TWO-PHASE PRESSURE DROP OF R-410A, R-407C AND CO_2 IN HORIZONTAL EVAPORATOR WITH MINICHANNELS

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ABSTRACT

Two-phase pressure drop during evaporation process of R-410A, R-407C and CO_2 were studied in horizontal minichannels of 1.5 and 3.0 mm inside diameters with heated length of 1.5, 2.0 and 3.0 m. Experiments were performed at mass flux ranges from 200 to 600 kg/m^{2}s, heat flux from 5 to 20 kW/m^2, and the inlet saturation temperature of 10^{o}C. For these refrigerants, the intermittent, wavy, and annular flow appear on the Wang *et al*. flow pattern map, whereas the intermittent, stratified-wavy, and annular flow appear on the Kattan *et al*. flow pattern map. The higher mass flux and heat flux give a higher pressure drop. The experimental pressure drop of R-407C is higher than that of R-410A and CO_2, successively, and the pressure drop in 1.5-mm tube is higher than that in 3.0 mm. The experimental results were then compared against six previous two-phase pressure drop prediction methods. By using 666 data points of R-410A, R-407C, and CO_2, a new correlation of two-phase frictional pressure drop is developed on the basis of the Friedel correlation. The comparison of the two-phase frictional multiplier of the present study with the prediction of the new correlation shows 18.00% mean deviation and 0.03% average deviation.

Key Words***: two-phase flow, pressure drop, two-phase frictional multiplier, correlation, R-410A, R-407C, CO_2, evaporator, horizontal minichannel.***

1 INTRODUCTION

Two-phase pressure gradient has been a research subject for several decades, but only a few studies in the literature report on two-phase pressure gradient of refrigerant mixtures and CO_2 in minichannel, whereas in the future it is important in compact heat exchanger application due to their performance, harmlessness to the environment (zero ODP), and personal safety.

Chisholm (1968), by using steam-water, introduced a procedure to evaluate two-phase frictional multiplier based on pressure gradient for liquid alone flow. The Friedel (1979) correlation was obtained by optimizing an equation for the two-phase frictional multiplier using a large measurement database. Tran *et al*. (2000) measured two-phase flow pressure drop with refrigerants of R-134a, R-12, and R-113 in small round and rectangular channels. By modified Chisholm (1983) correlation, they proposed a new correlation. Yoon *et al*. (2004), using 7.53 mm horizontal stainless steel tube, developed a pressure drop correlation for CO_2.

The experimental results of this study were compared against the six two-phase pressure gradient prediction methods; Friedel (1979), Chisholm (1983), Tran *et al*. (2000), Jung-Radermacher (1993), Müller-Steinhagen and Heck (1986), and Yoon *et al*. (2004). A new correlation to predict two-phase frictional pressure drop is developed on the basis of the Friedel (1979) correlation.

2 TWO-PHASE PRESSURE GRADIENTS

Two-phase flow pressure gradients in horizontal tube are the sum of the frictional and the accelerational contributions.

$$\left(\frac{\mathrm{d}p}{\mathrm{dz}}\right)=\left(\frac{\mathrm{d}p}{\mathrm{dz}}F\right)+\left(\frac{\mathrm{d}p}{\mathrm{dz}}a\right) \tag{1}$$

where

$$-\left(\frac{\mathrm{d}p}{\mathrm{dz}}F\right)=\frac{1}{A}\left(\tau_{\mathrm{gw}}P_{\mathrm{gw}}+\tau_{\mathrm{fw}}P_{\mathrm{fw}}\right) \tag{2}$$

is the frictional pressure gradient,

$$-\left(\frac{\mathrm{d}p}{\mathrm{dz}}a\right)=G^2\,\frac{\mathrm{d}}{\mathrm{dz}}\left(\frac{x^2\upsilon_{\mathrm{g}}}{\alpha}+\frac{(1-x)^2\upsilon_{\mathrm{f}}}{(1-\alpha)}\right) \tag{3}$$

is the accelerational pressure gradient. In the present study, the void fraction α is obtained from the Steiner (1993).

$$\alpha=x\upsilon_{\mathrm{g}}\left[(1+0.12(1-x))(x\upsilon_{\mathrm{g}}+(1-x)\upsilon_{\mathrm{f}})+\frac{1.18}{G^2}(1-x)\upsilon_{\mathrm{f}}^{0.5}\left[g\sigma\left(\frac{1}{\upsilon_{\mathrm{f}}}+\frac{1}{\upsilon_{\mathrm{g}}}\right)\right]^{0.25}\right]^{-1} \tag{4}$$

Using the considered experimental data, the accelerational pressure gradient can be calculated. Then the experimental two-phase frictional pressure gradient is obtainable from Eq. (1) by subtracting the calculated accelerational pressure gradient from the measured pressure gradient. The experimental frictional two-phase pressure gradient assuming total flow to be liquid over a quality range x=xa to x=x_b can be calculated using the separated flow model.

$$-\left(\frac{\mathrm{d}p}{\mathrm{d}z}F\right)=-\left(\frac{\mathrm{d}p}{\mathrm{d}z}F\right)_{\mathrm{fo}}\phi_{\mathrm{fo}}^{2}=\left[\frac{2f_{\mathrm{fo}}G^{2}\upsilon_{\mathrm{f}}}{D}\right]_{\mathrm{fo}}\phi_{\mathrm{fo}}^{2} \tag{5}$$

and

$$\overline{\phi}_{\mathrm{fo}}^{2}=\frac{1}{\left(x_{\mathrm{b}}-x_{\mathrm{a}}\right)}\int_{x_{\mathrm{a}}}^{x_{\mathrm{b}}}\overline{\phi}_{\mathrm{fo}}^{2}(x)\mathrm{d}x \tag{6}$$

In order to obtain the two-phase frictional multiplier based on pressure gradient for total flow assumed liquid ϕ_{fo}^{2} the calculated two-phase frictional pressure gradient is divided by the calculated frictional two-phase pressure gradient assuming total flow to be liquid. The friction factor in Eq. (5) is obtained using the Blasius equation.

3 EXPERIMENTAL APPARATUS AND METHODS

Figure 1 is a schematic of the test facility, which consists mainly of a condenser, subcooler, receiver, refrigerant pump, mass flow meter, preheater, and test section. A variable AC-output motor controller controls the refrigerant flow rate. To control quality at the test section inlet, the preheater was installed. For evaporation at the test section, a certain heat flux was conducted from a variable AC voltage controller.

Fig. 2 shows a detail of the test section. The test sections are stainless steel smooth tubes, with inner diameters of 1.5 mm and 3.0 mm and heated lengths of 1500 mm, 2000 mm and 3000 mm, well isolated. It is uniformly and constantly heated directly through the tube wall. The differential pressure was measured with bourdon tube type pressure gauges and differential pressure transducer, with an accuracy of ±0.5%, at the inlet, middle, and outlet of the test section. To visualize the flow, sight glasses with the same inner diameter as the test section were installed.

The experimental conditions performed in this study are shown in Table 1. It underwent steady-state conditions. The measured saturation pressure was used to determine the saturation temperature and hence the physical properties of the refrigerant using REFPROP 6.

The vapor quality at measurement locations were determined based on the refrigerant physical properties

$$x = \frac{i - i_{\mathrm{f}}}{i_{\mathrm{fg}}} \tag{7}$$

4 EXPERIMENTAL RESULTS AND DISCUSSION

4.1 Flow Pattern

The flow pattern of the experimental results was drawn using Wang *et al*. (1997) and Kattan *et al*. (1998) flow pattern maps. The Wang *et al*. flow pattern map is a modified Baker map, developed using R-22, R-134a, and R-407C inside a 6.5 mm horizontal smooth tube. By using the Wang *et al*. map, the experimental results for overall test conditions lie on the intermittent, wavy, and annular flow. The flow pattern of selection experimental results is shown in Fig. 3.

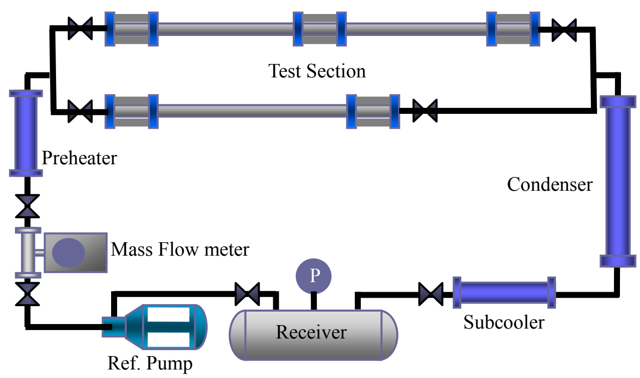

Fig. 1. Experimental test facility

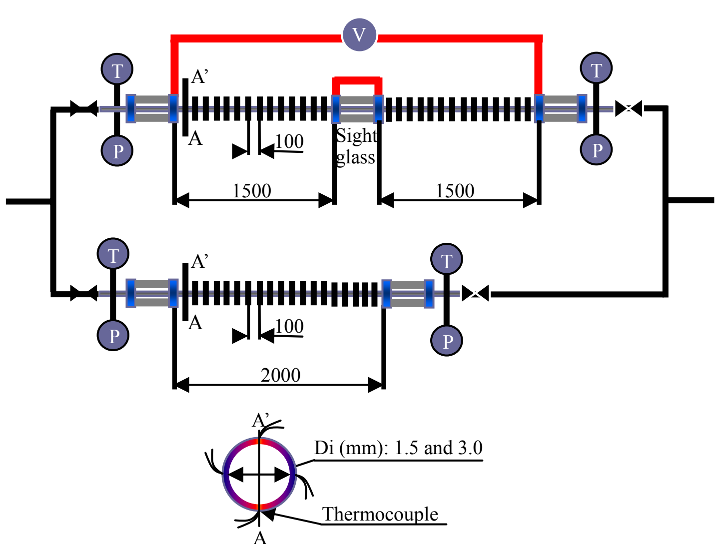

Fig. 2. Experimental test section for R-410A, R-407C, and CO_2

Table 1. Experimental conditions

Conditions	Refrigerants	
	R-410A, R-407C	CO_2
Tube Length (mm)	1500, 3000	2000
Inlet T_{sat} (^oC)	10	10
Inner Diameter (mm)	1.5, 3.0	1.5, 3.0
Test Section	Smooth Horizontal stainless steel	
Mass Flux (kg/m^2s)	300 – 600	200 – 600
Heat Flux (kW/m^2)	5 – 20	5 – 15
Vapor Quality	0.0 - 1.0	0.0 - 1.0

Kattan *et al*. used five refrigerants of R134a, R-123, R-402A, R-404A, and R-502 inside 12 mm and 10.92 mm (only for R-134a) tubes, which were heated by hot water flowing counter-currently to develop their flow pattern maps on the basis of Steiner (1993) flow pattern map. Different to the flow pattern using Wang *et al*., by using the Kattan *et al*. flow pattern map, the overall experimental results lie on stratified wavy, intermittent, and annular flow depend strongly on their mass flux, as shown in Fig. 4.

Figures 5 and 6 illustrate the CO_2 experimental results on the Wang *et al*. and Kattan *et al*. flow pattern maps, respectively. Each map, with the same test condition, shows different flow pattern at the middle vapor quality.

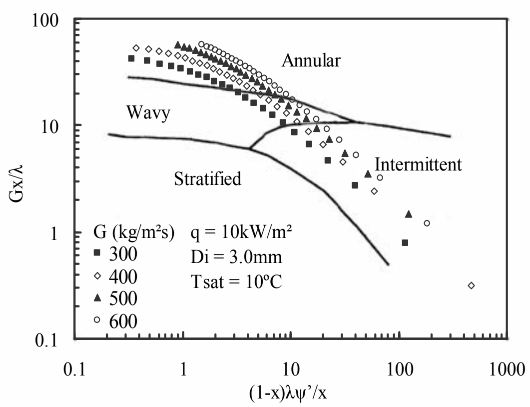

Fig. 3. R-410A experimental data on the Wang *et al*. flow pattern map

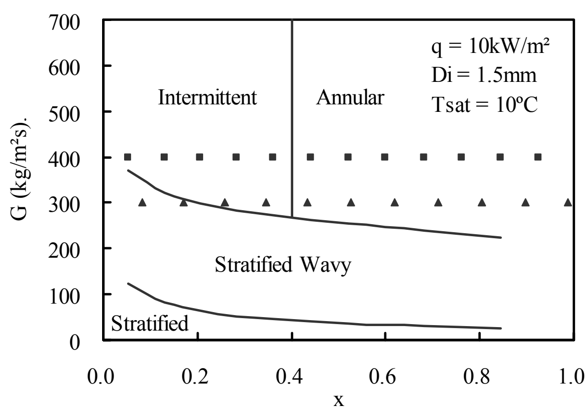

Fig. 4. R-407C experimental data on the Kattan *et al*. flow pattern map

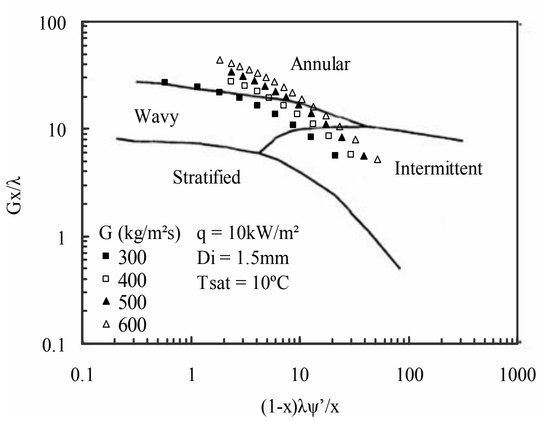

Fig. 5. CO_2 experimental data on the Wang *et al*. flow pattern map

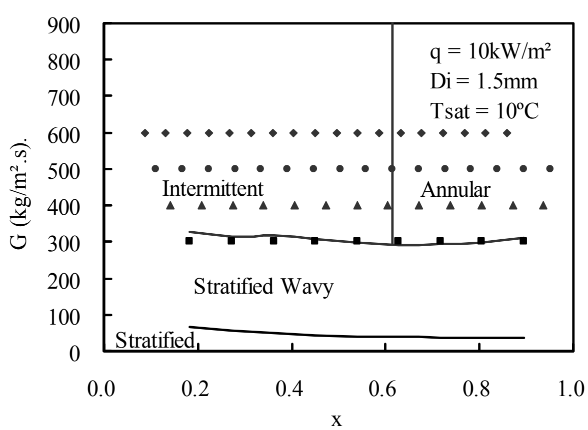

Fig. 6. CO_2 experimental data on the Kattan *et al*. flow pattern map

The Wang *et al*. map does not fit with the test result; about 38% of the overall experimental result shows that their initial dry-out occurs before the appearing of annular flow. The experimental results on the Kattan *et al*. map show that about 40% of them do not fit. Generally both flow pattern maps do not fit for the test data; it is likely due to the physical properties degradation of CO_2, inside small diameter in the test section, and the heating method for evaporation on the test tube. It shows a necessity to develop a new flow pattern map for mixture refrigerant and CO_2 in minichannels.

4.2 Pressure Gradient

The pressure gradient increases with the increasing of mass and heat fluxes for the test refrigerants as illustrated in Figs. 7 and 8. The experimental result showed that the pressure gradient, at the same test condition, of R-407C is higher than that of R-410A and CO_2, successively, as shown in Fig. 7, and the pressure gradient in 1.5 mm tube is higher than that in 3.0mm tube as shown in Fig. 8. Therefore, the pressure drop should be considered as an important factor, when designing the minichannels in a heat exchanger.

The pressure gradients of the present study were compared against the six previous two-phase pressure gradient prediction methods as are shown in Table 2. Figure 9 shows pressure gradient comparison of R-410A at mass flux of 300 kg/m2s and heat flux of 10 kW/m2 in 3.0 mm tube. The experimental pressure gradient increases at low vapor quality and then decreases at vapor quality of beyond 0.6 likely due to the initial dry-out. The Tran *et al*. method predicts these data best with 26.63% mean deviation.

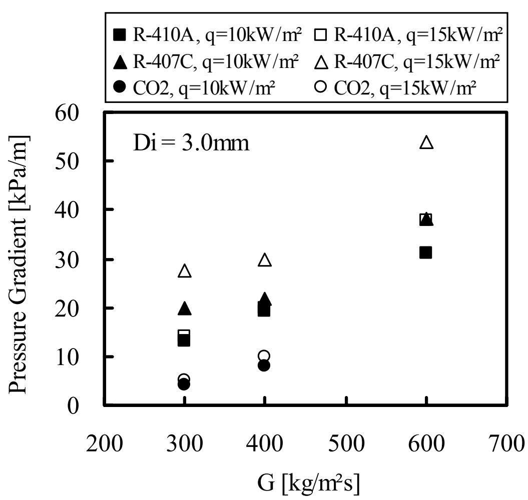

Fig. 7. Effect of heat flux on pressure gradient at various mass fluxes in 3.0 mm tube

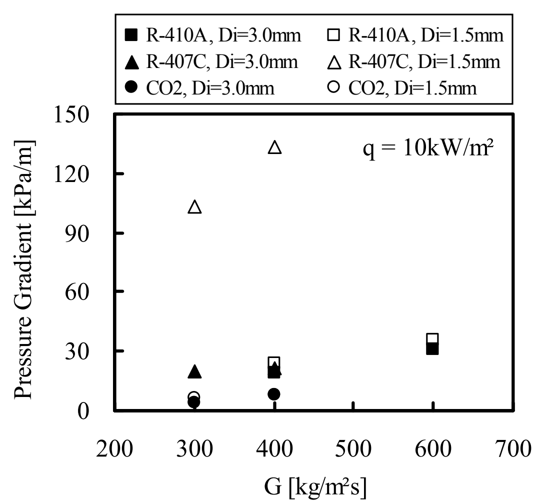

Fig. 8. Effect of inner tube diameter on pressure gradient at different mass flux and heat flux

Table 2. Previous correlations

Friedel (1979)	$\phi_{fo}^2 = A_1 + \frac{3.24 A_2 A_3}{\mathrm{Fr}^{0.045}\mathrm{We}^{0.035}}$ $A_1 = (1-x)^2 + x^2\left[(\rho_f f_{go})/(\rho_g f_{fo})\right]$, $A_2 = x^{0.78}(1-x)^{0.224}$ $A_3 = (\rho_f/\rho_g)^{0.91}(\mu_g/\mu_f)^{0.19}\left[1-(\mu_g/\mu_f)\right]^{0.7}$ $\mathrm{Fr} = \frac{G^2}{gD\bar{\rho}^2}$, $\mathrm{We} = \frac{G^2 D}{\bar{\rho}\sigma}$	Jung-Radermacher (1997)	$\Delta P = \frac{2 f_{fo} G^2 L}{D\rho_f}\left[\frac{1}{\Delta x}\int_{x1}^{x2}\phi_{tp}^2 dx\right]$ $\phi_{tp}^2 = 12.82 X_{tt}^{-1.47}(1-x)^{1.8}$ $f_{fo} = 0.046\,\mathrm{Re}^{-0.2}$
Chisholm (1983)	$\phi_{fo}^2 = 1 + (\Gamma^2 - 1)\left[Bx^{0.875}(1-x)^{0.875} + x^{1.75}\right]$ $\Gamma^2 = \frac{(dp/dz)_{go}}{(dp/dz)_{fo}}$	Müller-Steinhagen and Heck (1986)	$\left(\frac{dp}{dz}F\right) = G(1-x)^{1/3} + bx^3$ $G = a + 2(b-a)x$, $a = \left(\frac{dp}{dz}F\right)_{fo}$, $b = \left(\frac{dp}{dz}F\right)_{go}$
Tran *et al.* (2000)	$\phi_{fo}^2 = 1 + (4.3\Gamma^2 - 1)\left[N_{conf}x^{0.875}(1-x)^{0.875} + x^{1.75}\right]$ $\Gamma^2 = \frac{(dp/dz)_{go}}{(dp/dz)_{fo}}$ and $N_{conf} = \frac{\left[\sigma/(g(\rho_f - \rho_g))\right]^{0.5}}{D}$	Yoon *et al.* (2004)	$\phi_{fo}^2 = 1 + 4.2(\Gamma^2 - 1)\left[\frac{B}{\mathrm{We}_D}x^{0.875}(1-x)^{0.875} + x^{1.75}\right]$

Chisholm (1983):

Γ	G (kg/m²s)	B
≤ 9.5	≤ 500	4.8
	500<G<1900	$2400/G$
	≥ 1900	$55/G^{0.5}$
$9.5<\Gamma<28$	≤ 600	$520/(\Gamma G^{0.5})$
	> 600	$21/\Gamma$
≥ 28	-	$\Gamma^2 G^{0.5}$

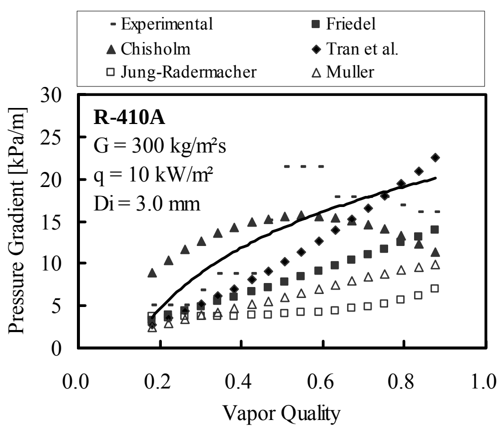

Fig. 9. Pressure gradient comparison of R-410A at G=300 kg/m²s, q=10 kW/m² in 3.0-mm tube

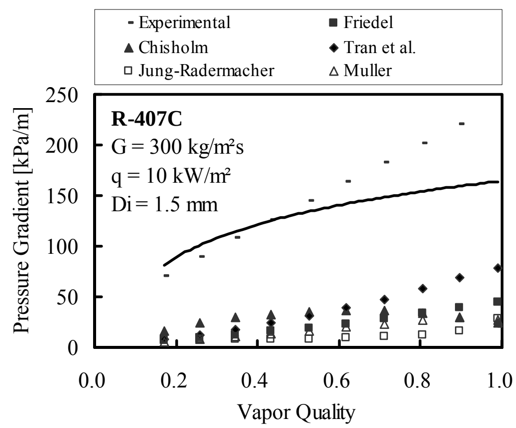

Fig. 10. Pressure gradient comparison of R-407C at G=300 kg/m²s, q=10 kW/m² in 1.5 -mm tube

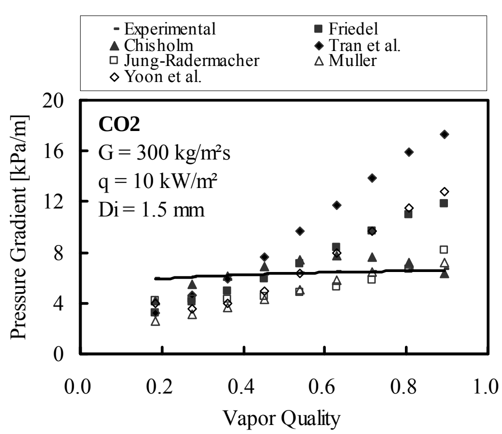

Fig. 11. Pressure gradient comparison of CO_2 at G=300 kg/m²s, q=10 kW/m² in 1.5-mm tube

Figure 10 depicts pressure gradient comparison of R-407C at mass flux of 300 kg/m^{2}s and heat flux of 10 kW/m^2 in 1.5 mm tube. The experimental pressure gradient increases and is higher than that of the prediction during evaporation. The Chisholm method gives the best prediction of pressure gradient on this figure. Figure 11 illustrates the pressure gradient comparison of CO_2 at mass flux of 300 kg/m^{2}s and heat flux of 10 kW/m^2 in 1.5 mm tube. For overall CO_2 experimental results, vapor quality does not have significant effect on pressure gradient. The Chisholm method predicts these data best with 13.42% mean deviation.

Table 3 summarizes the deviation of the pressure gradient comparison. For the overall data in 1.5 mm and 3.0 mm tubes, the best prediction is given with Jung and Radermacher (1993) and Friedel (1979) methods, respectively. For the overall data, the best prediction is given by Friedel (1979) method. The average deviation on Table 3 shows that the pressure gradient of the study is generally higher than that of the prediction using the previous methods.

Table 3. Percentage deviation of the pressure gradient comparison of the experimental results and the predictions of the previous methods

		Friedel (1979)		**Chisholm (1983)**		**Tran *et al*. (2000)**	
		M	**A**	**M**	**A**	**M**	**A**
Overall data	1.5 mm	50.71	-8.93	72.49	29.78	78.48	29.40
	3.0 mm	35.73	-29.78	46.61	-1.55	46.56	-21.80
	all	40.58	-23.03	49.03	14.50	50.45	0.54
R-410A	1.5 mm	51.94	42.73	165.09	165.09	124.65	121.05
	3.0 mm	35.57	-33.90	42.74	25.75	31.66	-22.93
	all	38.39	-20.73	63.77	49.70	47.64	1.81
R-407C	1.5 mm	78.80	-75.77	63.93	-63.42	69.19	-61.96
	3.0 mm	32.94	-27.79	36.52	-9.24	38.25	13.05
	all	52.15	-47.88	48.00	-31.94	51.21	-18.37
CO_2	1.5 mm	33.07	5.75	31.37	18.60	61.02	38.94
	3.0 mm	38.11	-22.63	28.44	-19.66	47.40	-12.25
	all	35.77	-9.43	29.80	-1.88	53.73	11.54

		Jung-Radermacher (1993)		**Müller-Steinhagen and Heck (1986)**		**Yoon (2004) (only for CO_2)**	
		M	**A**	**M**	**A**	**M**	**A**
Overall data	1.5 mm	34.38	-25.16	45.50	-29.62	—	—
	3.0 mm	62.93	-56.85	58.38	-57.84	—	—
	all	45.77	-38.77	46.63	-41.21	—	—
R-410A	1.5 mm	19.85	0.70	37.13	17.09	—	—
	3.0 mm	54.13	-43.43	48.75	-48.33	—	—
	all	48.24	-35.85	46.75	-37.09	—	—
R-407C	1.5 mm	85.02	-84.03	81.42	-80.50	—	—
	3.0 mm	63.58	-63.58	42.12	-41.90	—	—
	all	72.56	-72.14	58.58	-58.07	—	—
CO_2	1.5 mm	10.95	-2.41	27.91	-22.13	33.72	-3.73
	3.0 mm	36.12	-35.80	47.55	-46.99	41.57	-29.66
	all	24.42	-20.28	38.42	-35.44	37.92	-17.61

$$\mathrm{M} = \text{Mean Deviation} = \frac{1}{n}\sum_{1}^{n}\left\|\left[\frac{(dp/dz)_{pred} - (dp/dz)_{exp}}{(dp/dz)_{exp}} \times 100\right]\right\|, \mathrm{A} = \text{Average Deviation} = \frac{1}{n}\sum_{1}^{n}\left[\frac{(dp/dz)_{pred} - (dp/dz)_{exp}}{(dp/dz)_{exp}} \times 100\right]$$

Table 4. The new correlation of two-phase frictional pressure drop

$$\phi_{fo}^2 = A_1 + A_2 \mathrm{Fr}^a \mathrm{We}^b$$

where

$$A_1 = (1-x)^2 + x^2\Gamma^2,\quad \Gamma^2 = \frac{(\mathrm{d}p/\mathrm{d}z)_{go}}{(\mathrm{d}p/\mathrm{d}z)_{fo}},\quad X = \left(\frac{1-x}{x}\right)^{0.9}\left(\frac{\rho_g}{\rho_f}\right)^{0.5}\left(\frac{\mu_f}{\mu_g}\right)^{0.1}$$

$$\mathrm{Fr} = \frac{G^2}{gD\bar{\rho}^2},\quad \mathrm{We} = \frac{G^2 D}{\bar{\rho}\sigma}$$

For $X \geq 1$ $\quad A_2 = 2.533\times10^{10}x^{0.353}(1-x)^{-1.35}\left(\frac{\rho_f}{\rho_g}\right)^{-3.401}\left(\frac{\mu_f}{\mu_g}\right)^{2.161}\left(1-\frac{\mu_f}{\mu_g}\right)^{62.017}$

$a = -0.329$ and $b = 0.302$

For $X < 1$ $\quad A_2 = 2.728\times10^{-8}x^{1.363}(1-x)^{0.589}\left(\frac{\rho_f}{\rho_g}\right)^{-4.133}\left(\frac{\mu_f}{\mu_g}\right)^{-13.715}\left(1-\frac{\mu_f}{\mu_g}\right)^{-16.852}$

$a = -0.488$ and $b = 0.542$

Table 5. Two-phase frictional pressure drop comparison of the test results and the prediction of the new correlation

Refrigerant	Deviation (%)	
	M	A
R-410A	18.72	0.28
R-407C	20.31	1.08
CO_2	16.59	-0.51
Overall the experimental data	**18.00**	**0.03**

M = Mean Deviation = $\frac{1}{n}\sum_1^n\left[\left|\frac{(\mathrm{d}p/\mathrm{d}z)_{pred} - (\mathrm{d}p/\mathrm{d}z)_{exp}}{(\mathrm{d}p/\mathrm{d}z)_{exp}}\times100\right|\right]$, A = Average Deviation = $\frac{1}{n}\sum_1^n\left[\frac{(\mathrm{d}p/\mathrm{d}z)_{pred} - (\mathrm{d}p/\mathrm{d}z)_{exp}}{(\mathrm{d}p/\mathrm{d}z)_{exp}}\times100\right]$

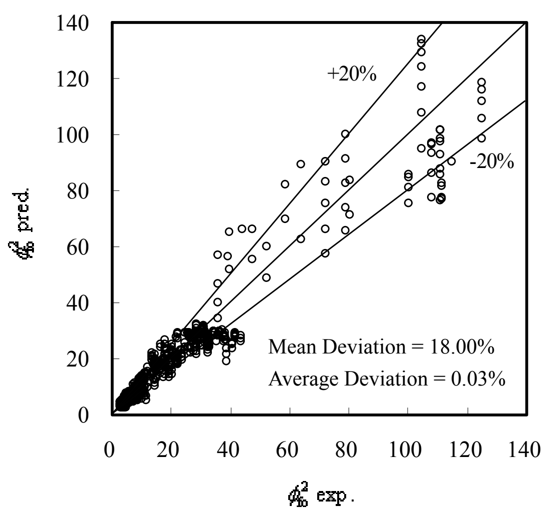

Fig. 12. Two-phase frictional pressure drop comparison of the test results and the prediction using the new correlation

Based on Friedel (1979) correlation, a new two- phase frictional pressure drop is developed using regression method with 666 data points. The summary of the new correlation is shown in Table 4. The comparison of two-phase frictional pressure drop between the test results and the predicted of the new correlation shows 18.00% mean deviation and 0.03% average deviation; it is shown in Table 5 and Fig. 12.

5 CONCLUSION

Two-phase evaporative flow pattern and pressure drop study using mixture refrigerants of R-410A, R-407C and CO_2 in horizontal minichannels is presented. The Wang *et al*. (1997) and Kattan *et al*. (1998) flow pattern maps do not fit for the experimental data. The experimental results show it a necessary to develop a new flow pattern map for mixture refrigerants and CO_2 in minichannel.

At the same test condition, the pressure gradient of R-407C is higher than that of R-410A and CO_2, successively, and the pressure gradient in 1.5 mm tube is higher than that in 3.0 mm tube. For the overall data in 1.5 mm and 3.0 mm tubes, the best prediction is given with Jung and Radermacher (1993) and Friedel (1979) methods, respectively. For the overall data, the best prediction is given by Friedel (1979) method.

Based on Friedel (1979) correlation, a new two-phase frictional pressure drop is developed using 666 data points. The comparison of two-phase frictional pressure drop between the test results and the predicted of the new correlation shows 18.00% mean deviation and 0.03% average deviation.

NOMENCLATURE

D Diameter (m)

Fr Froude number

f friction factor

$f$fo friction factor based on total flow assumed liquid

G Mass flux (kg/m2s)

g Acceleration due to gravity (m/s2)

P Pressure (N/m2)

q Heat flux (kW/m^2)

Re Reynolds number

T Temperature (K)

υ Specific volume (m^3/kg)

We Weber number

X Martinelli parameter

x Vapor quality

Greek letters

α Void fraction

μ Viscosity (Pa s)

σ Surface tension (N/m)

ϕ_{fo}^2 two-phase frictional multiplier based on pressure gradient for total flow assumed liquid

ϕ_f^2 two-phase frictional multiplier based on pressure gradient for liquid alone flow

Subscripts

exp Experimental value

f Saturated liquid

g Saturated vapor

i Inside tube

pred Predicted value

sat Saturation

TP Two-phase

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