Two-Fluid Model Of The Flow Of Refrigerant In A Capillary Tube

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ABSTRACT

The flow characteristic of refrigerant in a capillary tube is determined by the flow in the two-phase region. There is thermodynamic non-equilibrium between liquid and vapor in the two-phase region. In addition, there are two decisive transitions of flow pattern in this two-phase region, one is from bubble flow to churn-turbulent flow, and the other is from churn-turbulent flow to annular flow. Aiming at simulating the flow of refrigerant in the two-phase region, a two-fluid model is established based on thermodynamic non-equilibrium between liquid and vapor. The simulation results agree well with the experimental data that verifies the two-fluid model. The result shows that slip velocity between bubbles and liquid is small in bubble flow regime, grows slowly in the churn-turbulent flow region, and increases rapidly in the annular flow region. It also shows that mass flow rate of refrigerant increases with inlet pressure and increases with increase of the subcooled degree of refrigerant at the inlet.

Keywords: refrigerant capillary tubes two-fluid model

NOMENCLATURE

A: Area	B: coefficient
C: Mass coefficient, adjustable coefficient	C_0 : distribution parameter

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C_d : Resistance coefficient of a single bubble

d: diameter

h : Heat transfer coefficient

h_{lv} : potential heat of liquefaction

p : Pressure

R : radius

T : Temperature

u : velocity

Y: Material parameter

ΔP_{lo} : friction resistance

ρ : Density

α : void fraction

Γ : Vaporization rate

τ : shearing stress

η : Constant

subscript

a: annular flow

b : bubble flow

i : interface

l : liquid

s : saturation

v : vapor

w : wall

INTRODUCTION

Capillary is widely used as a throttling component in small refrigeration apparatus. Although its configuration is very simple, the mechanism of the flow of refrigerant in a capillary and its mathematic description are very complicated. As an adiabatic capillary tube is concerned, usually, refrigerant enters the tube as subcooled liquid, as it flows in the capillary, its pressure drops linearly till its saturation point, behind the saturation point, liquid vaporize and the temperature and pressure drop rapidly as the refrigerant flow forward in the capillary till the outlet of the tube. As the flow process behind the saturated point is concerned, there are three different viewpoints. The first is Bolstab and Jordan's viewpoint that vapor and liquid is always in the state of thermodynamic equilibrium, Hence they established the homogeneous flow model; the second is Mikol's viewpoint that there is a transient thermodynamic non-equilibrium state just behind the saturation point but vapor and liquid is in a state of thermodynamic equilibrium in most part of the two phase flow region, a slip-flow model is set up according to this viewpoint; The last viewpoint is Koizumi's viewpoint that there must be thermodynamic non-equilibrium in the whole two-phase flow region (as shown in Figure.1) to maintain the necessary temperature difference for the vaporization of refrigerant, however there is no mathematic model which concerned the thermodynamic non-equilibrium in the whole two-phase flow region.

In fact, the flow of refrigerant in a capillary is a flash flow, in order to maintain the vaporization of refrigerant; there must be a temperature difference between vapor and liquid. Only if the interface area between vapor and liquid were infinitely large, would the temperature difference of heat transfer tend to be zero, i.e., there must exist thermodynamic non-equilibrium in the two-phase region. A two-fluid model will be established to simulating the flow process in the two-phase region according to the above opinion in this paper.

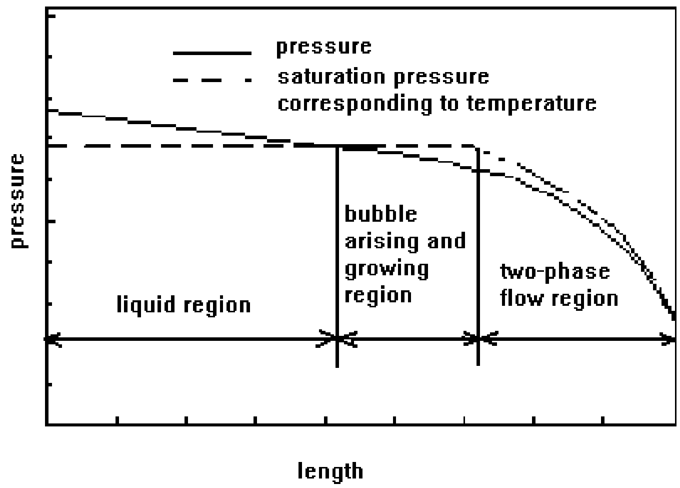

Figure 1 Two-phase flow region of refrigerant in capillary tubes

TWO-FLUID MODEL OF THE TWO-PHASE FLOW REGION

In this paper, the flow process of refrigerant in a capillary is divided into liquid flow region bubble arising and growing region and two-phase flow region as figure 1 shown. The region ahead of the saturation point is the liquid flow region which can be simulated with liquid steady flow model; the region between the saturation point and the point where the distribution parameter $C_0 = 1$ is bubble arising and growing region which can be simulated with flash flow model developed by Cao; the other is the two phase flow region for which a two-fluid model will be introduced to simulating the flow process of refrigerant in this paper.

Control Equations

The following hypothesizes should be made when developing the two fluid model:

- The flow is steady and one dimensional;
- The velocity of vapor may be different from that of liquid;
- Gravity, compressibility of liquid are ignored;
- Mass transfer is lead by heat transfer between liquid and vapor.

The mass and momentum equations for vapor and liquid phases are as follows:

$$\rho_v u_v \frac{d\alpha}{dz} + \alpha u_v \frac{d\rho_v}{dz} + \alpha \rho_v \frac{du_v}{dz} = \Gamma \tag{1}$$

$$-\rho_l u_l \frac{d\alpha}{dz} + (1-\alpha)\rho_l \frac{du_l}{dz} = -\Gamma \tag{2}$$

$$\alpha \frac{dp}{dz} + \alpha \rho_v u_v \frac{du_v}{dz} = -\eta (u_v - u_l)\Gamma - \tau_{lv} - \tau_{wv} \tag{3}$$

$$(1-\alpha)\frac{dp}{dz}+(1-\alpha)\rho_l u_l \frac{du_l}{dz}=(1-\eta)(u_l-u_v)\Gamma+\tau_{lv}-\tau_{wl} \tag{4}$$

In the above equations, $\rho, p, u, \alpha, \Gamma, \tau, \eta$ respectively represent density, pressure, velocity, void fraction, vaporization rate, shearing stress and a coefficient; Subscripts l, v, w represent liquid, vapor and wall. As the interface between vapor and the tube wall is supposed to be little, τ_{wv} is set to be naught.

In this two-fluid model, the key factors are the interaction terms at the interface between vapor and liquid and that between the liquid and wall. The interaction terms at the interface are decided by the geometrical shape of the interface and the local driving force, and the geometrical shape of the interface is nearly related to the flow pattern. Here it is supposed that the flow pattern converts from bubble flow to churn-turbulent flow at void fraction =0.25 and from churn-turbulent flow to annular flow at void fraction =0.8 according to Saha and Abufa's results.

Shearing Stress Between Vapor And Liquid Phases

The shearing stress on the interface section can be calculated with Richter's result:

$$\tau_{lv}=\frac{2C_{fi}}{d}\sqrt{\alpha}(u_v-u_l)|u_v-u_l|+C\alpha\rho_l u_v \frac{d(u_v-u_l)}{dz} \tag{5}$$

Where, d and C is diameter, mass coefficient and the shearing stress factor C_{fi} is :

$$C_{fi}=\begin{cases} C_d\sqrt{\alpha}(1-\alpha)^{-1.7}\dfrac{\rho_l}{\rho_v}\dfrac{d}{2R_b} & (bubble\quad flow) \\ 0.005(1+75(1-\alpha)) & (annular\quad flow) \\ \left[(\alpha-0.25)C_{fi}\big|_{\alpha=0.25}+(0.8-\alpha)C_{fi}\big|_{\alpha=0.8}\right]/(0.8-0.25) & (churn-turbulent\quad flow) \end{cases} \tag{6}$$

Where, R_b is bubble radius; C_d is resistance coefficient of a single bubble.

Shearing Stress Between Liquid Phase And Wall Surface

The shearing stress between liquid phase and wall surface can be calculated with Chisholm's method:

$$\tau_{wl}=\left\{1+\left(Y^2-1\right)\left[Bx^{(2-n)/2}(1-x)^{(2-n)/2}+x^{2-n}\right]\right\}\Delta P_{lo} \tag{7}$$

Where n and B are coefficients; ΔP_{lo} is friction resistance while supposing all of the refrigerant is liquid; Y is a material parameter which is defined as the square root of the ratio of the frictional pressure drop while supposing all of the refrigerant is vapor to ΔP_{lo}.

Evaporation Rate

It is assumed that the liquid is in superheated state and the vapor is in saturated state. As a result, the local evaporation rate is related to the temperature difference at the interface:

$$\Gamma_v = \frac{hA_i\left(T_l - T_s(p)\right)}{h_{lv}} \tag{8}$$

where h, A_i, T_l, $T_s(p)$, h_{lv} respectively represent heat transfer coefficient, interface area, liquid temperature, saturated temperature corresponding to vapor pressure and potential heat of vaporization.

Interface Area

The interface areas for different flow patterns are as follow:

$$A_i = N_b \pi \left(\frac{6\alpha}{N_b \pi} \right)^{2/3} \quad \text{(bubble flow region)} \tag{9}$$

$$A_i = A_{ib} + \frac{\alpha - \alpha_b}{\alpha_a - \alpha_b}\left(A_{ia} - A_{ib}\right) \quad \text{(churn-turbulent flow region)} \tag{10}$$

$$A_i = C\frac{4\sqrt{\alpha}}{d} \quad \text{(annular flow)} \tag{11}$$

where subscripts a and b represent bubble flow and annular flow; C is a adjustable coefficient. A_{ib} and A_{ia} respectively represent interface area of bubble flow when α =0.25 and that of annular flow when $\alpha = 0.8$.

RESULTS AND DISGUSSION

The simulation result of the distribution of pressure and temperature in a capillary are shown in Figure 2 that agrees well with the experimental data, which verified the reliability of the model. In the subcooled liquid region, the pressure drops linearly but the temperature keeps unchanged. In the bubble arising and developing region, obvious thermodynamic non-equilibrium emerges as the driving force for the arising and developing of bubbles. However, in the two-phase region, as the bubble density has reached definite scale and the interface area between vapor and liquid become large, liquid mainly evaporates through the mass transfer on the interface between vapor and liquid. At the same time, liquid is still in superheated state in order to maintain the driving potential needed for the mass and energy transfer between vapor and liquid, but the superheated level is relatively small.

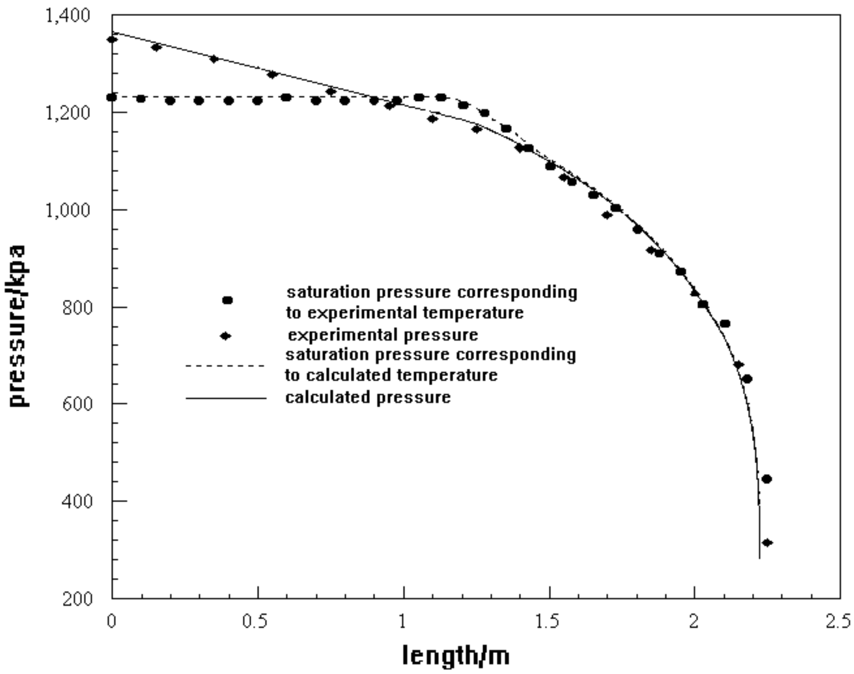

Figure 2 The distribution of pressure and temperature along capillary tubes in two-phase region

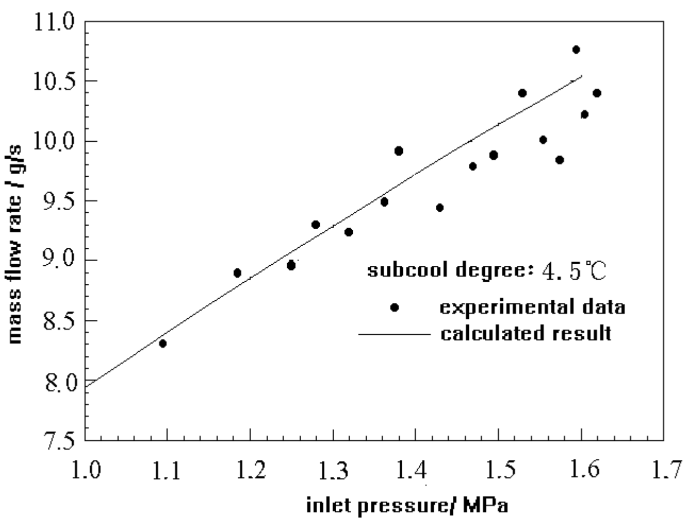

Figure 3 mass flow rate vs inlet pressure

The variation of mass flow rate versus inlet pressure and subcooled level of the inlet refrigerant is demonstrated in Figure 3 and Figure 4. With the increase of the inlet pressure, the mass flow rate increases linearly. With the increase or the subcooled level, the mass flow rate also increase. This change tendency agree with that provided by ASHRAE handbook.

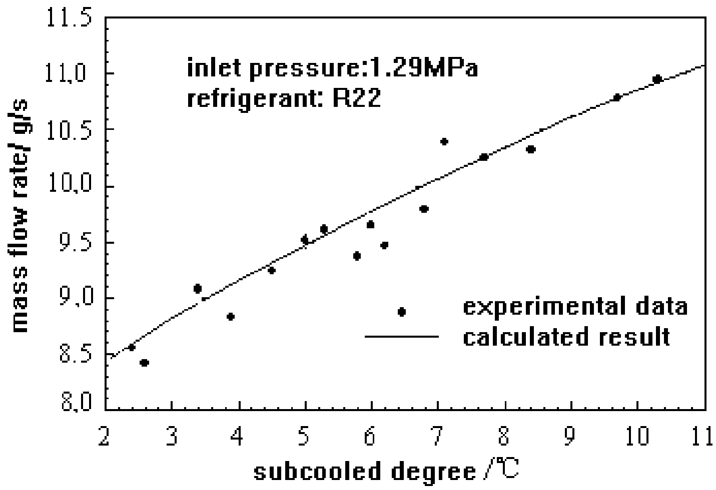

Figure 4 mass flux veruss subcooled degree of the inlet refrigerant

The velocity distribution of vapor and liquid is shown in Figure 5. Liquid begin to evaporate at 1.15 m behind of which the flow in bubble flow pattern. With the increasing of the vapor, the flow pattern changed to churn-turbulent flow pattern. In the bubble flow region and churn-turbulent flow region, the difference of the velocity of vapor and liquid is not high for the intense interaction of liquid and vapor. Void fraction reach 0.8 at 2.2 m, behind of which, the flow enter annular flow region, the shearing stress between the liquid and vapor decrease rapidly as a result, the velocity difference between the two phases increases rapidly.

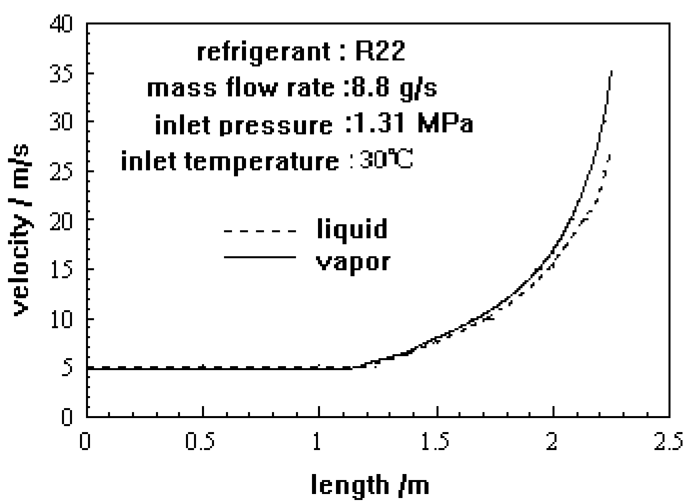

Figure 5 distribution of the velocity of vapor and liquid

CONCLUSIONS

The flow of refrigerant in a capillary is divided into liquid region, bubble arising & developing region and two-phase flow region. The two-phase region can be further divide into bubble flow region, churn-turbulent flow region and annular flow region according to void fraction. A two-fluid model of the flow of refrigerant in a capillary is established to explore mechanism of the physical phenomenon occurred in the capillary.

The result shows that slip velocity between bubbles and liquid is small in bubble flow region, grows slowly in the churn-turbulent flow region, and increases rapidly in the annular flow region. It also shows that mass flow rate of refrigerant increases with inlet pressure and increases with increase of the subcooled degree of refrigerant at the inlet.

REFERENCES

Bolstad M. M., Jordan R. C., “The theory and use of the capillary tube expansion device”, Refrigeration Engineering, vol.56, No.12, pp:519-523, 1948.

Mikol E. P., Dudley J. C., “A visual and photographic study of the inception of vaporization in adiabatic flow”, Trans of the ASME. Series D: Journal of Basic Engineering, vol.6, pp 257-263, 1964.

Koizumi H., Yokoyama K., “Characteristics of refrigerant flow in a capillary tube”, ASHRAE Trans, vol.86, pp:19-27,1980.

Cao X.L., “Characteristic of the flow of refrigerant/oil in a capillary”, Ph.D thesis, Xi’an Jiatong University, 1999.

Saha P., Abuaf N., Wu B. J. C., “A non-equilibrium vapor generation model for flashing flows”, Journal of Heat Transfer, vol.106, No.1, pp:198-203,1984.

Richter H. J., “Separated two-phase flow model application to critical two-phase flow”, International Journal of Multiphase Flow, vol. 9, No.5, pp:511-530, 1983.

Chisholm D., “Pressure gradient due to friction during the flow of evaporating two-phase mixture in smooth tubes and channels”, Journal of Heat Transfer, vol.16, pp:347～358, 1973.

ASHRAE. Equipment Handbook. Capillary Tubes, Chapter 19 PartⅣ.1988