N/m
ρ	density, kg/m^3
μ	viscosity, Pa.S
ϕ	filled ratio
κ	ratio of specific heat

Subscript

a	adiabatic section
ave.	averaging
c	condenser
cold	condenser side
e	evaporator
f	pressure drop
hot	evaporator side
i	ith liquid plug or vapor bubble
l	liquid
m	average value

n	total number of liquid plugs
v	vapor
sat	saturation

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ABSTRACT

A mathematical model describing the oscillation characteristics of slug flow in a capillary tube is presented. The model considers the vapor bubble as the gas spring for the oscillating motions in a capillary tube including effects of capillary force, gas spring constant, dimensions, gravitational force, and initial pressure distribution of the working fluid. Numerical results indicate that the isentropic bulk modulus generates stronger oscillations than the isothermal bulk modulus. While it demonstrates that the capillary tube diameter, bubble size, and unit cell numbers determine the oscillation, the capillary force, gravitational force, and initial pressure distribution of the working fluid significantly affect the frequency and amplitude of oscillating motion in the capillary tube. An experimental study of a five-turn closed loop oscillating heat pipe has been conducted The oscillating heat pipes charged with HPLC grade water, acetone and ethanol have been tested respectively. In a vertical orientation, the oscillating motion of the slug flow in the oscillating heat pipe has been observed.

Chapter 1.   Introduction

1.1.   Background

Developing a miniature, low cost and high efficient heat transfer device is becoming more and more important due to the rapid development of electronics and computer industries. The conventional heat pipes such as copper grooved heat pipes and sintered particle heat pipes have played an important role in the heat dissipation in the laptop computers. Starting in 2004, more than 100 million desktop computers sold annually could potentially use the heat pipe technology. Today, many computer manufacturers are employing heat pipe thermal solutions in their desktop, notebook and server computers, which has opened a greater market to the heat pipe with a greater demand. With the continuous increase of power density in the electronic equipment and computers, it requires that the thermal engineers or researchers develop the advanced heat pipe technology or other innovative cooling technologies.

Akachi [1] presented a novel concept of heat and mass transfer device named as pulsating heat pipe. Owing to its potential heat transport capability, simple structure and low cost of construction, a lot of researchers have investigated it experimentally and theoretically. The latest results reported by Vasiliev [2] showed that the thermal resistance of a flat aluminum multi-channel pulsating heat pipe with propane as working fluid can reach as low as 0.05 K/W. This value really represents a very good performance of the heat pipe, in particular, for the heat transport in a long distance.

 Similar to a conventional heat pipe, the pressure difference between the evaporator and condenser of the oscillating heat pipe is imperative, and must be maintained at a certain or critical value to generate a self-sustaining oscillation of liquid and vapor slugs

in the heat pipe. The heat pipe is filled with a working fluid to form vapor bubbles and liquid plugs (a liquid-vapor mixture) dependent on the filled ratio. When the heat pipe is in operation, the saturated pressure of the liquid-vapor mixture varies from the evaporator section, adiabatic section to condenser section depending on the operating temperature. Obviously, when the evaporator section is heated, the vapor pressure at this end increases. And liquid at this end is superheated before vaporization takes place at the wall surface. Once the vapor bubble is formed in the superheated liquid, its growth rate is very rapid especially in a small limited space. This explosive formation of vapor is often a source of instability since it is accompanied by a sharp local increase in static pressure which may reduce, stop, or even reverse the flow in the upstream section of the channel. At another cooling end of the heat pipe, when the vapor bubbles are cooled, the bubbles collapse and the condensing liquid film is formed inside the channel. The temperature of the vapor-liquid mixture is determined by the cooling surface area, wall temperature and heat transfer coefficient in the condenser section. The pressure in the condenser is dependent on the temperature of the vapor-liquid mixture. If liquid in the condenser section is cooled further, a subcooled liquid will appear in this area. Once the vapor bubbles and liquid plugs travel to the adiabatic section, where no heat addition or rejection occurs, a mass-spring model may be used to describe the oscillating motions of vapor bubbles and liquid slugs inside this section. When the liquid-vapor mixture of working fluid flows through the evaporator and condenser repeatedly, an enhanced heat/mass transfer process occurs due to the phase-change heat transfer and forced convection. This process of the oscillating bubble-train flow is a typical non-equilibrium and transient heat transfer process.

1.2.   Working Mechanism of Oscillating Heat Pipes

A typical oscillating heat pipe is illustrated in Figure 1.1. As heat is added to the evaporating section, vaporization occurs. When heat is removed from the condensing section, the vapor condensation takes place. The volume expansion due to the liquid vaporization and contraction due to the vapor condensation cause an oscillating motion of the liquid slugs and vapor bubbles delivering vapor to the condenser and returning liquid to the evaporator [2−11, 13-14]. The oscillatory motion of liquid slugs and vapor bubbles is self-sustaining as long as heating and cooling conditions are maintained. These statements provide a very general description of mechanisms of oscillating heat pipe. Shafii *et al*. [3] presented analytical models for both unlooped and looped pulsating heat pipes without considering the presence of adiabatic section. In their models, the total number of vapor bubbles is reduced to the total number of heating sections. The oscillating motions of position, pressure and temperature of the liquid-vapor mixture were obtained for both looped and unlooped pulsating heat pipes.
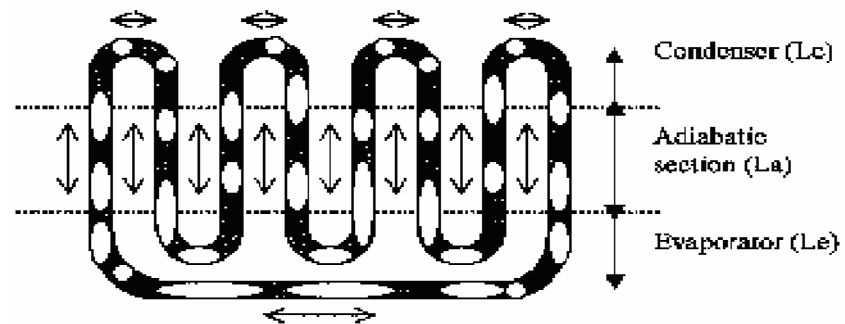
(a) with one closed loop
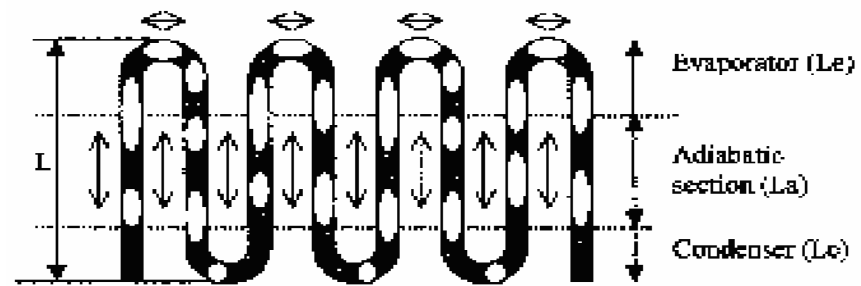
(b) with two-open ends
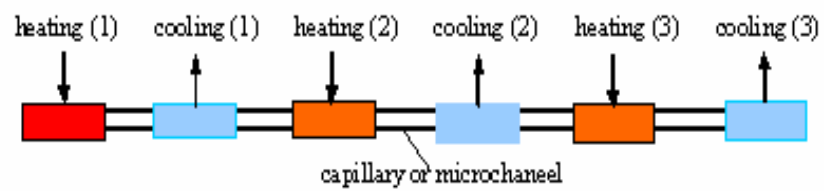
(c) heating and cooling

Figure 1.1 Loop and unloop oscillating heat pipes

Their results show that the oscillating pressure exists which may be the source of driving force inside the oscillating heat pipe if heat is added on the evaporating section and rejected from the condensing section. Obviously, the oscillating characteristics of the vapor-liquid mixture in the adiabatic section should be considered. Liang *et al*. [4] presented a mass-spring model to describe the oscillating motions of the slug flow in the adiabatic section of the heat pipe. The effects of isentropic bulk modulus and isothermal bulk modulus, tube diameters, fluid structure, pressure distribution, gravity and surface tension on the velocity, pressure and displacement of vapor bubbles and liquid slugs in the oscillating heat pipe are discussed. Zuo *et al*. [5] reported a simplified theoretical model which is capable of accurately predicting the effect of the proper filled ratio on the performance the oscillating heat pipes. Groll *et al*.[6] gave a review of design rules and some parameter effect on the heat transfer performance of the oscillating heat pipes. They pointed out that the slug-annular transition existed at a relatively higher heat flux, even in a capillary tube with a diameter of 2.0 mm for fluids like water, ethanol and R-123.

1.3. Experimental Investigation of Oscillating Heat Pipes

1.3.1. Oscillating and Pulsating Motion of Working Fluids

In the current available literatures, the oscillating heat pipe is also called as the pulsating heat pipes. Nishio [7] conducted an experimental study on the oscillating heat pipe consisting of four straight glass tubes connected by four U-shaped tubes with an inner diameter of 2.4 mm. The heat pipe was charged with R141b and a filled ratio of 40 %. The heat pipe was tested at a temperature difference of $\Delta T=(T_e-T_c)=40$ K. Visual observation showed that the flow of working fluid was pulsating with an almost

5

unidirectional circulation. In the heating section, when the flow went upward along the tube, vapor bubbles were generated. When the vapor plugs arrived at the cooling section of this tube, the liquid film between the vapor plug and the tube wall became highly disturbed. In the cooling section, the flow pattern is a long vapor plug with a liquid film. As the flow inside the tube went down, the disturbances of the liquid film became less, and the liquid film thickness δ was measured as from 0.2 to 0.3 mm. This thickness for water was between 0.1 and 0.2 mm, and for ethanol between 0.2 and 0.3 mm. When the flow went downward in the tube, the vapor plug progressively condensed, and the liquid slug portion started to increase. Khandekar and Groll [8] conducted an experimental study for a closed-loop pulsating heat pipe using one-turn glass tube with an inner diameter of 2.0 mm. The total height of the heat pipe was 190.0 mm and the length of the adiabatic section was 100.0 mm. With a filled ratio of α=60 % (ethanol), the flow pattern of the working fluid was dependent on the input heat power. At the heat power input was low, low amplitude oscillations with slug flow in both sections of the heat pipe were observed. As the heat input was increased, the oscillation amplitude increased. Simultaneously, there was a considerable improvement in the heat transfer performance of the heat pipe. A complete circulation of working fluid started either in the clockwise or anti-clockwise direction. When the input power was further increased, the flow direction reversal completely stopped. The circulation flow was only in one direction. Vasiliev [2] reported that the circulation flow of the working fluid (propane) for a flat aluminum pulsating heat pipe was stable with a filled ratio of near 60%. The configuration parameters of the flat heat pipe panels were as follows: the total width=70.0 mm, the total thickness=7.0 mm, the total length=700.0 mm, the evaporator length=98.0 mm, and the

condenser length=50.0 mm. The motion of working fluid was continuous due to the interplay between the driving and restoring forces. During the experiments the circulation and oscillation of working fluid were observed depending on the inclination angle and filled ratio.

At the heat input is low, the working liquid in the oscillating or pulsating heat pipe can maintain oscillating motion around an average position between the evaporator and condenser of the heat pipe. When the heat power input increases and reaches at a certain level, the balance of the oscillating system is broken and then one direction circulation motion of the working fluid appears in the heat pipe. At this stage, the local oscillating motions of vapor bubbles and liquid slugs inside the capillary tube of the heat pipe still exist. The circulation phenomenon may be caused by the instability of the two phase-change fluid flow in the heat pipe.

1.3.2.   Thermal Resistance

Vasiliev [2] reported a high efficient pulsating heat pipe—a flat aluminum multi-channel heat pipe shown in Figure 1.2. The thermal resistance, R, could reach as low as 0.05 K/W when the heat pipe worked in a vertical position. The heat transfer coefficients at the evaporator and condenser sides were 8500.0 W/m^2K and 2500.0 W/m^2K, respectively. Propane was chosen as the working fluid in the heat pipe. Zuo *et al.*[5] developed a pulsating heat pipe combing with the capillary force shown in Figure 1.3. The heat pipe was charged with water. Experimental results showed the thermal resistance could reach 0.16°C/W at a heat flux of 220 W/cm^2. The thin layer of sintered powders coated on the flow channel surface of the heat pipe enhanced boiling heat

transfer. Based on the concept of the pulsating heat pipe, Cao *et al* [9] developed a

wickless network heat pipe. Experimental results showed that at
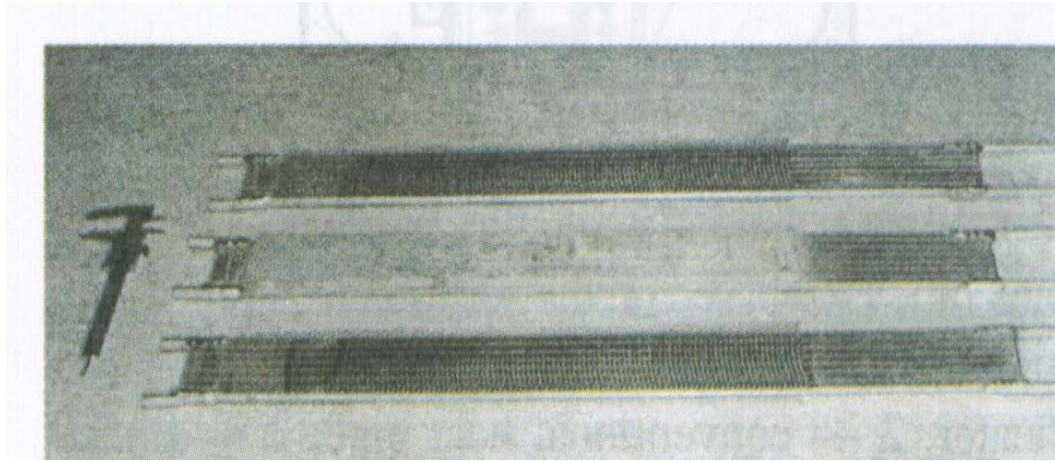
Figure 1.2 Flat aluminum multi-channel pulsating heat pipe with propane as a working fluid (Vasiliev[2])

Figure 1.3 Combined pulsating and capillary heat pipe (cross-section)(Zuo[5])

a heat flux of 110 W/cm^2 the thermal resistance of the heat pipe was 0.05 °C/W. The

working fluid was water with a filled ratio of 65%.

1.3.3.   Temperature and Pressure Measurements of Evaporator

Measuring the wall surface temperature of evaporator and condenser is a relatively

simple method to describe the flow patterns inside the oscillating heat pipe. Khandekar

and Groll [8] measured the wall surface temperatures corresponding to the observed flow

patterns in the closed-loop pulsating heat pipe using one-turn glass tube. As shown in Figure 1.4, there were only the oscillating motions of the vapor liquid mixture in the heat pipe, and the temperatures T_1 and T_2 which represent the right and left sides of the heat pipe respectively, were nearly same. When the heat power input increased, the circulation of the vapor-liquid mixture appeared and then changed the flow direction of the working fluid randomly. The difference between the temperature T_1 and T_2 as shown in Figure 1.4(b) increased up to ten degree. At a higher power input, an almost unidirectional circulation of the working fluid was observed shown in Figure 1.4(c), and the temperature T_2 was higher than T_1. The vapor-liquid mixture from the condenser of the heat pipe carried the "cold" energy into the adiabatic section to cause the reduction of the temperature T_1. Lee *et al*. [10] measured the pressure oscillation in a ten-turn oscillating heat pipe. The total length of the heat pipe was 220 mm. The cross section of the rectangular channel is 1.5x1.5 mm^2. As shown in Figure 1.5, the oscillating pressure waves in the evaporator of the heat pipe were recorded directly. These oscillating pressure waves can be considered as the oscillating sources or driving forces in the oscillating heat pipes. Vasiliev [2] measured the wall surface temperature variations of evaporator, adiabatic section and condenser of the heat pipe shown in Figure 1.6. In this high efficient oscillating heat pipe, the
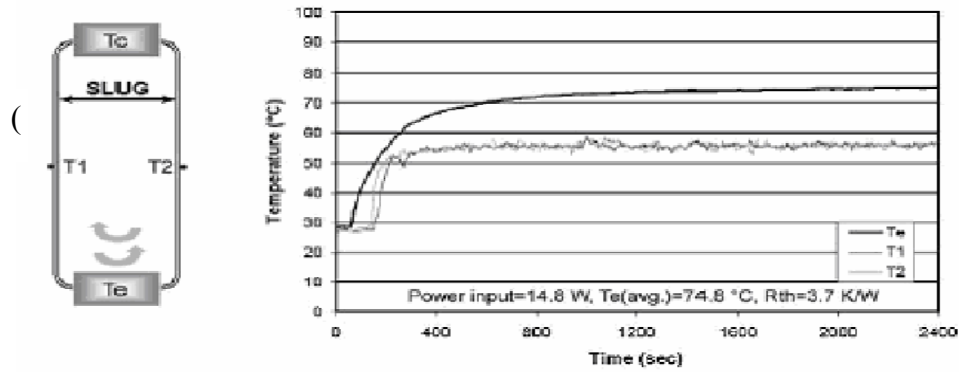
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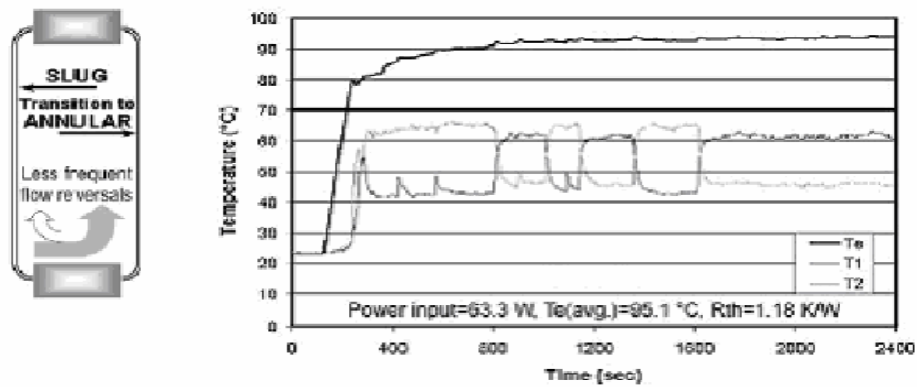
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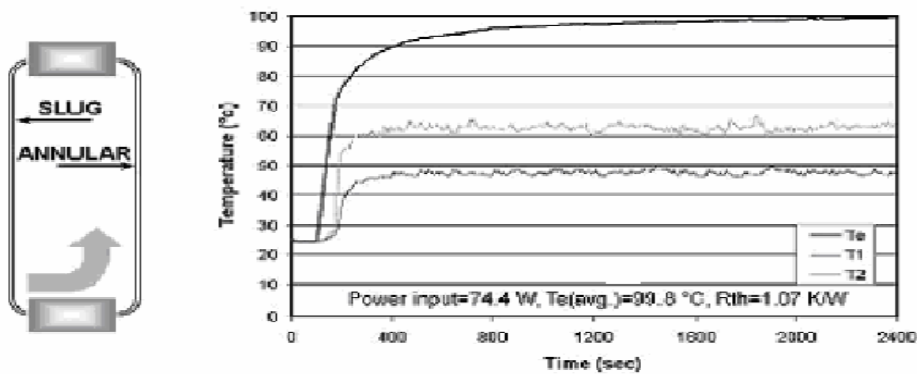
(c)

Figure 1.4 Observed flow patterns in the loop and corresponding temperature profiles.[8]
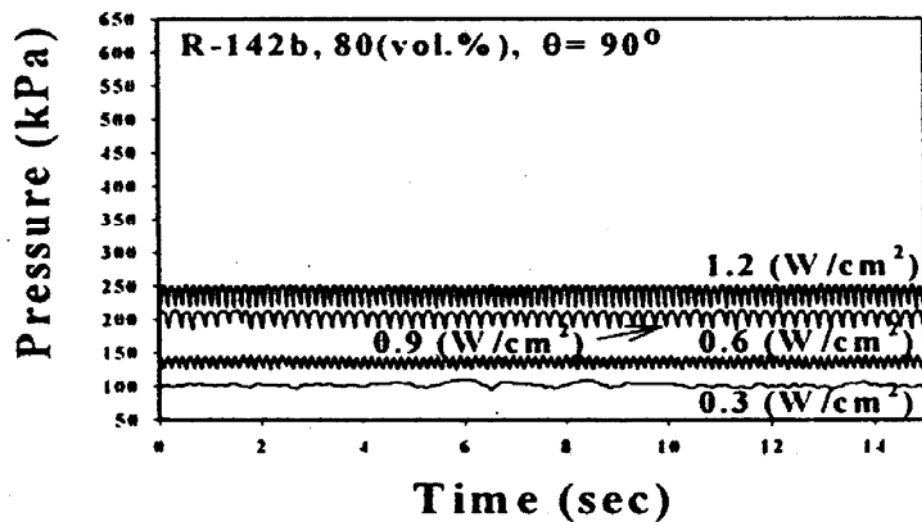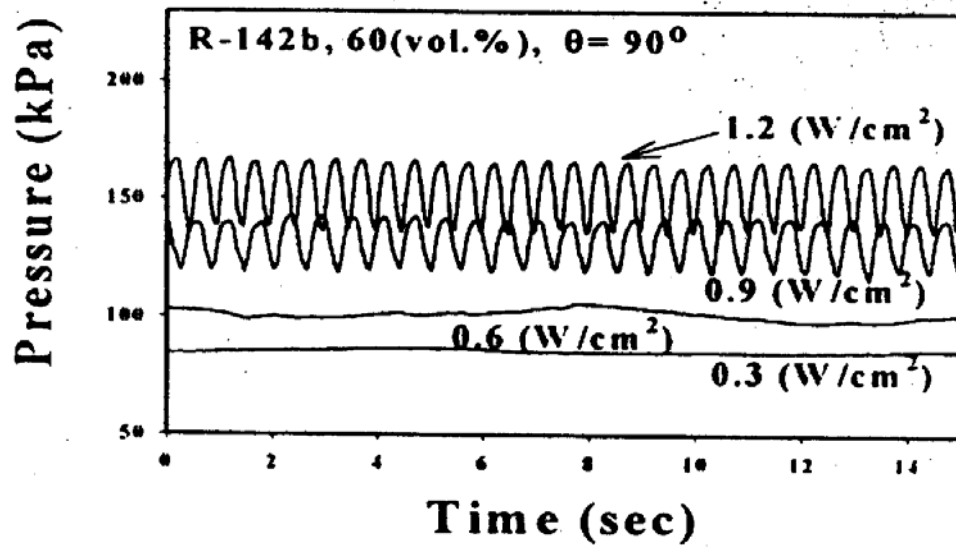
Figure 1.5 Oscillating pressure at evaporator of the heat pipe (Lee[10])
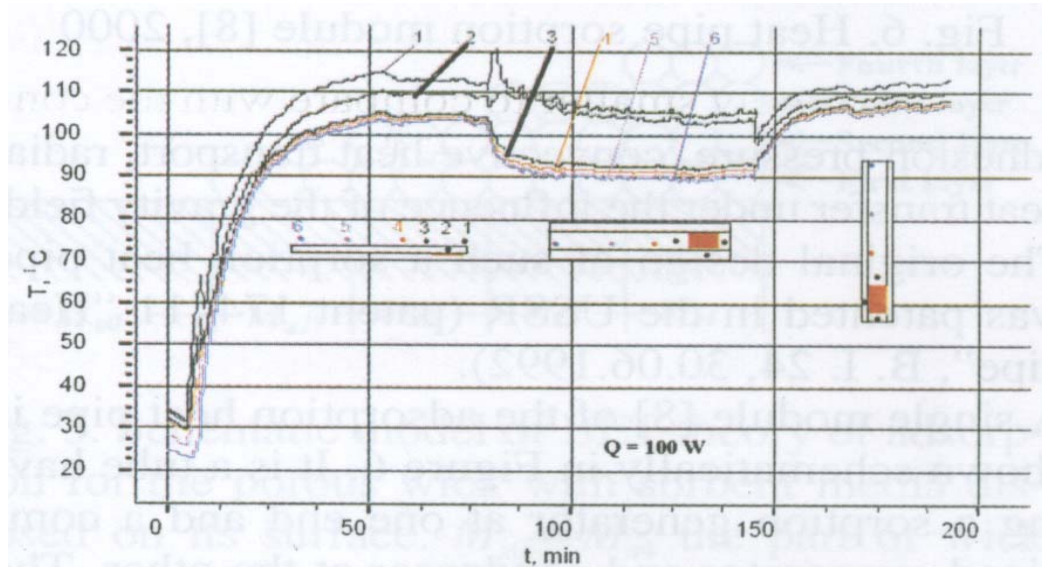
Figure 1.6 Temperature field evolution for different design of pulsating heat pipe panels orientation in space. $T_1;T_2$-evaporator; T_3-transport zone;$T_4;T_5;T_6$-condenser. Heat pipe size=700x70x7 mm., Thermal resistance R=0.05 K/W. The liquid circulation depends on the heat input and its velocity increases with the increase in the heat power. (Vasiliev[2])

oscillating motions of the vapor-liquid mixture of the working fluid made the temperature distribution of the working fluid in the adiabatic section of the heat pipe be uniform.

1.3.4. Working Fluids

Until now, water, acetone, ethanol, R141b, R123, FC-72, propane, HFC134a and butane have been tested as the working fluids in the oscillating/pulsating heat pipe. Most

of them are not successful to be used as the working fluids for the oscillating heat pipes. Researchers from TS Heattronics Company in Japan suggested that butane and HFC134a could be used as the working fluids in the oscillating/pulsating heat pipes.

Choosing a proper working fluid for an oscillating heat pipe is becoming an important element for the heat pipe to function well. Although it has been found that $(dP/dT)_{sat}$, viscosity, latent heat, thermal conductivity, liquid density, specific heat, surface tension and saturated temperature/pressure affect the heat transfer performance of heat pipe, the primary properties are still not known. Further theoretical analysis and more experimental evidences both are needed to better understand the heat transfer mechanisms occurring in the oscillating heat pipe.

1.3.5.   Micro Oscillating Heat Pipes

When the tube diameter of the oscillating heat pipe reduces, the effect of surface tension on the working fluid increases and the structure of the vapor bubbles and liquid slugs in the channel of the heat pipe becomes stable. In other words, the slug flow in the heat pipe is hardly stratified into an annular flow at a higher heat flux. This will help to result in a strong oscillating motion of the vapor-liquid mixture in the heat pipe. The heat transfer performance of the heat pipe will improve. Nishio [11] developed a self-excited micro oscillating heat pipe. The heat pipe used in their experiments was a twin-turn tube consisting of four straight tubes. The tube was made of copper, and the total length of the loop was 1836 mm. The height of the heat pipe was 396 mm. The cooling section was 55 mm and the heating section was also 55 mm. The inner diameter of the tube was 0.5 mm, and the working fluid tested in the experiments was R141b. With a filled ratio of 60%,

the maximum heat transport rate Q_{max} could reach as high as 25.0 W. The value is ten times higher than the one from the conventional micro heat pipe with the same dimension.[12]

1.4. Theoretical Modeling of Oscillating Heat Pipe

Owing to the complicated vapor-liquid flow and heat transfer of the working fluid in the oscillating heat pipe, the mechanisms governing the two-phase oscillating/pulsating motion have not been fully understood. Wong *et al*. [13] gave a simplified model to predict the transient pressure waves for a slug flow in an unheated pulsating heat pipe. Ma *et al*. [14] presented a model for a single loop pulsating heat pipe and studied the effect of filled ratio, tube diameter and working fluid on the oscillating motion of the heat pipe. Zuo *et al*. [5] used a simplified theoretical model to predict the effect of the filled ratio on the oscillating motion of oscillating heat pipes. For such a complicated phenomenon occurring in the oscillating heat pipe, it is very difficult to describe its working mechanism based on a simplified model. Shafii *et al*. [3] presented an analytical model for both unlooped and looped pulsating heat pipes without considering the effect of the adiabatic section. They stated that the sensible heat transfer in the oscillating heat pipe was a key in the total heat transport in the heat pipe. In their calculations, the heat transfer coefficients in the evaporator and condenser of the heat pipe were chosen as 150.0 W/m^2K and 100.0 W/m^2K, respectively.

For an oscillating heat pipe shown in Figure 1.1, the pressure distribution of the working fluid along the meandering capillary tube of the heat pipe is dependent on the local temperature in the evaporator and condenser of the oscillating heat pipe. Obviously,

the saturated pressure in the evaporator is higher than the one in the condenser. As discussed in Introduction, vapor bubbles are formed in the superheated liquid and their growth rates are very rapid especially in a small limited space. This explosive formation of vapor is often a source of instability. Combining the oscillating pressure sources in the evaporator with the mass-spring structures of slug flow of the working fluid in the adiabatic section of the heat pipe, the vapor-liquid mixture of the working fluid will maintain a self-sustaining oscillation.

Transient and two-phase heat transfer in the oscillating heat pipe includes two components: sensible and latent heat transfer. If the latent heat transfer is negligible, heat transfer by applying an oscillating motion for the working fluid especially in liquid plug will be dominated by the sensible heat transfer. Kurzweg *et al* [15,16] studied the heat transfer enhancement of the oscillating liquid in capillary tubes. They assumed a fully developed unsteady flow in the tubes. Thulasidas *et al*[18-21] investigated experimentally a dispersion during bubble-train flow in capillaries, but no oscillating motion existed. In an oscillating heat pipe, there is an oscillating slug flow in the capillary tubes. Intensified transient heat and mass transport process in the slug structure in particular in liquid plug dominates the heat transfer mechanism in the device.

1.5. Summary

From the review as presented above, the following conclusions are obtained:

1. The oscillating motions occurring in an oscillating heat pipe may result from: 1) the oscillating pressure existing in the evaporators of the heat pipe; 2) a slug flow or bubble-train flow existing in the adiabatic section of the heat pipe, which

actually is a mass-spring system (vapor bubbles as gas springs and incompressible liquid plugs as pistons) and 3) a wavy pressure distribution along the meandering channel of the heat pipe existing between the evaporator and condenser of the heat pipe.

2. Heat and mass transport in the heat pipe is dependent on the oscillating motions of the vapor-liquid mixture in the channel of the heat pipe. The intensified oscillation can dramatically enhance heat and mass transfer in the heat pipe.

3. Working fluid in the oscillating heat pipe is a significant factor determining and affecting the heat transfer performance of the oscillating heat pipe. However, the primary properties of a working fluid affecting the performance are not clear.

4. The heat transfer performance of the micro oscillating heat pipe may be better than a conventional micro heat pipe.

Chapter 2.   Oscillating Motions of Slug Flow in Capillary Tubes

2.1.   Overview

Slug flow of vapor bubbles and liquid plugs as one fundamental two-phase flow has attracted many researchers' attentions due to applications and unique features of structure properties. Recently, the pulsating or oscillating heat pipe as an active cooling device [1-12,14-16,23,24] has stimulated an interest in the two-phase flow in these capillary tubes. The PHP, characterized with a typical structure of vapor bubbles and liquid plugs, consists of an interconnected capillary tube bent into many turns and the evaporating and condensing sections are located at these turns. The diameter of the PHP tube must be sufficiently small ranging from 0.1 mm to 5 mm so that liquid plugs can be formed by the capillary force.

Wong *et al.*[13] presented a theoretical modeling of the PHP based on the Lagrangian approach to describe the slug flow in a tube. By using a pressure pulse caused by the local heat input into the vapor bubble, the oscillation variations of pressure and velocity were obtained. However, the model did not consider the effects of liquid thin films and surface tension on the oscillation. Based on thin film evaporation and film condensation, Shafii *et al.* [3] established a heat transfer model and presented the pressure oscillation characteristics in the PHP, and concluded that the surface tension has little effect on the frequency and amplitude of the oscillation, and the model also shown that the effect of gravitational force on the oscillating motion can be neglected.

In the current investigation, utilizing the sawtooth alternating component of pressure drop as the excitation of the oscillating motion in the capillary tube, a mathematical

model describing the oscillating motion is developed. The effects of the isentropic bulk modulus and the isothermal bulk modulus are investigated in order to better understand the oscillating motions occurring in a PHP. A mass-spring model is employed to describe the displacements, velocities and pressures of the slug flow in a capillary tube. In addition, the effects of surface tension, dimensions, and gravitation force are included to determine how these factors affect the oscillating characteristics in the capillary tube filled with the vapor bubbles and liquid plugs.

2.2. Theoretical Analysis

As heat is added on a PHP, the oscillating motions combining with the phase-change process transfers heat from the evaporating section to the condensing section. In order to determine the primary factors affecting the oscillating motions occurring in the PHP, the slug flow of vapor bubbles and liquid plugs flowing through a capillary tube is considered. As shown in Figure 2.1, the slug flow is divided into n unit cells and each unit cell contains one vapor bubble and one liquid plug. A coordinate system shown in Figure 2.1 is taken and the slug flow is moving along the z-direction. The shear stress acting on the solid surface by the liquid plug is much higher than the one by the vapor bubble. Wallis [22] showed that the pressure distribution of the working fluid over unit cells could be described by approximately triangular or sawtooth alternating components shown in Figure 2.1. And this triangular or sawtooth alternating component of pressure drop can excite the oscillating motion in two-phase circuits where slug flow exists. In order to simplify the problem and find the primary factors affecting the oscillating motion

occurring in the capillary tube, it is assumed that the vapor bubbles are uniformly distributed with a constant pressure for a given bubble as shown in Figure 2.1.
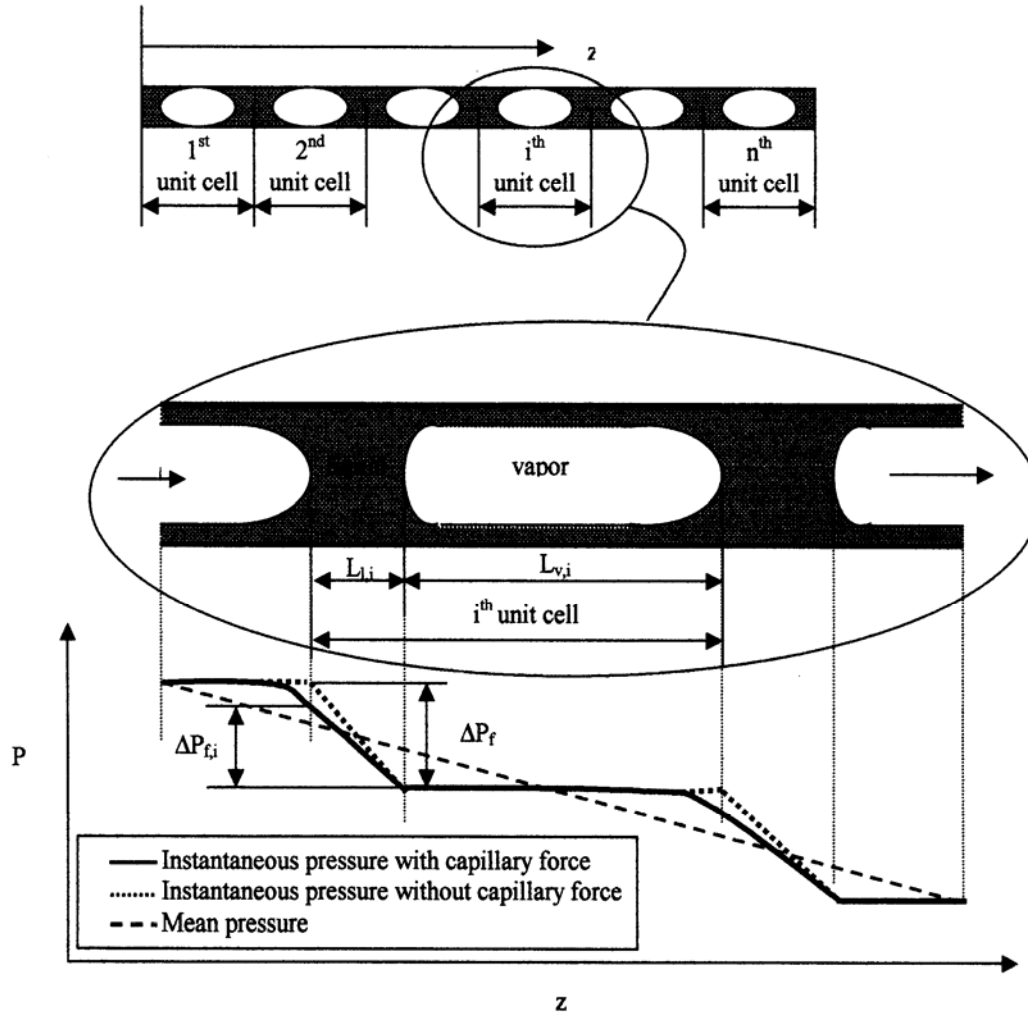
Figure 2.1 Slug Flow of Vapor bubbles and Liquid Plugs and Pressure Distributions

The pressure in the thin film region (i.e. between the cylindrical section of the bubble and the tube wall) can be approximately equal to the vapor pressure of the bubbles if the diameter of capillary tube is not so small. As the vapor bubble is forming and moving, the receding contact angle is less than the advancing contact angle. As a result, the liquid

pressure near the nose region of vapor bubble decreases due to smaller meniscus radius. For example, the pressure drop of ith liquid slug is reducing to $\Delta P_{f,i}$ from ΔP_f where the surface tension is not taken into account. The liquid pressure near the tail region of vapor bubble is very close to the liquid pressure due to larger advancing contact angle. It can be concluded that the pressure distributions of two-phase slug flow along the z-direction of tube can be approximately expressed as below

$$p = A_t \sin z - B_t z \tag{2.1}$$

where A_t and B_t are constants.

The vapor pressure in the vapor bubble can be described by the mean pressure p_m and the oscillating pressure, $p^{'}$, i.e.,

$$p = p^{'} + p_m \tag{2.2}$$

where the mean pressure, p_m, is dependent on the inlet and outlet pressures of slug flow, lengths and numbers of liquid plugs, inner diameters of tube, and liquid properties. Considering

$$dp = \left(\frac{dp}{d\rho} \right) d\rho \tag{2.3}$$

$$\frac{d\rho}{\rho} = -\frac{dV}{V} = -\frac{A dz}{V} \tag{2.4}$$

the oscillating pressure, $p^{'}$, can be found as

$$p^{'} = -\rho_m \left(\frac{dp}{d\rho} \right) \frac{A}{V_m} \Delta z = -K \frac{\Delta z}{A} = -B \frac{A\Delta z}{V_m} \tag{2.5}$$

where the effective spring constant, K, and the bulk modulus, B, of the vapor bubble can be expressed as

$$K = \rho_m \left(\frac{dp}{d\rho} \right) \frac{A^2}{V_m} \tag{2.6}$$

and

$$B = \rho_m \left(\frac{dp}{d\rho} \right) \tag{2.7}$$

respectively. When the vapor bubble experiences an isothermal process, which can occur if the oscillating frequency is slow, the vapor volume small, and the thermal conductivity of the gas large enough, the bulk modulus, B, can be written as

$$B = B_T \equiv \rho_m \left(\frac{\partial p}{\partial \rho} \right)_T = p_m \tag{2.8}$$

where B_T is called the isothermal bulk modulus. Considering Eq. (2.8), the gas spring constant for the isothermal process of vapor bubble can be determined by

$$K = K_T = B_T \frac{A^2}{V_m} = \frac{p_m A^2}{V_m} \tag{2.9}$$

In another limiting case, there is no heat transfer between the vapor bubble and the surrounding liquid, i.e., the vapor bubble experiences an adiabatic process, which might occur if the thermal conductivity of vapor phase is low, the vapor bubble volume large, the system frequency high, or/and the tube wall perfectly insulated. The bulk modulus, B, can be written as

$$B = B_S \equiv \rho_m \left(\frac{\partial p}{\partial \rho} \right)_S = \kappa p_m \tag{2.10}$$

where B_s is called the isentropic bulk modulus. And the effective spring constant K of the vapor bubble becomes

$$K_s = B_s \frac{A^2}{V_m} = \frac{\kappa p_m A^2}{V_m} \tag{2.11}$$

It should be noted that Eqs. (2.8-2.11) can be readily employed for the ith unit cell if the mean pressure, P_m, and the mean volume, V_m, of vapor bubble are replaced by the local instantaneous vapor pressure, P, and the local instantaneous vapor volume, $V_{v,i}$, respectively.

For the ith unit cell shown in Figure 2.2, the liquid pressures at two cap ends of liquid plug can be determined by

$$P_{v,i-1} - P_{l,i}^{\ 1} = \frac{2\sigma}{r_{i,1}} \tag{2.12}$$

and

$$P_{v,i} - P_{l,i}^{\ 2} = \frac{2\sigma}{r_{i,2}} \tag{2.13}$$
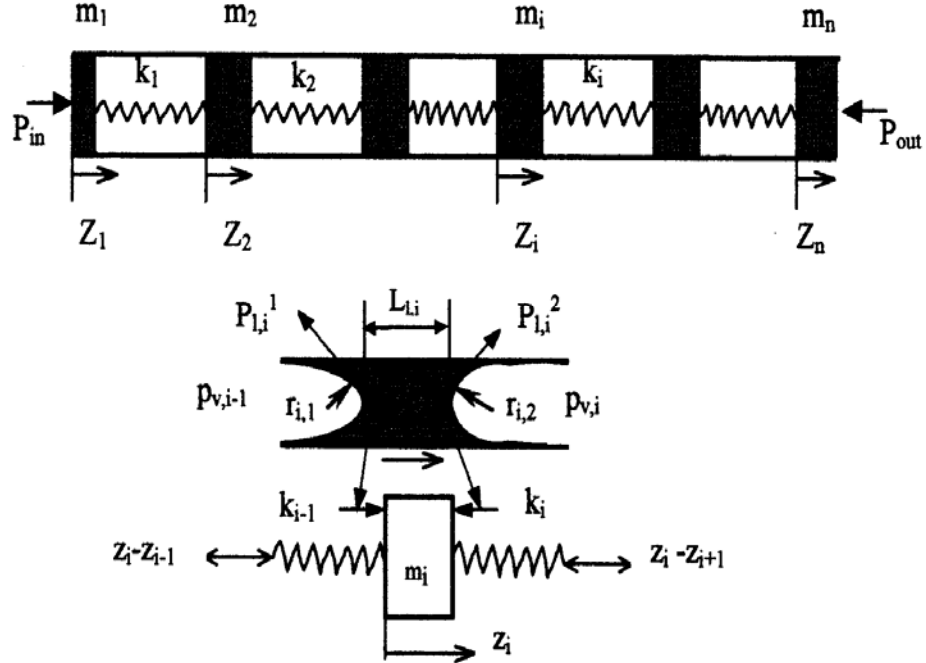

Figure 2.2 Mass-Spring Modeling of Slug Flow in a Capillary Tube

respectively, where $r_{i,1}=(d/2)/\cos\alpha_r$ and $r_{i,2}=(d/2)/\cos\alpha_a$, and α_r and α_a are the receding and advancing contact angles, respectively. The pressure difference, ΔP_i, between the two cap ends of the liquid plug for the ith unit cell can be found by

$$\Delta P_i = P_{l,i}{}^1 - P_{l,i}{}^2 = P_{v,i-1} - P_{v,i} + \left(\frac{1}{r_{i,2}} - \frac{1}{r_{i,1}}\right)2\sigma \qquad (2.14)$$

where $P_{v,i}$ and $P_{v,i-1}$ are the vapor pressures in the ith and i-1th bubbles, respectively.

The pressure drop ΔP_{fi} occurring in the ith liquid plug in the straight tube can be calculated as follows:

$$\Delta P_{fi} = \begin{cases} 4*(16/\mathrm{Re}_l)(L_{l,i}/d)(\rho_l u_i{}^2/2) & \mathrm{Re}_l < 2300 \\ 4*0.0791\mathrm{Re}_l{}^{-\frac{1}{4}}(L_{l,i}/d)(\rho_l u_i{}^2/2) & \mathrm{Re}_l > 2300 \end{cases} \qquad (2.15)$$

where $\mathrm{Re}_l=(\rho_l u_i d)/\mu_l$. While the pressure drop in the vapor bubble is negligible as it is compared with the pressure drop in the liquid plug, the pressure drop in a vapor bubble due to the nose and tail effect produces a noteworthy contribution to the total pressure drop. The total pressure drop occurring in the ith unit cell for all Reynolds numbers can be approximately expressed as Eq. (2.16),

$$\Delta p_{fi,u.c.} = 4C_f \frac{1}{2}\rho_l u_i^2 \frac{L_{li} + 4d}{d} \qquad (2.16)$$

where C_f is determined from Eq. (2.15), and L_{li} is the liquid plug length. As the vapor bubbles and liquid plugs flow through turns in the PHP, there exists an additional pressure loss, which can be described by

$$\Delta P_{fi} = K_l \frac{1}{2}\rho_l u_i{}^2 \qquad (2.17)$$

where K_l is the loss coefficient.

According to Newton's Laws, i.e., $\sum F = m \dfrac{d^2 x}{d\tau^2}$, the equation governing the motion

of the ith unit cell can be found as

$$m_i \frac{d^2 z_i}{dt^2} = \Delta P_i A - \Delta P_{fi} A - K_{i-1}(z_i - z_{i-1}) - K_i(z_i - z_{i+1}) \tag{2.18}$$

where z_i is the position of the ith liquid plug in the tube. It should be noted that if the

capillary tube is working in a vertical position, the gravity, $\rho_l g A L_{li}$, should be included in

Eq. (2.18). The total mass corresponding to the ith unit cell can be calculated by

$$m_i = \rho_l A L_{l,i} + \rho_v A L_{v,i} \tag{2.19}$$

And the local instantaneous velocity for the ith unit cell is defined as

$$u_i = \frac{dz_i}{dt} \tag{2.20}$$

Following the similar procedure to the ith unit cell, the equations governing the motions

for the 1st to the nth unit cell can be determined by

$$\left.\begin{array}{l} m_1 \dfrac{d^2 z_1}{dt^2} = m_1 \dfrac{du_1}{dt} = \Delta p_1 A - \Delta P_{f1} A - K_1(z_1 - z_2) \\[2mm] \vdots \\[2mm] m_i \dfrac{d^2 z_i}{dt^2} = m_i \dfrac{du_i}{dt} = \Delta P_i A - \Delta P_{fi} A - K_{i-1}(z_i - z_{i-1}) - K_i(z_i - z_{i+1}) \\[2mm] \vdots \\[2mm] m_n \dfrac{d^2 z_n}{dt^2} = m_n \dfrac{du_n}{dt} = \Delta P_n A - \Delta P_{fn} A - K_n(z_n - z_{n-1}) \\[2mm] u_1 = \dfrac{dz_1}{dt}, \cdots, u_i = \dfrac{dz_i}{dt}, \cdots, u_n = \dfrac{dz_n}{dt} \end{array}\right\} \tag{2.21}$$

2.3.   Results and Discussion

In order to verify the model presented in the paper, the numerical results are compared with results obtained by Wong *et al* [13] and Shafii *et al* [3] by using the same initial and boundary conditions, i.e., 1) the slug flow in the closed end tube is in a horizontal position; 2) a pressure pulse is applied to a plug at one end of the tube; 3) a total of 10 unit cells with each length of 0.12 m are considered; and 4) an initial pressure of 1.1 times higher than the rest is applied to the 10th vapor slug. As shown in Figures 2.3(a) and (b), the results predicted by the current model agree very well with the results obtained by Wong *et al* [13] and Shafii *et al* [3]. In addition, the model can predict the effect of capillary force on the oscillating motions. As shown in Figures 2.3(c) and (d), the capillary force will damp the oscillation. It should be noted that this conclusion is true only for the smooth capillary tube, i.e., no wick structures on the inner tube surface.
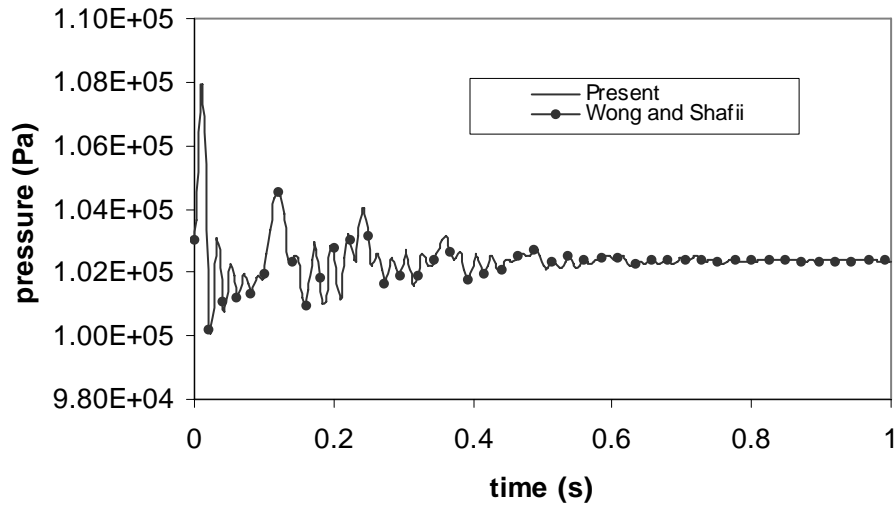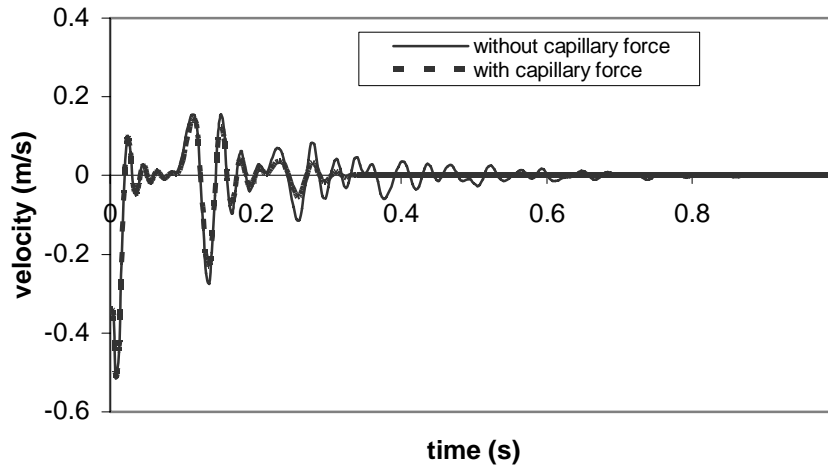

(a)
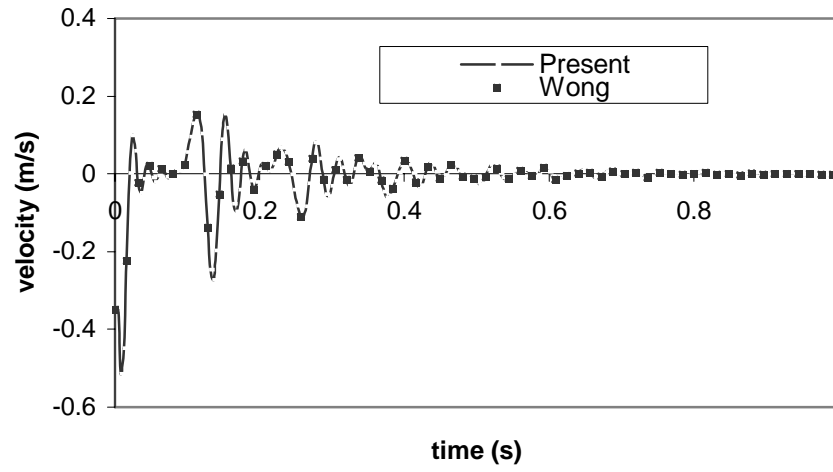
(b)
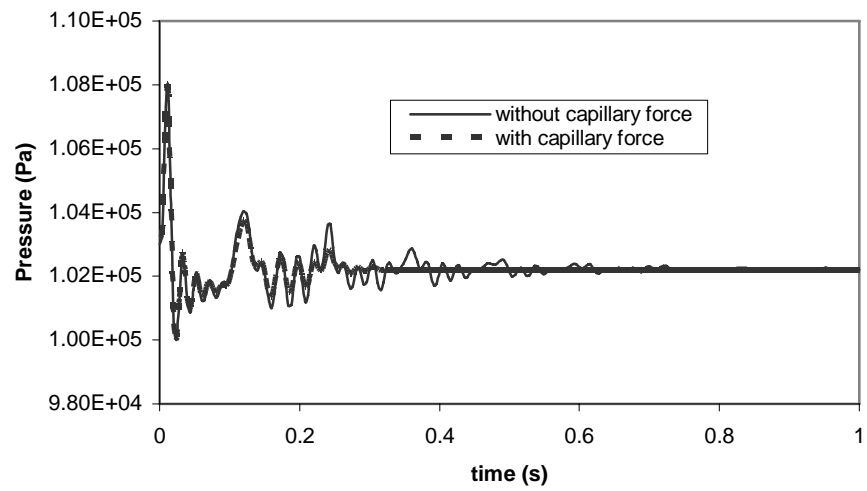
(c)

(d)

Figure 2.3 Comparison of the pressure and velocity variations with time: (a) and (b) comparison with two previous models without capillary force; (c) and (d) with capillary force

Unless stated otherwise, the following conditions for each of the studies are as follows: 1) the slug flow in the tube is assumed to be under the isothermal process; 2) the slug flow consists of 10 liquid slugs (water) and 9 bubbles (air); 3) the tube works in a horizontal orientation; and 4) the properties for water and air are based on the operating temperature of 20 °C; and 5) the third unit cell is taken as an example. As discussed previously, the oscillating motions depend on the thermodynamic process as shown in Eqs. (2.9) and (2.11). Figure 2.4 describes the effects of the isothermal bulk modulus and the isentropic bulk modulus of the vapor bubbles on the oscillation characteristics of the slug flow in the capillary tube. As shown, the isentropic bulk modulus generates larger amplitudes and higher frequencies of the oscillating velocities and pressures of the slug flow than the isothermal bulk modulus.
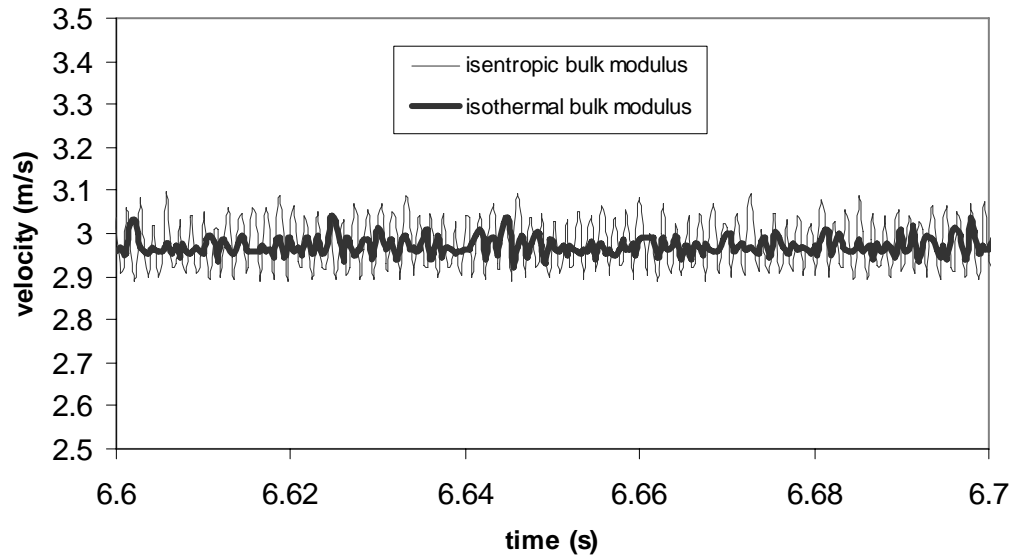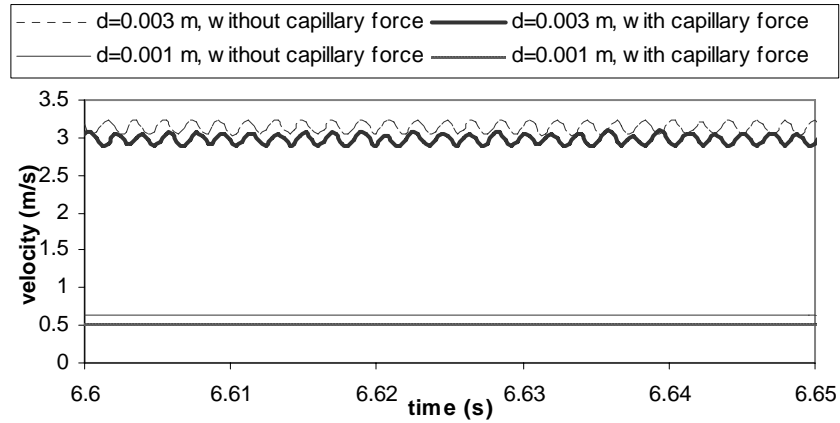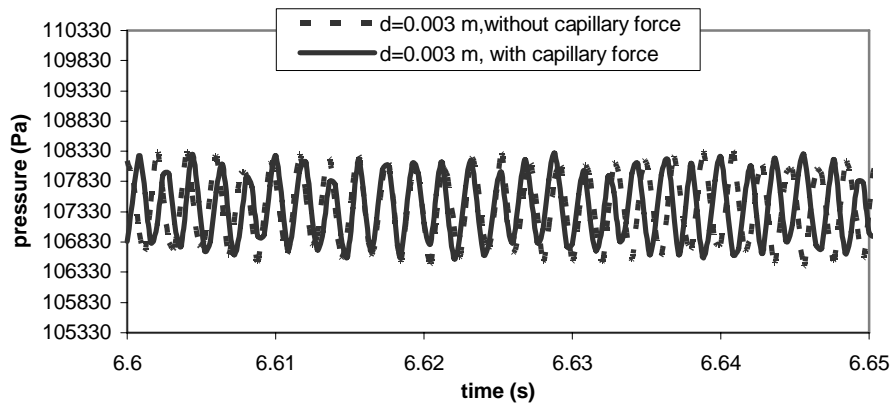
(a) velocity
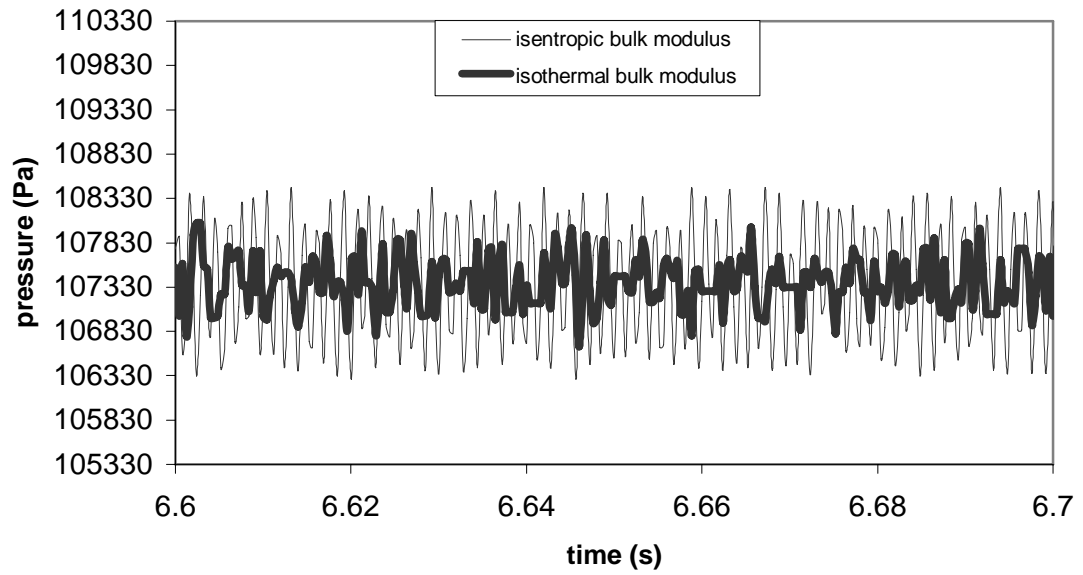
(b) pressure

Figure 2.4 Comparison of isentropic bulk modulus and isothermal bulk modulus

The tube diameter plays an important role in the oscillating motions of slug flow in the capillary tube. As the tube diameter decreases from 0.003 m to 0.001 m, as shown in Figure 2.5(a), the velocity of slug flow significantly decreases and depends on the capillary force. Figures 2.5(b) and 2.5(c) illustrate the effect of tube diameter on the pressure oscillation and show that the pressure drop in the capillary tube increases with the decrease of the tube diameter. As shown in Figures 2.5(b) and 2.5(c), the capillary force significantly damps the oscillation of slug flow in the tube, particularly, for a smaller diameter as illustrated in Figure 2.5(c).
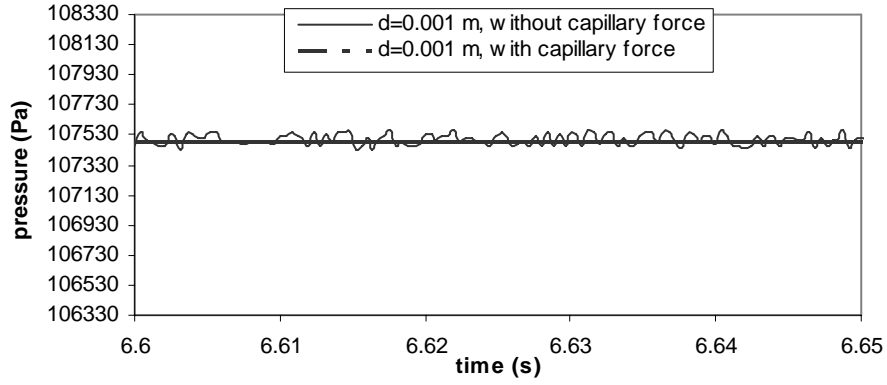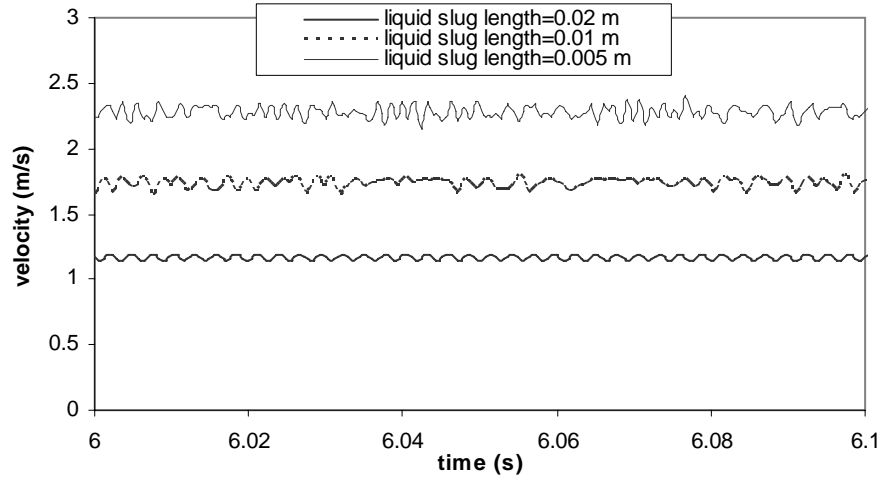

(a) velocity

(b) pressure (d=0.003 m)

(22)

(c) pressure (d=0.001 m)

Figure 2.5 Diameter effect on velocity and pressure of slug flow in tubes

The structures of slug flow in the tube are controlled by the lengths of liquid plugs and vapor bubbles and play a key role in oscillating motions of slug flow in the tube. As the length of liquid plug increases from 0.005 mm to 0.020 m and other parameters are kept constant, i.e., d=0.003 m;. L_v=0.005 m; P_{in}=108330.0 P_a; and P_{out}=101330.0 P_a, as shown in Figures 2.6(a) and 2.6(b), while the amplitude and frequency of oscillating velocity decrease, the amplitude and frequency of oscillating pressure increase. When the length of vapor bubble decreases from 0.02 m to 0.005 m, and the other parameters are kept constant, i.e., d=0.005 m; L_l=0.005 m; P_{in}=105330.0 P_a; and P_{out}=101330.0 P_a, as shown in Figure 2.7, the oscillating motions of slug flow in the tube become stronger, i.e., the amplitudes and frequencies of velocities and pressures increase.

(a) velocity
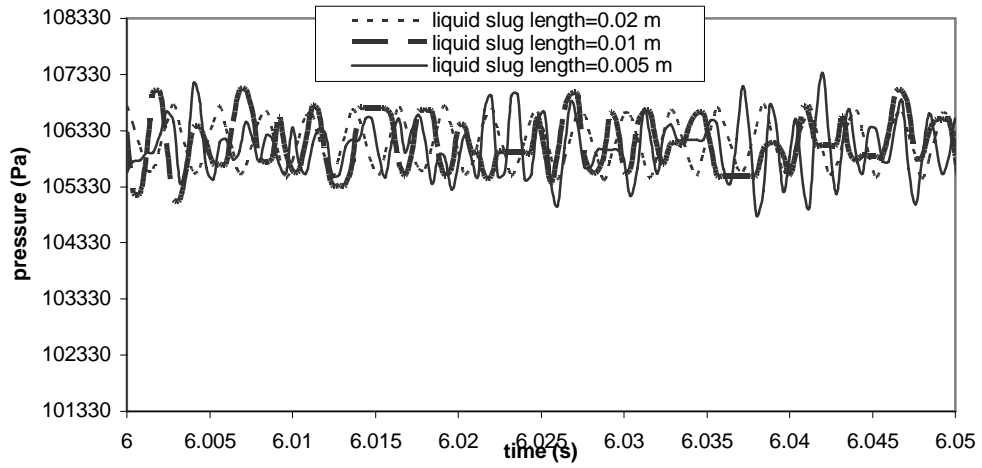
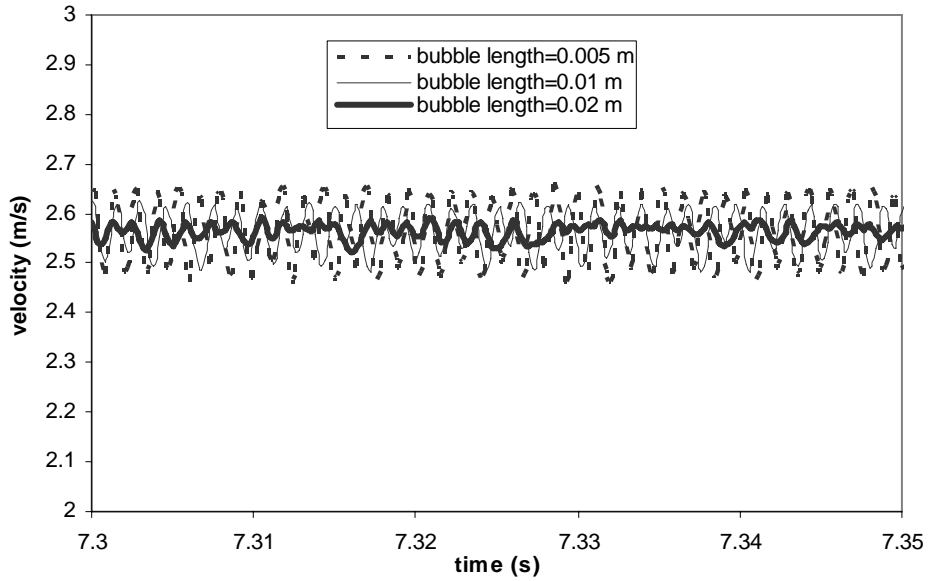
(b) pressure

Figure 2.6 Velocity and pressure variation with liquid slug lengths (d=0.003 m;lv0=0.005 m)

Based on the solutions of oscillating pressure and Eq. (1), the pressure gradient driving the oscillating motion of two-phase slug flow can be expressed as

$$-\frac{1}{\rho}\frac{\partial p}{\partial z} = A_t^{'}\cos\omega t^{'} + B_t^{'} \qquad (2.22)$$

It should be noticed that B'_t in Eq. (2.22) is the mean value of the pressure gradient, which is the driving force superimposed by a sinusoidal component shown in Eq. (2.1) for the oscillatory flow occurring in the capillary tube. The average pressure distribution of slug flow in the tube is dependent on the inlet and outlet pressures, which also affects the shape of instantaneous pressure distributions of the slug flow. In order to find the effect of the pressure difference on the oscillating motions, it is assumed that the inlet pressure, P_{in}, increases from 104330 Pa to 110330 Pa and the outlet pressure is kept constant, i.e., P_{out}= 101330 Pa. The numerical results shown in Figures 2.8(a) and (b) indicate that as the inlet pressure increases, the oscillating motions of slug flow in the tubes are intensified.

(a) velocity
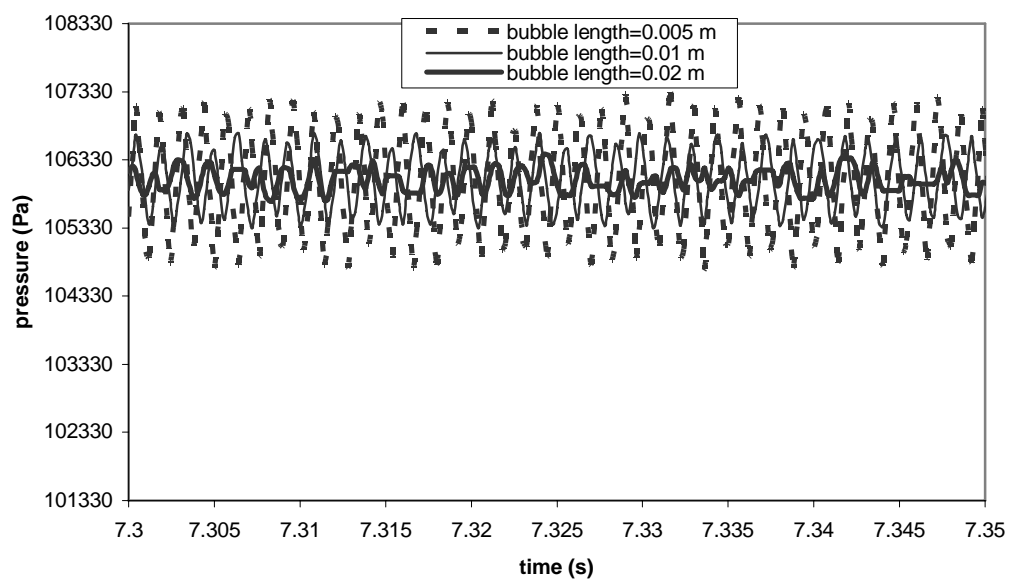
(b) pressure

Figure 2.7 Velocity and pressure variation with bubble lengths (d=0.005 m;l_{l0}=0.005 m)
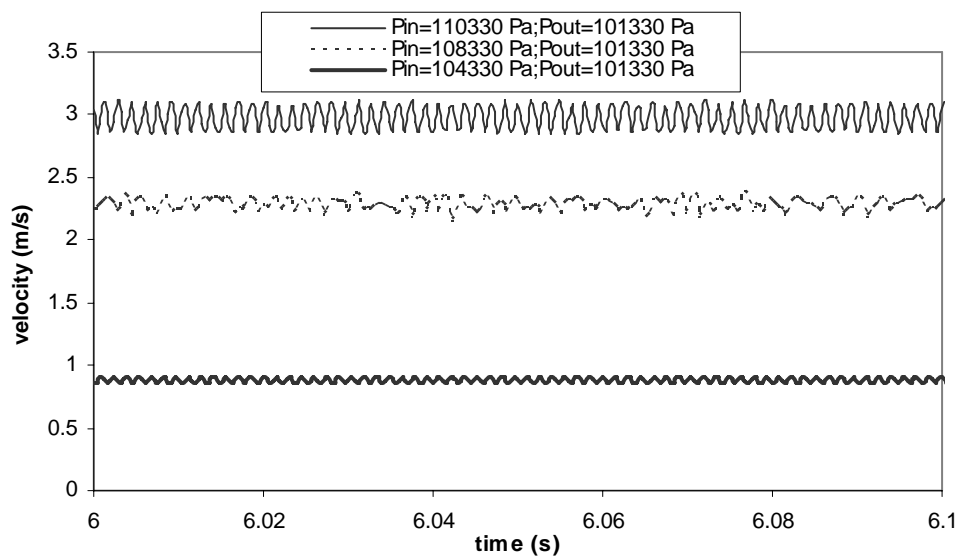
(a) velocity
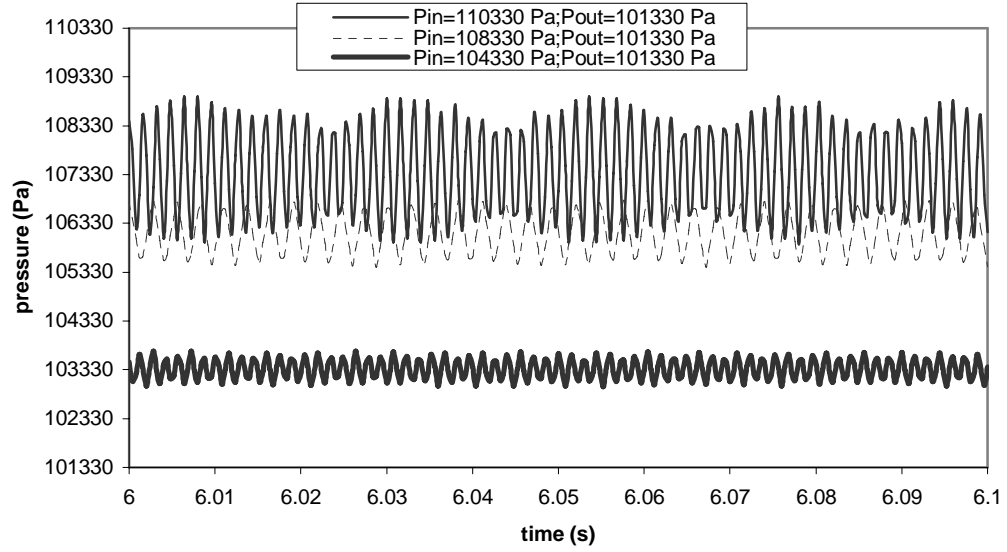
(b) pressure

**Figure 2.8 Effect of inlet and outlet pressure on the velocity and pressure distribution
(d=0.003 m;ll0=lv0=0.005 m)**

Figure 2.9 illustrates the effect of gravitational force effect on the oscillating motion in the capillary tube. As shown in Figures 2.9(a) and (b), the gravitational force will decrease the amplitudes of both velocity and pressure for the conditions of d=0.01 m, $L_l=L_v=0.005$ m, $P_{in}=105330$ Pa, and $P_{out}=101330$ Pa. When the lengths of liquid plug and vapor bubble increase from 0.005 m to 0.015 m, respectively, and other parameters are kept unchanged, as shown in Figures 2.9(c) and (d), the gravitational force can help to obtain a more stable oscillating motion of slug flow.

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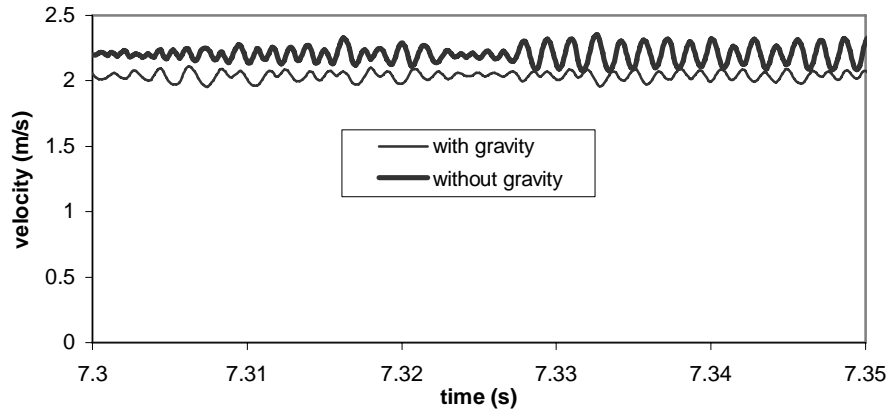
(a) velocity ($L_l=L_v=0.005$ m)
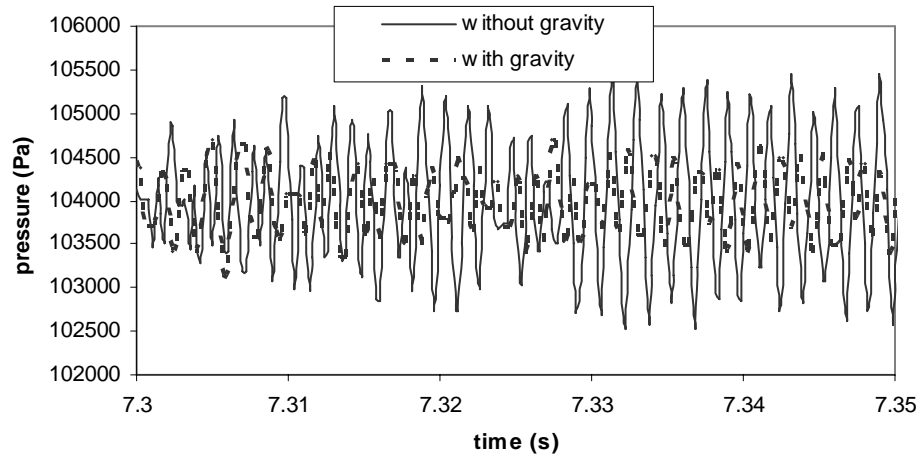
(b) pressure($L_l=L_v=0.005$ m)
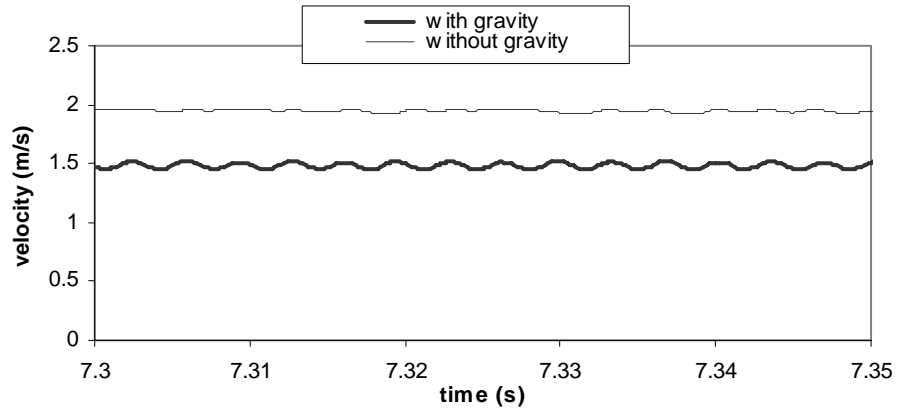
(c) velocity($L_l=L_v=0.015$ m)
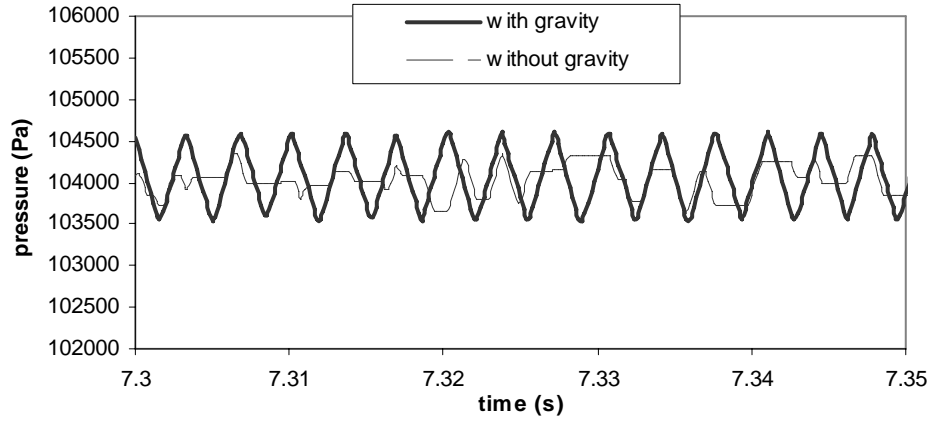
(d) pressure (L_l=L_v=0.015 m)

**Figure 2.9 Effects of gravity on the velocity and pressure
(d=0.01 m, Pin=105330 Pa, Pout=101330 Pa)**

2.4.   Summary

Utilizing the sawtooth alternating component of pressure drop as the excitation of the oscillating motion, a mathematical model describing the oscillation characteristics of slug flow of vapor bubbles and liquid plugs in capillary tubes is presented including the effects of capillary forces, gas spring constants, dimensions, gravitational forces, and initial pressure distributions of working fluids. The model considers the vapor bubble as the gas spring for the oscillating motions in the capillary tubes.   Numerical results indicate that the isentropic bulk modulus generates stronger oscillations than the isothermal bulk modulus. While it demonstrates that the diameters of capillary tubes, bubble sizes, and liquid plugs determine the oscillating motions, the capillary force, gravitational forces, and initial pressure distributions of the working fluid significantly affect the frequency and amplitude of oscillating motions in the capillary tubes. While

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the gravitational force makes the oscillation damp, the gravitational force helps to stabilize the oscillating motions of slug flow in the tube for some situation, and it can be concluded that the oscillating motions of slug flow in such tubes are very sensitive to the tube orientation.   In order to maintain the self-sustained oscillating motions of the slug flow, the frictional pressure drops of liquid plugs and vapor bubbles in the tubes should be minimized.

Chapter 3. Experimental Study of the Oscillating Heat Pipe

3.1.   Overview

Comparing with the convenient heat pipe, the oscillating heat pipe is unique in both its structure and mechanisms. Since there is no wick structure inside an oscillating heat pipe, the construction of the heat pipe is simple and the manufacturing cost is relatively low. The potential application of the heat pipe is very prospective. Many experimental investigations of the oscillating heat pipes [1-11,13,14] have been conducted in recent years While most of these experimental studies could not obtain the expected results, these investigations, however, have experimentally found that working fluids, tube dimensions and heating/cooling load influence the heat transfer performance of oscillating heat pipes. In order to compare with the theoretical analysis presented in Chapter 4 and better understand the heat transfer mechanisms of the oscillating heat pipe, an experimental investigation on a 5-turn OHP was conducted.

3.2.   Experimental Set-up

A prototype of the oscillating heat pipe shown in Figure 3.1 was fabricated. The five-turn oscillating heat pipe was made of a copper tube with an inner diameter of 3.0 mm and outside diameter of 6.35 mm. Glass tubes with an inner diameter of 3.0 mm and outside diameter of 7.0 mm were constructed in the adiabatic section of the heat pipe and used as an observation window observing the oscillating motions of vapor bubbles and liquid plugs. Through this window, a laser beam could be used to measure the oscillating frequency of slug flow in the oscillating heat pipe.   Epoxy adhesive was used to seal the connections between the glass tubes and copper tubes. Two aluminum cold plates were

(a)

(b)

Figure 3.1 Photography of the oscillating heat pipe

clamped on both sides of the condenser sections of the heat pipe. The evaporator is attached by an electrical flat heater. Twelve T-type thermocouples are used to measure

the temperature distribution along the surface of the heat pipe. These thermocouples are connected to a USB data acquisition system to record the temperatures. OmegaThermal 200 conductive paste has been applied to reduce contact resistance between the resistor and heat pipe walls. A DC power supply (E3645A from Agilent) is connected to the flat resistor and its voltage and current are recorded simultaneously. The flat resistor is insulated by fiberglass to protect heat losses to the environment. Heat losses to the environment for a working heat pipe are closely approximated (less than 0.5 percent) versus operating temperature or free convection. When heat is removed by two aluminum cold blocks, the heat pipes are placed in a vertical position with the heater at bottom and two cold blocks are tightly contacted with the heat pipe condenser section. Contact resistance at the cold block/heat pipe external wall interface is reduced by applying OmegaThermal 200 conductive paste as well. Cooling water is pumped through the cold blocks from a water tank under the room temperature.

copper plate (thickness=3.5 mm)

condenser section
(114.0 mm)

adiabatic section
(94 .0 mm)

evaporator section
(27.0 mm)
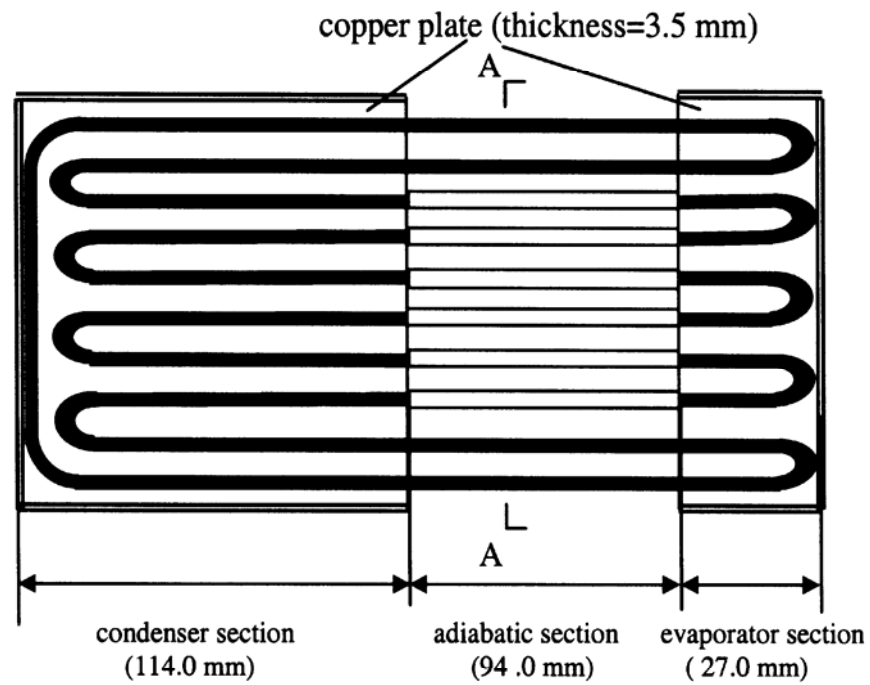
(a) geometry of the OHP

A-A

108.0 mm

12.0 mm
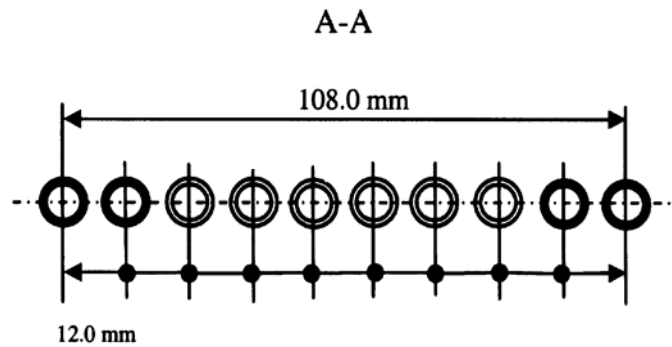
(b) cross-sectional view of the OHP

copper tube (OD= 6.35 mm; ID=3.0 mm)
glass tube   (OD=7.0 mm; ID=3.0 mm)
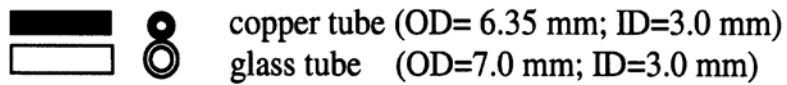
Figure 3.2 Schematic of the oscillating heat pipe including the detailed dimensions

Figure 3.3 shows a picture of the typical experimental set-up for the oscillating heat pipe.

(a)

(b)

Figure 3.3 Photos of he experimental system for the oscillating heat pipe

3.3.   Results and Discussion

3.3.1   Thermal Resistance

Figure 3.4 illustrates the experimental results of thermal resistances of the heat pipe. The heater is placed on the bottom of the heat pipe. The working fluid in the heat pipe is Acetone and the filled ratio is 0.53. When the
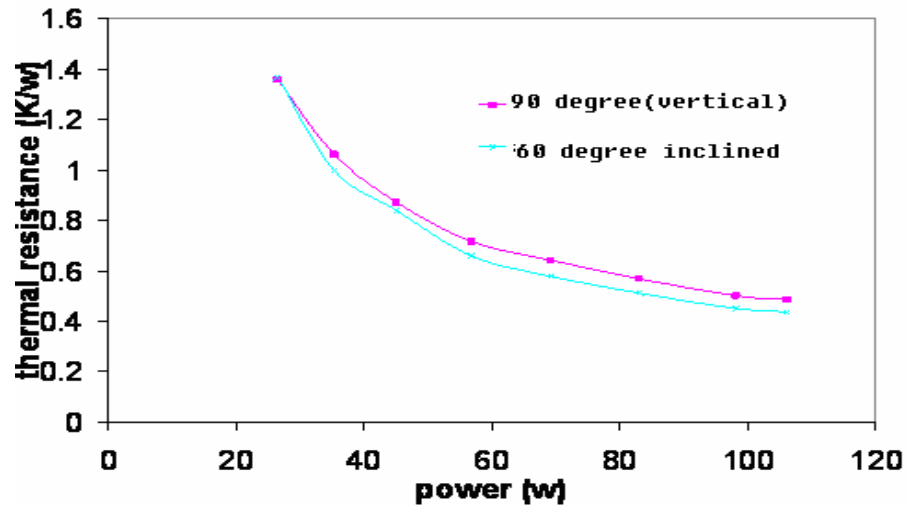
Figure 3.4 The thermal resistance of the oscillating heat pipe

input power was lower, it could be observed that the oscillating motion of vapor bubbles and liquid plugs was very weak through the glass tubes in the adiabatic section of the heat pipe. As the heat load increases, the slug flows in the heat pipe oscillate stronger resulting in a higher heat transfer rate. When the orientation of the heat pipe inclined from 90 degree (vertical) to 60 degree, the performance of the heat pipe became a little better as shown in Figure 3.4. Through the observation of flow patterns in the adiabatic section of the heat pipe, the annular flow appears especially for the vertical orientation of the heat pipe. When the orientation of the heat pipe inclined from 90 degree (vertical) to 60

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degree, the slug flow dominates the flow pattern. Oscillating slug flow of the working fluid enhances heat transfer in the heat pipe.

When the working fluid is taken place by water, the vapor bubbles appears a little and the oscillating motions of liquid or vapor is hardly observed.

3.3.2   Observation of Slug Flow Structure

A photo of slug flow in the adiabatic section of the oscillating heat pipe is shown in Figure 3.5. When the heat pipe is working, a clear oscillating structure of slug flow in the heat pipe could be observed.
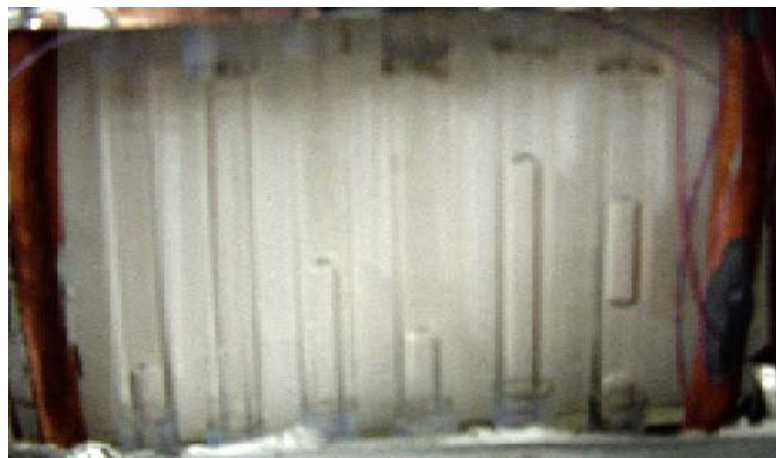
Figure 3.5 Photo of structure of slug/bubble-rain flow in the glass capillary tubes of the adiabatic section of the OHP

By using an infrared camera, the temperature distribution along the surfaces of the six glass tubes of the adiabatic section of the heat pipe has been recorded as well, as

shown in Figure 3.6. The real temperature distribution at the glass tubes of the adiabatic section of the heat pipe should be measured by using thermocouples.
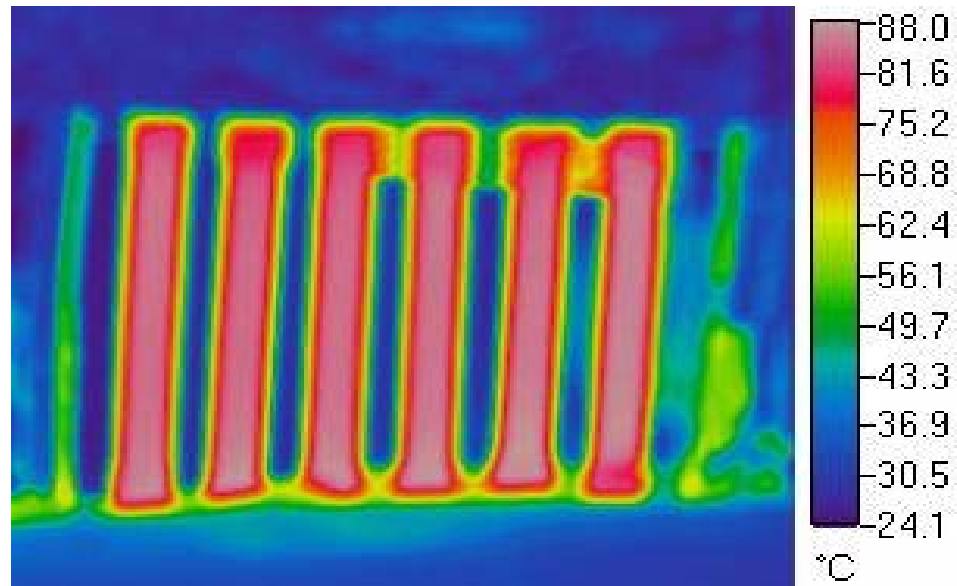
Figure 3.6 Temperature distributions along the glass capillary tubes (By an infrared camera)

3.3.3   Oscillating Frequency Measurement of Slug Flow

Using the Polytec PI PSV-200 scanning laser vibrometer, the measurement of the oscillating frequency, a significant feature of slug flow in an oscillating heat pipe, was conducted in the Lab. Six glass tubes in the adiabatic section of the oscillating heat pipe consist of a window for observing the oscillating motions of the slug flow structure. The PSV-200 scanning laser vibrometer can provide non-contact, remote, high frequency bandwidth, and accurate measurements for a vibrating movement. The experimental

results show that the laser beam from the vibrometer can capture the oscillating motions of the interfaces between bubbles and liquid slugs. Dependent on the moving directions of the interfaces and the related time intervals between the two neighbor signals, the average oscillating frequency of slug flow can be calculated. Figure 3.7 shows the measuring results by using the Polytec PI PSV-200 scanning laser vibrometer.
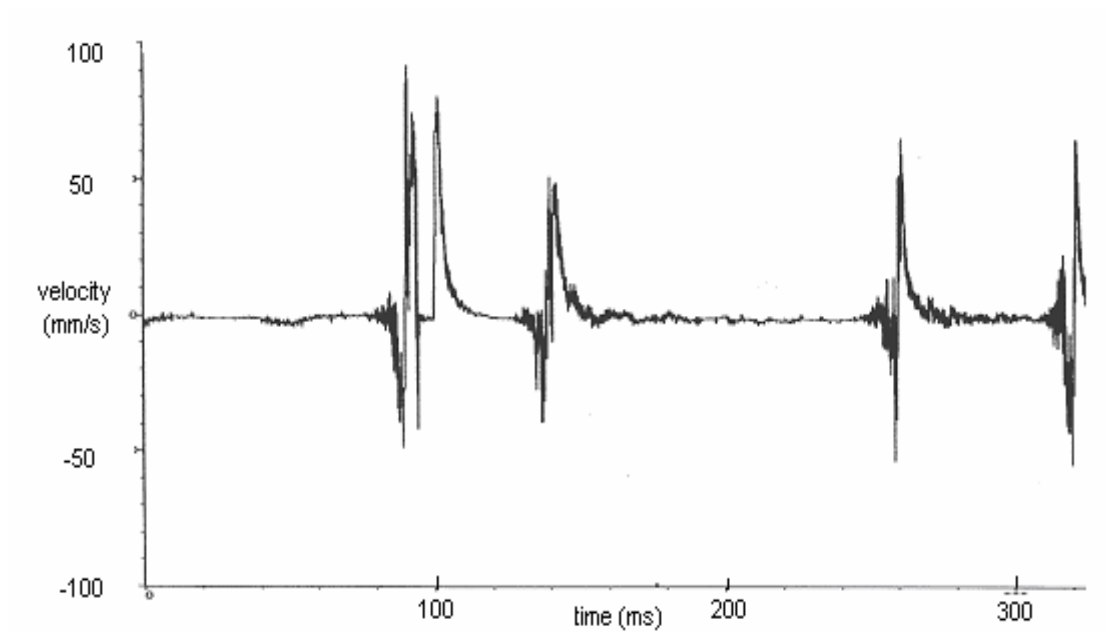
(a)
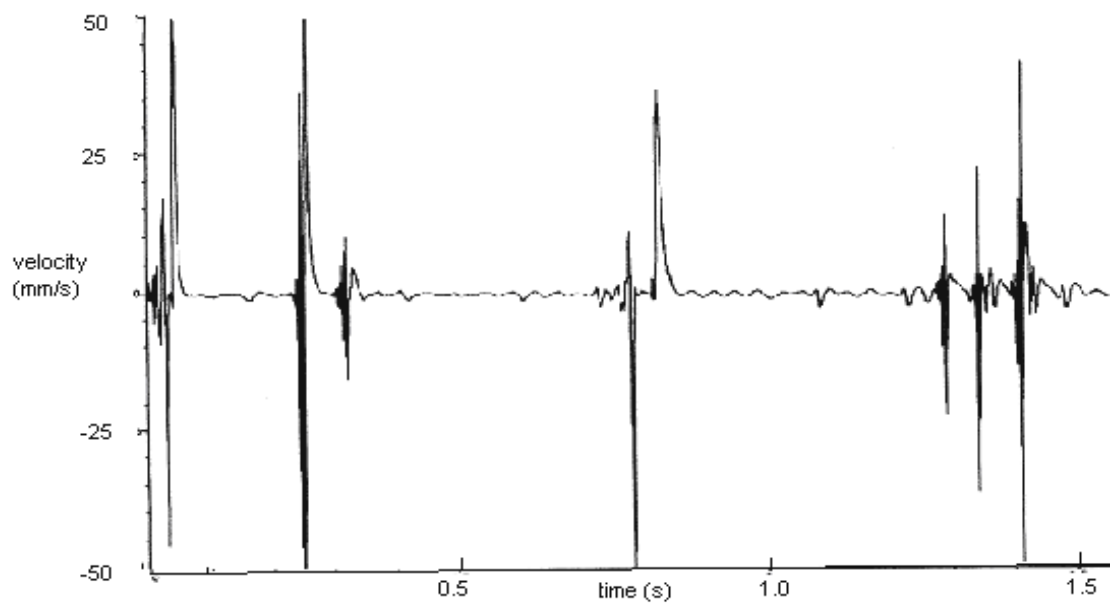
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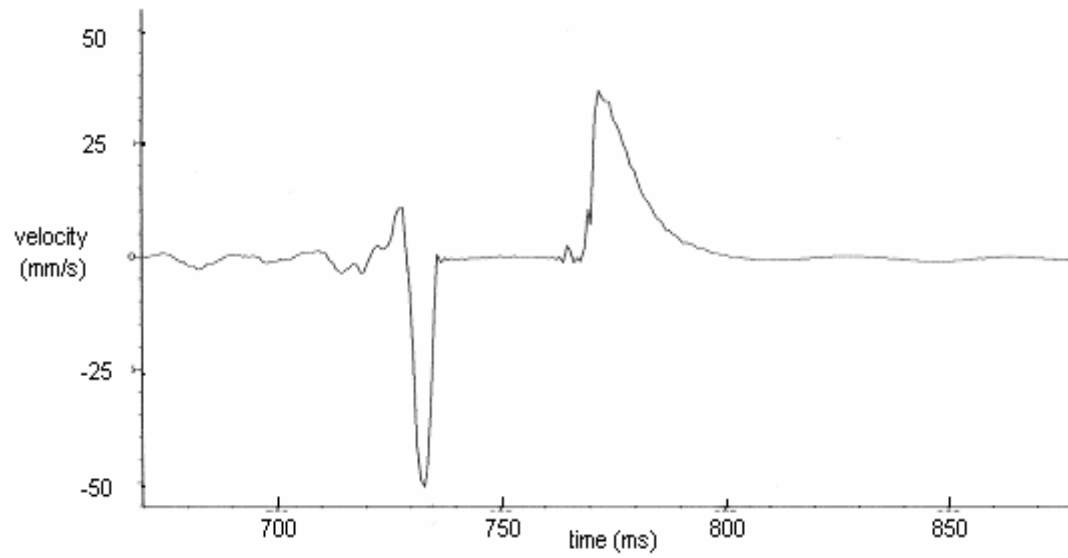
(c)

Figure 3.7 Oscillating waves of slug flow in the adiabatic section of the OHP

The average frequency of slug flow in the adiabatic section of the heat pipe was measured about 2.0-10.0 Hz.

3.4. Summary

The five-turn oscillating heat pipe with Acetone as the working fluid can function well in a vertical position where the evaporator was at the bottom of the heat pipe. When the orientation of the heat pipe changed from 90 degrees to 60 degrees, the heat transfer performance of the heat pipe became better. At the horizontal position, the heat pipe did not function. A thermal resistance of 0.5 k/w is obtained for the current heat pipe. Water cannot be used the working fluid of the current oscillating heat pipe. The average frequency of slug flow in the adiabatic section of the heat pipe is about 2.0-10.0 Hz.

Chapter 4. Conclusions

The oscillating motions occurring in an oscillating heat pipe may result from: 1) the oscillating pressure existing in the evaporators of the heat pipe; 2) a slug flow or bubble-train flow existing in the adiabatic section of the heat pipe, which actually is a mass-spring system (vapor bubbles as gas springs and incompressible liquid plugs as pistons) and 3) a wavy pressure distribution along the meandering channel of the heat pipe existing between the evaporator and condenser of the heat pipe.

Heat and mass transport in the heat pipe is dependent on the oscillating motions of the vapor-liquid mixture in the channel of the heat pipe. The intensified oscillation can dramatically enhance heat and mass transfer in the heat pipe.

Working fluid in the oscillating heat pipe is a significant factor determining and affecting the heat transfer performance of the oscillating heat pipe. However, the primary properties of a working fluid affecting the performance are not clear. The heat transfer performance of the micro oscillating heat pipe may be better than a conventional micro heat pipe.

Utilizing the sawtooth alternating component of pressure drop as the excitation of the oscillating motion, a mathematical model describing the oscillation characteristics of slug flow of vapor bubbles and liquid plugs in capillary tubes is presented including the effects of capillary forces, gas spring constants, dimensions, gravitational forces, and initial pressure distributions of working fluids. The model considers the vapor bubble as the gas spring for the oscillating motions in the capillary tubes. Numerical results indicate that the isentropic bulk modulus generates stronger oscillations than the isothermal bulk modulus. While it demonstrates that the diameters of capillary tubes,

bubble sizes, and liquid plugs determine the oscillating motions, the capillary force, gravitational forces, and initial pressure distributions of the working fluid significantly affect the frequency and amplitude of oscillating motions in the capillary tubes. While the gravitational force makes the oscillation damp, the gravitational force helps to stabilize the oscillating motions of slug flow in the tube for some situation, and it can be concluded that the oscillating motions of slug flow in such tubes are very sensitive to the tube orientation. In order to maintain the self-sustained oscillating motions of the slug flow, the frictional pressure drops of liquid plugs and vapor bubbles in the tubes should be minimized.

The five-turn oscillating heat pipe with Acetone as the working fluid can function well in a vertical position where the evaporator was at the bottom of the heat pipe. When the orientation of the heat pipe changed from 90 degrees to 60 degrees, the heat transfer performance of the heat pipe became better. At the horizontal position, the heat pipe did not function. A thermal resistance of 0.5 k/w is obtained for the current heat pipe. Water cannot be used as the working fluid of the current oscillating heat pipe. The average frequency of slug flow in the adiabatic section of the heat pipe is about 2.0-10.0 Hz.

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