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Prediction of Nucleate Pool Boiling Heat Transfer Coefficients of Ternary Refrigerant R407C

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Key Words : Prediction of nucleate pool boiling, R407C, R-32, R-125, R-134a, Thome's method

Abstract

The nucleate boiling heat transfer experiments are performed using a ternary refrigerant R407C which is a candidate of alternatives of HCFC 22. The boiling phenomena of R-32, R-125 and R-134a which are the constituent refrigerants of R407C are also investigated. The nucleate boiling heat transfer coefficients of R407C are less than those of HCFC 22 which have the similar physical and transport properties. In our experimental pressure range, which is similar to the operational pressure of air conditioning system, the deterioration of boiling heat transfer coefficients of mixture refrigerant R407C does not appear for moderate wall superheat region. Since nucleate boiling heat transfer coefficients cannot be obtained from ideal mixing law of mixture, Thome's method was used to predict. To account for the heat flux effect and system pressure in Thome's method, the correcting factor, $\alpha(P, \Delta T)$, was introduced and obtained from experiments for ternary refrigerant R407C.

Nomenclature

h	: nucleate boiling heat transfer coefficient, [W/m^{2}K]
Pr	: reduced pressure ($P_{system}/P_{critical}$)
q	: heat flux, [W/m^2]
T	: temperature, [°C]
ΔT	: wall superheat (T_w - T_s), [°C]
ΔT_{bp}	: maximum rise in boiling temperature, [°C]
$\tilde{x}$	: mole fraction

Greek Letters

α	: correcting factor

Subscripts

1, 2, 3	: mixture components
act	: experimental data

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cal : data from Thome's method
I : ideal mixing of mixture
pred : data from present model
s : saturation of refrigerant
w : wall

1. Introduction

The application of ternary refrigerant R407C (mixture mass fraction 23/25/52 of refrigerant R32/R125/R134a) in air conditioning systems is now an important research area in the development of hydrochlorofluorocarbon 22 (HCFC 22) alternatives. The major reason using this non-azeotropic refrigerants mixture (NARM) in a vapor-compression refrigerant system is that the work load of the compressor and the thermodynamic irreversibilities in the heat exchangers (condenser and evaporator) can be theoretically reduced. However, a lot of researches are now being performed to investigate the applicability of R407C in air conditioning system. Main focuses are on the performance test of compressor, solubility of lubricating oil in R407C, and evaluation of heat transfer coefficient and pressure drop in heat exchanger.

In the field of air conditioning and refrigeration, experimental relations of phase-chang heat transfer coefficients are usually used to design evaporators and condensers. The empirical heat transfer coefficient relations, especially for evaporators, are composed of two parts (Chen,1986; Kandlikar, 1990); one comes from boiling contribution and the other from evaporating contribution. To put the boiling contribution in the equation, pool boiling heat transfer coefficient of refrigerants should be known. Although there are many suggested empirical relations for single component refrigerants (Forester and Zuber, 1955; Rohsenow, 1952; Mostinskii, 1963; Bier et al., 1983; Cooper, 1984), they usually cannot be applied directly to multi-component refrigerants since the behavior of these multi-component refrigerants is far different from that of the linear combination of single component refrigerants (Alpay and Balkan, 1989; Thome, 1983). Relatively lots of researches have been done for binary mixtures (Gorenflo et al., 1988; Reddy and Lienhrd, 1989), however, researches on nucleate boiling for ternary mixtures hardly have been done so far due to its complex phenomena. Especially for the newly developed alternative refrigerants, almost no researches on nucleate boiling have been done. The boiling phenomena of ternary refrigerant R407C, which is a candidate of replacing the refrigerant HCFC 22, is also different from the single component refrigerant and cannot be obtained from the linear combination of boiling heat transfer coefficients of its constituent refrigerants.

The purpose of this study is composed of two parts. One is to give the nucleate boiling heat transfer coefficients by performing the boiling experiments for ternary refrigerant R407C and its constituent refrigerants R-32, R-125 and R134a. The experimental conditions are similar to the operational conditions of domestic air conditioning system using R-22 as refrigerant. The other purpose of this study is to develop (or modify) a model to predict nucleate boiling heat transfer coefficients of mixtures. Although our results are confined to a ternary refrigerant R407C, it could be used as a basic data for theoretical research on developing the prediction model for nucleate boiling heat transfer coefficients of mixtures.

2. Experimental Apparatus And Procedures

The experimental apparatus is devised to perform nucleate boiling experiments for the ternary refrigerant R407C and its components: R-32, R125, and R134a. The experimental apparatus is composed of boiling vessel, boiling surface and heating block, data acquisition system, and chiller. Figure 1 shows the schematic of experimental apparatus. The boiling vessel contains the test refrigerant. The dimension of the boiling vessel is 150×150×300mm rectangular and stainless steel (SUS 304) of thickness of 15 mm is used to sustain the system pressure of up to 1.0 MPa. A sight glass is attached at the front side of the vessel to see the boiling phenomena at the boiling surface during the experiments. A condenser is attached at the upper part of the vessel to condense the refrigerant during the experiments and coolant is circulated through the three side walls to maintain the saturate state of the refrigerant. A pressure transducer is located at the upper part of the vessel to measure the system pressure and four T-type thermocouples are used to measure the temperature of refrigerant. The boiling surface is a flat plate. The heating surface is made of a 99.99 percent pure copper cylinder to obtain the uniform temperature distribution at the boiling surface and has a diameter of 50 mm and height of 160 mm. The other end of the cylinder is drilled to fit four cartridge heaters, each rated at 500 W. Sixteen T-type thermocouples are positioned along the vertical axis within the cylindrical heating block at four locations; 1, 7, 15, 35 mm from the boiling surface. Figure 2 shows the locations of various thermocouples. Seven thermocouples are located just below the boiling surface to check the one dimensional temperature distribution at the boiling surface. Heat flux at the boiling surface is calculated by solving one dimensional heat conduction equation along the axis from the measured temperatures within the heating block (Bui and Dhir, 1985). Fluke datalogger F2285N and Hioki 3191 digital power meter are used to measure the temperature and input power to the heating block. The measured temperatures, power, and system

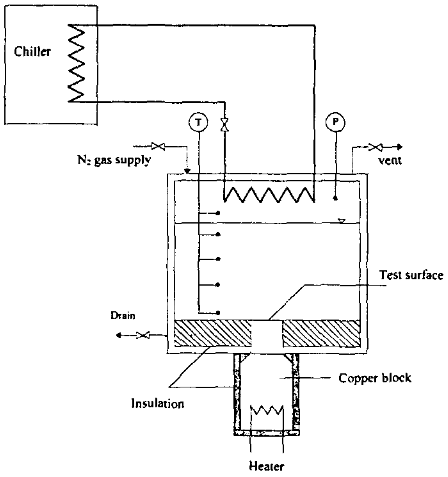

Fig.1 Schematic diagram of the experimental apparatus

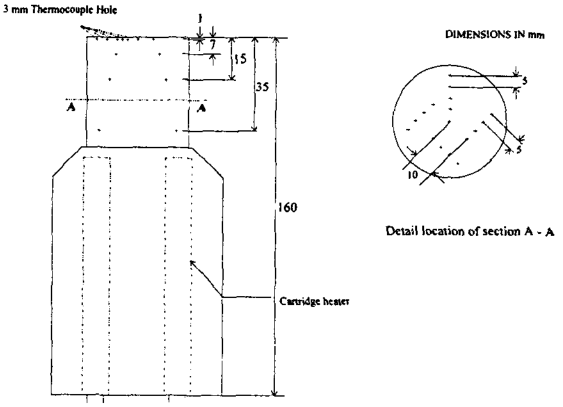

Fig.2 Detail of heating block and the location of thermocouples

pressure are transferred to a PC. The chiller (capacity of 3.9kW, minimum temperature of -20°C) is used to condense the boiled refrigerants and maintain the saturation state of the test refrigerant in a boiling vessel. Power supplied to the cartridge heaters, circulating coolant energy gain from boiling vessel, and calculated heat amount at the boiling surface are compared each other to check the energy balance during the experiments. The calculated heat amount at the boiling surface is utmost 8% less at high heat flux than the supply power to the cartridge heaters due to heat loss to the boiling vessel and surroundings. Since the temperature of the circulating coolant is very low compared to the surrounding temperature, the circulating coolant gains some energy from the surroundings even though the outside of the boiling vessel is heavily insulated and the total energy gain of circulating coolant is approximately 2% higher than the supply power by the cartridge heaters during the experiments.

System pressure during the experiments varied form 0.4 to 0.9MPa which is the operating pressure ranges of the evaporator in vapor compression air conditioning systems. The following shows the experimental procedures.

1) After evacuating the boiling vessel, fill the test vessel with refrigerant. The liquid level is maintained at about 150 mm above the boiling surface to minimize the turbulent fluctuation effects during the boiling experiments.

2) Maintain the saturated state of the refrigerant at the required system pressure by circulating the cooling solution from the chiller.

3) Set the power of the heaters using a variable power transformer.

4) Measure the data when the system is in steady state.

5) Increase the power of the heaters and perform the experiments.

6) Increase the system pressure and perform the experiments by the above procedures.

Boiling heat transfer coefficients can be obtained from calculated heat flux at the boiling surface and measured temperatures.

$$h=\frac{q}{T_w-T_s} \tag{1}$$

Here q is heat flux at the boiling surface, T_w and T_s is the temperature of boiling surface and refrigerant, respectively.

3. Experimental Results

In steady state, the deviation of one dimensional temperature distribution along the axial direction of heating block is found to be less than 0.7℃. The deviation of one dimensional temperature distribution just below the boiling surface (1 mm below) is small compared to those of other locations and has maximum of 0.3°C at high heat flux. The boiling surface temperature is obtained by extrapolating the temperatures profile within heating block to the boiling surface and heat flux at the boiling surface is calculated by solving Fourier's one dimensional heat conduction equation using measured temperature profile. The error of the calculated heat flux at the boiling surface mainly comes from the assumption of one dimensional temperature distribution within the heating block. The uncertainty of the heat flux at the boiling surface for the experiments is maximum of 11% at high heat flux and decreases as heat flux decreases. The error of heat transfer coefficients from equation (1) comes from the uncertainties of temperature measurements and calculating heat flux. The uncertainty of boiling heat transfer coefficients is 12%.

Nucleate boiling experiments for the refrigerant HCFC 22 are performed at first. Since there exist experimental results and empirical relations for HCFC 22, our experimental results on HCFC 22 can be compared to those of HCFC 22 from other researches. Figure 3 shows the nucleate boiling experimental results for HCFC 22 under system pressure of 0.53MPa. Boiling heat transfer coefficients from the existing empirical relations, Rohsenow (1952), Mostinskii (1963), Bier (1983), and Cooper (1984) are shown together for the comparison. Since nucleate boiling heat transfer coefficients are strongly affected by the smoothness of the boiling surface, it has to be very careful when this kind of comparisons are made. Each empirical relation gives the different boiling heat transfer coefficients and our experimental results are between Bier's and Cooper's. Since the existing empirical relations give different nucleate boiling heat transfer coefficients even for a single component refrigerant, it hardly can be used to predict nucleate boiling heat transfer coefficients for the multi-component refrigerants. For newly developed single component refrigerant and mixtures, the nucleate boiling heat transfer coefficients must be obtained from the experiments and can be used to develop the theoretical model to predict the behavior of multi-component refrigerants.

Figure 4 shows the nucleate boiling heat transfer coefficients of HCFC 22 for the various system pressures. The nucleate boiling heat transfer coefficients are between 4,000W/m^2K and 20,000W/m^2K. Experimental results show a trend of increasing boiling heat transfer coefficient with increasing system pressure since the wall superheat for the initial nucleate boiling decreases as pressure increases. The experimental results show the similar behavior with Mostinskii relation. Mostinskii relation uses reduced pressure Pr ($P_{system}/P_{critical}$) to predict the system pressure effect on the boiling heat transfer coefficient. Mostinskii relation is modified to develop an experi-

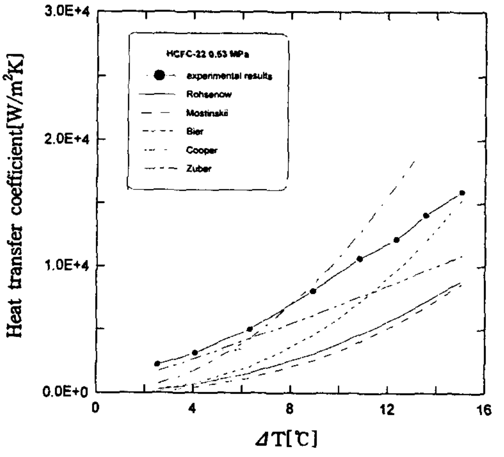

Fig.3 Nucleate boiling transfer coefficients for HCFC 22 under system pressure of 0.53MPa

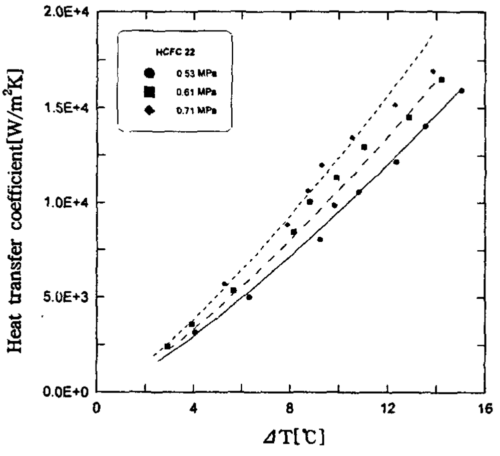

Fig.4 Nucleate boiling heat transfer coefficient of HCFC-22

mental correlation, equation (2). This relation contains two terms; one is for the temperature difference between boiling surface and refrigerant (ΔT^n) and the other is for the effect of system pressure ($F(Pr)$).

$$h_{Moskinskii\ type} = F(Pr)\ \Delta T^n \quad (2)$$

Although it is known that nucleate boiling heat transfer coefficients are proportional to ΔT^2 in developed nucleate boiling region (Rohsenow, 1952), our results gives $\Delta T^{1.28}$ proportionality. The experimental correlation of nucleate boiling heat transfer coefficient for HCFC 22 is in equation (3).

$$h = (9.0Pr^{0.17} + 4.6Pr^{1.2})\Delta T^{1.28} \quad (3)$$

Nucleate boiling experiments are performed for single component refrigerant R-32, R-125 and R-134a. Figure 5, 6 and 7 show the experimental results for R-32, R-125 and R-134a, respectively. The experimental results for nucleate boiling heat transfer coefficients show the similar behavior with HCFC 22, but with different F(Pr) and n for each refrigerant. R-134a has the largest nucleate boiling heat transfer coefficients. Nucleate boiling heat transfer coefficients of R-32 and R-125 are similar. The effect of wall superheat is eminent in R-32 (proportional to $\Delta T^{2.2}$). The equation (4), (5), and (6) is the experimental correlations of nucleate boiling heat transfer coefficients for R-32, R-125 and R-134a, respectively.

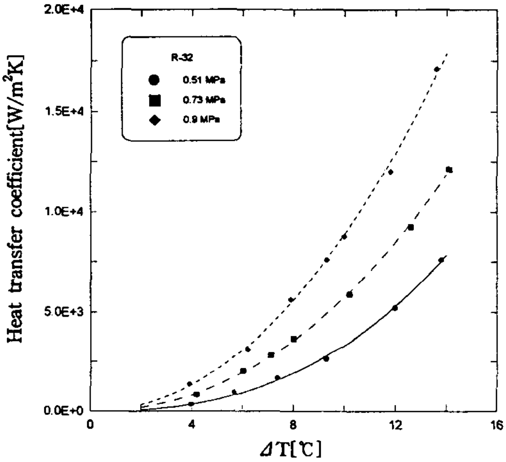

Fig.5 Nucleate boiling heat transfer coefficient of R-32

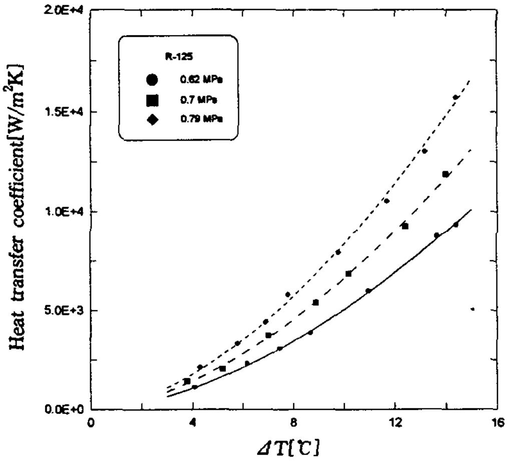

Fig.6 Nucleate boiling heat transfer coefficient of R-125

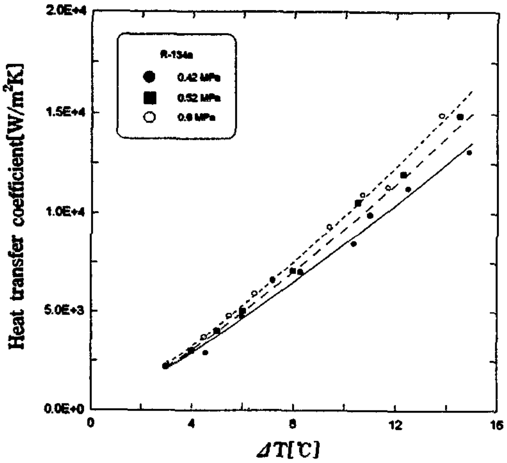

Fig.7 Nucleate boiling heat transfer coefficient of R-134a

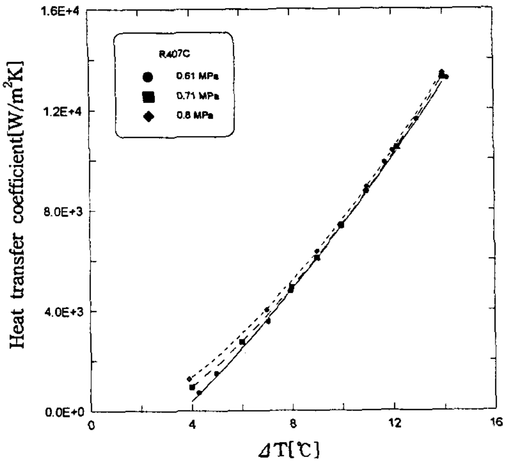

Fig.8 Nucleate boiling heat transfer coefficient for ternary refrigerant R407C

$$h=(-10.9Pr^{0.17}+557.4Pr^{1.2})\Delta T^{2.2} \quad (4)$$

$$h=(-84.6Pr^{0.17}+1412.5Pr^{1.2})\Delta T^{1.7} \quad (5)$$

$$h=(681.3Pr^{0.17}+835.3Pr^{1.2})\Delta T^{1.24} \quad (6)$$

Figure 8 shows nucleate boiling heat transfer coefficients of ternary mixture refrigerant R407C under the various system pressures and wall superheats. Though R407C is a strong candidate for HCFC 22 alternatives due to similar thermodynamic properties with HCFC 22, nucleate boiling heat transfer coefficients of R407C is less than those of HCFC 22. The nucleate boiling heat transfer coefficients increase as wall superheat and system pressure increase. The system pressure effect in nucleate boiling heat transfer coefficients of R407C becomes weak as the wall superheat increases. The nucleate boiling heat transfer coefficients under different system pressures approach with each other as wall superheat increases. The nucleate boiling heat transfer coefficients of single component refrigerant are proportional to the power of wall superheat and each refrigerant has its own order of power. Therefore, the effect of system pressure becomes distinguished as wall superheat increases. The nucleate boiling heat transfer coefficients of R407C show different behavior from other single component refrigerant, thus an experimental correlation different from Mostinskii's is proposed. Equation (7) shows the experimental correlation of nucleate boiling heat transfer coefficients for R407C.

$$h=A(Pr)\Delta T^2+B(Pr)\Delta T+C(Pr) \quad (7)$$

$$A(Pr)=-1499.1Pr^2+468.6Pr+1.29 \quad (7a)$$

$$B(Pr)=20717.8Pr^2-7424.5Pr+1207.0 \quad (7b)$$

$$C(Pr)=16801.2Pr^2+15942.9Pr-4758.5 \quad (7c)$$

4. Prediction Model

Numerous methods for predicting the nucleate pool boiling heat transfer coefficients for multi-component mixtures have been previously proposed. They attempted to predict the variations in heat transfer coefficient or wall superheat with different compositions at a constant heat flux. It is well known that the linear mixing law in heat transfer coefficient overestimates the actual value, and evaluating single-component nucleate pool boiling correlations with non-linear variations of physical properties are not sufficiently accurate for predicting boiling heat transfer coefficients of mixtures. Thome (1983) reviewed various predictive methods for mixture boiling heat transfer coefficient. Under 5 criteria for selecting the ultimate method for predicting boiling heat transfer coefficient, the Stephan-

Korner and Thome's T_{bp} equations are shown to be good. Stephan-Korner (Stephan and Korner, 1969) developed a simpler method for correlating binary mixture boiling heat transfer coefficients using an excess function approach, common to the prediction of mixture physical properties. Their equation needs an empirical quantity which has to be determined at an intermediate heat flux level for each mixture system. Thome used the similar formula with Stephan-Korner equation. He postulated that the rise in the local saturation temperature for the mixture boiling on a smooth tube or plate is controlled by total rate of evaporation at the heated surface. This postulation gives easy implementation method of temperature rise, T_{bp}, in the local boiling point of the liquid adjacent to the heated surface. T_{bp} can be determined from the knowledge of only the phase equilibrium diagram at the pressure of interest. This equation incorporating T_{bp} demonstrated that it is quite accurate for heat fluxes well below the peak heat flux. Here we follow the Thome method, which is conceptually easy to follow and only needs a phase equilibrium diagram. This equation gives good prediction of boiling heat transfer coefficients for several binary mixture, and two things have to be noted: one is that this equation is strictly only true at the peak heat flux and the other is that this equation is validated on binary mixtures. The first note is important in the actual application of Thome's method to our results since heat exchangers (especially, condenser and evaporator for air conditioning system) are designed to operate at heat fluxes well below the peak heat flux.

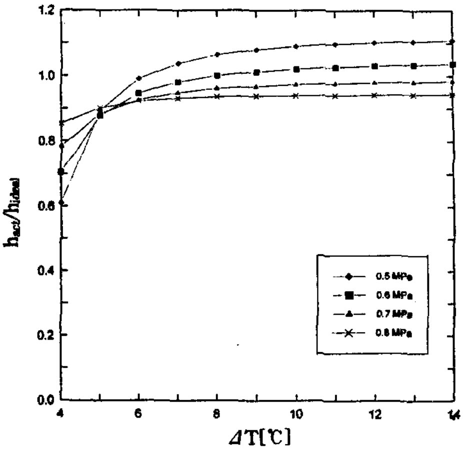

Fig.9 The ratio h_{act}/h_{ideal} of R407C for various system pressures

Figure 9 shows the comparison of nucleate boiling heat transfer coefficients for ternary refrigerant R407C and those of ideal mixing of constituent refrigerants (see equation (10)) at system pressure of 0.5, 0.6, 0.7 and 0.8MPa. Our experimental correlations are used for nucleate boiling heat transfer coefficients. However, it is usually known that there is a deterioration of nucleate boiling heat transfer for the mixture due to the existence of mass transfer resistance, the results show rather higher nucleate boiling heat transfer coefficients of R407C when the system pressure is 0.5MPa except for a small wall superheat value (initial nucleate boiling). As system pressure increases, nucleate boiling heat transfer coefficients of R407C increase but become less than those from ideal mixing of mixture (above 0.7 MPa). The effect of system pressure in nucleate boiling heat transfer coefficients of R407C becomes small as wall superheat increases (see Figure 8). This implies that the increase of nucleate boiling heat transfer coefficients of R407C is relatively small compared to the other constituent refrigerants as wall superheat increases when system pressure is high. For the higher system pressure, nucleate boiling heat transfer coefficients of R407C are always less in the whole

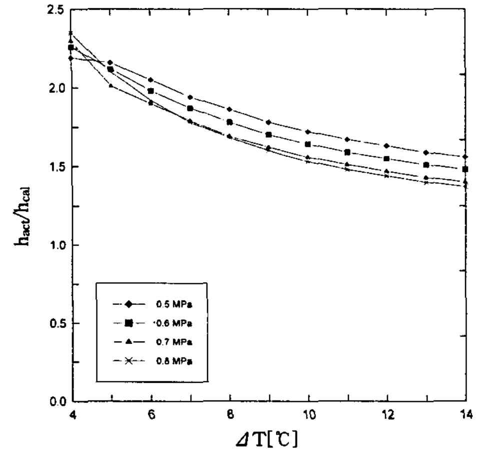

Fig.10 The ratio h_{act}/h_{cal} of R407C for various system pressures

range of wall superheat than those from ideal mixing of mixture.

Figure 10 shows the comparison between nucleate boiling heat transfer coefficients of R407C and the calculated results from Thome's method for the system pressure of 0.5, 0.6, 0.7 and 0.8 MPa. In the figure, h_{act} is nucleate boiling heat transfer coefficients from our correlations based on experiments and h_{cal} is from Thome's predicting model. Nucleate boiling heat transfer coefficient h_{cal} from Thome's predicting model for the mixture is shown in equation (8).

$$\frac{h_{cal}}{h_I}=\frac{\Delta T_I}{\Delta T_I+\Delta T_{bp}} \tag{8}$$

Here ΔT_I is the ideal mixing law superheat and defined at a given heat flux

$$\Delta T_I=\tilde{x}_1\Delta T_1+\tilde{x}_2\Delta T_2+\tilde{x}_3\Delta T_3 \tag{9}$$

where $\tilde{x}_i$ and ΔT_i are mole fraction and the wall superheat for each component of mixture, respectively. Ideal nucleate boiling heat transfer coefficients of mixture are defined as

$$h_I=\frac{1}{(\tilde{x}_1/h_1)+(\tilde{x}_2/h_2)+(\tilde{x}_3/h_3)} \tag{10}$$

The ideal nucleate boiling heat transfer coefficients for R-32, R-125, and R134a are obtained from our experimental correlations. ΔT_{bp} in Thome's model is the maximum rise in temperature at the peak heat flux and obtained from a phase equilibrium diagram at a constant pressure. This increase, ΔT_{bp}, is defined as the temperature difference between the dew line and the bubble line at the bulk liquid mole fraction. This value is obtained using refrigerant data of REFPROP (NIST, 1993). ΔT_{bp} for the pressure of 0.5, 0.6, 0.7 and 0.8MPa are 6.33℃, 6.20℃, 6.08℃ and 5.97°C, respectively. Equation (8) says nucleate boiling heat transfer coefficients predicted from Thome's model have to be always less than those from ideal mixing of mixture. However, Figure 9 shows that nucleate boiling heat transfer coefficients of R407C are higher than those from ideal mixing law, especially at low system pressure. If nucleate boiling heat transfer coefficients of R407C follow Thome's predicting model, the ratio h_{act}/h_{cal} is approximately unity. The ratio in Figure 10 is always higher than unity at all system pressures. When the system pressure is high, the ratio h_{act}/h_{cal} has smaller value compared to that at lower system pressure. The ratio h_{act}/h_{cal} decreases as wall superheat increases. Though the ratio seems to approach to unity as wall superheat increased, it is not quite sure with present experimental results since our experiments are performed well below the peak heat flux (relatively small wall superheat region). Thome's predicting model is strictly true only at the peak heat flux and, therefore, the difference between our results and predicting model is thought to come mainly from the level of heat flux. However, Thome's method is conceptually easy to apply in predicting nucleate boiling heat transfer coefficients of mixture and needs only phase equilibrium diagram, it is meaningful to use Thome's approach even for ternary mixture R407C. Here a correcting factor is added to Thome's model. Nucleate boiling heat transfer coefficients of R407C, h_{pred}, can be obtained using the correcting factor, $\alpha(P, \Delta T)$, which accounts for the effect of heat flux (in terms of wall superheat) and system pressure.

$$h_{pred} = \alpha(P, \Delta T)\ h_{cal} \tag{11}$$

P is the system pressure and ΔT is the wall superheat (difference between wall temperature and refrigerant temperature). Empirical correcting factor $\alpha(P, \Delta T)$ for R407C is obtained from Figure 10 excluding small wall superheat region

$$\alpha(P, \Delta T) = (2.95P^2 - 5.36P + 5.79)\ \Delta T^{-0.35} \tag{12}$$

where pressure P is in MPa. Equation (11) can be used to predict nucleate boiling heat transfer coefficients of R407C with heat flux values below peak heat flux and pressure range of 0.4 to 0.9MPa.

5. Summary and Conclusion

The nucleate boiling heat transfer experiments are performed using a ternary refrigerant R407C which is a candidate of alternatives of HCFC 22. The boiling phenomena of R-32, R-125, and R-134a which are the constituent refrigerants of R407C are also investigated. The nucleate boiling heat transfer coefficients of R407C are less than those of HCFC 22, even though both of which have the similar physical and transport properties. In the tested experimental pressure range, which is similar to the operational pressure of air conditioning system, the deterioration of boiling heat transfer coefficients of mixture refrigerant R407C does not appear for moderate wall superheat region. Since nucleate boiling heat transfer coefficients cannot be obtained from ideal mixing law of mixture, Thome's method was applied to predict the coefficients. To account for heat flux effect and system pressure effect in Thome's method, a correcting factor $\alpha(P, \Delta T)$ was introduced and the value was obtained from experiments for ternary refrigerant R407C.

Acknowledgements

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