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The Evaporation Flow Patterns and Heat Transfers of R-22 and R-134a in Small Diameter Tubes

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세관내 R-22 and R-134a의 증발 유동양식과 열전달

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ABSTRACT

본 논문은 세관(ID<7 mm) 내 R-22와 R-134a의 증발 열전달과 유동양식에 대한 실험적 연구이다. R-22와 R-134a의 유동양식을 관찰하기 위해 내경 2와 8 mm의 파이렉스 튜브를 사용하였고, 열전달계수는 내경 1.77, 3.36, 5.35 mm의 수평 평활동관에 대해서 측정하였다. 증발 유동양식에서 내경 2 mm의 환상류 영역이 내경 8 mm에 비해 저건도 영역에서 발생하는 것을 확인할 수 있었고, 내경 2 mm의 유동양식은 Mandhane의 선도와 많은 오차를 보였다. 세관(ID<7 mm) 내 증발 열전달 계수는 종래의 대구경관(ID>7 mm)에 비해 관직경에 대한 영향이 많이 나타나는 것을 알 수 있었다. 내경 1.77 mm의 열전달 계수는 내경 3.36 mm와 5.35 mm에 비해서 20내지 30% 정도 높은 것을 나타났다. 또한 종래의 열전달 상관식(Shah's, Jung's, Kandlikar's and Oh-Katsuda's correlation)과 비교한 결과, 실험데이터는 상관식과 많은 이탈 정도를 보였다. 따라서 실험데이타를 기초로 세관내 R-22와 R-134a에 적용할 수 있는 증발 열전달 상관식을 새로이 제안하였다.

KEY WORDS : alternative refrigerant(대체냉매), evaporation heat transfer coefficient(증발열전달계수), mixture refrigerant(혼합냉매), small diameter tube(세관)

Nomenclature

d : diameter of tube, m
G : mass flux, kg/m^{2}s
h : heat transfer coefficient, kW/m^{2}K
i_{fg} : latent heat, kJ/kg
ID : inner diameter, mm
k : thermal conductivity, kW/m · s
Q : heat capacity, kW
q : heat flux, kW/m^2
T : temperature, K
x : quality
z : tube length, m

Subscripts

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cal : calculated
e : evaporator
exp : experimental
ID : inner diameter
l : liquid
L : local
OD : outer diameter
r : refrigerant
TP : two phase

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 (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 R-134a in small diameter tubes with ID 0.75 and 1.0 mm, for mass flux from 240 to 720 kg/m^2·s, vapor 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 R-22 and R-134a were measured in smooth horizontal copper tubes with ID 1.77, 3.36 and 5.35 mm, respectively.

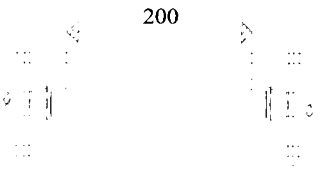
2. Experimental Apparatus and Methods

2.1 Test Facility

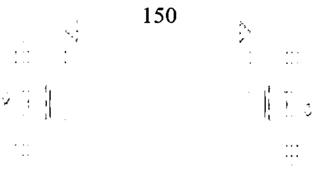
The test facility consists of a refrigerant loop and brine loop. Fig. 1 shows the schematic diagram of experimental apparatus. The refrigerant loop contains a refrigerant pump, a mass flow-meter, a pre-heater, an evaporator(test section for evaporating heat transfer experiment), a pyrex sight glass tube(test 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 accuracy 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 evaporator, T-type thermocouples are used to measure temperatures. 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 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.



(a) ID 8 mm sight glass tube



(b) ID 2 mm sight glass tube

Fig. 2 Drawing of pyrex sight glass tube

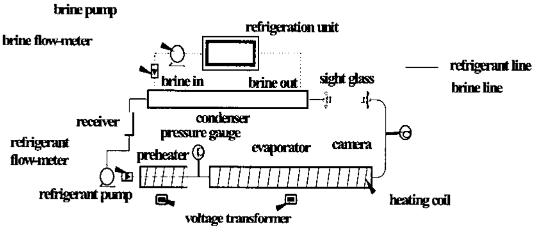


Fig. 1 Schematic diagram of experimental apparatus for evaporating flow patterns and heat transfer

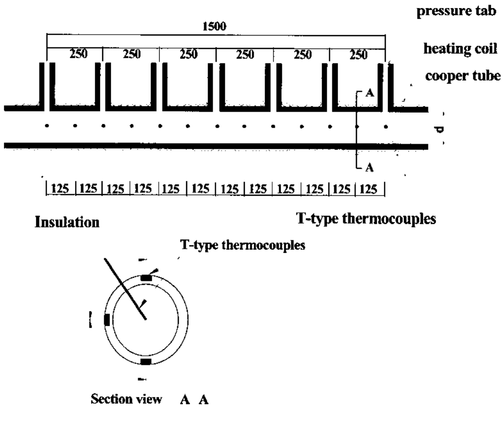


Fig. 3 Drawing of test section for evaporating heat transfer

Table 1 Experimental conditions for evaporating flow patterns and heat transfer

Refrigerant	R-22	R-134a
ID of sight glass tube (mm)	2, 8	
ID of copper tube (mm)	1.77, 3.36, 5.35	
Mass flux (kg/m^2s)	100~1000	
Vapor quality (/)	0~1.0	

Table 2 Parameters and estimated uncertainties

Parameters	Uncertainty
T, [℃]	±0.1℃
P, [Pa]	±1000Pa
G, [kg/m^2s]	±2%
Q, [kW]	±3%
h, [kW/m^2K]	±8%

2.2 Data Reduction

The circumferential local heat transfer coefficient of refrigerant during evaporating process is calculated by the following equation (1).

$$h_{e,r,L} = \frac{q_{e,r}}{(T_{e,wi} - T_{e,r})} \qquad (1)$$

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. The vapor quality of refrigerant is calculated as equation (2) at each subsection.

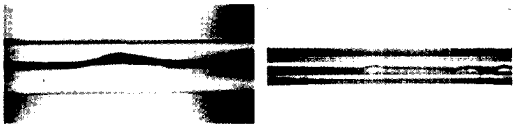
$$x = x_{e,IN} + \frac{\pi \cdot d_{ID}}{G_{e,r} \cdot i_{e,fg}} \int_{z1}^{z2} q_{e,r} dz \qquad (2)$$

where, $G_{e,r}$ is mass flux and $i_{e,fg}$ is an evaporating latent heat.

3. Results and Discussions

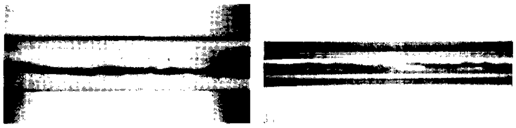
3.1 Evaporation Flow Patterns

Fig. 4 shows photographs of experimental flow patterns in ID 8 mm and ID 2 mm sight glass tube respectively when mass flux of R-134a is 200 kg/m^2s. Wavy flows happened to ID 8 mm tube from vapor quality 0.3. But, the transitions from stratified flow to wavy flows have already started to ID 2 mm tube from vapor 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 R-22 in ID 2 mm tube (and) was compared to Mandhane[7]'s flow pattern map. The solid lines are associated with Mandhane's flow pattern and the alphabets in Fig. 5 represent real flow ID 8 mm glass tube ID 2 mm glass tube patterns observed through the experiment. "W" symbolizes wavy flow pattern, "W-A" represents



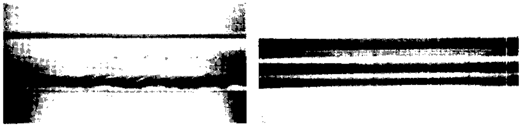
(a) x=0.1
Stratified Flow

(a) x=0.1
Stratified Flow



(b) x=0.3
Wavy Flow

(b) x=0.3
Wavy-Annular Flow



Wavy flow

Annular Flow

Flow direction

Fig. 4 Photograph of experimental flow patterns for R-134a in ID 8 mm and ID 2 mm tubes

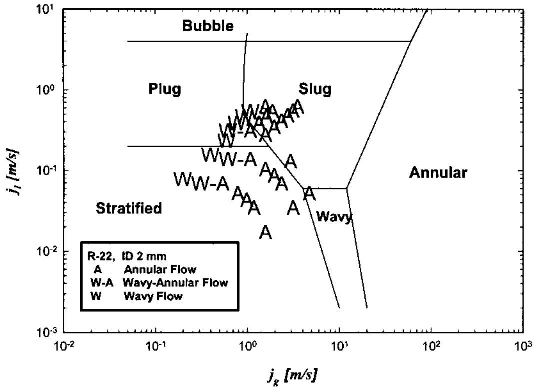


Fig. 5 Comparison of experimental flow patterns with Mandhane's flow pattern map in ID 2 mm tube

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 vapor quality, compared to larger diameter tube like ID 8 mm tube.

3.2 Evaporation Heat Transfer

Fig. 6 represents local evaporating heat transfer coefficients of R-22 with vapor quality in ID 3.36 mm and 5.35 mm copper tube respectively and Fig. 7 shows local evaporating heat transfer coefficients of R-134a in ID 1.77 mm and 3.36 mm copper tube. Here, the coefficients are calculated by the equation (1). 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 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 as described in the "3.1 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[8].

3.3. Comparison of Existing Heat Transfer Correlations

It is important to compare the present data in small diameter 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[9] has proposed the following correlation (3) for boiling heat transfer in vertical and horizontal tubes and annuli. Shah 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;

$$h_{TP} = \psi \cdot h_l \tag{3}$$

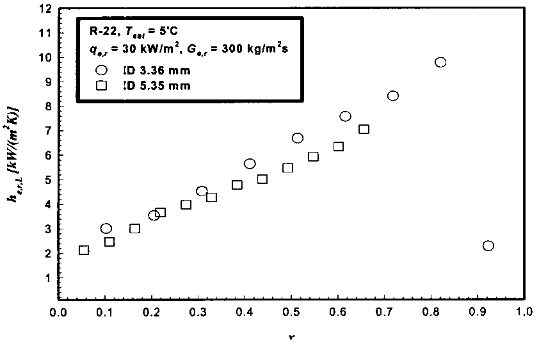


Fig. 6 Comparison of local evaporating heat transfer coefficients with vapor quality in ID 3.36 mm and 5.35 mm tube

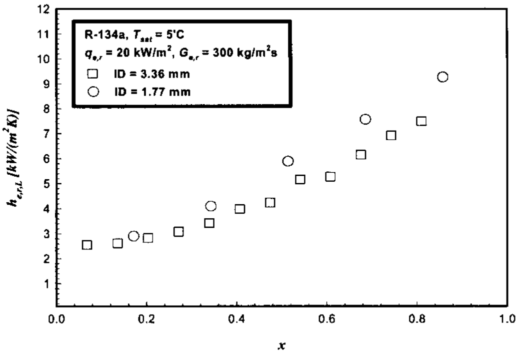


Fig. 7 Comparison of local evaporating heat transfer coefficients with vapor quality in ID 1.77 mm and ID 3.36 mm tube

$$h_l = 0.023\left[\frac{G\cdot(1-x)\cdot d_i}{\mu_l}\right]^{0.8}\mathrm{Pr}_l^{0.4}\frac{k_l}{d_{ID}} \tag{4}$$

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 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[10] 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;

$$h_{TP} = h_{nbc} + h_{cec} = N \times h_{SA} + F_p \times h_l \tag{5}$$

where, h_{nbc} is nucleate boiling contribution heat transfer coefficient and, h_{cec} is convective evaporating contribution heat transfer coefficient. A simple correlation was developed earlier by Kandlikar[11] 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. Kandlikar's correlation is as follows;

For vertical flow and horizontal flow with Frl> 0.04,

$$h_{NBD} = (0.6683Co^{-0.2} + 1058.0Bo^{0.7}F_{fl})h_l \tag{6}$$

$$h_{CBD} = (1.1360Co^{-0.9} + 667.2Bo^{0.7}F_{fl})h_l \tag{7}$$

Oh and Katsuta[4] have performed the experiment for mass flux from 240 to 720 kg/m²·s, vapor 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;

$$h_{TP}=\frac{240}{X_{tt}}\left(\frac{1}{\mathrm{Re}_l}\right)^{0.6}h_{LZ} \tag{8}$$

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

$$h_{LZ}=0.0177\left[\frac{G\cdot(1-x)\cdot d_{ID}}{\mu_l}\right]^{0.8}\mathrm{Pr}_l^{0.4}\frac{k_l}{d_{ID}} \tag{9}$$

Fig. 8 shows the experimental data of R-22 compared to the previous correlations. In Fig. 8, Shah's and Kandlikar's correlations over-predicted the data at ranges from vapor 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 (10) and the deviation em between the experimental data and predicted data was calculated by equation (11).

$$Nu_e=0.034\,\mathrm{Re}_l^{0.8}\,\mathrm{Pr}_l^{0.3}f_e(Xtt) \tag{10}$$

$$f_e(Xtt)=\left[1.58\left(\frac{1}{Xtt}\right)^{0.87}\right] \tag{11}$$

$$e_m=\frac{1}{N}\left(\sum_{1}^{N}\frac{\left|Nu_{\mathrm{exp}}-Nu_{cal}\right|}{Nu_{\mathrm{exp}}}\right)\times 100 \tag{12}$$

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

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

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

$$10\le q_{e,r}\le 30,\ 1000\le \mathrm{Re}_l\le 20000,$$

$$2\le \mathrm{Pr}_l\le 5$$

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 proposed correlation for evaporating heat transfer in small diameter tubes.

4. Conclusion

Evaporating flow patterns and heat transfer coefficients for R-22 and R-134a 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, 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 ±8.3%, based on an analogy between heat and mass transfer, is proposed to predict the experimental data successfully.

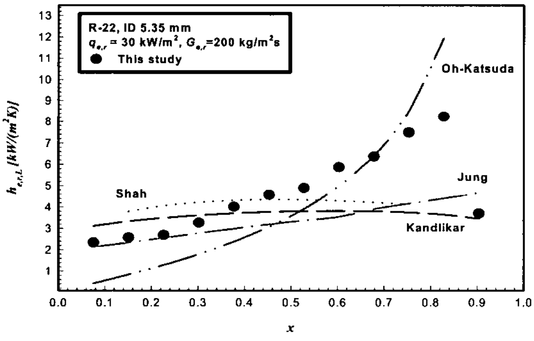


Fig. 8 Comparison of experimental $h_{e,r,L}$ and h_{cal} using the previous correlations in ID 5.35 mm tube

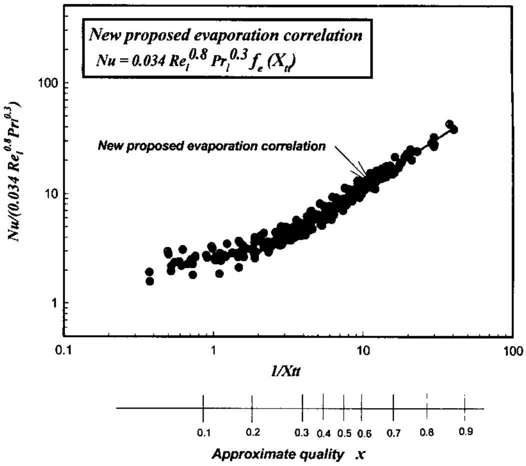


Fig. 9 Comparison of experimental Nu and calculated Nu_e using the new proposed evaporating correlation

참 고 문 헌

1) Webb, R. L., Zhang, M. and Narayanamurthy, R., Condensation Heat Transfer in Small Diameter Tubes, Proc. of 11th IHTC, Vol. 6, 1998, pp. 403-408.
2) Oh, H. K. and Hong, J. W., Condensing heat transfer characteristics of alternative refrigerants in small diameter tubes, J. of SAREK, Vol. 28, No. 5, 1999, pp. 396-402.
3) Wambsganss, M. W., Jendrzejczyk, J. A. and France, D. M., Two-phase flow patterns and transitions in a small, horizontal, rectangular channel, Int. J. Multiphase Flow, Vol. 17, No. 3, 1991, pp. 327-342.
4) Peng, X. F. and Wang, B. X., Forced convection and flow boiling heat transfer for liquid flow through micro-channels, Int. J. Heat and Mass Transfer, Vol. 36, No. 14, 1993, pp. 3421-3427.
5) Oh, H. K., Katsuta, M. and Shibata, K., Heat

transfer characteristics of R-134a in a capillary tube heat exchanger, Proceedings of 11th IHTC, Vol. 6, 1998, pp. 131 -136.

6) Gallagher, J., McLinden, M., Morrison, G. and Huber, M., NIST Thermodynamic Properties and Refrigerant Mixtures Database (REFPROP), Version 5.0, National Institute of Standards and Technology, Gaithersburg, MD, U.S.A., 1996.

7) Mandhane, J. M., A flow pattern map for gas-liquid flow in horizontal pipes, Int. J. Multiphase flow, Vol. 1, 1974, pp. 357-554.

8) Oh, H. K. and Hong, J. W., Study on the Flow Characteristics of R-22, R-134a in Small Diameter Tubes, Trans of SAREK, Vol. 14, No. 9, 2002, pp. 756-765.

9) Shah, M. M., Chart correlation for saturated boiling heat transfer equations and further study, ASHRAE Tran., Vol. 88, 1982, pp. 185-196.

10) Jung, D. S., McLinden, M., Randermacher, R. and Didion, D., A study of flow boiling heat transfer with refrigerant mixtures, Int. J. Heat and Mass Transfer, Vol. 32, No. 9, 1989, pp. 1751-1764.

11) Kandlikar, S. G., A general correlation for saturated two-phase flow boiling horizontal and vertical tubes, Trans. ASME, Vol. 112, pp. 219-228.