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Measurements and correlations of frictional single-phase and two-phase pressure drops of R-410A flow in small U-type return bends

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Abstract

This study presents single-phase and two-phase frictional data for R-410A in four U-type return bends with tube diameter $D = 3.3$ and 5.07 mm and curvature ratio ($2R/D$) ranged from 3.91 to 8.15, and their frictional performances are investigated. The friction factor f_C and two-phase pressure gradient in the return bend considerably increase with the decrease of curvature ratio. For $D = 5.07$ mm and $G \geqslant 200$ kg m^{-2} s^{-1}, the ratio of $(dp/dz)_C/(dp/dz)_S$ is relatively independent of the vapor quality x. However, a considerable rise of this ratio is encountered at $x < 0.5$ and $G = 100$ kg m^{-2} s^{-1}. The significant increase of this ratio may be attributed to the change of flow pattern from stratified flow to annular flow. In contrast, for $D = 3.3$ mm and $G \geqslant 300$ kg m^{-2} s^{-1}, the higher pressure gradient ratio at lower x was not observed. The flow pattern at low vapor quality is slug flow and no dramatic change of flow pattern across the return bend is seen. For the single-phase results, existing correlations give fair agreements with the present f_C data. For two-phase results, the Geary correlation shows a better agreement with the data. A modified two-phase friction factor based on the Geary correlation is then proposed. The proposed correlation gives a good agreement to the present R-410A data and Geary's R-22 data with a mean deviation of 19.1%.

Keywords: Return bend; Friction factor; Two-phase pressure gradient

1. Introduction

Curved tubes and bends are widely employed in heat exchangers and flow transmitting devices. The curved channels can be in the form of helical, spiral, or U-tube return bend. For typical evaporator and condenser in refrigerators and air-conditioners that incorporated two-phase flow inside the consecutive U-type return bends is very common. As expected, the U-type return bends will cause higher pressure drop than those of straight tubes. The magnitude of frictional loss in curved tubes is obviously increased with a decrease of curvature ratio due to the presence of secondary flow induced by the centrifugal force [1]. In addition, the higher pressure drop in curved pipes may significantly affect the refrigerant distribution and saturation temperature in the circuitry. In essence, the frictional characteristics of the refrigerant flow in a consecutive U-type return bend is very important for the design of air-cooled heat exchanger.

Single-phase flow characteristics in curved channels had been extensively investigated both theoretically and experimentally [2–4]. For single-phase flow inside U-type return bends, the investigations by Popieil and Wojtkowiak [5] and Wojtkowiak and Popieil [6] are probably the most informative. Their friction factor data were presented for a wide range of the curvature

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Nomenclature

(dp_L/dz)	pressure gradient for liquid-phase flow alone, $Pa\,m^{-1}$
(dp_G/dz)	pressure gradient for gas-phase flow alone, $Pa\,m^{-1}$
$(dp/dz)_C$	pressure gradient in the U bend, $Pa\,m^{-1}$
$(dp/dz)_S$	pressure gradient in the straight tube, $Pa\,m^{-1}$
D	internal diameter of tube, m
Dn	new Dean number $(Re/(2R/D))$
f	two-phase U bend friction factor
f_C	U bend friction factor
F	Froude parameter $(\rho_G/(\rho_L-\rho_G))^{0.5}\times(U_{G,S}/(Dg)^{0.5})$
F_d	Froude number defined in Eq. (7)
Fr	liquid Froude number $(U_{L,S}^2/gD)$
g	gravitational acceleration, $m\,s^{-2}$
G	mass flux, $kg\,m^{-2}\,s^{-1}$
L	spacer length, m
L_S	straight length in the upstream for pressure drop measurement, m
L_{ST}	total straight length in the test section, m
$\dot{m}_r$	refrigerant flowrate, kg/s
$\dot{m}_{water}$	water coolant flowrate, kg/s
p	pressure, Pa
ΔP_S	pressure drop across the straight test section, Pa
ΔP_T	total pressure drop across the test section, Pa
R	radius of centerline in the U bend, m
Re	Reynolds number $(\rho U_m D/\mu)$
Re_G	gas Reynolds number $(\rho_G U_{G,S} D/\mu_G)$
Re_L	liquid Reynolds number $(\rho_L U_{L,S} D/\mu_L)$
Re_m	combined vapor and liquid Reynolds number (Re_G+Re_L)
$U_{G,S}$	superficial velocity, gas-phase (Gx/ρ_G), $m\,s^{-1}$
$U_{L,S}$	superficial velocity, liquid-phase $(G(1-x)/\rho_L)$, $m\,s^{-1}$
U_m	mean axial velocity, $m\,s^{-1}$
We	Weber number $(G^2D/\rho_G\sigma)$
x	vapor quality
X	Martinelli parameter
z	axial flow direction, m
Greek symbols	
μ	viscosity, $N\,s\,m^{-2}$
ρ	density, $kg\,m^{-3}$
σ	surface tension, $N\,m^{-1}$
$\Phi_{C,L}$	two-phase frictional multiplier in bend based on liquid flow alone
Subscripts	
U	upstream
C	U bend or curved pipe
D	downstream
G	gas-phase flow alone
L	liquid-phase flow only
S	straight tube

ratio ($2R/D = 6.62$–27.85) and of the Reynolds number ($Re = \rho U_m D/\mu = 500$–$20000$, where ρ: fluid density, μ: viscosity, U_m: mean velocity). A Darcy friction factor equation was proposed using a new Dean number ($Dn = Re/(2R/D)$ [5], i.e.,

$$\ln\left(\frac{f_C Re}{64}\right) = a + b(\ln(Dn))^2, \quad \text{where} \quad a = 0.021796 \text{ and } b = 0.0413356 \tag{1}$$

In contrast to the investigations of the frictional performance of single-phase flow, the two-phase pressure drop data for curved channels are comparatively few. Despite some data were reported for coiled tubes, the two-phase pressure drop data for U-type return bends are very rare. Only some models and correlations are available in the literature. For instance, Pierre [7,8] conducted R-12 and R-22 two-phase pressure drops in straight tube and return bend with tube diameter of 11.2 mm and curvature ratio of 6.6 and 13.2. Pierre's results indicated little influence of the curvature ratio on the resulting pressure drop. Traviss and Rohsenow [9] performed R-12 experiments in return bends with tube diameter of 8 mm having curvature ratios of 3.17 and 6.35. The resultant two-phase pressure drops were algebraically increased with the rise of total mass flux and vapor quality, and the decrease of bend radius. However, they neither compared with other predictions nor developed any correlation for their data. Geary [10] proposed a correlation of the two-phase pressure drop in return bends based on his R-22 data with tube diameter of 11.4 mm and curvature ratios from 2.2 to 6.7. The aforementioned refrigerant data were mainly conducted in larger diameter tubes ($d > 8$ mm). The Geary's correlation for the two-phase pressure gradient in the return bend was expressed as a type of single-phase pressure drop equation, $(dp/dz)_C = f\rho_G U_{G,S}^2/(2D)$. In addition, the effects of vapor quality and curvature ratio were included in the two-phase friction factor correlation.

$$f = \frac{(5.58 * 10^{-6}) Re_G^{0.5}}{\exp\left(\frac{0.215*2R}{D}\right) x^{1.25}} \tag{2}$$

where $Re_G = \rho_G U_{G,S} D/\mu_{G,}$, $U_{G,S} = Gx/\rho_G$.

Recently, Chen et al. [11] had conducted frictional measurement of water in U-type return bends with inner diameters ranged from $D = 3.43$–8.29 mm having curvature ratios ranged from 3.76 to 7.87. They proposed a new empirical correlation of Fanning friction factor for the return bends.

$$f_C = \frac{16}{Re}\left[1 + 29e^{\left(\frac{-2R}{D}\right)}\right]e^{\left(A+\left(\frac{L}{D}\right)B\right)} \tag{3}$$

where

$$A = 0.07 + 0.04\ln(Dn)^2$$

and

$$B = 0.36 - 0.035\ln Re^{0.9} - 0.0145(L/D)^{2.5} + 0.005(L/D)^3$$

and L is the space length between two consecutive U bends.

Also, based on the Chisholm correlation, Chen et al. [12] developed an empirical equation from the air–water data to calculate the two-phase pressure drop $(\mathrm{d}p/\mathrm{d}z)_C$ for U-type return bends.

$$\Phi^2_{C,L} = 0.9116X^{-0.0546}Fr^{0.0785}\left(1 + \frac{10}{X} + \frac{1}{X^2}\right) \tag{4}$$

where the liquid Froude number is defined as $Fr = U^2_{L,S}/gD$ and $U_{L,S} = G(1 - x/\rho_L$ is the liquid superficial velocity. The two-phase frictional multiplier $(\Phi_{C,L})$ based on the pressure gradient for liquid flowing alone $(\mathrm{d}p_L/\mathrm{d}z)$, and the Martinelli parameter X are defined as

$$\Phi^2_{C,L} = \frac{(\mathrm{d}p/\mathrm{d}z)_C}{\mathrm{d}p_L/\mathrm{d}z} \quad X^2 = \frac{\mathrm{d}p_L/\mathrm{d}z}{\mathrm{d}p_G/\mathrm{d}z} \tag{5}$$

In Eq. (5), the calculations of the pressure gradients for liquid and gas-phase flowing alone in the curved tube are made with friction factor Eq. (3).

Based on the single-phase friction factors in helical tubes, Awwad et al. [13] developed a correlation by utilizing the Lockhart and Martinelli relationship. It was found that the frictional pressure drop multiplier $(\Phi_{C,L})$ is not only a function of the Martinelli parameter (X), but also depends on the curvature ratio $(2R/D)$ and the superficial liquid velocity $(U_{L,S})$. An empirical correlation for two-phase flow in coiled tubes was proposed to correlate the frictional pressure drops, i.e.,

$$\Phi^2_{C,L} = \left[1 + \frac{X}{(AF^n_d)}\right]^2\left(1 + \frac{12}{X} + \frac{1}{X^2}\right) \tag{6}$$

$$F_d = \left(\frac{U^2_{L,S}}{gD}\right)\left(\frac{D}{2R}\right)^{0.1} \tag{7}$$

For $F_d < 0.3$, $A = 7.79$ and $n = 0.576$; for $F_d > 0.3$, $A = 13.6$ and $n = 1.3$. The empirical correlations of f_C for laminar flow by Manlapaz and Churchill [14] and turbulent flow by Ito [3] were adopted by Awwad et al. [13] to calculate the single-phase pressure gradients for liquid and gas flow alone in the same tube $(\mathrm{d}p_L/\mathrm{d}z$, $\mathrm{d}p_G/\mathrm{d}z)$.

Very recently, Wang et al. [15] conducted the two-phase pressure drop of R-410A and R-22 in a 5-mm diameter return bend with a curvature ratio of 6.63. For test results of the two-phase flow at mass flux, $G \geqslant 200$ kg m^{-2} s^{-1}, the ratio of the pressure gradients of curved bend to the straight tube was found approximately to be 1.8 and is relatively independent of the vapor quality x. However, at a smaller mass flux of 100 kg m^{-2} s^{-1}, this ratio shows a dramatic increase to 5 for $x = 0.1$. This significant change may be due to the change of the flow pattern from stratified to annular flow pattern [16].

For reducing the impact to the ozone layer, R-134a has successfully replaced R-12 in automobile application, and R-410A is recently regarded as the major substitute of R-22 for the residential application [17]. For small system application, the use of small diameter tube is very common for reducing refrigerant inventory [18]. For the two-phase pressure drop calculation, the knowledge of the single-phase frictional factor is normally required. However, the friction factor correlations [2,3,5,6,11] were only based on the water data. Extrapolations of these correlations to other working fluids, such as refrigerants, require further evaluations. In this regards, the purpose of this study is to examine the applicability of the related correlations either in single-phase or two-phase flow conditions with the environmentally friendly R-410A refrigerant. The tube configurations under examination are two 3.3 mm diameter return bends with $2R/D = 3.91$ and 8.15, and one 5.07 mm return bend with $2R/D = 5.18$. Previous results of the R-410A return bend data with $2R/D = 6.71$ and $D = 5.07$ mm by Wang et al. [15] are also included in the data analysis.

2. Experiments

The test rig is designed to be capable of conducting single-phase and two-phase tests for various refrigerants. Schematic of the test rig and the details of the test section are shown in Fig. 1. The test rig is composed of three independent flow loops. Namely, a refrigerant loop, a heating water flow loop, and a glycol flow loop. The refrigerant flow loop consists of a variable speed gear pump which delivers subcooled refrigerant to the preheater. The preheater is well insulated with foam material. The thermal conductivity of the foam material is much less than 0.1 W/m K. The thickness of the insulation material is about 2 cm thick. Estimation of the heat loss from the surface of the insulation material relative to the total heat transfer rate is always less than

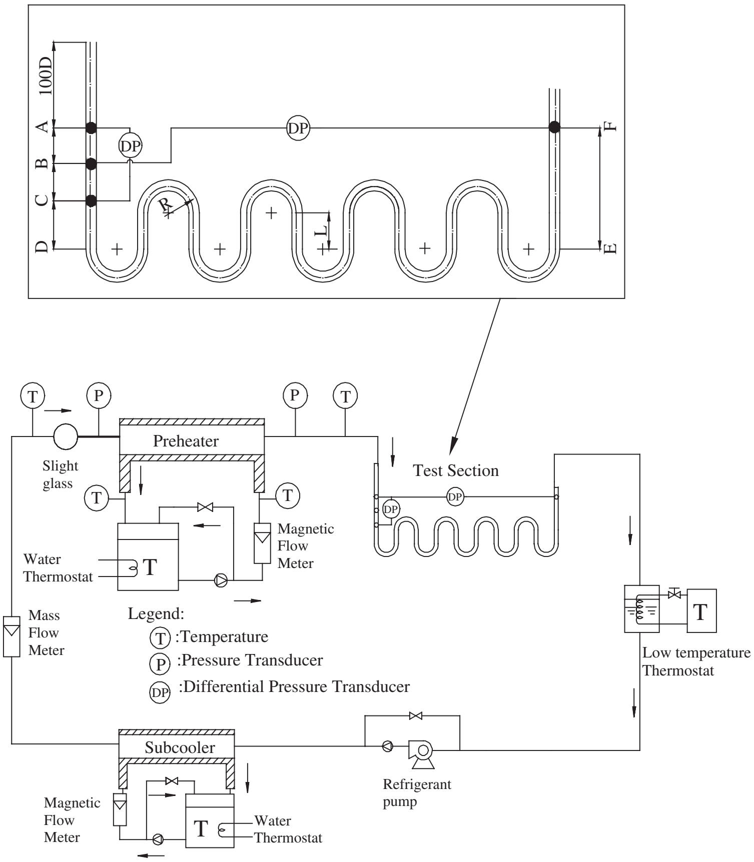

Fig. 1. Schematic of the test rig and the wavy test section.

2%. The refrigerant pump can provide refrigerant mass flux ranging from 100 to 900 $\mathrm{kg\,m^{-2}\,s^{-1}}$. The inlet temperatures of R-410A at the inlet were tested at near 10 and 25 °C. Detailed description of the test apparatus and the relevant reduction of the frictional performance can be found from previous studies [19].

Three copper U-type wavy pipes contain nine consecutive return bends were tested in this study. The wavy pipes tested in the loop are also insulated with foam material. Relevant geometrical parameters of the three wavy tubes along with the one tested by Wang et al. [15] ($D = 5.07$ mm) are tabulated in Table 1. As shown in Fig. 1, a straight entrance length of $100D$ is located at the upstream of the straight test section to achieve a fully developed flow condition. A differential pressure transducer is used to measure the pressure drop (ΔP_S) across the upstream straight test section ($L_S = 100D$) to serve as a reference measurement of the pressure gradient between the U bend and the straight tube. A straight length of $130D$ is directly connected to the U bend outlet for the flow recovery. Also, the other differential pressure transducer is utilized to measure the total pressure drop (ΔP_T), which includes the loss of the whole test section and the loss from the straight portions of the upstream ($L_U = 110D$) and downstream ($L_D = 130D$) straight tubes.

Table 1
Geometric parameters of the test sections

Tube no.	1	2	3	4
D (mm)	3.3	3.25	5.07	5.07
R (mm)	13.45	6.35	13.15	17
L (mm)	23.5	24.5	23	22
$2R/D$	8.15	3.91	5.18	6.71
$\overline{AC}$ (mm)	334	337	492	500
$\overline{CD}$ (mm)	211	211	315	315
$\overline{EF}$ (mm)	435	425	660	660
Data points	60	36	36	70

The single-phase and two-phase pressure drop gradients in U bend of the test section are obtained by subtracting the equivalent straight tube pressure drop having the length, $L_{ST} = L_U + 8L + L_D$, from the measured total pressured drop (ΔP_T), and then divided by the total axial length of the 9 U bends ($L_C = 9\pi R$). Therefore, the total pressure loss gradient due to U bends in the wavy tube can be expressed as: $(\mathrm{d}p/\mathrm{d}z)_C = \{\Delta P_T - L_{ST}(\Delta P_S/L_S)\}/L_C$. The equivalent bending friction factor, $f_C = (\mathrm{d}p/\mathrm{d}z)_C/(2\rho U_m^2/D)$ is then calculated

Table 2
Summary of estimated uncertainties

Primary measurements		Derived quantities		
Parameter	Uncertainty	Parameter	Uncertainty $G = 100$ kg/m^2 s	Uncertainty $G = 900$ kg/m^2 s
$\dot{m}_r$	±0.3–1.0%	G	±1.1%	±0.5%
$\dot{m}_{water}$	±0.5%	Re_L, Re_G	±0.6%	±0.6%
ΔP	±0.5%	$\Phi^2_{C,L}$	±21%	±2%
T	±0.05 °C	x	±3.3%	±4.4%

for single-phase flow in the U bend of the wavy tube, where U_m is the mean axial velocity in the tube and ρ is the fluid density. Resolution of the pressure differential transducers is ±0.5% of the measurements. The derived maximum uncertainty of the friction factors and two-phase multipliers, following the single-sample analysis proposed by Moffat [20], are ±2.7% and ±21%, respectively. The highest uncertainties are associated with the lowest mass flux. Details of the uncertainties are given in Table 2.

3. Results and discussion

The test results of f_C and f_S verse Re were plotted in Fig. 2. The base lines are the Fanning friction factor from the well-known Blasius equations for turbulent flow ($f_S = 0.0791Re^{-0.25}$ for $Re < 20000$ and $f_S = 0.046Re^{-0..20}$ for $Re > 20000$). As seen, the straight tube data, f_S, agree favorably with the base lines. The derivation of the measured f_S data to the values of Blasius equations is within ±7%. The good agreements shown for the straight tube data substantiate the accuracy of the instrumentation and the experimental apparatus. For the friction factor of curve tubes (f_C), one can see

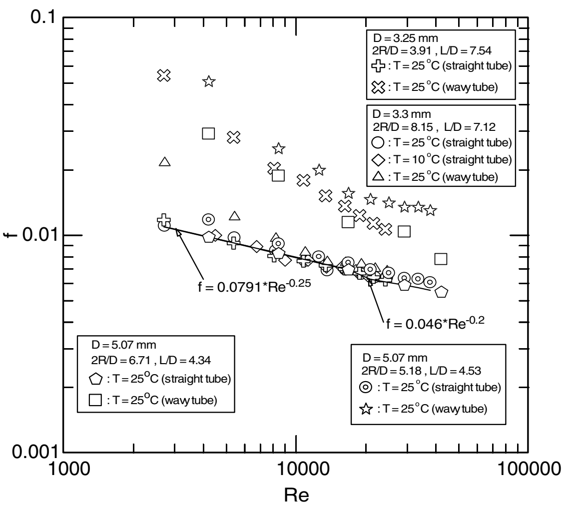

Fig. 2. Friction factor data of the straight tube and U bend.

that f_C exceeds those of straight tube considerably and the difference is increased with the decrease of curvature ratio ($2R/D$). It should be pointed out that the effect of curvature ratio is rather small for $2R/D = 8.15$. The results implied the swirled motion caused by the return bend is negligible when $2R/D = 8.15$ which is similar to the previous results [5,11]. However, the significant increase at $2R/D = 3.3$ indicates that the strength of the secondary flow, which increases the disturbance in flow in the curved tubes. The vortical motion is augmented noticeably as the curvature ratio is further reduced. This phenomenon can be further validated from the influence of Reynolds number. As can be seen from the Fig. 2, the ratio of f_C/f_S decreases when the Reynolds number is increased. This is due to the comparatively increase of the turbulence level that eventually surpasses the effect of curve return bend.

The measured single-phase pressure gradient data, $(dp/dz)_C$, are compared with three existing correlations [2,5,11]. It is found that the mean deviation of the measured data to the predictions by Ito [2], Popieil and Wojtkowiak [5] and Chen et al. [11] correlations are 27.0%, 27.5% and 30.8%, respectively. Note that the mean deviation is evaluated as $\frac{1}{N}\left(\sum_1^N |\Delta P_{pred} - \Delta P_{exp}|/\Delta P_{exp}\right) \times 100\%$. The Ito [2] correlation shows slightly better predictions than the others, however, significant under-prediction is observed at lower mass flux ($Re \approx 2600$). This is because the applicable range of Ito correlation is only valid for turbulent flow.

Analogously, the two-phase pressure gradient data in the return bend are compared with the measured pressure gradient data in the corresponding upstream straight tube, termed as $(dp/dz)_C/(dp/dz)_S$, verse vapor quality x for various mass flux are shown in Figs. 3 and 4 with the tube diameters of 5.07 and 3.3 mm, respectively. Likewise, the $(dp/dz)_C/(dp/dz)_S$ ratio increases with the decrease of the curvature ratio as those shown in single-phase results. Also shown in Fig. 3, for $G \geqslant 200$ kg m^{-2} s^{-1}, the ratio of $(dp/dz)_C/(dp/dz)_S$ is relatively independent of the vapor quality x and is slightly increased with the rise of mass flux. This is because the dominant flow pattern is annular flow which prevails in both straight tube and curve portion. The $(dp/dz)_C/(dp/dz)_S$ ratio spans from 2.3 to 3.1 for $2R/D = 5.18$ and from 1.6 to 2.4 for $2R/D = 6.71$. However, one can

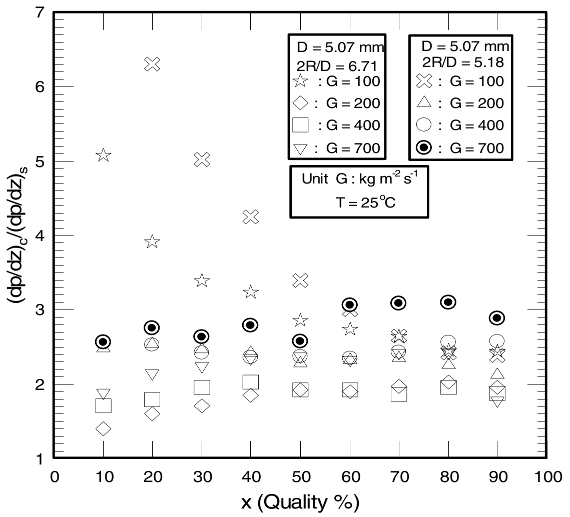

Fig. 3. $(\mathrm{d}p/\mathrm{d}z)_C/(\mathrm{d}p/\mathrm{d}z)_S$ vs. vapor quality at various mass flux for $D = 5.07$ mm.

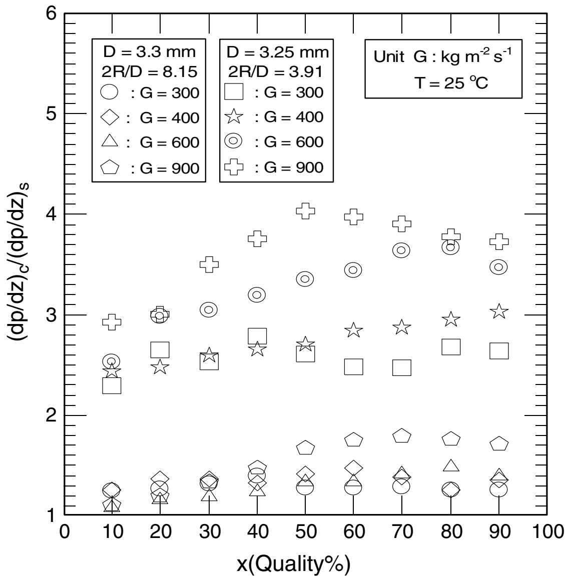

Fig. 4. $(\mathrm{d}p/\mathrm{d}z)_C/(\mathrm{d}p/\mathrm{d}z)_S$ vs. vapor quality at various mass flux for $D = 3.03$ mm.

see a pronounced increase of $(\mathrm{d}p/\mathrm{d}z)_C(\mathrm{d}p/\mathrm{d}z)_S$ when $G = 100\ \mathrm{kg\,m^{-2}\,s^{-1}}$ and at a low quality ($x < 0.5$). Explanations of the results can be attributed to the change of flow pattern. As depicted from the Taitel and Dukler flow regime map [21], for R-410A at 25 °C with $G = 100\ \mathrm{kg\,m^{-2}\ s^{-1}}$ and $x = 0.5$, the flow pattern in straight tube can be identified as wavy stratified flow because of the calculated $F = 0.277$ and $X = 0.537$. Note that F is the Froude parameter $(\rho_G/(\rho_L - \rho_G))^{0.5} \times (U_{G,S}/(Dg)^{0.5})$ and X is the Martinelli parameter. However, as the stratified wavy flow managed to come across the return bend, the wavy or stratified flow was observed momentarily changed to annular flow after the return bend [16]. In that regard, considerable increase of pressure drop is expected because the liquid is spread around periphery of the tube. Thus, the value of $(\mathrm{d}p/\mathrm{d}z)_C/(\mathrm{d}p/\mathrm{d}z)_S$ at $x = 0.2$ reaches approximately 3.8 and 6.3 for $2R/D = 6.71$ and $2R/D = 5.18$, respectively.

However, the higher pressure gradient ratio at lower vapor quality was not observed in Fig. 4 for $D = 3.3$ mm. This is because the temporary flow pattern transition phenomenon in a 3 mm return bend from stratified to annular flow was not so pronounced [22]. It is likely due to the relative dominance of the surface tension effect on flow patterns in a 3 mm diameter tube than that in a 5 mm diameter tube. Also, the R-410A flow patterns at lower vapor quality in the 3.3 mm straight tube at lower vapor quality for $G = 300\ \mathrm{kg\,m^{-2}\,s^{-1}}$ are likely to be in the slug/plug flow region [23,24] where no dramatic change of the flow pattern may be encountered for flow across the return bend. Hence the ranges of this pressure gradient ratio are from 2.3 to 4.0 for $2R/D = 3.91$ and span from 1.1 to 1.8 for $2R/D = 8.15$. Also noted in Fig. 4, one can see that the value of $(\mathrm{d}p/\mathrm{d}z)_C/(\mathrm{d}p/\mathrm{d}z)_S$ for $G \geqslant 400\ \mathrm{kg\,m^{-2}\,s^{-1}}$ is highly influenced by the curvature ratio. This ratio is generally increased with the increase of the vapor quality and mass flux for $2R/D = 3.91$ since the interface of annular flow is perturbed and entrained considerably by the vapor shear and the centrifugal force at a smaller curvature ratio.

The two-phase pressure drop data are compared with the correlations of Awwad et al. [13] and Chen et al. [12] with a mean deviation of 53.4% and 38.4%, respectively. Results are shown in Figs. 5 and 6. The poor predictive ability by [12,13] is not surprised. Firstly, the previous

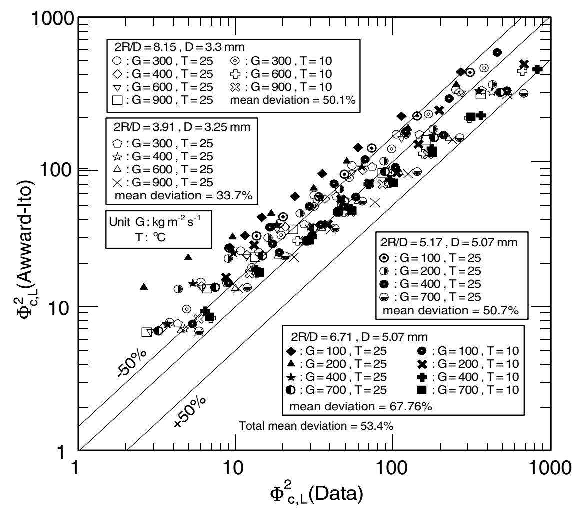

Fig. 5. Predictions of Awwad et al. correlation [13] using Ito f_C correlation [2].

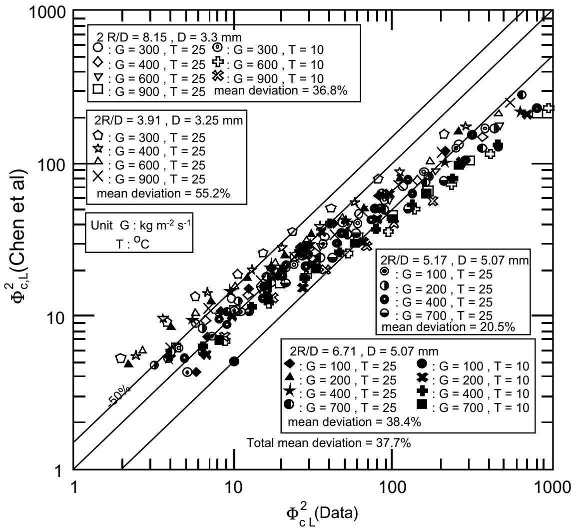

Fig. 6. Predictions of Chen et al. correlation [12] using Chen et al. f_C correlation [11].

correlations are developed based on air–water data. Secondly, the aforementioned correlations need a single-phase correlation in return bend. The erroneous in single-phase results may be amplified in two-phase predictions. As shown previously, the mean deviations of the predictive ability of the single-phase friction factors from Ito [2] and Chen et al. [11] are 27.0% and 30.8%. In contrast, a fair prediction of 24.8% mean deviation by Geary correlation [10] is shown in Fig. 7. Notice that the Geary correlation [10] is based on refrigerant data. Thus, the Geary's two-phase friction factor f defined in Eq. (2) may be more appropriate for refrigerant. Since the friction resistance is the composition of gas and liquid flows, a combined vapor and liquid Reynolds number ($Re_m = Re_G + Re_L$) is then utilized for data correlation. Surface tension becomes more significant to change the flow patterns in small tubes, and the change of flow pattern will affect the two-phase frictional pressure drop. Its influence is counted in the Weber number ($We = G^2D/\rho_G\sigma$) which has the ratio between gas inertia and liquid surface tension. Therefore, based on the correlation form of Geary [10], we have extended the applicability of his correlation by including Geary's R-22 database (145 points) [10] and the present R-410A results (202 points) along with the combined Reynolds number (Re_m), x and $2R/D$, as well as the Weber number. A new f correlation is proposed from the empirical fit of the present data and Geary's data.

$$f = \frac{10^{-2} Re_m^{0.35}}{We^{0.12} \exp\left(0.194 \frac{2R}{D}\right) x^{1.26}} \tag{8}$$

The two-phase pressure gradient in the return bend can be calculated as: $(dp/dz)_C = f \rho_G U_{G,S}^2/(2D)$. Detailed comparison of the predictions of the return bend using Eq. (8) against the present R-410A data and Geary's R-22 data has a mean deviation of 19.1% as shown in Fig. 8. Note that the mean deviation of Geary correlation to his 145 points data is 29.3% [10], while the proposed correlation Eq. (8) only has a mean deviation of 22.9% with Geary's data. Very good agreements of the data and the predictions are observed in Fig. 8. Only a few data points with very low vapor quality for $G = 100\ \mathrm{kg\,m^{-2}\,s^{-1}}$ and $D = 5.07$ mm were under-prediction. It may be attributed to the flow pattern change as discussed in Fig. 3.

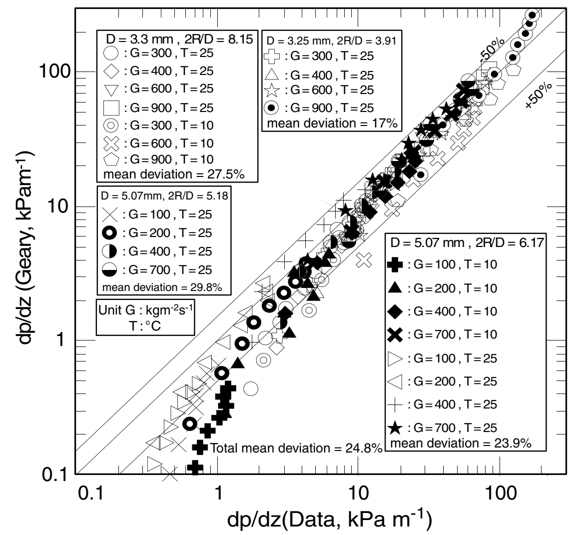

Fig. 7. Predictions of Geary correlation [10] vs. two-phase $(dp/dz)_C$ data in the U bend.

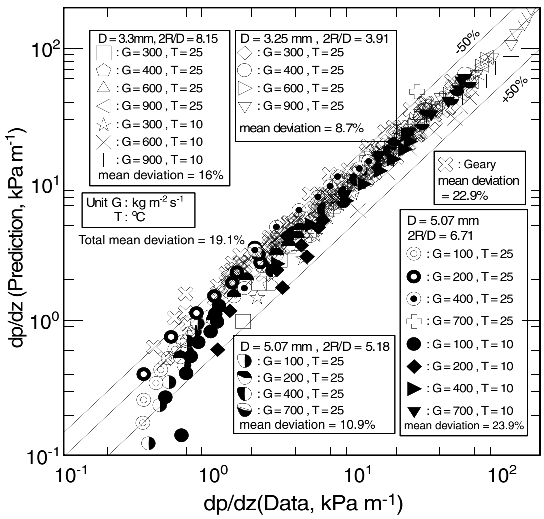

Fig. 8. Predictions of the proposed Eq. (8) vs. the present data and Geary's data [10].

4. Conclusions

The influence of the return bend on the frictional performance of R-410A is examined. The measured single-phase and two-phase pressure drop data are compared with the available correlations. Results of this study are summarized as:

1. The f_C and two-phase pressure gradient data in the return bend considerably increase with the decrease of curvature ratio ($2R/D$). The two-phase pressure gradient ratio of $(dp/dz)_C/(dp/dz)_S$ is also increased with the increase of mass flux.
2. For the single-phase results, three existing correlations of Ito [2], Popieil and Wojtkowiak [5] and Chen et al. [11] give fair agreements with the present data. The associated mean deviations are 27%, 27.5% and 30.8%, respectively.
3. For $D = 5.07$ mm and $G \geqslant 200$ kg m^{-2} s^{-1}, the ratio of $(dp/dz)_C/(dp/dz)_S$ is relatively independent of the vapor quality x. However, a considerable rise of this ratio is encountered at $x < 0.5$ and $G = 100$ g m^{-2} s^{-1}. The significant increase of this ratio may be attributed to the momentarily changed of flow pattern from stratified flow to annular flow after the return bend.
4. For $D = 3.3$ mm and $G \geqslant 300$ g m^{-2} s^{-1}, the higher pressure gradient ratio at lower vapor quality is not observed. This is because the flow pattern at low vapor quality is slug flow and no dramatic change of flow pattern is encountered for flow across return bend. This $(dp/dz)_C/(dp/dz)_S$ ratio is generally increased with the increase of x and G for $2R/D = 3.91$. This is because of the relatively increase of the vapor shear and the liquid entrainment occurring at the annular flow interface at a smaller curvature ratio.
5. The two-phase pressure drop data are compared with the predictions of Awwad et al. [13], Chen et al. [12] and Geary [10] with a mean deviation of 53.4%, 38.4%, and 24.8%, respectively. A modified two-phase friction factor based on the Geary correlation [10] is proposed. The proposed correlation gives a good agreement to the present data and Geary's data with a mean deviation of 19.1%.

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