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Characteristics of R-22 and R-134a Two-Phase Flow Vaporization in Horizontal Small Tubes

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ABSTRACT: Characteristics of R-22 and R-134a two-phase vaporization in horizontal small tubes were investigated experimentally. In order to obtain the local heat transfer coefficients, the test was ran under heat flux range of 10 to 40 kW/m², mass flux range of 200 to 600 kg/m²s, saturation temperature range of 5 to 10°C, and quality up to 1.0. The test section, which was made of stainless steel tube and heated uniformly by applying an electric current to the tube directly, have inner tube diameters of 0.5, 1.5 and 3.0 mm, and lengths of 0.33 and 2.0 m. The effects on heat transfer coefficient of mass flux, heat flux and inner tube diameter were presented. The experimental heat transfer coefficients were compared with the predictions using existing heat transfer coefficient correlations. A new boiling heat transfer coefficient correlation based on the superposition model, with considering the laminar flow, was developed.

Nomenclature

Bo	: Boiling number
C	: Chisholm parameter
D	: Diameter [m]
F	: Convective two-phase multiplier
f	: Friction factor
G	: Mass flux [kg/m²s]
h	: Heat transfer coefficient [kW/m²K]
i	: Enthalpy [kJ/kg]
L	: Length of test section [m]
Q	: Electric power [kW]
q	: Heat flux [kW/m²]
Re	: Reynolds number
S	: Suppression factor of nucleate boiling
T	: Temperature [K]
W	: Mass flow rate [kg/s]
X	: Martinelli parameter
x	: Mass quality

Greek symbols

μ	: Dynamic viscosity [Ns/m²]
ρ	: Density [kg/m³]
σ	: Surface tension [N/m]
ϕ^2	: Two-phase frictional multiplier

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Gradients and Differences

(dp/dz) : Pressure gradient [N/㎡m]

Subscript

f : Saturated liquid
g : Saturated vapor
in : Physical property based on inlet temperature
i : Inner tube
nbc : Nucleate boiling contribution
pb : Nucleate pool boiling
sat : Saturation
sc : Subcooled
t : Turbulent
tp : Two-phase
v : Laminar
w : Wall

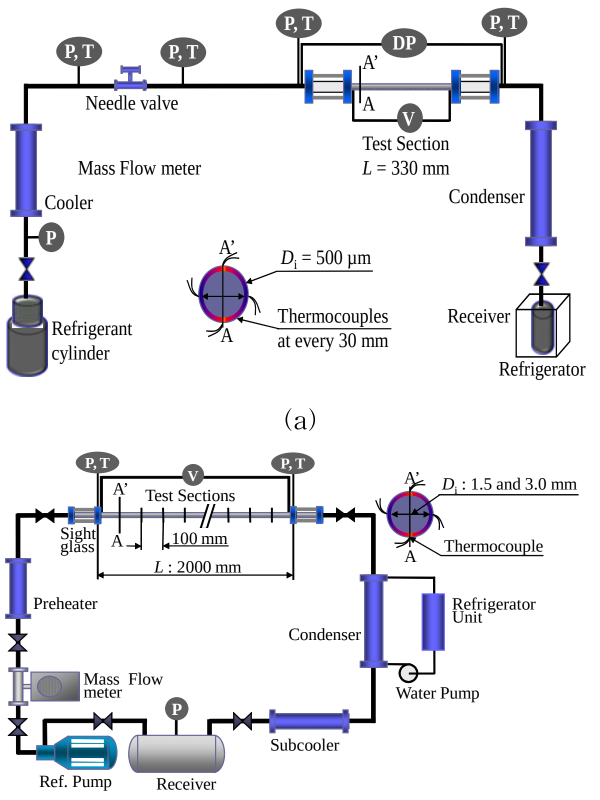
1. Introduction

A demand for smaller evaporators in the refrigeration has been led by recent awareness of the advantages of process intensification. However, the heat transfer of two-phase flow in small tubes cannot be properly predicted using existing procedures and correlations for large tubes. There has been little data published relating to two-phase flow heat transfer in small tubes compared with the data for large tubes. Compared with large tubes, evaporation in small tube may provide a higher heat transfer coefficient due to its higher contact area per unit volume of fluid. In evaporation with small tubes as reported in [1-5] the contribution of nucleate boiling is predominant and laminar flow appears.

In the present paper, the flow boiling heat transfer coefficients of R-22 and R-134a were measured in a horizontal smooth small tubes. The experimental results were compared with the predictions of six existing heat transfer correlations. A new correlation for refrigerants in small tubes was developed based on the superposition due to the limitations in the correlation for forced convective boiling in small tubes.

2. Experimental Apparatus

Fig. 1 shows a schematic diagram of the experimental facility. The test facility consisted of a condenser, a subcooler, a receiver, a pump, a mass flow meter, a preheater, and test sections. A variable A.C output motor controller was used to control the flow rate of refrigerant for the test with 1.5 and 3.0 mm tubes. For the test with 0.5 mm tube, the flow rate was controlled with the needle valve. A weighing balance was used to measure the refrigerant flow rate for the test with 0.5 mm tube, whereas a Coriolis-type mass flow meter was used for the



(b)

Fig. 1 The experimental test facility and test section: (a) Di = 0.5 mm, (b) Di = 1.5 and 3.0 mm

Table 1 Experimental condition

Working refrigerant	R-22	R-134a
Inner diameter (mm)	1.5, 3.0	0.5, 1.5, 3.0
Tube length (mm)	2000	330, 2000
Mass flux (kg/m²s)	300–600	200 – 400
Heat flux (kW/m²)	10 – 40	10 – 40
Inlet T_{sat}(°C)	10	5 – 10
Test section	Horizontal smooth minichannels	
Quality	0.0 – 1.0	

test with 1.5 and 3.0 mm tubes. The quality at the test section inlet was controlled by installing a preheater. For evaporation at the test section, a certain heat flux was conducted from a variable A.C voltage controller. The vapor refrigerant from the test section was condensed in the condenser, and then supplied to the receiver.

The outside tube wall temperatures at the top, both sides, and bottom were measured at certain axial intervals from the start of the heated length with thermocouples at each measured site. The tubes were well insulated with rubber and foam. The local saturation pressure, which was used to determine the saturation temperature, was measured using bourdon tube type pressure gauges at the inlet and the outlet of the test section. Table 1 lists the experimental test setup specifications in this study.

3. Data Reduction

The local heat transfer coefficients along the length of the test-section were defined as follows:

$$h = \frac{q}{T_{wi} - T_{sat}} \tag{1}$$

The inside tube wall temperature, T_{wi}, was determined using steady-state one-dimensional radial conduction heat transfer through the wall with internal heat generation. The local mass quality was determined based on the thermodynamic properties. The subcooled length was calculated using Eq. (2) to determine the initial point of saturation. The outlet mass quality was determined using Eq. (3).

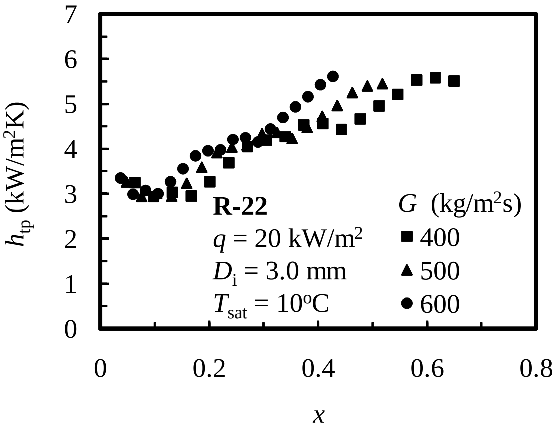
$$Z_{sc} = L\frac{i_f - i_{f,in}}{\Delta i} = L\frac{i_f - i_{f,in}}{Q/W} \tag{2}$$

$$x_0 = \frac{\Delta i + i_{f,in} - i_f}{i_{fg}} \tag{3}$$

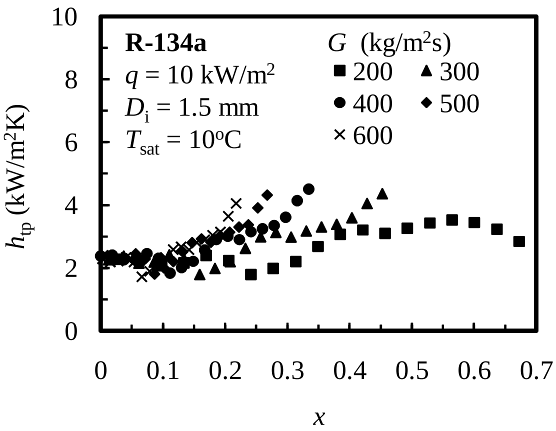
4. Result and Discussion

Figs. 2a and b show the effect of mass flux on heat transfer coefficient for R-22 and R-134a, respectively. The insignificant effect of mass flux on heat transfer coefficient at low quality region indicates that nucleate boiling heat transfer is predominant. Several studies with small tubes [1-5] reported that nucleate boiling is predominant in small tubes, which is opposite that of the predominantly convective-dominated heat transfer in conventional channel. At the intermediate quality region, heat transfer coefficients increase with increasing mass flux. It is similar to the results reported by [6].A higher mass flux provides greater heat transfer coefficient at intermediate-high quality due to the increasing convective boiling heat transfer contribution. For the higher mass flux condition in the convective boiling region, the increase in the heat transfer coefficient appears at a lower quality, which can be explained by the annular flow becoming dominant with increasing quality. Nucleate boiling suppression appears earlier for the higher mass flux, which means that convective heat transfer appears earlier under the higher mass flux condition.

Figs. 3a and b show that a strong dependence of the heat transfer coefficients on the heat flux appears at the low quality region for



(a)

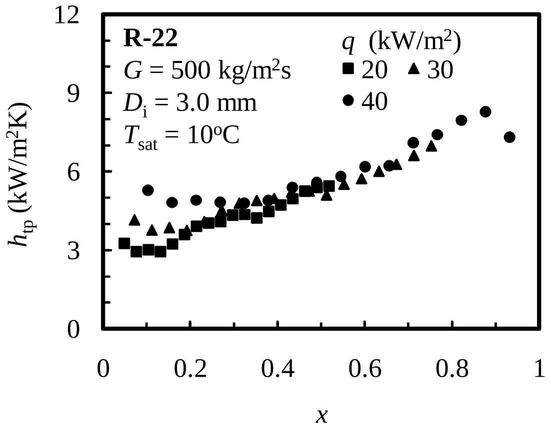


(b)

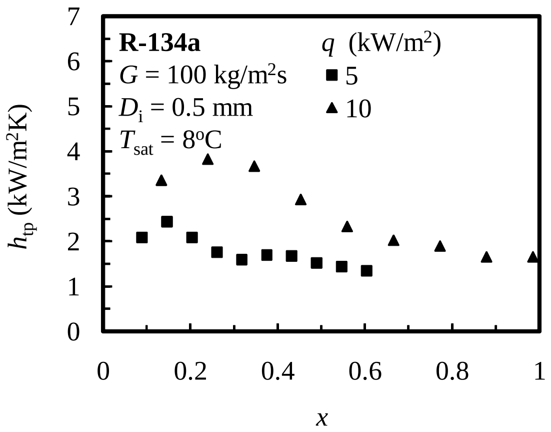
Fig. 2 The effect of mass flux on heat transfer coefficient: (a) R-22, (b) R-134a

R-22 and R-134a, respectively. At the low quality region, the heat transfer coefficients increased with increasing heat flux. Nucleate boiling is known to be dominant in the initial stage of evaporation, particularly under high heat flux conditions. Nucleate boiling is suppressed at intermediate-high quality where the effect of heat flux on heat transfer coefficient becomes lower. The trend illustrated in Fig. 3 agrees with previous studies, e.g. [3, 6 and 7].

Figs. 4a and b illustrates the effect of inner tube diameter on heat transfer coefficient for R-22 and R-134a, respectively. At low quality region, smaller inner tube diameter shows higher heat transfer coefficient. This is due to a more active nucleate boiling in a smaller di-



(a)



(b)

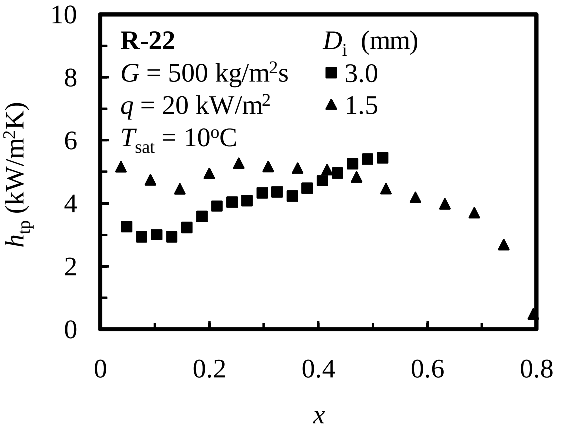
Fig. 3 The effect of heat flux on heat transfer coefficient: (a) R-22, (b) R-134a

ameter tube. As the tube diameter becomes smaller, the contact surface area of the heat transfer increases. The more active nucleate boiling causes dry-patches to appear earlier. Therefore, at intermediate-high vapor quality, smaller inner tube diameter provides lower heat transfer coefficient.

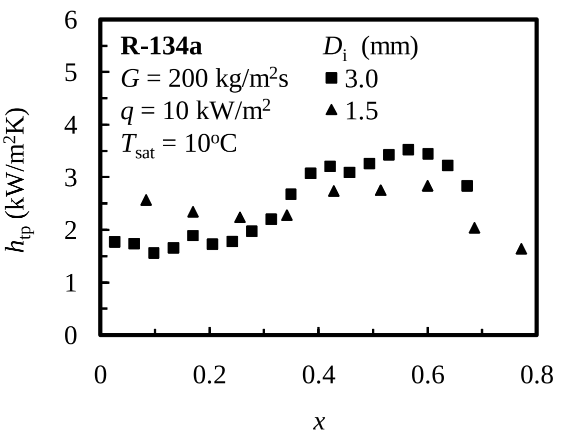
Fig. 5 shows a comparison of heat transfer coefficient of R-22 and R-134a. The heat transfer coefficient of R-22 is little higher than that of R-134a due to their almost similar physical properties. R-22 has lower viscosity ratio μ_f/μ_g than R-134a, which means that the liquid film of R-22 is easier for breaking. R-22 has also lower density ratio ρ_f/ρ_g than R-134a,

Table 2 Deviation of the heat transfer coefficient comparison between the present data and the previous correlation

Deviation (%)	**Tran *etal.* [2]**	**Shah [8]**	**Chen [9]**	**Gungor-Winterton [10]**	**Wattelet [11]**	**Jung *etal.*[12]**
Mean	28.80	33.69	35.30	40.24	40.55	49.97
Average	-11.88	19.68	2.76	35.03	36.65	45.26



(a)



(b)

Fig. 4 The effect of inner tube diameter on heat transfer coefficient: (a) R-22, (b) R-134a

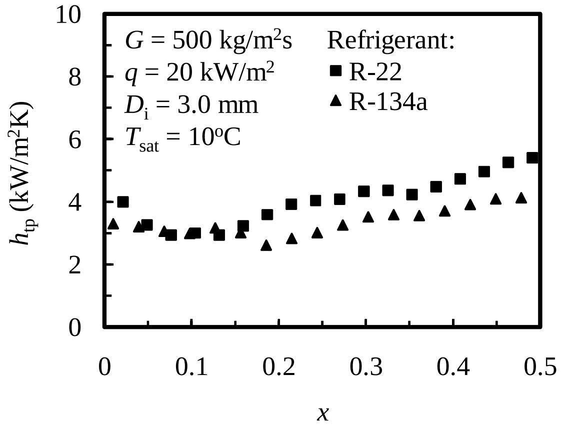


Fig. 5 Heat transfer coefficient comparison for R-22 and R-134a

which causes a lower vapor velocity. A lower vapor velocity causes a lower suppression of nucleate boiling.

The heat transfer coefficients of the present study were compared using six previous heat transfer coefficient correlations, as are shown in Table 2. Overall, the Tran *et al.*'s [2] correlation gave the best prediction of all six. The correlation reported by Tran *et al.* was developed for flow boiling heat transfer in small channels. The large deviation using the Shah [8], Chen [9], Gungor-Winterton [10], Jung *et al.* [11] and Wattelet *et al.*'s [12] correlations because the correlations were developed for the conventional channel. The large deviation in the prediction because the previous correlations fail to predict a higher nucleate boiling heat transfer contribution for evaporative refrigerants in small channels, and the appearance of laminar flow.

5. New Correlation Development

Because of its high boiling nucleation, the appearance of convective heat transfer for evaporative in small channels is delayed compared with that in conventional channels. Therefore, the prediction of convective heat transfer contribution in small channels will be different from that in large channels.

Chen [9] introduced a multiplier factor $F=\mathrm{fn}(X_{tt})$ to account for the increase in convective turbulence due to the presence of a vapor phase. Chen [9] reported the factor F which needs to be evaluated again physically for flow boiling heat transfer in small channels which has laminar flow condition. The liquid-vapor flow condition of the present study shows 37% laminar-turbulent and 2% turbulent-laminar. By considering the laminar or turbulent flow, Zhang *et al.* [1] introduced a relationship between the factor F and the two-phase frictional multiplier ϕ_{f}^2,, $F=\mathrm{fn}(\phi_{\mathrm{f}}^2)$, where ϕ_{f}^2 is a general form for four conditions according to Chisholm [13],

$$\phi_{\mathrm{f}}^2 = 1 + \frac{C}{X} + \frac{1}{X^2} \tag{4}$$

For liquid-vapor flow conditions of turbulent-turbulent (tt), laminar-turbulent (vt), turbulent-laminar (tv), and laminar-laminar (vv), the values of Chisholm parameter C are 20, 12, 10, and 5, respectively. The Martinelli parameter is defined as follows:

$$X = \sqrt{\frac{(dp/dz)_{\mathrm{f}}}{(dp/dz)_{\mathrm{g}}}} = \left(\frac{f_{\mathrm{f}}}{f_{\mathrm{g}}}\right)^{1/2}\left(\frac{1-x}{x}\right)\left(\frac{\rho_{\mathrm{g}}}{\rho_{\mathrm{f}}}\right)^{1/2} \tag{5}$$

The friction factors were obtained by considering the flow conditions of laminar (for $\mathrm{Re}<2300$, $f=16\mathrm{Re}^{-1}$) and turbulent (for $\mathrm{Re}>3000$, $f=0.079\mathrm{Re}^{-0.25}$). The two-phase Re was evaluated using several methods wherein the Cicchitti *et al.* [14] correlation gave the best prediction to develop the F factor. The liquid heat transfer is defined by the Dittus Boelter correlation. A new factor F as shown in Fig. 6 was developed with a regression method using the present experimental data.

A higher mass flux is corresponding to a

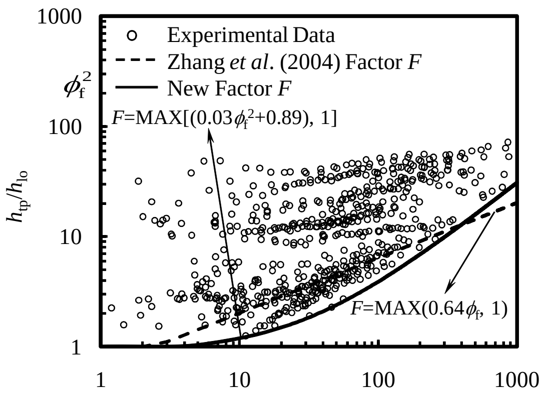


Fig. 6 Two-phase heat transfer multiplier as a function of ϕ_{f}^2

higher suppression nucleate boiling. For evaporation in a minichannel, the suppression is lower than that in a large channel.

The nucleate boiling heat transfer for the experimental data was predicted using the Cooper [15] correlation.

Jung et al. [12] proposed a convective boiling heat transfer multiplier factor N as a function of X_{tt} and Bo to represent the strong effect of nucleate boiling in flow boiling by comparing it with that in nucleate pool boiling, h_{nbc}/h_{pb}. In the present study, in order to consider laminar flow in minichannels, the Martinelli parameter, Xtt, is replaced by the two-phase frictional multiplier,ϕ_{f}^2. Using the present experimental data, a new nucleate boiling suppression factor, a ratio of h_{nbc}/h_{pb}, is proposed as follows:

$$S = 0.734(\phi_{\mathrm{f}}^2)^{0.028} Bo^{0.014} \tag{6}$$

The new heat transfer coefficient correlation was developed using a regression method with 607 experimental data points (R-22 and R-134a). The comparison of the experimental heat transfer coefficient and the prediction heat transfer coefficient showed a good agreement with 12.95% mean deviation and -2.87% average deviation.

6. Concluding Remarks

Convective boiling heat transfer experiments were performed in horizontal small tubes with R-22 and R-134a. Mass flux has an insignificant effect on the heat transfer coefficient at the low quality region. At the intermediate quality region, the heat transfer coefficients increase with mass flux. A strong dependence of the heat transfer coefficients on the heat flux appears at the low quality region. The smaller inner tube diameter provides a higher heat transfer coefficient at low quality region. The heat transfer coefficient of R-22 is little higher than that of R-134a. The Tran et al.'s [2] correlation gave the best prediction among the six reported correlations.

Laminar flow appears during flow boiling in small tubes. Therefore, in this study, a modified correlation of the multiplier factor on the convective boiling contribution, F, and the nucleate boiling suppression factor, S, was developed using laminar flow consideration.

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