Исследование картины течения и теплопроводности R22 и R134a при испарении в трубах малого диаметра

До недавнего времени использовались трубы большого диаметра. Однако в настоящее время широко применяются трубы малого диаметра из-за их высокой эффективности по теплопроводности и низкой стоимости. В данной статье рассматриваются результаты экспериментального исследования картины течения и коэффициентов теплопроводности при испарении R22 и R134a в трубах малого диаметра. Наблюдали за течением R22 и R134a при испарении в стеклянных смотровых трубках с внутренним диаметром 2 и 8 мм соответственно, а коэффициенты теплопроводности измеряли в ровных горизонтальных медных трубках с внутренним диаметром 1,77; 3,36 и 5,35 мм.

В картинах течения при испарении видны кольцевые потоки в стеклянной трубке диаметром 2 мм или при относительно низком качестве массы в трубке диаметром 8 мм. Картины течения в стеклянной трубке диаметром 2 мм немного не совпадали с картами моделей потоков Мэндхэйна. Коэффициенты теплопроводности при испарении в трубках малого диаметра (7 мм), по наблюдениям, в значительной степени зависят от диаметров труб и отличаются от предполагаемых величин в трубах большого диаметра. Коэффициенты теплопроводности медной трубки с внутренним диаметром 1,77 мм на ≈ 20 – 30 % превышали таковые медной трубы с внутренним диаметром 3,36 мм и 5,35 мм. Кроме того, обнаружено, что некоторые известные предварительные величины (корреляция Шаха, Юнга, Кандликара и О-Катсуды) очень трудно применить в отношении труб малого диаметра. На основании полученных данных, предполагается новая корреляция для нахождения коэффициентов теплопроводности R22 и R134a при испарении в трубах малого диаметра.

По желанию авторов представленная ниже статья по материалам доклада публикуется на английском языке.

Study on the evaporating flow patterns and heat transfers of R22 and R134a in small diameter tubes

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ABSTRACT

Large diameter tubes have been used until comparatively lately. However, small diameter tubes are largely used these days because of their high efficiency in heat transfer and low cost. This study focuses on the experimental research of the flow patterns and heat transfer coefficients during evaporating process of R22 and R134a in small diameter tubes. The evaporating flow patterns of R22 and R134a were observed in pyrex sight glass tubes with ID 2 and 8 mm, respectively, and heat transfer coefficients were measured in smooth horizontal copper tubes with ID 1.77, 3.36 and 5.35 mm.

In the flow patterns during evaporating process, the annular flows in ID 2 mm glass tube occurred at a relatively lower mass quality compared to ID 8 mm glass tube. The flow patterns in ID 2 mm glass tube have been fairly discordant with the Mandhane's flow pattern maps. The evaporating 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 ~ 30 % than those of ID 3.36 mm copper tube and ID 5.35 mm copper tube. 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 evaporating heat transfer coefficients of R22 and R134a in small diameter tubes.

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;

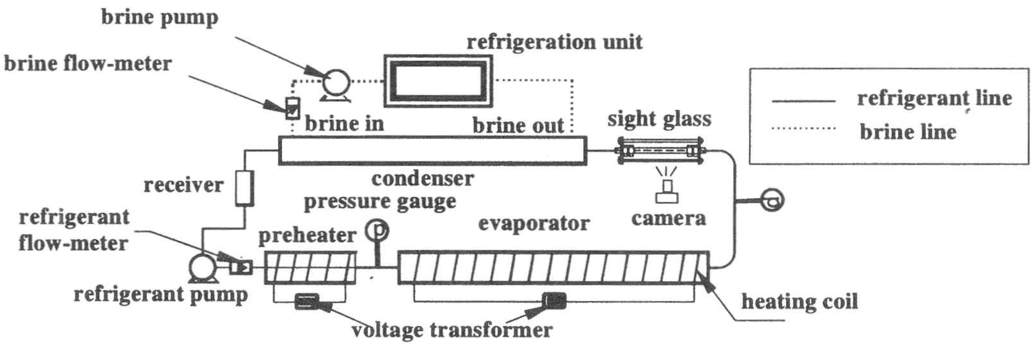


Fig. 1. Schematic diagram of experimental apparatus for evaporating flow patterns and heat transfer

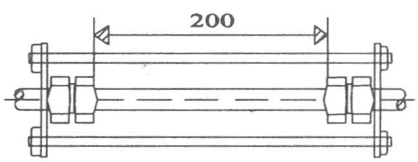
Wambsganss et al [3] studied horizontal two-phase flow in a small cross-sectional-area rectangular channel. The data from the small rectangular channel of the present study were in poor agreement with the generalized rectangular two-phase flow pattern results that were based on larger channels. Peng 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 (that) 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 R134a in small diameter tubes with ID 0.75 and 1.0 mm, 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·s) and reported (that)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 evaporating heat transfer characteristics in small diameter tubes differ from those in large diameter tubes. In this study, evaporating flow patterns were observed in horizontal pyrex sight glass tubes of ID 2 mm and 8 mm respectively. Also, heat transfer coefficients of R22 and R134a were measured in smooth horizontal copper tubes with ID 1.77, 3.36 and 5.35 mm, respectively.

1. EXPERIMENTAL APPARATUS AND PROCEDURES

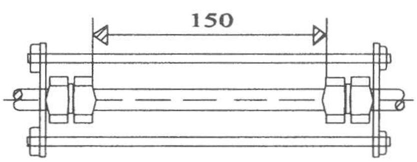
1.1. Test Facility

The test facility consists of a refrigerant loop and brine loop. Fig. 1 shows the schematic diagram of experimental apparatus. The refrigerant loop contains a refrigerant pump, a mass flow-meter, a pre-heater, an evaporator (test section for evaporating heat transfer experiment), a pyrex sight glass tube(test section for evaporating flow patterns experiment) , a condenser and a receiver etc. 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 is controlled by a valve that restricts the flow of brine. 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 schematic drawings of pyrex sight glass tubes. In Fig. 2, inner diameters of sight glass tubes are 2 and 8 mm, respectively. Fig. 3 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 350 mm length of an evaporator. The evaporator is instrumented with temperatures and pressure sensors. In the



(a) ID 8 mm sight glass tube



(b) ID 2 mm sight glass tube

Fig. 2. Drawing of pyrex sight glass tube

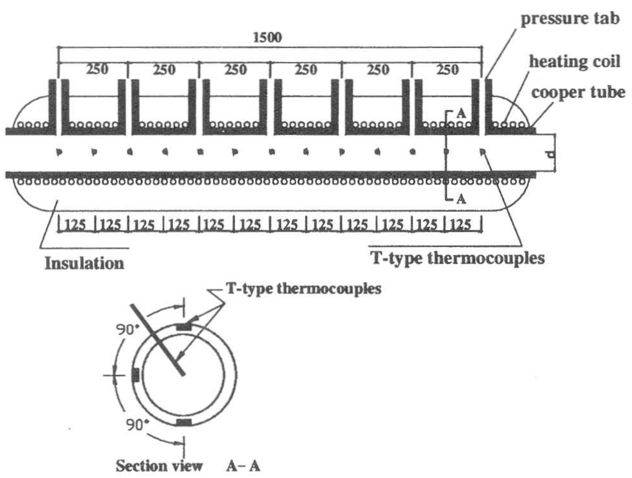


Fig. 3. Drawing of test section for evaporating heat transfer

evaporator, 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). Channel output signals from instrumentation points are fed to a data acquisition and control unit, and processed by desktop computer, which communicate directly via an interface bus. The test facility is allowed to come to steady state before the data acquisition. A summary of test conditions during testing is given in Table 1.

1.2. Data Reduction

An analysis is needed to calculate the evaporating heat transfer coefficients from the experimental data. The data reduction process is described in the following. Before measuring the evaporating 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)

$$Q_{coil} = \zeta VI, \tag{1}$$

where ζ – a heating coefficient;

V – input voltage;

Table 1

Experimental conditions for evaporating flow patterns and heat transfer

Refrigerant	R22	R134a
ID of sight glass tube(mm)	2, 8	
ID of copper tube(mm)	1.77, 3.36, 5.35	
Mass flux(kg/m² · s)	100 ~ 1000	
Mass quality (/)	0 ~ 1.0	

I – an input electric current.

$$Q_{e,r} = M_{e,r} \cdot c_{p,e,r} \int_{Te,r,in}^{Te,r,out} dz, \tag{2}$$

where $M_{e,r}$ – a refrigerant mass flow rate, kg/h;

$T_{e,r,in}$ – an inlet temperature of refrigerant, K;

$T_{e,r,out}$ – an outlet temperature of refrigerant, K;

$c_{p,e,r}$ 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).

$$q_{e,r} = \frac{Q_{coil}}{\pi \cdot d_{IN} \cdot dz}, \tag{3}$$

where dz indicates the effective length of a subsection;

d_{ID} – inner diameter of copper tube;

Q_{coil} – also calculated as equation (1).

The circumferential local heat transfer coefficient of refrigerant during evaporating process, kW/[m²·K], 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).

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

where $T_{e,wo}$ – outside wall surface temperature of copper tube and it is averaged by measuring the top, side and bottom temperature;

k_w – a thermal conductivity of copper tube.

The mass quality of refrigerant is calculated as equation (6) at each subsection.

$$x = x_{e,IN} + \frac{\pi \cdot d_{ID}}{G_{e,r} \cdot i_{e,fg}} \int_{Z1}^{Z2} q_{e,r} dz, \tag{6}$$

where, $G_{e,r}$ – mass flux [kg/m²·s];

$i_{e,fg}$ – an evaporating latent heat.

In this study, all refrigerant properties are calculated by REFPROP(version 5.0) made by NIST(National Institute of Standards and Technology)[6].

2. RESULTS AND DISCUSSION

2.1. Evaporating flow patterns

Fig. 4 shows photographs of experimental flow patterns in ID 8 mm and ID 2 mm sight glass tube respectively when mass flux of R134a is 200 kg/(m²·s). Wavy flows happened to ID 8 mm tube from mass quality 0.3. But, the transitions from stratified flow to wavy flows have already started to ID 2 mm tube from mass quality 0.1. Also, the transitions from stratified flow or wavy flow to annular flow in ID 2 mm tube were faster than those in ID 8 mm tubes. Fig. 5 shows the result obtained from R22 in ID 2 mm tube and was compared to Mandhane's flow pattern map. The solid lines are associated with Mandhane's flow pattern and the alphabets in Fig. 5 represent real flow patterns observed

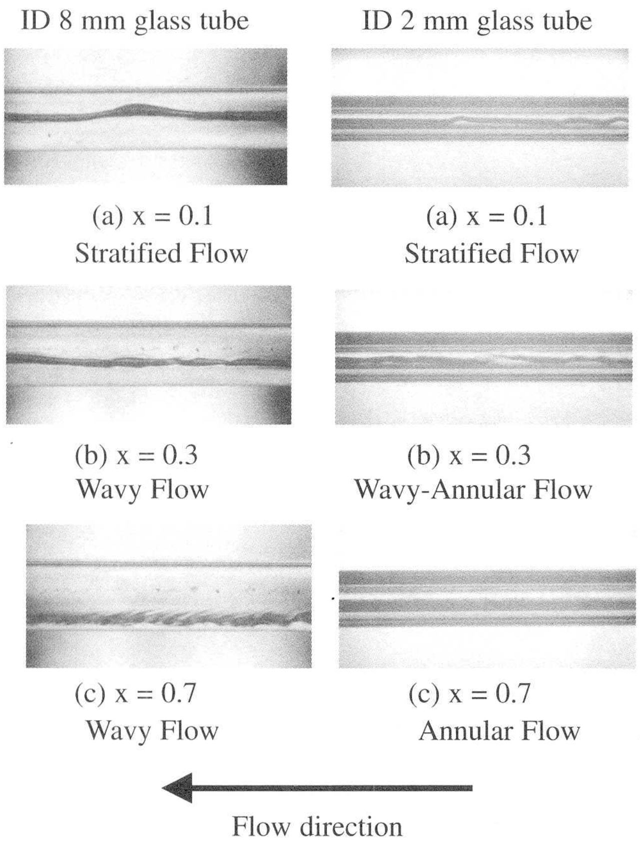


Fig. 4. Photograph of experimental flow patterns for R134a in ID 8 mm and ID 2 mm tubes

through the experiment. "W" symbolizes wavy flow pattern, "W-A" represents wavy-annular flow pattern and "A" indicates annular flow pattern. As shown in Fig. 5, flow patterns in ID 2 mm tube are fairly discordant with the Mandhane's flow pattern map proposed from the experimental result obtained in large diameter tubes. This result proves that Mandhane's flow pattern map could not explain enough that annular flows happen faster to small diameter tube, like ID 2 mm tube, from lower mass quality, compared to larger diameter tube like ID 8 mm tube.

2.2. Evaporating heat transfer

Fig. 6 represents local evaporating heat transfer coefficients of R22 with mass quality in ID 3.36 mm and 5.35 mm copper tube respectively and Fig. 7 shows local evaporating heat transfer coefficients of R134a in ID 1.77 mm and 3.36 mm copper tube. Here, the coefficients are calculated by the equation (4). In Fig. 6, local evaporating heat transfer coefficients of ID 3.36 mm tube is about 15 % higher than those of ID 5.35 mm tube and Fig. 7 shows the evaporating heat transfer coefficients of ID 1.77 mm tube is about 20 % higher than those of ID 3.36 mm. Also, the coefficients have been changed a lots with quality in all tubes. Specially, the elevations of coefficients were distinct at the ranges from quality 0.5 to 0.8 as the reduction of inner diameter reduced. It is 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, like the comment in "2.2 Evaporating flow pattern". Through the experiment for evaporating flow patterns, 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[7].

2.3. Comparison of evaporating heat transfer correlations

It is important to compare the present data in small diam-

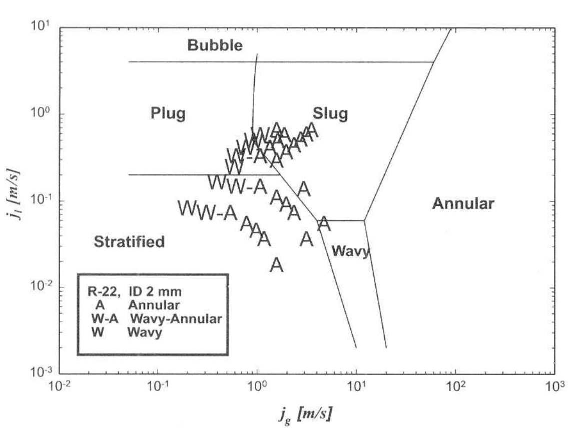


Fig. 5. Comparison of experimental flow patterns with Mandhane's flow pattern map in ID 2 mm tube

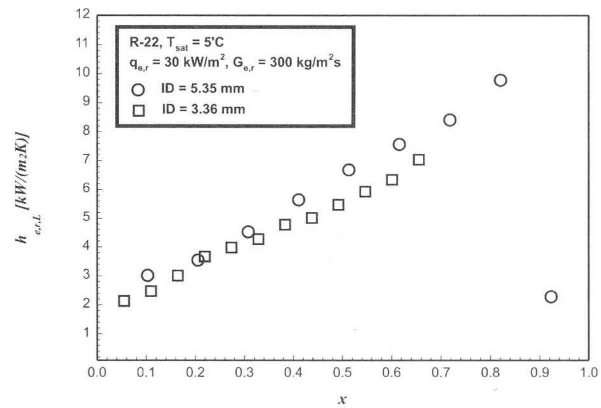


Fig. 6. Comparison of local evaporating heat Transfer coefficients with mass quality in ID 3.36 mm and 5.35 mm tube

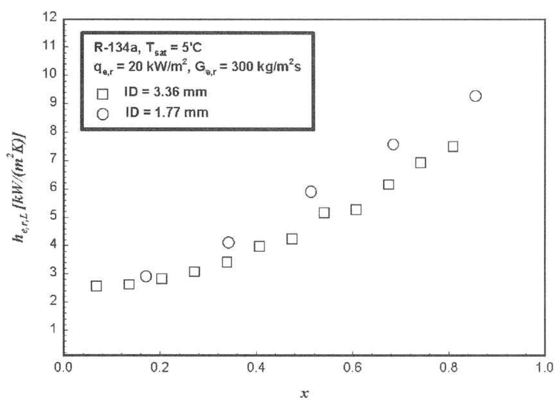


Fig. 7. Comparison of local evaporating heat transfer coefficients with mass quality in ID 1.77 mm and ID 3.36 mm tube

eter tubes to the previous correlations. In this paper, Shah's, Jung's and Kandlikar's 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[8] 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;

$$h_{TP} = \psi \cdot h_l; \tag{7}$$

$$h_l = 0.023\left[\frac{G\cdot(1-x)\cdot d_i}{\mu_l}\right]^{0.8} \mathrm{Pr}_l^{0.4}\,\frac{k_l}{d_{ID}}; \tag{8}$$

where h_{TP} – sum of heat transfer coefficients;

h_l – the liquid-only heat transfer coefficient and parameter is decided by values of Fr_l, Bo, Co.

The three parameters of Fr_l, *Bo*, *Co* used in Shah's correlation are rather well-known dimensionless parameters used in many other engineering correlations. Jung's correlation [9] 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;

$$h_{TP} = h_{nbc} + h_{cec} = N\times h_{SA} + F_p\times h_l, \tag{9}$$

where h_{nbc} – nucleate boiling contribution heat transfer coefficient;

h_{cec} – convective evaporating contribution heat transfer coefficient.

A simple correlation was developed earlier by Kandlikar [10] to predict saturated flow boiling heat transfer coefficients inside horizontal and vertical tubes. It incorporated a fluid-dependent parameter F_{fl} in the nucleate boiling term. His correlation is as follows;

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

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

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

Oh and Katsuta [5] have performed the experiment for mass flux from 240 to 720 kg/m²·s, mass quality from 0.1 to 1, heat flux from 10 to 20 kW/m². 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;

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

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

$$h_{LZ} = 0.0177\left[\frac{G\cdot(1-x)\cdot d_{ID}}{\mu_l}\right]^{0.8} \mathrm{Pr}_l^{0.4}\,\frac{k_l}{d_{ID}}. \tag{13}$$

Fig. 8 shows the experimental data of R22 compared to the previous correlations. In Fig. 8, 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 evaporating 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 evaporating heat transfer characteristics better than the previous correlations. It is predicted that it is very difficult to apply the previous correlations to small diameter tubes. Based on an analogy between heat and mass transfer, like Oh-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 e_m between the experimental data and predicted data was calculated by equation (16).

$$Nu_e = 0.034\,\mathrm{Re}_l^{0.8}\,\mathrm{Pr}_l^{0.3}\,f_e(Xtt); \tag{14}$$

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

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

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

$$1.8 \le \left(\frac{1}{Xtt}\right) \le 40,\quad 1.5mm \le d_{ID} \le 6mm,\quad 200 \le G_{e,r} \le 800,$$

$$0.15 \le x \le 0.85,\quad 10 \le q_{e,r} \le 30,\quad 1000 \le \mathrm{Re}_l \le 20000,\quad 2 \le \mathrm{Pr}_l \le 5.$$

Fig. 9 shows the comparison of experimental data and calculated data using the proposed correlation. As shown in Fig. 9, 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

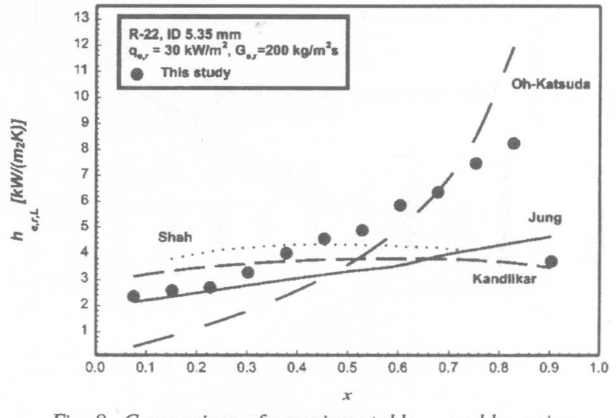


Fig. 8. Comparison of experimental $h_{e,r,L}$ and h_{cal} using the previous correlations in ID 5.35 mm tube

proposed correlation for evaporating heat transfer in small diameter tubes.

3. CONCLUSIONS

Evaporating flow patterns and heat transfer coefficients for R22 and R134a were measured in small diameter tubes. The following conclusions were acquired from the experiment.

(1) In flow patterns during evaporating process, annular flows in ID 2 mm sight glass tube occurred at the relatively lower mass quality comparing to ID 8 mm sight glass tube. The flow patterns in ID 2 mm tube have been fairly discordant with the Mandhane's flow pattern maps.

(2) Evaporating 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 evaporating heat transfer coefficients of ID 3.36 mm copper tube is about 15 % higher than those of ID 5.35 mm copper tube, Fig. 7 shows that the evaporating 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. Therefore, the new correlation with accuracy of Ўs 8.3 %, based on an analogy between heat and mass transfer, is proposed to predict the experimental data successfully.

NOMENCLATURE

c_p – specific heat, kJ/(kg·K);
d – diameter of tube, m;
G – mass flux, kg/m²·s;
h – heat transfer coefficient, kW/(m²·K);
i_{fg} – latent heat, kJ/kg;
ID – inner diameter, mm;
k – thermal conductivity, kW/(m·s);
M – mass flow rate, kg/h;
Q – heat capacity, kW;
q – heat flux, W/m²;

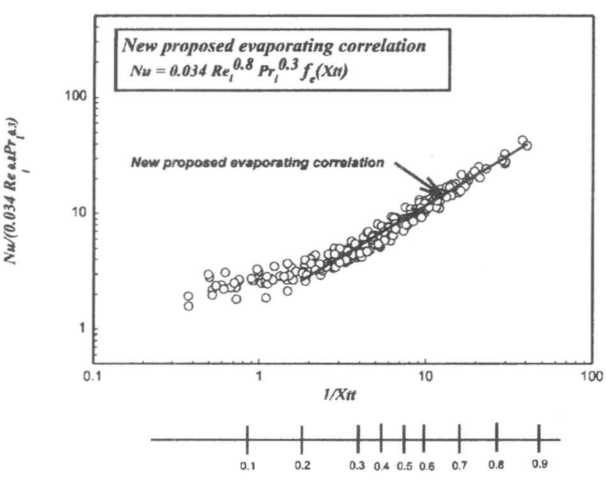


Fig. 9. Comparison of experimental Nu and Calculated Nu_e using the new proposed evaporating correlation

T – temperature, K;
x – quality;
z – tube length, m.

Subscripts

cal	calculated
e	evaporator
exp	experimental
ID	inner diameter
in	inlet
l	liquid
L	local
OD	outer diameter
out	outlet
r	refrigerant
TP	two phase
w	wall
wi	inside wall
wo	outside wall

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