Journal of the Korean Society of Marine Engineering, Vol.31, No.3, pp.224~234, 2007(ISSN 1226-9549)

Study on the evaporation Heat Transfer Characteristics of R-134a in Small Diameter Tubes

Geon-Sang Roh† · Hoo-Kyu Oh*

(Manuscript : Received NOV 14, 2006 ; Revised DEC 28, 2006)

Abstract : Large diameter tubes have been used until comparatively lately. However, small diameter tubes are largely used because of their high efficiency in heat transfer and low cost, recently. This study focuses on the experimental research of the heat transfer coefficients during evaporation process of R-22 and R-134a in small diameter tubes. The evaporation heat transfer coefficients were measured in smooth horizontal copper tubes with ID 1.77, 3.36 and 5.35 mm. The evaporation heat transfer coefficients in the small diameter tubes (ID <7 mm) were observed to be strongly affected by the size of tube diameters and to differ from those of general predictions in the large diameter tubes. The heat transfer coefficients of ID 1.77 mm copper tube were higher by 20 and 30 % than those of ID 3.36 mm, ID 5.35 mm copper tubes respectively. Also, it was found that it was very difficult to apply some well-known previous predictions (Shah's, Jung's, Kandlikar's and Oh-Katsuda's correlation) to small diameter tubes. Based on the data, the new correlation is proposed to predict the evaporation heat transfer coefficients of R-22 and R-134a in small diameter tubes.

Key words : Refrigerant, Evaporation heat transfer coefficient, Small diameter tube

Symbols

c_p	specific heat	[kJ/kgK]
G	mass flux	[kg/m^{2}s]
h	heat transfer coefficient	[kW/m^{2}K]
ID	inner diameter of tube	[m]
i_{fg}	latent heat	[kJ/kg]
κ	thermal conductivity	[kW/mK]
M	mass flow rate	[kg/h]
Q	heat capacity	[kW]
q	heat flux	[kW/m^2]
T	temperature	[K]
x	quality	[/]
z	tube length	[m]

Dimensionless Number

Bo	Boiling number
Co	Convection number
Nu	Nusselt number
Fr	Froude number
Pr	Prandtl number
Re	Reynolds number

---

† Corresponding Author(Tongmyong University, Dept. of Environmental Equipment), E-mail : rohgs@tu.ac.kr, Tel : 051)620-3522

* Pukyong National University

Subscripts

E	evaporation
ID	inner diameter
in	inlet
L	liquid
loc	local
OD	outer diameter
out	outlet
R	refrigerant
V	vapour
wi	inside wall
wo	outside wall

1. Introduction

The studies for alternative refrigerants have been carried out actively from 1980's because of the use restriction of CFCs and HCFCs refrigerants, and the researches for heat exchanger with high efficiency have been also done together. In the middle of these researches, it is very peculiar to apply small diameter tubes (ID < 7 mm) to heat exchanger. Large diameter tubes have been used until comparatively lately. However, small diameter tubes have been largely used these days because of many merits[1], [2]. The design guide of heat exchanger is rightly changed, if working fluids in it become different. Therefore, many recent researches tend to focus on carrying out studies for alternative refrigerants and heat exchanger with small diameter tubes together. So, the main studies for alternative refrigerants are highly related to the studies for heat exchanger with small diameter tubes. The relevant literatures are briefly reviewed as follows: Wambsganss et al[3] studied horizontal two-phase flow in a small cross-sectional-area rectangular channel. The data from the small rectangular channel of the present study were in poor agreement with the generalized rectangular two-phase flow pattern results that were based on larger channels. Peng et al[4] conducted a measurement of the single-phase forced-flow convection and boiling characteristics of subcooled liquid flowing through micro-channels with a cross-section of 0.6 × 0.7 mm, made on the stainless steel plate with 2 mm thickness, and found the single-phase convection and boiling flow pattern characteristics in micro-channels were quite different from those in normally sized tubes. They also found that the mass flux and liquid subcooling appeared to have no obvious effect on the nucleate boiling flow in small diameter tubes. Oh-Katsuda et al[5] investigated boiling heat transfers of alternative refrigerant R-134a in small diameter tubes with ID 0.75 and 1.0 mm, and reported the heat transfer in the forced convection region was more influenced by the mass flux than by Boiling number and the heat transfer coefficient were controlled by Reynolds number. In addition, they proposed the new correlation for convective heat transfer in small diameter tubes. Above literature review mentioned clearly indicates that evaporation heat transfer characteristics in small diameter tubes differ from those in large diameter tubes. In this study, the evaporation heat transfer coefficients of R-22 and R-134a were measured in smooth horizontal copper tubes with ID 1.77, 3.36 and 5.35 mm.

2. Experimental Apparatus and Procedures

2.1 Test facility

Fig. 1 shows the schematic diagram of experimental apparatus. The test facility consists of a refrigerant loop and brine loop. The refrigerant loop contains a refrigerant pump, a mass flow-meter, an evaporator(test section for evaporation heat transfer experiment), a sight glass, a condenser and a receiver etc.

As shown in Fig. 1, the subcooling liquid of refrigerant in receiver was circulated through the mass flow meter by means of magnetic gear pump. The refrigerant leaving the mass flow meter in subcooling phase enters the pre-heater. The pre-heater is installed to obtain the desired inlet quality and pressure of refrigerant. The refrigerant enters the test section and then it is evaporated with flowing through the tube. The refrigerant leaving the evaporator is completely condensed in sub-cooler and enters the receiver. The brine chiller is set up to control the given saturation temperature. The refrigerant flow rate is measured by a mass flow-meter with an accuracy of ± 0.5 %. The brine loop consists of a centrifugal pump and a refrigeration unit for cooling. The mass flow rate of brine is controlled by a valve. The temperature of brine entering into a condenser is adjusted by the refrigeration unit. The brine mass flow rate is also measured by a turbine flow meter with an accurate of ± 1.0 %.

Fig. 2 shows a drawing of evaporator. The evaporator consists of horizontal copper tubes with ID 1.77, 3.36 and 5.35 mm respectively. All copper tubes have 0.7 mm tube wall thickness. The evaporator's length is 1,500 mm and contains 6 subsections along with 250 mm length of an evaporator. The electronic power for the pre-heater and evaporator was regulated by the auto voltage transformer and the electronic power is provided for nichrome wire winding the outer wall of inner tube.

As can be seen in Fig. 2, the evaporator is instrumented with temperatures and pressure sensors. In the evaporator,

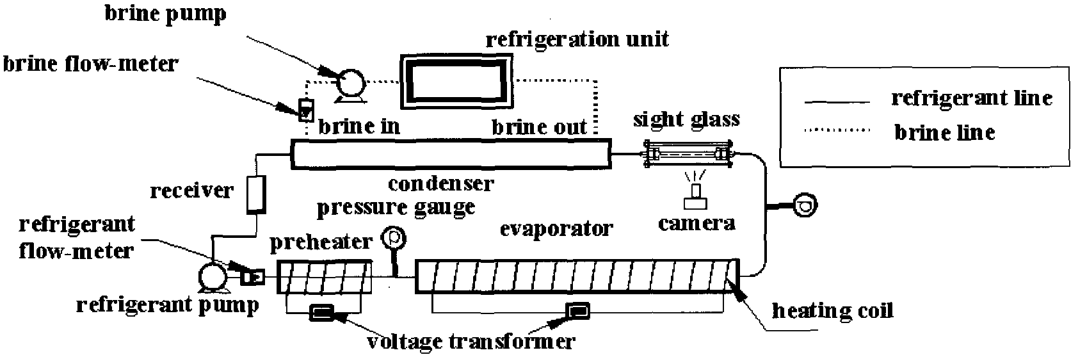

Fig. 1 Schematic diagram of experimental apparatus for evaporation heat transfer

T-type thermocouples are used for temperature measurement. All thermocouples are used after being revised with a standard thermometer. The wall surface temperatures of copper tubes are measured at three points(top, bottom, and a side).

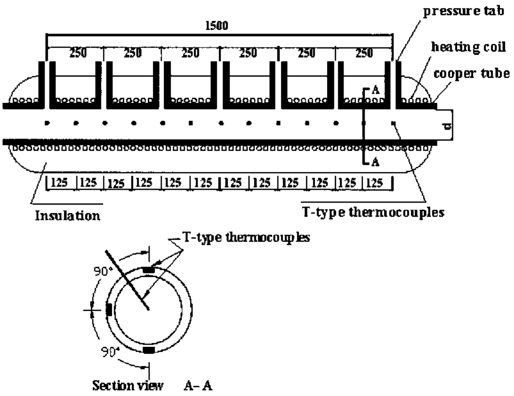

Fig. 2 Test section for evaporation heat transfer

2.2 Experimental Procedure

As mentioned above, the test rig can be used to conduct the evaporation heat transfer test. The thermodynamic properties of the refrigerants under test were incorporated in the data-acquisition system consisting of a data logger, interface card (HPIB), and a compatible PC. The data was analyzed in real time using PC and a data reduction program (MS-Excel with a Visual Basic). All of the information about the test conditions and data were displayed on the monitor during the test. The test conditions were changed based on this information. All channels in the data-acquisition system were scanned five times and the averaged. The data collection took about two minutes for each run. The system was allowed to come to steady state before any data were recorded. The steady-state condition of experiment was reached when the refrigerant inlet pressure/temperature/quality, exit temperature/quality, mass flow rate and water mass flow rate and inlet and outlet temperature keep in stationary state. The test conditions in this study are summarized in Table 1.

Table 1 Experimental conditions for evaporation heat transfer

Refrigerant	R-22	R-134a
ID of sight glass tube (mm)	2, 8	
ID of evaporator (mm)	1.77, 3.36, 5.35	
Mass velocity (kg/m^{2}s)	100 ~ 1000	
Heat flux (kW/m^2)	5 ~ 30	
Quality	0.0 ~ 1.0	

2.3 Data Reduction

An analysis is needed to calculate the evaporation heat transfer coefficients from the experimental data. The data reduction process is described in the following. Before measuring the evaporation heat transfer coefficient, an initial single-phase heat transfer test was conducted to check the energy balance in the test section. The heat transfer rate Q_{coil} supplied from electric coil to outside wall surface of copper tube in an evaporator is calculated as equation (1) and the heat transfer rate $Q_{E,R}$ supplied from inside wall surface of copper tube to refrigerant is calculated as equation (2)

$$Q_{coil} = \zeta \cdot V \cdot I \tag{1}$$

$$Q_{E,R} = M_{E,R} \cdot c_{P,E,R} \int_{T_{E,Rin}}^{T_{E,Rout}} dz \tag{2}$$

where, ξ is a heating coefficient, V is input voltage, I is an input electric current, $M_{E,R}$ is a refrigerant mass flow rate[kg/h], $T_{E,R,in}$ is an inlet temperature of refrigerant [K], $T_{E,R,out}$ is an outlet temperature of refrigerant [K] and $c_{p,E,R}$ is a specific heat [kJ/kg·K]. The heat flux $q_{E,R}$ supplied from electric coil to outside wall surface of copper tube is calculated as equation (3).

$$q_{E,R} = \frac{Q_{coil}}{\pi \cdot d_{ID} \cdot dz} \tag{3}$$

where, dz indicates the effective length of a subsection, d_{ID} is inner diameter of copper tube. The circumferential local heat transfer coefficient of refrigerant during evaporation process is calculated by the following equation (4).

$$h_{E,R,L} = \frac{q_{E,R}}{T_{E,wi} - T_{E,R}} \tag{4}$$

where, the condition in test section is supposed as saturation condition and refrigerant temperature $T_{E,R}$ measured in copper tube is used as saturation temperature of refrigerant. In addition, the heat transfer condition from outside wall surface of copper tube to inside wall surface of copper tube is also supposed under one-dimension steady-state heat conduction and then, $T_{E,wi}$ is calculated by equation (5).

$$T_{E,wi} = T_{E,wo} - Q_{E,R} \cdot \frac{\ln(d_{OD}/d_{ID})}{(2 \cdot \pi \cdot dz \cdot \kappa_w)} \tag{5}$$

where, $T_{E,wo}$ is outside wall surface temperature of copper tube and it is averaged by measuring the top, side and bottom temperature, and κ_w is a thermal conductivity of copper tube. The quality of refrigerant is calculated as equation (6) at each subsection.

$$x = x_{E,IN} + \frac{\pi \cdot d_{ID}}{G_{E,R} \cdot i_{E,fg}} \int_{Z_1}^{Z_2} q_{E,R} \cdot dz \tag{6}$$

where, $G_{E,R}$ is mass flux and $i_{E,fg}$ is an evaporation latent heat. In this study, all refrigerant properties are calculated by REFPROP(version 6.0) made by NIST (National Institute of Standards and Technology)[6].

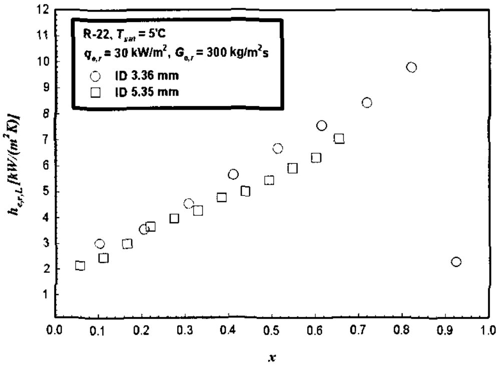

Fig. 3 Local evaporation heat transfer coefficients of R-22 with respect to vapor quality in ID 3.6, 5.35 mm

3. Results and Discussion

3.1 Evaporation heat transfer

(1) Effect of vapor quality and tube diameter

Fig. 3 represents local evaporation heat transfer coefficients of R-22 with respect to vapor quality in ID 3.36 mm and 5.35 mm copper tube respectively. In Fig. 3, local evaporation heat transfer coefficients of ID 3.36 mm tube is about 15 % higher than those of ID 5.35 mm tube. Fig. 4 shows local evaporation heat transfer coefficients of R-134a with respect to vapor quality in ID 1.77 mm and 3.36 mm copper tube. As shown in Fig. 4, the evaporation heat transfer coefficients of ID 1.77 mm tube is about 20 % higher than those of ID 3.36 mm.

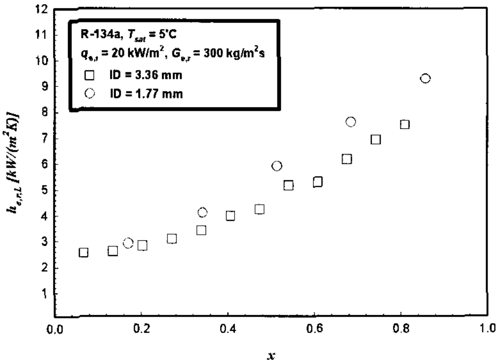

Fig. 4 Local evaporation heat transfer coefficients of R-134a with respect to vapor quality in ID 1.7, 3.6 mm

As shown in Fig. 3~4, the evaporation heat transfer coefficients increased with the reduction of inner tube diameter. Specially, the elevations of evaporation heat transfer coefficients were distinct at the ranges from quality 0.5 to 0.8 as the inner diameter reduced. From the result of previous related paper for the trend mentioned in above, several researchers[4], [7], [8] explained that the reason is the effect of surface tension, the dominant of force convection boiling, the increase of contact heat transfer area, the difference of flow pattern etc. This reasons were not made clear theoretically. But some researchers[7], [8] concluded that the increase of evaporation heat transfer coefficient results from the difference of evaporation flow pattern through their experiment. In other words, they predicted that this resulted from diminishing of liquid film of annular flow and fast transition from stratified flow or wavy flow to annular flow in small diameter tubes.

Also, through the addition experiment for evaporation flow patterns of ID 2 and 8 mm, it has been observed the thickness of liquid film of annular flow happened to ID 2 mm tubes were thinner than those of ID 8 mm tubes and transitions from stratified flow or wavy flow to annular flow in ID 2 mm tube were also faster than those in ID 8 mm tubes[9].

(2) Effect of heat flux

Fig. 5~7 represents the evaporation heat transfer coefficient of R-22 and R-134a with respect to variation of heat flux in ID 1.77, 3.36 and 5.35 mm. As shown in Fig. 5~7, the heat transfer coefficient for the fixed tube diameter hardly increases as heat flux increases. And this trends were also observed for all tube diameters. This reason is that the convective boiling heat transfer which is not influenced by heat flux is dominant in evaporator of ID 1.77, 3.36 and 5.35 mm. Therefore, the rise of heat flux is hardly influenced on the elevation in evaporation heat transfer in a small diameter tube.

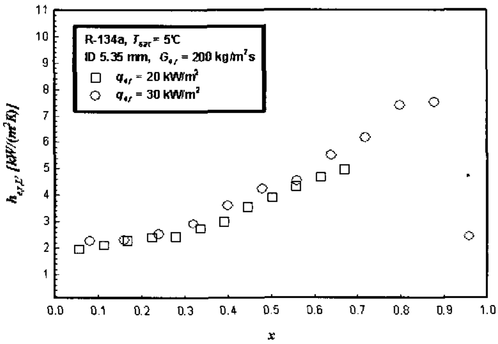

Fig. 5 Comparison of local evaporation heat transfer coefficients with heat flux in ID 5.35 mm.

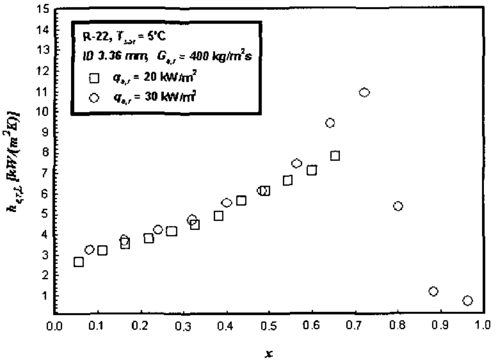

Fig. 6 Comparison of local evaporation heat transfer coefficients with heat flux in ID 3.36 mm.

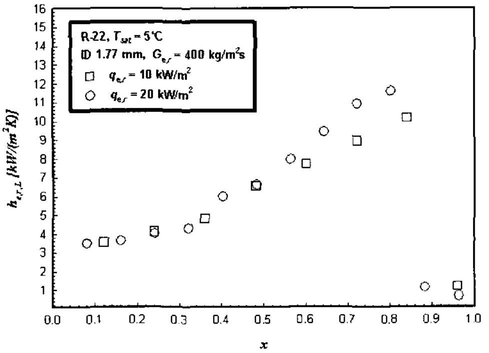

Fig. 7 Comparison of local evaporation heat transfer coefficients with heat flux in ID 1.77 mm.

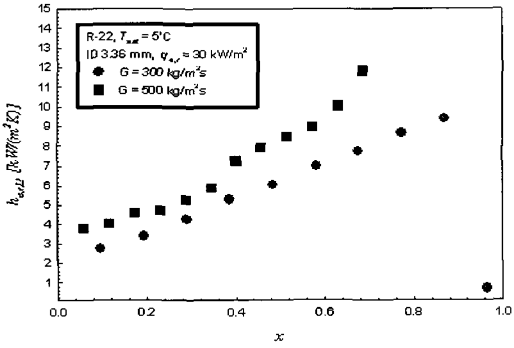

Fig. 8 Comparison of local evaporation heat transfer coefficients with mass flux in ID 3.36mm.

(3) Effect of mass flux

Fig. 8 shows the evaporation heat transfer coefficient of R-22 and R-134a with respect to the variation of mass flux in ID 3.36 mm. In Fig. 8, the evaporation heat transfer coefficient of $G_{r_{e,r}}$= 500 kg/m^{2}s is about 20 ~ 50 % higher than that of $G_{r_{e,r}}$= 300 kg/m^{2}s at the range of low and high vapor quality. This represents that the variation of mass flux has a great effect on nucleate boiling of low quality and convective boiling of high quality. Especially, this trend is distinct over the high quality of 0.4 which is dominated by annular flow. It is concluded that this resulted from diminishing of liquid film of annular flow.

3.2 Evaporation heat transfer correlations

It is important to compare the present data in small diameter tubes to the previous correlations. In this paper, Shah's[10], Jung's[11] and Kandlikar's[12] correlations that are generally applied to large diameter tubes, and Oh-Katsuda's correlation which is proposed to small diameter tubes, are compared with the experimental data. In this paper, the above correlations are simply described as follows:

Shah has proposed the following correlation (7) for boiling heat transfer in vertical and horizontal tubes and annuli. He broke the boiling flow regime into three distinct regions; a nucleate-boiling-dominated regime, a bubble-suppression regime, and a convective-dominated regime. Shah's correlation has proposed as follows;

$$h_{TP} = \Psi \cdot h_L \tag{7}$$

$$h_L = 0.023\left[\frac{G(1-x)d_{ID}}{\mu_L}\right] \mathrm{Pr}_L^{0.4} \cdot \frac{\kappa_L}{d_{ID}} \tag{8}$$

where, h_{TP} is sum of heat transfer coefficients and h_L is the liquid-only heat transfer coefficient and parameter is decided by values of F_{rl}, Bo, Co.

Jung's correlation based on the supposition of Chen and using only phase equilibrium data to consider mixture effects are developed with mean deviations of 7.2 and 9.6 % for pure and mixed refrigerants. Jung's correlation for pure refrigerants and azeotrope is as follows:

$$h_{TP} = h_{nbc} + h_{ece} = N \times h_{SA} + F_P \times h_L \tag{9}$$

where, h_{nbc} is nucleate boiling contribution heat transfer coefficient and, h_{cec} is convective evaporation contribution heat transfer coefficient.

A simple correlation was developed earlier by Kandlikar to predict saturated flow boiling heat transfer coefficients inside horizontal and vertical tubes. It incorporated a fluid- dependent parameter F_{rl} in the nucleate boiling term. His correlation is as follows:

For vertical flow and horizontal flow with $Frl > 0.04$,

$$h_{NBD} = (0.6683 \cdot Co^{-0.2} + 1058.0 \cdot Bo^{0.7} F_{fl}) h_L \tag{10}$$

$$h_{CBD} = (1.1360 \cdot Co^{-0.9} + 667.2 \cdot Bo^{0.7} F_{fl}) h_L \tag{11}$$

Oh and Katsuta have performed the experiment for mass flux from 240 to 720 kg/m^{2}s, mass quality from 0.1 to 1, heat flux from 10 to 20 kW/m^2. From the data obtained, the experimental correlation which could be estimate the boiling heat transfer coefficients within small diameter tubes with accuracy of ± 30 % is proposed as follows:

$$h_{TP} = \frac{240}{X_{tt}} \left(\frac{1}{Re_L} \right)^{0.6} h_{LZ} \tag{12}$$

where, h_{LZ} is the new proposed correlation for single-phase heat transfer as follows:

$$h_{LZ} = 0.0177 \left[\frac{G(1-x) d_{ID}}{\mu_L} \right]^{0.8} \mathrm{Pr}_L^{0.4} \frac{\kappa_L}{d_{ID}} \tag{13}$$

Fig. 9 shows the experimental data of R-22 compared to the previous correlations. In Fig. 9, Shah's and Kandlikar's correlations over -predicted the data at ranges from mass quality 0 to 0.3. On the other hand, Jung's correlation predicted the data well. But, Shah's, Jung's and Kandlikar's correlation underestimated the data from the ranges over mass quality 0.6. It showed that the previous correlations could not explain the fact that the evaporation heat transfer characteristics have higher heat transfer coefficients at high quality regions, over quality 0.6, in small diameter tubes. Oh and Katsuda's correlation predicted the data very well at the ranges from quality 0.3 to 0.7, generally known the annular flow region in spite of miscalculating the data at the ranges from quality 0 to 0.3 and from 0.7 to 1. It is thought that Oh and Katsuda's correlation explains the evaporation heat transfer characteristics better than the previous correlations.

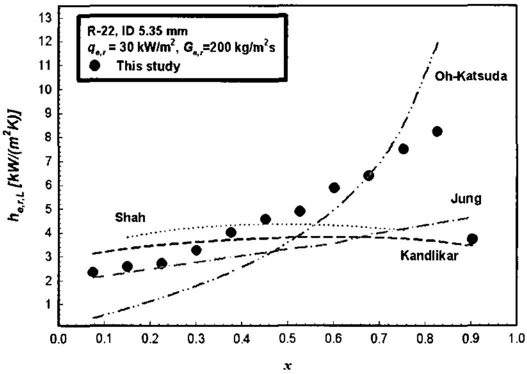

Fig. 9 Comparison of experimental $h_{e,r,L}$ and h_{cal} using the previous correlations in ID 5.35 mm

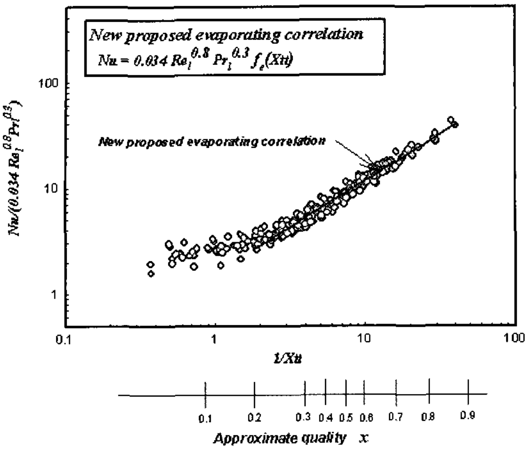

Fig. 10 Comparison of experimental Nu and calculated Nu using the new proposed evaporating correlation.

3.3 Evaporation heat transfer correlations development

Based on an analogy between heat and mass transfer, like Oh and Katsuta's correlation, the experimental correlation which could estimate the evaporating heat transfer coefficients within small diameter tubes with accuracy of ± 8.3 % is proposed as equation (14) and the deviation em between the experimental data and predicted data was calculated by equation (16).

$$Nu_e = 0.034\,Re_l^{0.8}\,Pr_l^{0.3}\,f_e(Xtt) \tag{14}$$

$$f_e(Xtt) = \left[1.58\left(\frac{1}{Xtt}\right)^{0.87}\right] \tag{15}$$

$$e_m = \frac{1}{N}\left(\sum_{1}^{N}\frac{\left|Nu_{exp} - Nu_{cal}\right|}{Nu_{exp}}\right) \times 100 \tag{16}$$

where, the application ranges of proposed correlation is as follows:

$$1.8 \le \left(\frac{1}{Xtt}\right) \le 40,\ 1.5mm \le d_{ID} \le 6mm,$$

$$200 \le G_{e,r} \le 800,\ 0.15 \le x \le 0.85,\ 10 \le q_{e,r} \le 30,$$

$$1000 \le Re_l \le 20000,\ 2 \le Pr_l \le 5$$

Fig. 10 shows the comparison of experimental data and calculated data using the proposed correlation. As shown in Fig. 10, the proposed correlation predicted the experimental data very well with Lochkart-Martinelli parameter and it is thought(that) Jung's correlation could be used restrictively at the rest ranges excepting the application ranges of proposed correlation for evaporating heat transfer in small diameter tubes.

4. Conclusion

The evaporation heat transfer coefficients for R-22 and R-134a were measured in small diameter tubes. The following conclusions were acquired from the experiment.

(1) The evaporation heat transfer coefficient of R-22 and R-134a has a tendency to increase with vapor quality for all tube diameters. The evaporation heat transfer coefficient has influenced on the variation of mass flux and tube diameter more than heat flux.

(2) The evaporation heat transfer characteristics in the small diameter tubes (ID < 7 mm) were observed to be strongly affected by inner diameter change and to differ from those in the large diameter tubes. The local evaporation heat transfer coefficients of ID 3.36 mm copper tube is about 15 % higher than those of ID 5.35 mm copper tube, And the evaporation heat transfer coefficients of ID 1.77 mm copper tube is about 20 % higher than those of ID 3.36 mm copper tube.

(3) It was very difficult to apply some well-known previous predictions (Shah's, Jung's and Kandlikar's correlation) to small diameter tubes. Oh-Katsuda's correlation represented the experimental data very well at the ranges from 0.3 to 0.7.

(4) It was very difficult to apply some well-known previous predictions (Shah's, Jung's and Kandlikar's correlation) to small diameter tubes. Therefore, the new correlation with accuracy of ± 8.3 %, based on an analogy between heat and mass transfer, is proposed to predict the experimental data successfully.

Reference

[1] Ralph L. Webb, Ming Zhang and R. Narayanamurthy, 1998,"Condensation Heat Transfer in Small Diameter Tubes", Proc. of 11th IHTC. vol. 6. p. 403-408.

[2] Oh, Hoo-Kyu, Park, Ki-Won, Roh, Geon-Sang and Hong, Jin-Woo, 2004, "Study on the Condensation Heat Transfer Characteristics in Small Diameter Tubes", J. of the Korea Society of Marine Engineers, vol. 28, no. 1, p.29-38.

[3] Wambsganss, M.W., Jendrzejczyk, J.A. and France, D. M., 1991, "Two-phase flow patterns and transitions in a small, horizontal, rectangular channel", Int. J. Multiphase Flow, vol. 17, no. 3, p. 327-342.

[4] Peng, X. F. and Wang, B. X. 1993, "Forced convection and flow boiling heat transfer for liquid flow through micro-channels", Int. J. Heat and Mass Transfer, vol. 36, no. 14, p. 3421-3427.

[5] Oh, Hoo-Kyu, Katsuta, M. and Shibata, K., 1998, "Heat transfer characteristics of R-134a in a capillary tube heat exchanger", Proceedings of 11th IHTC. vol. 6, p. 131-136.

[6] McLinden, M. O., Klein, S. A., Lemmon, E. W., Peskin, A. P., 1998, NIST Thermodynamic Properties and Refrigerant Mixtures Database (REFPROP), Version 6.01, National Institute of Standards and Technology, Gaithersburg, MD, U.S.A.

[7] Wilmarth, T. and Ishii, M., 1994, "Two-phase flow regimes in narrow rectangular vertical and horizontal channels", Int. J. Heat and Mass Transfer, vol. 37, no. 12, p. 1749-1758.

[8] Wambsganss, M. W., France, D. M. and Jendrzejczyk, J. A., 1993, "Boiling heat transfer in a horizontal small-diameter Tube", Trans. ASME, vol. 115, p. 963-972.

[9] Oh, Hoo-Kyu and Hong, Jin-Woo, 2002, "Study on the Flow Characteristics of R-22, R-134a in Small Diameter Tubes", Trans of SAREK, vol. 14, no. 9, p. 756-765.

[10] Shah, M. M., 1982, "Chart correlation for saturated boiling heat transfer equations and further study", ASHRAE Tran., vol.88, p. 185-196.

[11] Jung, Dong-Soo, McLinden, M., Randermacher, R. and Didion, D., 1989, "A study of flow boiling heat transfer with refrigerant mixtures",

Int. J. Heat and Mass Transfer, vol. 32, no. 9, p. 1751-1764.

[12] Kandlikar, S.G., "A general correlation for saturated two-phase flow boiling horizontal and vertical tubes", Trans. ASME, vol. 112, p. 219-228.

Author Profile

Geon-Sang Roh

He received his Ph. D in 1997 from Pukyong National University. He is currently a professor at Tongmyong University. His interests are in applications of high efficient refrigeration system and heat exchanger

Hoo-Kyu Oh

He received his Ph. D in 1975 from Waseda University, Japan. He is currently a professor at Pukyong National University. His interests are in applications of high efficient refrigeration system and heat exchanger using natural refrigerants.