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Technical Note

Frictional performance of R-22 and R-410A inside a 5.0 mm wavy diameter tube

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Abstract

The influence of return bend on the frictional performance of R-410A and R-22 in a 5-mm diameter tube is examined with a curvature ratio of 6.63. The existing single-phase correlations give fairly good agreements with the present single-phase data, but the existing two-phase correlations of the return bend fail to predict the present two-phase data. For test results of the two-phase flow at $G \geqslant 200\ \mathrm{kg\,m^{-2}\,s^{-1}}$, $((\mathrm{d}P/\mathrm{d}z)_c/(\mathrm{d}P/\mathrm{d}z)_s)$ is approximately equal to 1.8 and is relatively independent of the vapor quality x. However, at a smaller mass flux of $100\ \mathrm{kg\,m^{-2}\,s^{-1}}$, $((\mathrm{d}P/\mathrm{d}z)_c/(\mathrm{d}P/\mathrm{d}z)_s)$ decreases with x, reaching approximately 5 for $x = 0.1$. The significant increase of this ratio for G increased from 100 to $200\ \mathrm{kg\,m^{-2}\,s^{-1}}$ may be attributed to the change of the two-phase flow pattern.

1. Introduction

Curved tube and bends are widely employed in heat exchange devices and flow transmitting devices. The curved channel can be in the form of helical, spiral, and U-tube return bend. For HVAC&R application, exploitation of hairpin in air-cooled heat exchanger is often seen. It is well known that the centrifugal force results in the secondary flow in the single-phase flow system. As flow across the curved pipes, the centrifugal force drives the more rapid fluid in the concave part of the curve channel while the fluid in the convex part is slowing down. Thereby the occurrence of a secondary flow at right angle in the main flow is due to the centrifugal force [1].

Single-phase flow characteristics in curved channel has been extensively investigated both theoretically and experimentally [2–9]. The magnitude of such secondary flows is obviously increased with a decrease of bend radius, and with a increase of fluid velocity. For single-phase flow inside U-type wavy pipe, the investigations [7,8] are probably the most informative, they conducted the test with water in a total of six tubes and the data were nicely correlated. However, extrapolations of their correlations to vapor/gas phase still needs further examination due to the database contains only water. In this regard, one of the objective of this study is to examine the applicability of their correlation to the vapor phase.

Contrast to that of single-phase studies, most of the published data focused on the two-phase pressure drop in helical tubes. The two-phase frictional data in wavy/U-type pipe is very rare. Almost all the air-cooled evaporator and condenser contain hairpins. The consecutive bends will cause higher pressure drop than that of the corresponding straight tube. In addition, the higher pressure drop in return bends may significantly alter the refrigerant distributions were split or combined of the refrigerant circuitry encountered. The frictional performance is very crucial for engineers to design the air-cooled heat exchangers. Of the published literatures

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Nomenclature

d	internal diameter of tube, m
f_c	friction factor for a bend
f_s	friction factor for a straight tube
G	total mass flux, $\mathrm{kg\,m^{-2}\,s^{-1}}$
L_{ST}	total straight length in the test section, m
ΔP_s	pressure drop across the straight test section, Pa
ΔP_T	total pressure drop across the test section, Pa
dP/dZ	measured frictional pressure gradient, $\mathrm{N\,m^{-3}}$
R	radius of center line of bend, m
Re	Reynolds number $(\rho U_m d/\mu)$
U_m	mean axial velocity, $\mathrm{m\,s^{-1}}$
x	vapor quality
Greek symbols	
ρ	density, $\mathrm{kg\,m^{-3}}$
μ	viscosity, $\mathrm{N\,s\,m^{-2}}$
ϕ	$((dP/dz)_c/(dP/dz)_s)$
Subscripts	
c	curved tube
D	downstream
s	straight test tube
U	upstream

concerning the two-phase frictional performance, there were only some data and correlations available. For instance, Pierre [10,11] conducted two-phase pressure drops of R-12 and R-22 in straight tube and return bend with tube diameter of 11.2 mm having curvature ratios of 6.6 and 13.2, the results indicated little influence of the curvature ratio on the resulting pressure drop. Geary [14] pointed out the conclusion drawn by Pierre [10,11] is incorrect, he then 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 the curvature ratios ranging from 2.2 to 6.7. Travis and Rohsenow [13] conducted R-12 experiment in return bends with tube diameter of 8 mm having curvature ratios of 3.17 and 6.35. The resulted two-phase pressure drops were algebraically increased with increasing total mass flux and vapor quality, and decreasing bend radius. However, they did not compare with other predictions and no correlation was reported. The above reported data were mainly conducted in larger diameter tubes ($d > 8$ mm) in which the influence of surface tension is comparatively small. Recently, use of small diameter tube becomes more and more popular for better air-side performance and smaller refrigerant inventory. Hence, the main objective of this study is to examine the effect of return bend on the two-phase frictional performance in a 5-mm diameter tube. Refrigerants used for testing are R-22 and R-410A.

2. Experimental method

2.1. Test facility

The test rig is designed to be capable of conducting tests for the single- and two-phase mixtures for various refrigerants. Schematic of the test rig and the details of the test section is seen 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 refrigerant pump can provide refrigerant mass fluxes ranging from 100 to 700 $\mathrm{kg\,m^{-2}\,s^{-1}}$. Detailed description of the test apparatus and the relevant reduction of the frictional performance can be found from previous studies [14,15]. To verify the instrumentation and the measurement results, single-phase pressure drops of R-22 and R-410A were checked with the well-known Blasius equation ($f_s = 0.0791\ Re^{-0.25}$), the deviation of the measured data and the correlation is within ±7%. The derived uncertainties of the friction factors and two-phase multipliers, following the single-sample analysis proposed by Moffat [16], ranges from 2.7% to 21%, the highest uncertainties are associated with the lowest mass flux.

2.2. Data reductions of the frictional performance of the curved channel

The single-phase pressure drop of the wavy tube is calculated by subtracting the equivalent straight tube pressure drop having the total straight length, L_{ST} from the measured total pressured drop (ΔP_T). This leads to the definition of the equivalent friction factor, f_c, as

$$f_c = \frac{\left(\Delta P_T - \frac{4(L_{ST})}{d} f_s \frac{\rho U_m^2}{2}\right)}{\frac{4L_c}{d}\frac{\rho U_m^2}{2}} \quad (1)$$

where $L_c = 9\pi R$ is the total axial length of the nine U bends, R is the radius of center line of U bend, U_m is the mean axial velocity in the tube, ρ is the fluid density, and

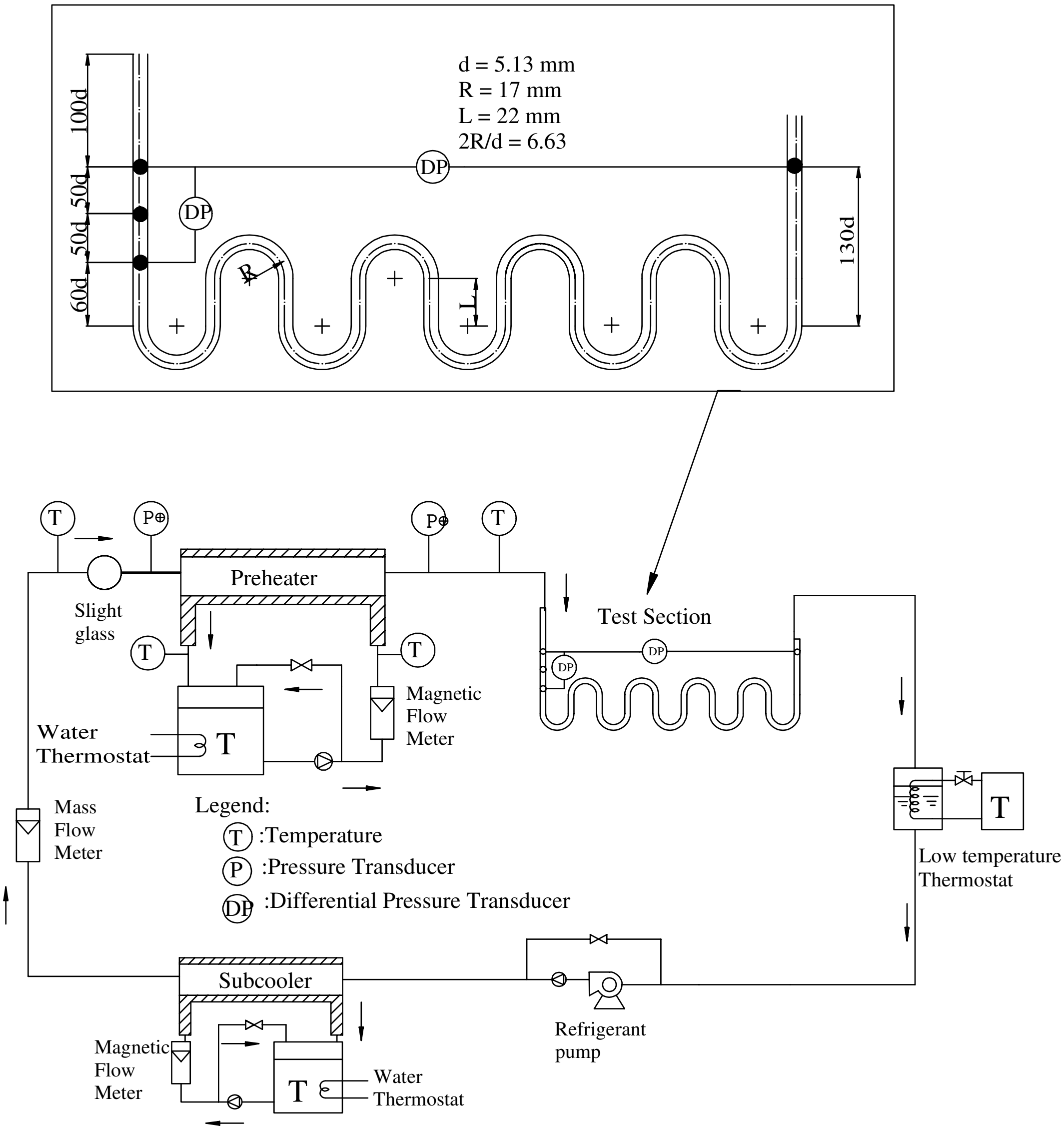

Fig. 1. Schematic of the experimental system and the test section.

the frictional factor for the straight tube, f_s, is obtained from the measured data.

The two-phase pressure drop data were analyzed using the concept of the two-phase multiplier. Tests were conducted adiabatically. Because the acceleration pressure gradient, ΔP_a, can be neglected in the adiabatic experiments, a more accurate calculation of the frictional gradient can be obtained thereby. The influence of the return bend was in terms of the ratios of frictional gradient in curved channel to that of the straight tube having the same length:

$$\phi = \frac{(\mathrm{d}P/\mathrm{d}z)_c}{(\mathrm{d}P/\mathrm{d}z)_s} \tag{2}$$

3. Results and discussion

Test results of the single-phase frictional performance of the return bend is also compared with several correlations [3,7]. Detailed results of comparison are shown in Fig. 2. As seen, the mean deviation of the correlation of Ito [3] and Popieil and Wojtkowiak [7] are 18.0% and 12.1%, respectively. Both correlations give fairly good predictive ability. The Ito correlation [3] shows significant under-prediction at a mass flux of 100 kg m^{-2} s^{-1} ($Re \approx 3500$). This is because the applicable range of the Ito correlation is valid for $Re > 20,000$. Analogously, the test results for two-phase flow were compared with the correlations of Pierre [11] and Geary [12]. As seen in

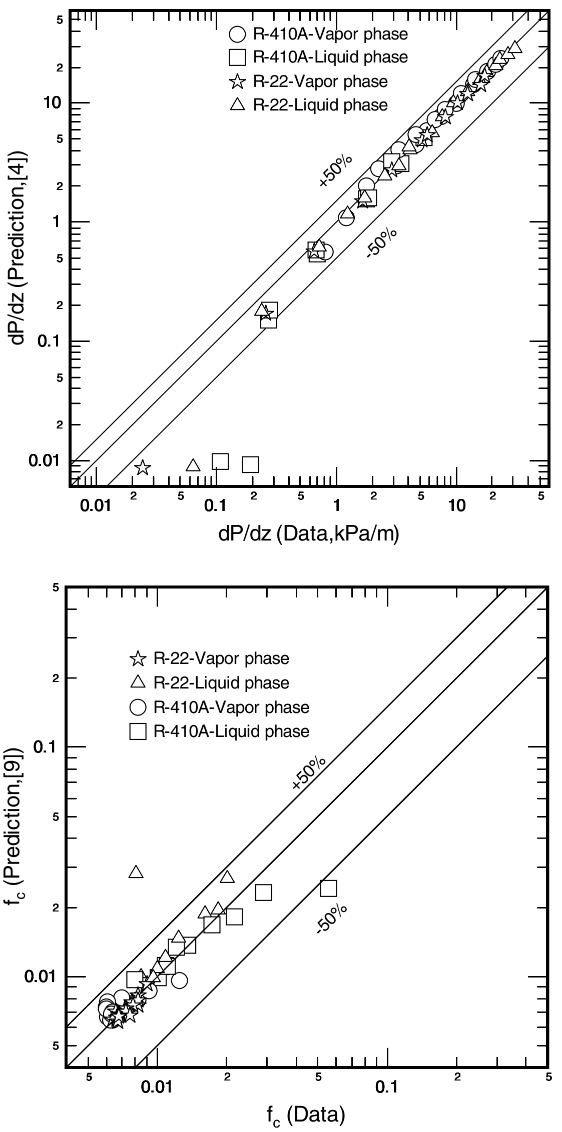

Fig. 2. Comparisons of the single-phase data of the return bend with the Ito [3] and the Popieil and Wojtkowiak [7] correlations.

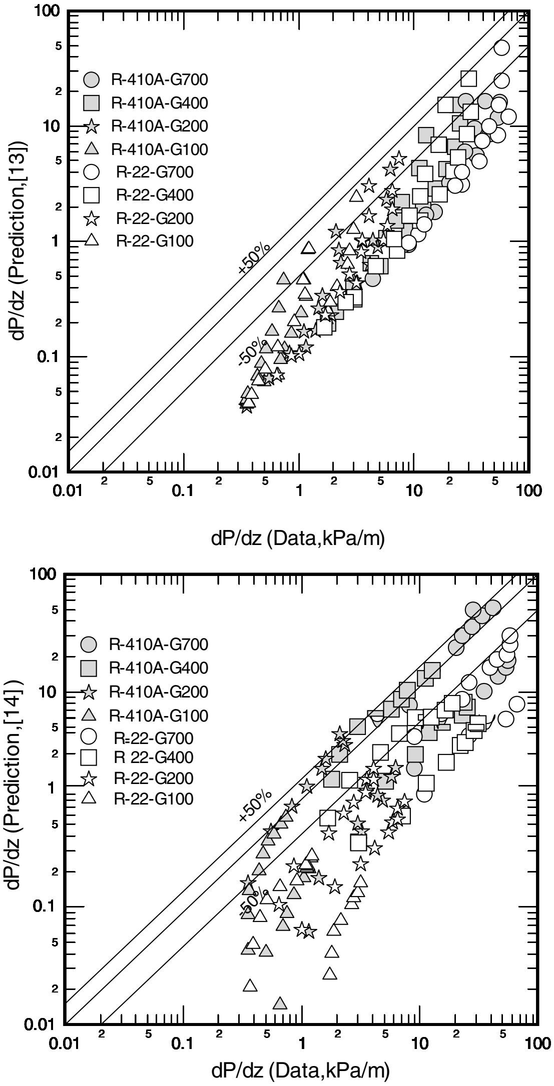

Fig. 3. Comparisons of the two-phase data of the return bend with the Pierre [11] and Geary [12] correlations.

Fig. 3, both correlations significantly under-predicts the test data. Notice that the relevant mean deviations are 75.4% and 66.7%, respectively. Part of the explanation of the pronounced deviation may be attributed to the smaller diameter of the present study.

For a further comparison of the influence of the return bend, the ratio of the frictional gradient $((\mathrm{d}P/\mathrm{d}z)_c/(\mathrm{d}P/\mathrm{d}z)_s)$ is shown in Fig. 4, the subscripts c and s denote the curved and straight tube, respectively. As seen in the figure, for $G \geqslant 200\ \mathrm{kg\,m^{-2}\,s^{-1}}$, $((\mathrm{d}P/\mathrm{d}z)_c/(\mathrm{d}P/\mathrm{d}z)_s)$ is approximately equal to 1.8, relatively independent of the quality x. At a smaller mass flux of $100\ \mathrm{kg\,m^{-2}\,s^{-1}}$, the ratio increases with x when $x < 0.3$, $((\mathrm{d}P/\mathrm{d}z)_c/(\mathrm{d}P/\mathrm{d}z)_s)$ reaches approximately 5 for $x = 0.1$. For the present flow condition of $G = 100\ \mathrm{kg\,m^{-2}\,s^{-1}}$, based on the flow observation results of Wang et al. [17] for R-22, R-407C, and R-134a flowing through a straight tube with diameter of 6.5 mm, it is expected that the two-phase flow pattern at lower quality region is stratified and is annular flow at higher quality region, as shown.

With the presence of return bend, it is suspected that the stratified flow may turn into annular flow which causes significant increase of pressure drop. The evidence can be found from a recent paper by Chen et al. [18] who conducted tests in a 6.9 mm diameter with curvature ratios ranging from 3 to 7, from which the

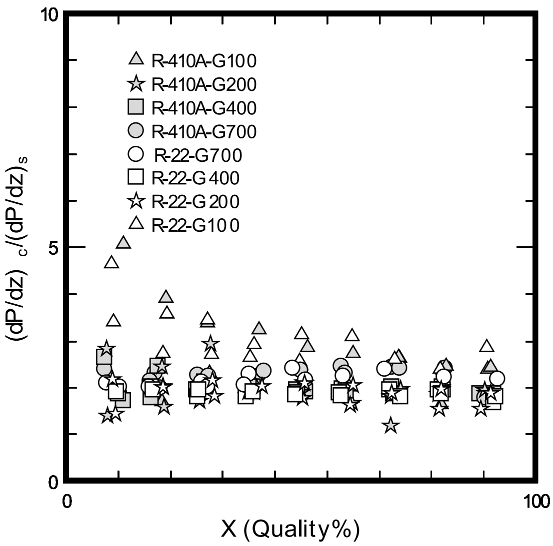

Fig. 4. The ratio of $((\mathrm{d}P/\mathrm{d}z)_c/(\mathrm{d}P/\mathrm{d}z)_s)$ vs. x at various mass fluxes.

two-phase flow across the test tube can be roughly classified into five regions [18]: (I) upstream region; (II) de-accelerating region; (III) return bend; (IV) recovery region; and (V) downstream region. However, with the presence of return bend, the flow pattern reveals a pronounced change in the return bend and in the recovery section. The liquid in the bottom is swirled along the concave part of the return bend while the vapor flow is forced towards the convex portion of the return bend. The swirled motion continues in the recovery region (IV) due to its inertia and the secondary force. Hence. the flow pattern in region (IV) was observed to turn into annular flow whereas the upstream region is in stratified flow. At a lower value of x, the flow pattern before entering the return bend, one can expect that the stratified flow pattern may turn into the annular flow after return bend. In this regard, the frictional performance is expected to be dramatically increased for the annular flow pattern as compared to that of the stratified flow. Thus, $((\mathrm{d}P/\mathrm{d}z)_c/(\mathrm{d}P/\mathrm{d}z)_s)$ can be increased as much as fivefold. Conversely, a further increase of vapor quality would change the flow pattern into wavy-annular or annular flow that eventually leads to a drop of $((\mathrm{d}P/\mathrm{d}z)_c/(\mathrm{d}P/\mathrm{d}z)_s)$ because no significant change of flow pattern will exist after the return bend. This can explain that test results for $G = 100\ \mathrm{kg\,m^{-2}\,s^{-1}}$ $((\mathrm{d}P/\mathrm{d}z)_c/(\mathrm{d}P/\mathrm{d}z)_s)$ at $x > 0.3$ is roughly the same with those of $G \geqslant 200\ \mathrm{kg\,m^{-2}\,s^{-1}}$.

4. Conclusion

The influence of return bend on the frictional performance of R-410A and R-22 in a 5-mm diameter tube is examined in this study. The range of mass flux is between 100 and 700 $\mathrm{kg\,m^{-2}\,s^{-1}}$. Conclusions of the present study include:

(1) For the single-phase results, the predictive ability for the correlations of Ito [3] and Wojtkowiak and Popieil [8] are fairly good. However, pronounced under-prediction is seen if $Re < 5000$.
(2) The existing two-phase correlations of the return bend fail to predict the present data. It is likely that the under-predictions are related to the smaller diameter tube.
(3) For $G \geqslant 200\ \mathrm{kg\,m^{-2}\,s^{-1}}$, $((\mathrm{d}P/\mathrm{d}z)_c/(\mathrm{d}P/\mathrm{d}z)_s)$ is approximately equal to 1.8, relatively independent of the vapor quality x. At a smaller mass flux of 100 $\mathrm{kg\,m^{-2}\,s^{-1}}$, $((\mathrm{d}P/\mathrm{d}z)_c/(\mathrm{d}P/\mathrm{d}z)_s)$ at $x > 0.3$ is roughly the same with those of $G \geqslant 200\ \mathrm{kg\,m^{-2}\,s^{-1}}$. However, the ratio increases with decreasing x when x is below 0.3, $((\mathrm{d}P/\mathrm{d}z)_c/(\mathrm{d}P/\mathrm{d}z)_s)$ reaches approximately 5 for $x = 0.1$. The significant increase of this ratio for G increased from 100 to 200 $\mathrm{kg\,m^{-2}\,s^{-1}}$ may be attributed to the change of two-phase flow pattern.

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