Mechanism Of Flash In The Flow Of Refrigerant In A Capillary

X. Cao
Xi'an Jiaotong University

Y. Wu
Xi'an Jiaotong University

G. Yan
Xi'an Jiaotong University

R. Zhu
Xi'an Jiaotong University

R12-9

MECHANISM OF FLASH IN THE FLOW OF REFRIGERANT IN A CAPILLARY[1]

*Xiaolin Cao, PhD, Lecturer, Department of Refrigeration & Cryogenics Engineering,
Xi'an Jiaotong University, Xi'an, 710049, P.R. China; Tel: 86-29-2672727;
Fax: 86-29-2668725; E-Mail: xcao@mail.xjtu.edu.cn *Author for Correspondence

Yezheng Wu, Professor, Department of Refrigeration & Cryogenics Engineering,
Xi'an Jiaotong University, Xi'an, 710049, P.R. China; Tel: 86-29-2669614;
Fax: 86-29-2668725; E-Mail: yzwu@mail.xjtu.edu.cn

Gang Yan, Lecturer, Department of Refrigeration & Cryogenics Engineering,
Xi'an Jiaotong University, Xi'an, 710049, P.R. China; Tel: 86-29-2668725
Fax: 86-29-2668725: E-Mail: yg71@sina.com

Ruiqi Zhu, Associate Professor, Department of Refrigeration & Cryogenics Engineering,
Xi'an Jiaotong University, Xi'an, 710049, P.R. China: Tel: 86-29-2668730
Fax: 86-29-2668725

ABSTRACT

Flash delay (non-equilibrium phenomenon) occurred in refrigerant flow in a capillary affects apparently the prediction accuracy of refrigerant flow rate in a capillary. "Combined nucleation" theory that accounts for both "homogeneous nucleation" and "wall nucleation" was developed, based on which, a flash flow model was established. Underpressure, an important parameter reflecting non-equilibrium phenomenon in a capillary, was obtained with this flash flow model. The simulation results agree well with the experimental data. The results show that underpressure increases with increase of the mass flow rate of refrigerant and also increases with decrease of inlet temperature.

Keywords: capillary flash flow nucleation model

NOMENCLATURE

A , B : Coefficient

C_0 :distributing parameter

Cp_l : Isobaric specific heat

d : diameter

[1] Supported by National Natural Science Foundation Of China (50076036)

f : Friction coefficient

h_{lv} : Potential heat

K_s : Spherical correcting factor

p : Pressure

t : Time

$\vec{u}_b$: Local velocity vector bubbles

x : Quality

ρ_{v0} : Initial bubble density

λ : Conductivity

α : Void fraction, diffusivity

Γ_v : Evaporation rate

ϕ_{si} : Bubble sink

h_0 : stagnant enthalpy

j : velocity of the central volume

N_b : local bubble number density

$R_b(t)$: radius of bubble

T : temperature

u : velocity

z : situation

ρ : density

u_{vj} : local shift flow velocity

Δp : underpressure

ϕ_{so} : bubble source

subsript

b : bubble

l : liquid

s : saturation

v : vapor

0 : initial state

INTRODUCTION

There exists thermal non-equilibrium phenomenon in the flow of refrigerant liquid in a capillary, which affect the prediction accuracy of mass flow rate apparently (Alamgir and Lienhar's result). Just for this thermal non-equilibrium of the refrigerant liquid, refrigerant liquid will flash in the capillary, the flash process is a process of bubble arising and growing. The key problems to study the flash process are how to establish bubble number density model and bubble growing model and how to relate micro parameters such as bubble number and bubble size to the macro parameters such as void friction, pressure and temperature. But so far, references related to bubble generation and bubble growing is aimed at the boiling of water at constant pressure or flash evaporation of water in a decompression condition, not account for the refrigerant bubble arising and growing in a capillary.

Aiming at the flash flow process of refrigerant in a capillary, the process of the bubble arising and growing is be studied in this paper. The relation of underpressure to bubble number density and bubble size area established to explore the mechanism of non-equilibrium phenomenon existing in a capillary and to study the effect of inlet conditions on the key parameter---underpressure.

MATHEMATIC MODEL

Bubble Number Density Model

The bubble transportation equation in the flash flow process is provided by Kocamustafaogullari et al:

$$\frac{\partial N_b}{\partial t}+\nabla\left(N_b\vec{u}_b\right)=\phi_{so}-\phi_{si} \tag{1}$$

where ϕ_{so}、 ϕ_{si} and $\vec{u}_b$ respectively represent bubble source for bubble arising, bubble sink for bubble combination and local velocity vector of bubbles; N_b is local bubble number density.

For the stable flow in a capillary with constant section area, it is assumed that the first bubble arises at the saturation point z_s, integrating equation (1) from the saturation point z_s to point z_1, the bubble transportation equation for flash flow of refrigerant in a capillary can be derived as

$$N_b\left(z_1\right)=\frac{1}{u_b\left(z_1\right)}\int_{z_s}^{z_1}\left(\phi_w+\phi_{ho}+\phi_{he}-\phi_{si}\right)dz \tag{2}$$

where ϕ_w is the wall nucleation source, adopting perimeter average value; ϕ_{ho},ϕ_{he} and ϕ_{si} respectively represent homogenous nucleation source, heterogeneity nucleation source and sink for bubble combination, adopting area average value; $u_b\left(z_1\right)$ is velocity of bubbles at the point z_1, adopting mass average value， $N_b\left(z_1\right)$ is the bubble number density at point z_1, which account for the contribution of all the bubbles generated in the upstream to the bubble number density at point z_1, Equation (2) combined the effects of wall nucleation, homogenous nucleation, heterogeneity nucleation and bubble combination on the bubble number density, not only account for one of the above aspects, Wu and Cao developed "combined nucleation" theory according to the above equation.

A new parameter $n_b\left(z_1,z\right)$ is introduced to express the contribution of the bubbles generated at the point z and arriving at the point z_1 to the bubble number density at the point z_1:

$$n_b\left(z_1,z\right)=\frac{\phi_w\left(z\right)+\phi_{ho}(z)+\phi_{he}(z)-\phi_{si}(z)}{u_b\left(z_1\right)} \tag{3}$$

Bubble Growing Model

It is assumed that liquid temperature at the liquid-vapor interface equals to vapor temperature and vapor temperature equals to saturation temperature corresponding to local pressure. The effects of gravity and surface tension are ignored. Cao derived the average radius of bubbles from the energy equation and mass equation:

$$R_b\left(t\right)=\left(\frac{\rho_{v0}}{\rho_v}\right)^{1/3}\left\{-\frac{2K_s\lambda_l\left(-Y\right)^{3/2}}{\rho_{v0}h_{lv}\sqrt{\pi a_l}}\int_0^{Yt}e^u\,(Yt-u)^{1/2}\cdot du\right\} \tag{4}$$

$$Y = \frac{fu^3 \rho_l (2T_l - B)}{dB \exp\left(A - {}^{B}\!/_{T_l}\right)} \qquad (5)$$

where $R_b(t)$ is the average radius of bubbles at time t; ρ_{v0}, ρ_v, ρ_l, λ_l, α_l and h_{lv} represent respectively initial vapor density, vapor density, liquid density, liquid conductivity, liquid diffusivity and potential heat; K_s is spherical correcting factor; f is friction coefficient; d is diameter of the capillary; u is velocity of refrigerant; T_l is liquid temperature; A and B is a constant related to physical property.

Flash Flow Model

Void fraction and average velocity of bubbles can be calculated with the bubble number density model and bubble growing model established above. The void fraction $\alpha(z_1)$ at z_1 is ratio of all of the bubbles generated in the upstream of the point z_1 and arriving at z_1 at the same time to the inner volume of the capillary per unit length, and can be calculated by:

$$\alpha(z_1) = \int_{z_s}^{z_1} \frac{4}{3}\pi \left(R_b(t)\right)^3 n_b(z_1, z) dz \qquad (6)$$

$$dz = u_b(z) dt \qquad (7)$$

where $n_b(z_1, z)$ is the contribution of the bubbles generated at the point z and arriving at the point z_1 to the bubble number density at the point z_1; u_b is the average velocity of bubbles.

In the above equation, the average velocity u_b is an unknown, and can be obtained from the mass equation of vapor that is:

$$\frac{\partial}{\partial t}(A\alpha\rho_v) + \frac{\partial}{\partial z}(A\alpha\rho_v u_b) = \Gamma_v A \qquad (8)$$

where Γ_v is evaporation rate and the equation for volume flow rate is

$$\frac{\partial}{\partial z}(Aj) = \Gamma_v A\left(\frac{\Delta\rho}{\rho_v \rho_l}\right) \qquad (9)$$

where j is the velocity of the central volume and $j = \alpha u_b + (1-\alpha)u_l$. In addition, the relative velocity can be obtained from the shift flow theory[5]

$$u_b = j + C_0 u_{vj} \qquad (10)$$

where C_0 is the distributing parameter, u_{vj} is local shift flow velocity, adopting area average value.

The void fraction α and the average velocity u_b of bubbles at the point z_1 can be obtained from the above equations. Velocity of liquid u_l can be obtained from mass equation:

$$\alpha\rho_v u_b + (1-\alpha)\rho_l u_l = \rho_{l0} u_{l0} \qquad (11)$$

And quality x can be expressed as:

$$x = \frac{1}{1 + \frac{1-\alpha}{\alpha}\frac{\rho_l}{\rho_v}\frac{u_l}{u_v}} \quad (12)$$

Liquid enthalpy h_l can be obtained from energy equation:

$$h_l = \left[h_0 - x\left(h_v + \frac{1}{2}u_v^2 \right) \right] \Big/ (1-x) - \frac{1}{2}u_l^2 \quad (13)$$

where h_0 is stagnant enthalpy, which can be calculated from liquid enthalpy and kinetic energy of the inlet liquid.

Liquid temperature T_L is:

$$T_l = T_s(p) + \frac{h_l - h_s(p)}{Cp_l} \quad (14)$$

where h_{lv} is potential heat; $h_s(p), T_s(p)$ represent enthalpy and temperature of saturated liquid corresponding to pressure p; Cp_l is isobaric specific heat.

According to the above equations, the pressure p and temperature T along the capillary can be obtained. And the important parameter, underpressure Δp, can be obtained from the distribution curve of pressure and temperature.

RESULTS AND DISCUSSION

Figure 1 is the distributions of void fraction along the capillary, the abscissa is distance from the saturation point l_{sat}, the coordinate is void fraction α. The void fraction α is decided by the two factors: bubble number density and bubbles size. Void fraction α is closed to zero in front of the point 0.15m as both bubble number density and bubble size are very small. But behind the point 0.2m, void fraction would increase rapidly as bubble number density increase rapidly and bubbles grow bigger.

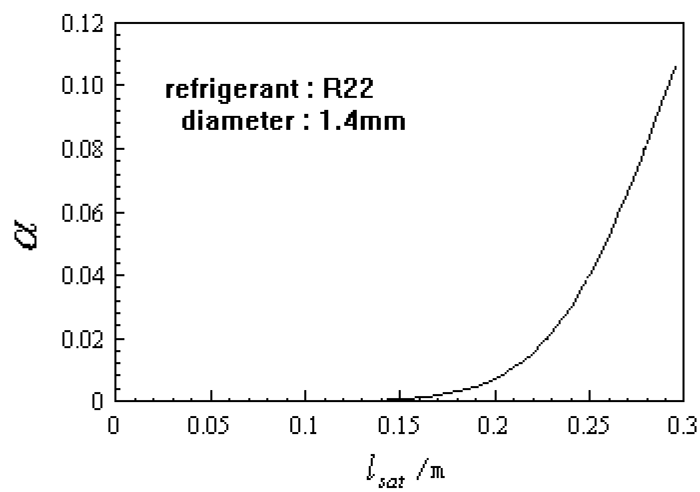

Figure 1 distribution of void fraction along capillary

Figure 2 is the distribution curve of the pressure and temperature in the bubble arising and growing region, the abscissa is the distance from the saturation point l_{sat}, the coordinate is the actual pressure and the saturation pressure responding to the temperature. The refrigerant is liquid ahead of the saturation point. Behind of the saturation point, the void fraction α is very low till the point 0.21m from the saturation point (we recognize this point as turning point later), as figure 1 shown. But behind of the turning point, the temperature of the liquid would decline apparently; the curve of saturation pressure corresponding to the temperature would turn downward, at this time, the difference between the saturation pressure corresponding to the temperature and the actual pressure reaches the maximum value and which is defined as underpressure. In the downstream, temperature decrease in a relative high rate, and the superheat degree would become small gradually.

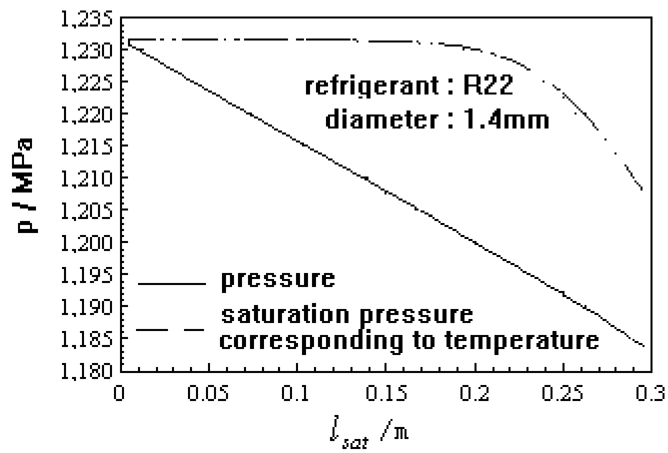

Figure 2 distributions of pressure and temperature along capillary

Figure 3 and Figure 4 are underpressure Δp versus mass flow rate $\dot{q}_m$ and inlet temperature T_{inlet}. The results agree qualitatively with the experimental data that verified the flash flow model. The results shows that underpressure increases as mass flow rate increase and also increases as inlet temperature decrease. It can be expressed that: as the mass flow rate increase, the velocity increase, the distance for the bubbles to grow to a same size will elongate and the turning point of the temperature curve would be delayed, the pressure curve is related to the friction resistance which increases as the velocity increases, the pressure decreases in a relative high velocity, the pressure curve become a little steep, the actual pressure at the turning point of the temperature curve would be lower, as a result, underpressure would increase, and as inlet temperature decrease, the viscidity increase which makes the pressure curve become steep and surface tension of the liquid increase which make it difficult for the bubbles to departure from the wall, and the resultant bubble number density decreases, as a result, the turning point of the temperature curve would be delayed, and underpressure would also increases.

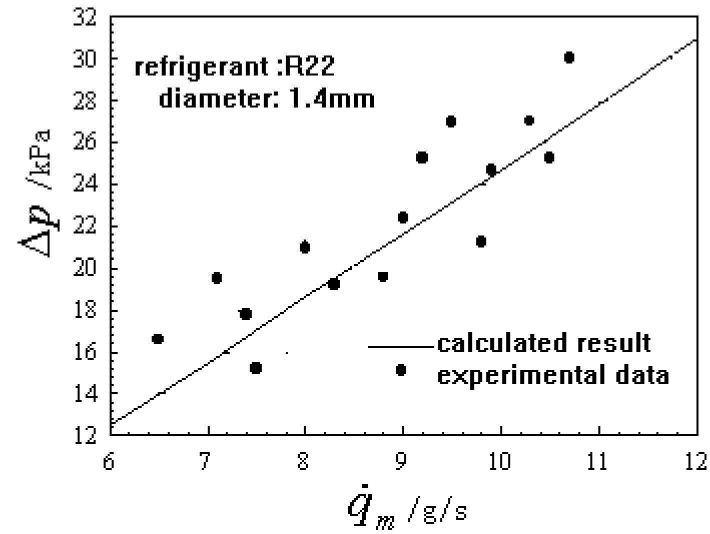

Figure 3 underpressure versus mass flow rate

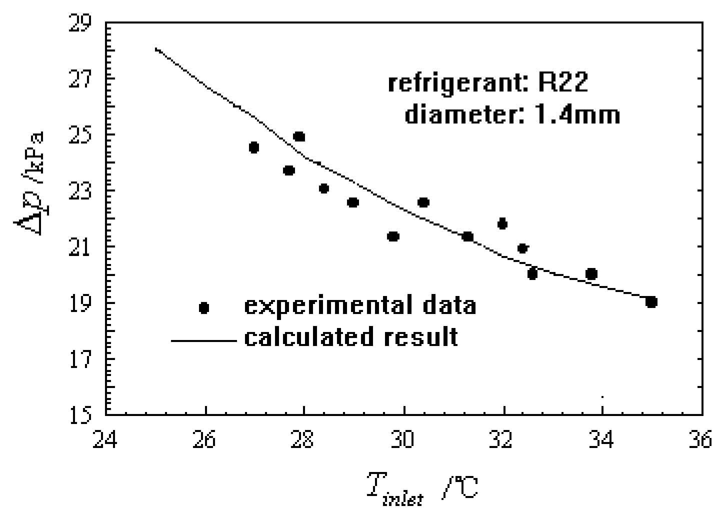

Figure 4 underpressure versus inlet temperature

CONCLUSIONS

Flash delay (non-equilibrium phenomenon) occurred in refrigerant flow in a capillary affects apparently the prediction accuracy of refrigerant flow rate in a capillary. “Combined nucleation” theory which accounts for both “homogeneous nucleation” and “wall nucleation” was developed, based on which, bubble number density model, bubble growing model and flash flow model were established. Underpressure, an important parameter reflecting non-equilibrium phenomenon in a capillary, was obtained with this flash flow model. The simulation results agree qualitatively well with the experimental data, which verified the models established in this paper. The results shows that underpressure increases as mass flow rate increase and also increases as inlet temperature decrease.

REFERENCES

Alamgir M, Lienhard J H., “Correlation of pressure undershoot during hot-water depressurization”. Journal of Heat Transfer, ASME, vol.103, No.1, PP:52-55.1981

Kocamustafaogullari G, Chen I Y, Ishii M., “Correlation for nucleation site density band its effect on interfacial area”, Journal of Heat & Mass Transfer, vol.25, pp:567-578, 1982.

Wu Y.Z., Zhu R.Q., Cao X. L., et al. ““Combined nucleation” theory and flash flow model of refrigerant in a capillary”, Journal of Xi’an Jiaotong University, 2002. (accepted)

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

Becker R., “The kinetic treatment of nuclear formation in super-saturated vapors”. Ann Physics, vol.24, PP: 719-752, 1935.