Investigation on the Characteristics of Flowing Refrigerant in Household Air-Conditioning Heat Exchanger

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Abstract. Most refrigerant quantities exist in condenser and evaporator for a household air-conditioner. Slip ratio and void fraction are typical parameters in two-phase region of air-conditioning heat exchanger. When R22 is the working medium, the void fraction of an air-conditioner heat exchanger is calculated with four models in this paper. Based on these calculating results, the characteristics of the four models are analyzed. The influence of refrigerant mass flux on Premoli model and Harms model is also presented. The analysis indicates that it's reasonable to calculate slip ratio and void fraction of two-phase refrigerant in household air-conditioner heat exchanger with Harms model at temperate refrigerant mass flux. The conclusions of this study could help realize the characteristics of flowing refrigerant in household air-conditioning system.

1 Introduction

Condenser and evaporator are heat exchangers in which refrigerant changes phase. Most refrigerant quantities exist in these two components when an air-conditioner operates on steady state condition. And refrigerants exist as single phase state and two-phase state in condenser and evaporator. There are different characteristics in different states [1-5]. And the characteristic of two-phase is even complicated [6]. Then it is important to analyze the two-phase flow in an air-conditioning heat exchanger. Chen *et al*. [7] compared a heat exchanger with vapor–liquid separation to a conventional heat exchanger and proposed the mechanisms of how the vapor–liquid separation enhances heat transfer coefficient during evaporation.

The phase fraction of gas-liquid two-phase flow includes void fraction and phase holdup of liquid mixture. Void fraction is the proportion of area occupied by vapor at a given gas and liquid two-phase. It is an important parameter for two-phase fluid. This study is focused on the analysis of the variation of slip ratio and void fraction in gas-liquid two-phase region of air-conditioning heat exchanger. The results could help realize the operating performance of household air-conditioning heat exchanger.

2 Calculating Models of Refrigerant Void Fraction

To investigate the fluid characteristics of two-phase flow, researchers have given some useful models to calculate the void fraction in two-phase fluid region [8]. It includes analytical models and empirical models.

Homogeneous model is a typical analytical model for analysis two-phase refrigerant flow [8]. When two-phase flow heat transfer of the heat exchanger was calculated and analyzed by homogeneous model, the velocities of liquid flow and gas flow in two-phase fluid region are equal. That means slip ratio *S*=1. Therefore, the thermal physical property parameters of two-phase state refrigerant are defined as:

$$\rho_{tp} = \alpha\rho_g + (1-\alpha)\rho_l \tag{1}$$

$$\mu_{tp} = x\mu_g + (1-x)\mu_l \tag{2}$$

$$\lambda_{tp} = x\lambda_g + (1-x)\lambda_l \tag{3}$$

where α is the void fraction of two-phase refrigerant; x is the mass quality of two-phase refrigerant; ρ_g is the gas density of refrigerant, Kg/m^3; ρ_l is the liquid density of refrigerant, Kg/m^3; μ_g is the gas dynamic viscosity of refrigerant, kg/ms; μ_l is the liquid dynamic viscosity of refrigerant, kg/ms; λ_g is the gas heat conductivity of refrigerant, W/mK; λ_l is the liquid heat conductivity of refrigerant, W/mK; and subscript *tp* represents two-phase.

For homogeneous model, the void fraction α is defined as:

$$\alpha = \frac{1}{1+\left(\frac{1}{x}-1\right)\frac{\rho_g}{\rho_l}} \tag{4}$$

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Zivi model [9] is another analytical model for analysis two-phase flow. The velocities of liquid flow and gas flow in two-phase fluid region are not equal for Zivi model. But the velocity ratio of liquid flow and gas flow in two-phase fluid region is constant for the refrigerant under a certain working condition. Slip ratio S is calculated as follow:

$$S=\left(\frac{\rho_g}{\rho_l}\right)^{-\frac{1}{3}} \tag{5}$$

Therefore, the void fraction α is calculated as:

$$\alpha=\frac{1}{1+\left(\frac{1}{x}-1\right)S\frac{\rho_g}{\rho_l}} \tag{6}$$

For Premoli model [8], which is an empirical model, the velocities of liquid flow and gas flow in two-phase fluid region are in constant change. Slip ratio S is calculated by following empirical relation:

$$S=1+F_1\left[\frac{y}{1+yF_2}-yF_2\right]^{1/2} \tag{7}$$

For above equation, factors F_1, F_2 and y are respectively given as:

$$F_1=1.578\,\mathrm{Re}_l^{-0.19}\left(\rho_l/\rho_g\right)^{0.22} \tag{8}$$

$$F_2=0.0273We_l\,\mathrm{Re}_l^{-0.51}\left(\rho_l/\rho_g\right)^{-0.08} \tag{9}$$

$$y=\frac{x\rho_l}{(1-x)\rho_g} \tag{10}$$

And, Reynolds number is calculated by:

$$\mathrm{Re}_l=\frac{(1-x)Gd}{\mu_l} \tag{11}$$

Weber number is calculated by:

$$We_l=\frac{\left[(1-x)G\right]^2d}{\sigma\rho_l} \tag{12}$$

where ρ_l is the liquid density of refrigerant, Kg/m^3; ρ_g is the gas density of refrigerant, Kg/m^3; G is the mass flux of refrigerant, kg/m^{2}s; d is the inside diameter of heat exchanger tube, m; x is the mass quality of two-phase refrigerant; σ is surface tension of refrigerant, N/m.

For Premoli model, the void fraction α could be calculated by equation (6).

Harms model [10] is another empirical model for analysis two-phase flow. The void fraction α is calculated by following empirical relation:

$$\alpha=\left[1-10.06\,\mathrm{Re}_l^{-0.875}\left(1.74+0.104\,\mathrm{Re}_l^{0.5}\right)^2\times\left(1.376+\frac{7.242}{X_{tt}^{1.655}}\right)^{-1/2}\right]^2 \tag{13}$$

where Lockhart-Martinelli parameter X_{tt} is defined as [11]:

$$X_{tt}=\left(\frac{1-x}{x}\right)^{0.9}\left(\frac{\rho_g}{\rho_l}\right)^{0.5}\left(\frac{\mu_l}{\mu_g}\right)^{0.1} \tag{14}$$

Slip ratio S is calculated by:

$$S=\frac{\rho_l}{\rho_g}\left(\frac{x}{1-x}\right)\left(\frac{1-\alpha}{\alpha}\right) \tag{15}$$

3 Comparison of four models

There are many simulating and experimental reports about the characteristics of air-conditioning system. Two-phase flow heat transfer of the heat exchanger was calculated and analyzed by above four models in this paper. Calculating conditions are as follows:

The working medium is R22 in a household air-conditioner. The air-conditioner are proposed to operate according to the standard refrigeration conditions of which the dry and wet bulb temperature for indoor and outdoor are 27/19°C and 35/24°C, respectively, and to the standard heating conditions of which the dry and wet bulb temperature for indoor and outdoor are 20/15°C and 7/6°C, respectively. Based on refrigeration theory and operational conditions, the experimental and empirical data, the temperature differences between the tube wall and refrigerant in the condenser are proposed as 10°C for superheated region and 5°C for both two-phase region and subcooled region in the following calculation. The temperature differences between the tube wall and refrigerant in the evaporator are also proposed as 5°C for both two-phase region and subcooled region in the following calculation.

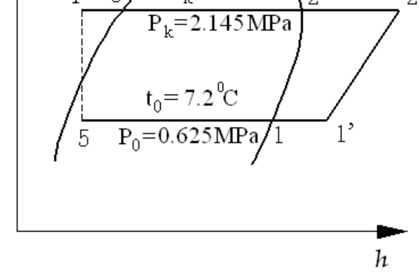

Fig. 1. Lg p-*h* diagram of refrigeration circulation

Operating conditions of refrigeration: condensation temperature t_k is 54.4°C; condensation pressure P_k is 2.145MPa; evaporation temperature t_0 is 7.2°C; evaporation pressure P_0 is 0.625MPa; subcooled temperature t_{sc} is 46.1°C; superheated temperature t_{sh} is 18.3°C. The diameter d of the air-conditioning heat exchanger is ϕ9.52mm. The mass fluxes of refrigerant G are respectively 240kg/m^{2}s and 400kg/m^{2}s. Figure 1 shows the logarithm pressure and enthalpy diagram on refrigeration conditions.

Figure 2 shows a typical refrigeration cycle of a household air-conditioning unit. The refrigeration system of an air-conditioner with heat pump usually consists of compressor, condenser, throttling part, evaporator and filter-drier all connected with tubing through which the refrigerant circulates. Refrigerant quantities existing in compressor and capillary are small. Most refrigerant quantities exist in condenser and evaporator when air-conditioning system operates on steady state condition. The difference of refrigerant quantities between condenser and evaporator is the difference of charged refrigerant quantities of the air-conditioning system between refrigeration and heating operating conditions. The optimal refrigerant charge quantity of one refrigeration system is different in summer air-conditioning operation and winter heat pump operation in this equipment. When outdoor temperature is lower in winter, the heating performance of heat pump will decrease. Refrigerant quantities in compressor and throttling part are small because inner volume of throttling part is small comparing with the total system; and the inner volume of compressor is bigger, but there is superheated gas with small density in it on steady state operation. In refrigeration circulation, there is no storing refrigerant in the liquid reservoir. And the whole charging refrigerant circulates round the refrigeration system. But in heating circulation, partial refrigerant stores in the liquid reservoir while the charging refrigerant passes by it. The rest refrigerant circulates in the heating system. The refrigerant can circulate in both refrigeration operating conditions and heating operating conditions in this system by changing the flowing direction of refrigerant through the reversing valve. This control method is required to consider the occupied space of liquid reservoir while designing the air-conditioning unit.

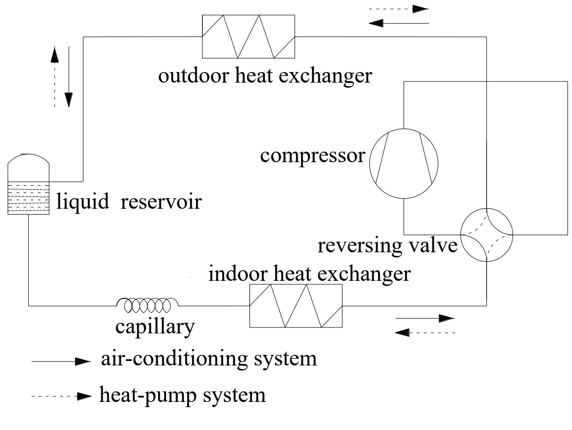

Fig. 2. Typical refrigeration cycle of a household air-conditioning unit.

Based on the calculated results, we plotted four figures which present calculating results of above four models. Figure 3 shows that Homogeneous model decreases the slip ratio across most of mass quality range. And Premoli model increases the slip ratio across most of mass quality range. Zivi model and Harms model are moderate. But Zivi model considers the slip ratio is constant while the mass quality varies. Therefore, Harms model is well situated to calculate the values of slip ratio in two-phase fluid region in household air-conditioner heat exchanger.

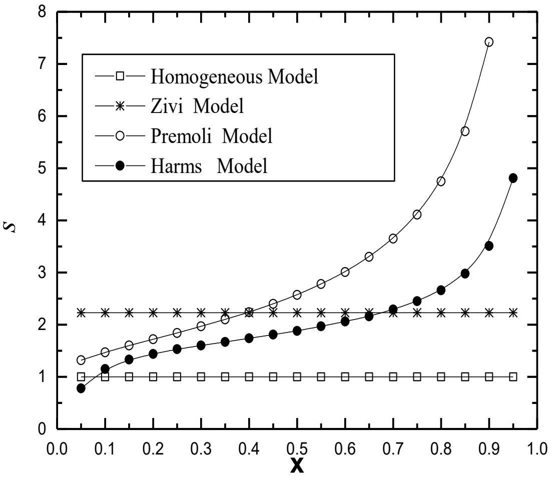

Fig. 3. Comparison of four models for the calculation of slip ratio.

Figure 4 shows that the void fraction varies with mass quality in two-phase fluid region. Homogeneous model considers the velocities of liquid flow and gas flow in two-phase fluid region are equal. It greatly underpredicts the slip ratio across the entire range of mass quality, and consequently increases the void fraction. Zivi model considers the velocity ratio of liquid flow and gas flow in two-phase fluid region is constant. It decreases the void fraction across most of mass quality range.

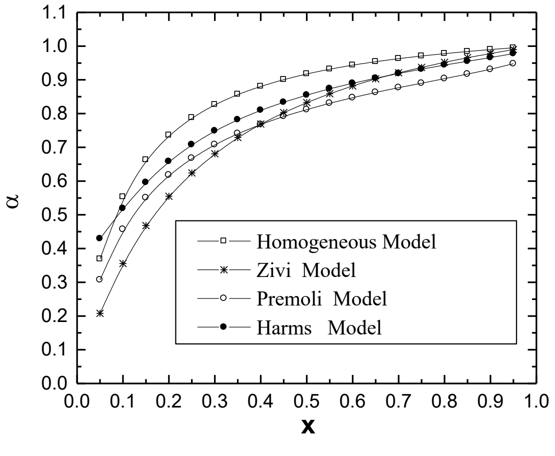

Fig. 4. Comparison of four models for the calculation of void fraction.

Analytical models such as Homogeneous model and Zivi model neglect the influence of refrigerant mass flux in calculating the void fraction. They may overpredicts or underpredicts the values of void fraction comparing with empirical models such as Premoli model and Harms model as Fig.4 shows. Therefore, the mass flux of refrigerant should be considered in calculating the void fraction of liquid flow and gas flow.

4 Influence of refrigerant mass flux

Refrigerant mass flux has influence on slip ratio and void fraction in Premoli model and Harms model. Figure 5 shows the influence of refrigerant mass flux on slip ratio. For both Premoli model and Harms model, slip ratio decreases with the increase of refrigerant mass flux. As refrigerant mass flux increases, liquid droplets entrain the gas core for the effect of shear stress at gas-liquid interface. As the droplets move at nearly the same velocity as the gas core, the slip ratio decreases [5]. Meanwhile, Fig.5 shows that refrigerant mass flux has much greater influence on slip ratio in Premoli model than that in Harms model.

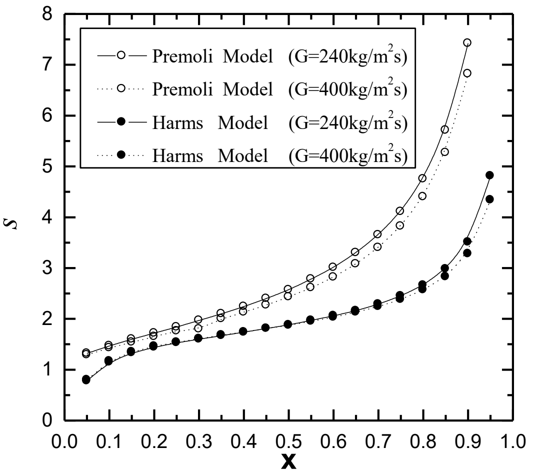

Fig. 5. Influence of refrigerant mass flux on slip ratio.

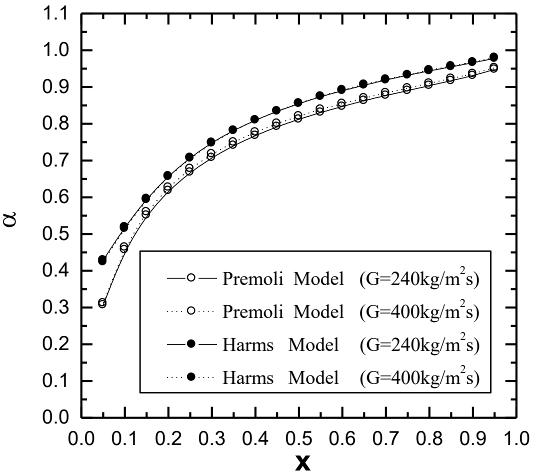

Fig. 6. Influence of refrigerant mass flux on void fraction.

Figure 6 shows the influence of refrigerant mass flux on void fraction. Since slip ratio decreases with the increase of refrigerant mass flux, void fraction increases with the increase of refrigerant mass flux for both Premoli model and Harms model. But they do not increase obviously. Especially for Harms model, refrigerant mass flux has little influence on void fraction because it has little influence on slip ratio.

Basing on above analysis of Fig.5 and Fig.6, both the variation of slip ratio and void fraction are much smaller in Harms model than those in Premoli model. Therefore, using Harms model to calculate slip ratio and void fraction in two-phase fluid region of air-conditioning heat exchanger is reasonable.

5 Conclusions

Since the refrigerant working medium R22 in condenser and evaporator mainly exists in gas and liquid two-phase states, it is necessary to use reasonable void fraction model for the calculation of flowing refrigerant mass in two-phase fluid region. Considering the influence of refrigerant mass flux, the empirical models such as Premoli model and Harms model predict the values of void fraction in two-phase fluid region preferably.

At temperate refrigerant mass flux flowing levels in household air-conditioner heat exchanger, it is suitable to calculate the void fraction in two-phase fluid region by Harms model. This result will be benefit to investigate the refrigerant characteristics of two-phase flow in household air-conditioning system.

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