Study on Heat Transport Mechanism in Pulsating Heat Pipes

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1. Introduction

The Pulsating Heat Pipe (PHP) is a promising heat transport device in the thermal management of micro and power electronics [1][2]. It consists of a single capillary tube or channel with many turns between evaporator and condenser sections as shown in Fig.1. The working fluid is filled partially (around 50% in volume) resulting in liquid slugs and vapor plugs due to capillary action. Oscillation of each liquid slug occurs driven by the pressure difference of vapor plugs, and the heat is transported from evaporator to condenser section by the oscillatory motion of the fluid. Many experimental works have been devoted to clarify the heat transport characteristics [3], however, the detailed mechanism of PHPs is not fully understood, and design methods have not yet been established. In the present study, a numerical method has been developed to predict heat transport performance of PHPs quantitatively.

2. Numerical method

Figure 2 shows the schematics of analytical model. The bends are not considered, and the PHP is modeled as a straight circular tube with the sequence of heating, adiabatic and cooling sections. The wall temperatures of heating and cooling sections are assumed to be constant at \( T_h \) and \( T_c \), respectively. The motion of fluid and the heat transport are solved for a horizontal mode operation.

The outline of the method is described below.

2.1 Liquid slug The two-dimensional unsteady velocity and temperature field in each liquid slug are solved numerically based on SMAC method, where the shape of liquid slug is assumed to be cylindrical as shown in Fig.3(a). The movement of each liquid slug is determined by the pressure difference of vapor plugs on both side of the liquid slug.

2.2 Vapor plug The pressure and temperature are assumed to be uniform in each vapor plug. The mass of each vapor plug is given by evaporation and condensation rates. The temperature of vapor plug is calculated based on energy conservation including compression and expansion works.

2.3 Phase change Evaporation or condensation rate at the surface of liquid slug is given by temperature field in the liquid, in which evaporation or condensation resistance at the interface is taken into account. In order to solve steep temperature gradient near the interface, the temperature field in the region within \( 1.5L_x \) from the liquid surface is solved by fine grid \( \Delta x \).

In addition, filmwise condensation is considered in the region of subcooled wall temperature as shown in Fig.3(b). It is assumed that the condensate liquid film is driven uniform \( dP/dx = (\Delta P)/L_f \) due to the surface tension pressure, \( \Delta P = 2\sigma/L \), where \( L_f \), \( \sigma \) and \( R \) are length of condensate film, surface tension and inner radius of tube. When the wall temperature at the liquid slug

Fig.1 Pulsating heat pipe

Fig.2 Calculation system

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surface is superheated, the evaporation rate at liquid surface in the region of \(y<\delta y/2\) is given by another numerical solution which considers evaporation rate very close to the wall with negligible liquid convection.

### 2.4 Adiabatic wall

The unsteady heat conduction of adiabatic wall is solved numerically by considering heat transfer with liquid slugs, where the wall temperature is assumed to be uniform in a cross section.

### 3. Calculated results

Calculations are made for a copper tube of 2mm i.d. and 3mm o.d. with number of turns \(N=12\). The lengths of heating, adiabatic and cooling sections are \(L_h = L_a = L_c = 100\)mm. Temperatures of heating and cooling walls are 30°C and 20°C. Grid sizes are \(\Delta x = 5\)mm and \(\Delta y_f = \Delta y = 0.05\)mm. The working fluid is water, and liquid charge ratio is 50%. Initially the liquid slugs are located in the cooling side. Pressure disturbances, 100Pa and -100Pa, are added to vapor plugs \(k=1\) and \(k=2\), respectively.

Figure 4 shows the development of oscillation for liquid slugs \(k=1\) and \(k=4\), where \(X_k^l\) denotes the displacement of \(k\)th liquid slug from its initial position. The amplitude of oscillation grows rapidly and reaches a periodic steady state. The heat transport rate increases up to nearly 30W with the development of oscillation, as shown in Fig.4. Figure 5 is a snapshot of oscillatory motion of liquid slugs. The gray-scale painting shows the temperature profile, and it is seen that the heat transport by the sensible heat of liquid is significant.

In order to examine the mechanism of oscillation, details of movement of neighboring liquid slugs are plotted with pressures of vapor plugs in Fig.6. The liquid slug \(k=6\) is driven by the pressure difference \(P_{v6} - P_{v7}\). It should be noted that the maximum point of the pressure difference is slightly delayed compared to the minimum point of displacement, \(X_6^l\). Such a delay of pressure is explained by the delay of evaporation as follows. The evaporation rate is small when the liquid slug enters the heating section, because the liquid is in a subcooled state at that time. On the other hand, the evaporation rate is large when the liquid leaves the heating section because the liquid temperature is raised. The phase lag of pressure difference and displacement due to the delay of evaporation seems to be the mechanism of the self-exciting oscillation.

### References

