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AN IMPROVED CORRELATION FOR TWO-PHASE PRESSURE DROP OF R-22 AND R-410A IN 180° RETURN BENDS

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Abstract. *A new correlation for two-phase flow pressure drop in 180° return bends is proposed based on a total of 241 experimental data points for R-22 and R-410A from two independent studies. The data span smooth tubes with inner diameters (D) from 3.3 mm to 11.6 mm, bend radiuses (R) from 6.4 mm to 37.3 mm, and curvature ratios (2R/D) from 2.3 to 8.2. The correlation consists of a two-phase pressure drop for straight tubes and a multiplier that accounts for the bend curvature. The Buckinham-PI Theorem was used to formulate the curvature multiplier in terms of refrigerant properties, flow characteristics, and bend geometry. The correlation predicts all data with a mean deviation of 15.7 %, and 75 % of the data fall within ± 25 % error bands.*

Keywords. *short return bends, two-phase pressure drop, curvature multiplier, Buckinham-PI theorem*

1. Introduction

Return bends are curved pipe fittings which connect parallel straight tubes in finned-tube heat exchangers, such as evaporators and condensers used in air conditioning and refrigeration systems. In such heat exchangers, the air flows outside through the finned region while refrigerant flows inside tubes. Although single-phase refrigerant flow may occur in the form of subcooled liquid refrigerant in the condenser or superheated vapour in the condenser and evaporator, the two-phase flow region occupies the major part of these coils. The proper design of compact heat exchangers requires the calculation of heat transfer rates and pressure drops. The heat transfer in return bends are insignificant, so the bends are usually considered as adiabatic. On the other hand, the pressure drops in the return bends may be of the same magnitude of those observed for straight tubes and must be taken into account.

Figure 1 shows a sketch of a 180° return bend connecting two parallel straight tubes. The upstream refrigerant flow follows the pattern of a typical two-phase flow in a straight-tube, whose characteristics depend on the refrigerant properties, mass flux, vapour quality, pressure, and tube diameter and inner surface. According to Hoang & Davis (1984), the two-phase pressure drop in the bend is affected not only by the secondary flow effects observed in single-phase flows, but also by the separation of the phases due to centrifugal forces which concentrates the liquid toward the concave (outside) portion, while the vapour flows toward the convex portion. This increases the relative motion between the phases and pressure drop. At the bend outlet, significant pressure drop is also caused by the remixing process, which extends to about 9 diameters downstream. The pressure drop in bends is significantly higher for two-phase than for single-phase flows.

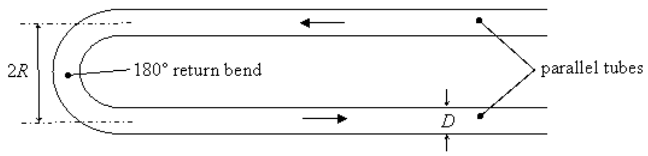

Figure 1. Schematic of a 180° return bend.

Several studies were conducted in order to quantify the pressure drops in 180° return bends, although most of them have considered only single-phase water flows (Ito 1960, Idelshik 1986, Wojtkowiak & Popiel 2000, Chen et al. 2003). The first study on two-phase pressure drops in return bends is attributed to Pierre (1964), who proposed a correlation based on experiments carried out with R-12 and R-22. Pierre (1964) assumed that the total pressure loss is divided into two major effects: friction and turning. The first was calculated considering the bend as a straight tube, while the second was obtained by subtracting the straight-tube pressure drop from the overall pressure drop. For the range of centre-to-centre distances he did not observe this parameter to be of a major influence and did not include it in his pressure drop correlation. The subsequent study by Geary (1975) with R-22 using various bend geometries pointed to the importance of the centre-to-centre distance. His correlation is based on a friction factor for the vapour flow and is applicable for qualities higher than 0.2 and lower than 0.8. Figure 2 presents validation of the Geary correlation with his data. The paper reports the prediction of 87 % of the experimental data within ±15 %.

Later, Chisholm (1983) and Paliwoda (1992) proposed correlations for two-phase pressure drops in return bends although did not provide validation of their correlations against experimental evidence. Recently, Chen et al. (2004a) and Chen et al. (2004b) studied water-air mixture and R-410A flows, respectively, through different bend geometries. Chen et al. (2004b) proposed a correlation with which they predicted both Geary's (1975) and their own experimental data within ±50 % error bands and a mean deviation of 19.1 %.

In the present work, a dataset of 241 experimental points obtained from Geary (1975) and Chen et al. (2004b) was used to derive a new, improved correlation that can be applied within the whole two-phase region for smooth-tube return bends. This study was partially reported in Domanski & Hermes (2006). All refrigerant property calculations were based on REFPROP (Lemmon et al. 2002).

2. Available Experimental Data and Correlations

2.1. Geary's (1975) Database and Correlation

Geary (1975) carried out experiments with two-phase, adiabatic flows of R-22 at 4.5 °C for bends with inner diameters of 11.4 mm to 11.6 mm, curvature ratios from 2.3 to 6.6, mass fluxes from 100 kg $s^{-1}m^2$ to 500 kg $s^{-1}m^2$, and vapour-quality range from 0.2 to 0.8, in a total of 145 experimental points. He tested two bends assembled in series and separated by a 190D length tube.

Our analysis of the two-phase flow pattern using the map proposed by Thome (2005) showed that the annular flow was present in almost 70 % of the experiments (101 points), the stratified/wavy flow was present in 20 % of the experiments (30 points), and the intermittent flow occurred in the remaining 10 % of the data points (14 points).

Geary (1975) correlated the two-phase pressure drop in return bends by using a single-phase pressure drop equation for vapor flow only, as follows:

$$\Delta p = f \frac{L}{D} \frac{G^2 x^2}{2\rho_v} \tag{1}$$

where ρ_v is the density of vapour phase [kg m^{-3}], $L=\pi R$ is the bend length [m], R is the curvature radius [m], D is tube diameter [m], G is refrigerant mass flux [kg $m^{-2}s^{-1}$], x is the vapour quality, and f is a dimensionless friction factor given by:

$$f = \frac{\mathrm{a}\mathrm{Re}_v^{0.5}}{\exp\left(0.215 \dfrac{2R}{D}\right) x^{1.25}} \tag{2}$$

where $a=8.03\cdot10^{-4}$, and $\mathrm{Re}_v=GxD/\mu_v$ is the vapour Reynolds number. Note that Geary's paper uses $a=5.58\cdot10^{-6}$ [ft^2 in^{-2}] to compensate for the British units he selected to use in equation (1). Consequently, Geary's friction factor is not dimensionless.

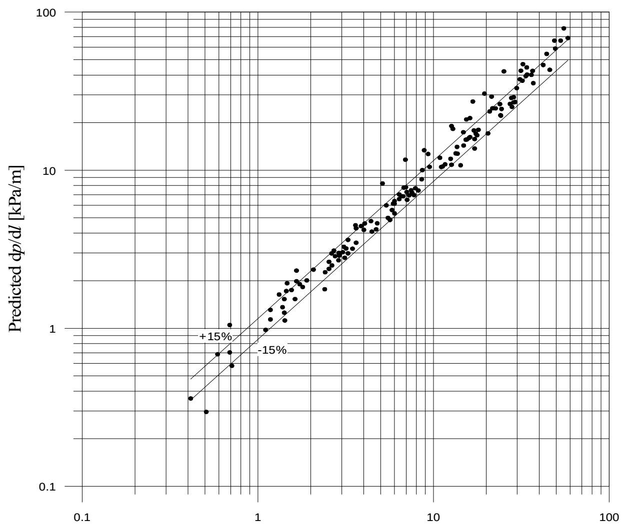

Figure 2. Comparisons between Geary's (1975) experimental data and predictions using his correlation.

2.2. Chen's et al. (2004b) Database and Correlation

Chen et al. (2004b) carried out experiments with two-phase, adiabatic flows of R-410A at 10 °C and 25 °C saturation temperatures spanning the vapour quality range from liquid to vapour. The inner diameters varied from 3.25 mm to 5.1 mm, the curvature ratios were from 3.9 to 8.2, and the mass fluxes were from 100 kg $s^{-1}m^2$ to 900 kg $s^{-1}m^2$, The test section comprised nine bends located in one plane, connected in series in a serpentine-type fashion. The neighbouring bends were connected by straight tubes. The measurements included both the pressure drop in the upstream straight tube and the overall pressure drop in the whole test section. The first measurement was used to estimate the pressure drop in the straight tubes connecting neighbouring bends, which then was subtracted from the overall pressure drop yielding the pressure losses in the bends alone. A total of 132 tests points were made available from the authors for three out of four geometries tested (Chen 2004). Table 1 presents details of these three bend arrangements.

Table 1. Bend geometries tested by Chen et al. (2004b)

	Bend #1	Bend #2	Bend #3
D, mm	3.3	3.25	5.07
R, mm	13.45	6.35	13.15
B, mm	23.5	24.5	23
2*R*/*D*	8.15	3.91	5.19
B/*D*	7.12	7.54	4.54
# data points	60	36	36

The two-phase flow pattern analysis of Chen et al. (2004b) data showed that annular flow was present in 51 % (67 points), while stratified/wavy flow and intermittent flow took place in 9 % (12 points) and 40 % (53 points) experiments, respectively. Figure 3 summarises the distribution of flow patterns for both the 145 points for R-22 and 132 points for R-410A. Most of the 277 points (60 %, 168 points) have shown annular flow pattern, 25 % (67 points) intermittent and 15 % (42 points) stratified/wavy.

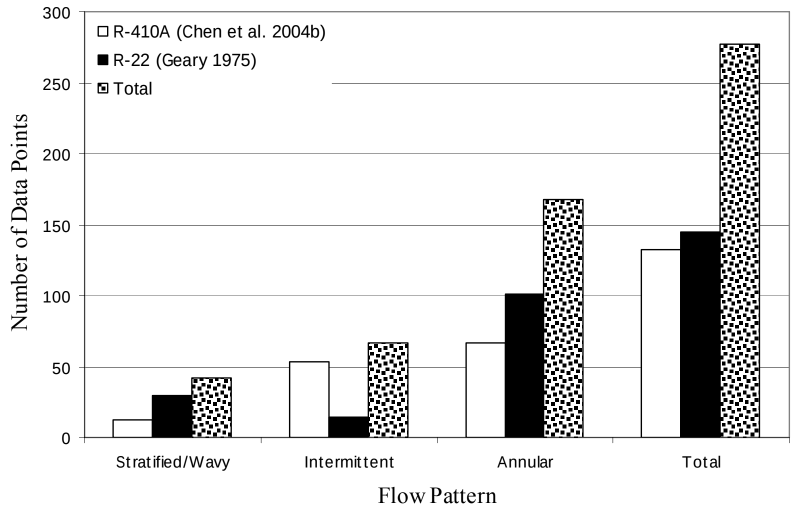

Figure 3. Flow pattern distribution for R22 and R410A data according to Thome's (2005) criteria.

Based on Geary's (1975) and their own data, Chen et al. (2004b) proposed a correlation which uses the formulation presented by Geary (1975) with a modifications in the friction factor equation. They included the Weber number, We=$G^2D/\rho v\sigma$, to account for the effects of liquid surface tension and gas inertia, and replaced the vapour Reynolds number by a combined vapour and liquid Reynolds number, $\mathrm{Re}_m=\mathrm{Re}_v+\mathrm{Re}_l$ ($\mathrm{Re}_v=xGD/\mu_v$, $\mathrm{Re}_l=xGD/\mu_l$), which yielded:

$$f=\frac{10^{-2}\,\mathrm{Re}_m^{0.35}}{\mathrm{We}^{0.12}\exp\left(0.194\dfrac{2R}{D}\right)x^{1.26}} \tag{3}$$

Figure 4 compares the predictions by the Chen et al. (2004b) correlation with all experimental data. The mean deviation of predictions is 19.1 % with most of the data located within the ±50 % error bands. Figure 5 shows a comparison of Geary's correlation and all data, where it may be seen some R-410A points were underpredicted.

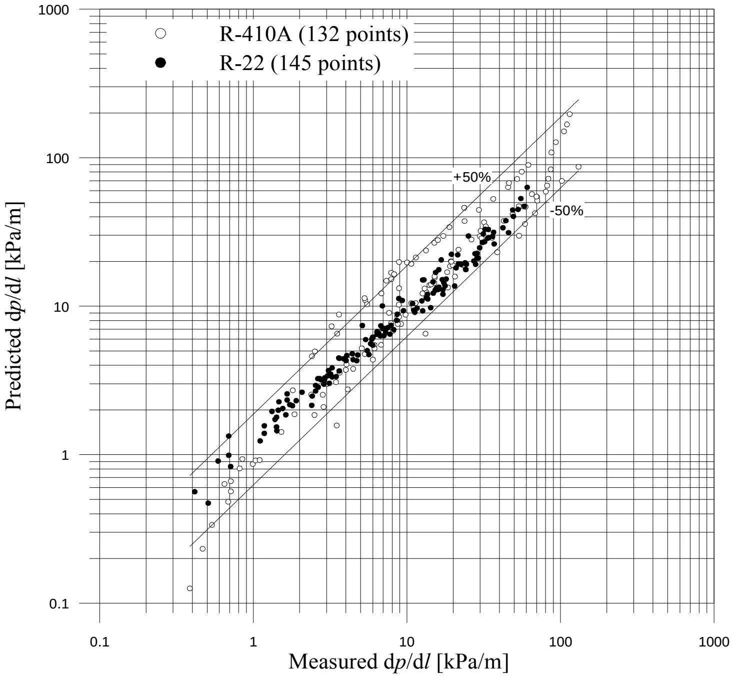

Figure 4. Comparison of all data with predictions by the Chen's (2004b) correlation.

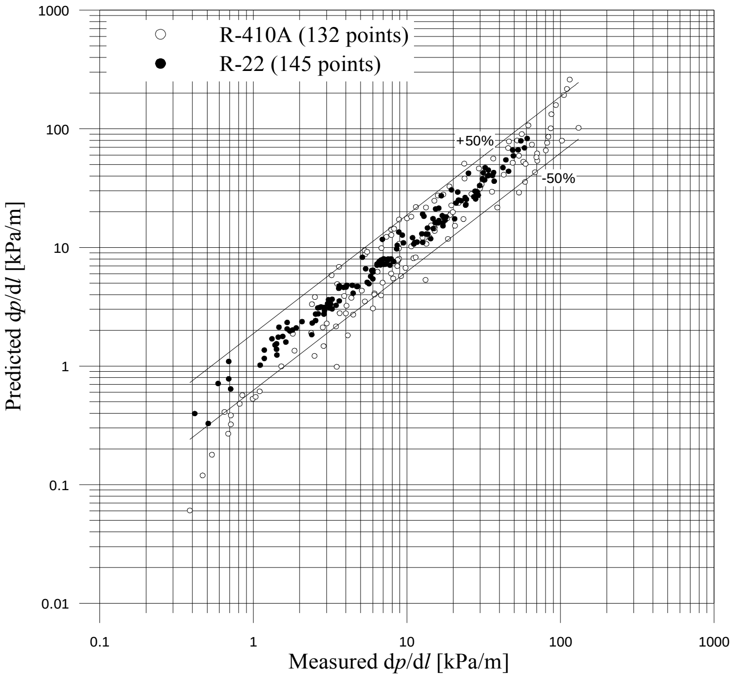

Figure 5. Comparison of all data with predictions by the Geary's (1975) correlation.

2.3. Chisholm / Idelshik Method

Chisholm (1983) proposed a two-phase multiplier Φ to calculate the pressure drop in return bends based on the pressure drop calculated for the single-phase, all liquid flow in a return bend, Δp_{sp}.

$$\Delta p = \Phi \Delta p_{sp} \tag{4}$$

where Φ is given by

$$\Phi = 1 + \left(\frac{\rho_l}{\rho_v} - 1 \right) x \left[b(1-x) + x \right] \tag{5}$$

where x is the vapour quality, ρ_l and ρ_v are the densities of the liquid and vapour phases [kg m^{-3}], and b is given by

$$b = 1 + \frac{2.2}{K_{sp}\left(2 + \frac{R}{D}\right)} \tag{6}$$

K_{sp} is the local pressure drop coefficient obtained for single-phase, all liquid flows. Idelshik (1986) suggested the following expression to estimate the K_{sp} parameter in 180^o bends:

$$K_{sp} = f_l \frac{L}{D} + 0.294\left(\frac{R}{D}\right)^{1/2} \tag{7}$$

where f_l is the single-phase friction factor, calculated as a function of the Reynolds number, $\mathrm{Re}_l = GD/\mu_l$, as follows:

$$f_l = 0.079\ \mathrm{Re}_l^{-0.25} \tag{8}$$

Equation (7) assumes the pressure drop has two terms. The first term accounts for the pressure drop as if the bend was a straight tube, while the second term provides a correction for the bend curvature. The single-phase pressure drop is then obtained as follows:

$$\Delta p_{sp} = K_{sp} \frac{G^2}{2\rho_l} \tag{9}$$

Figure 6 compares pressure drops predicted using the Chisholm/Idelshik method with the R22 and R410A experimental data. The mean deviation between the measurements and predictions is 44.4 %, and approximately 37 % of the points fall outside the ±50 % error bands. The flow pattern analysis using Thome's method (2005) indicated that the points whose flow pattern is annular are concentrated at the –50 % line, while the points with intermittent flow pattern are centered on the +50 % line.

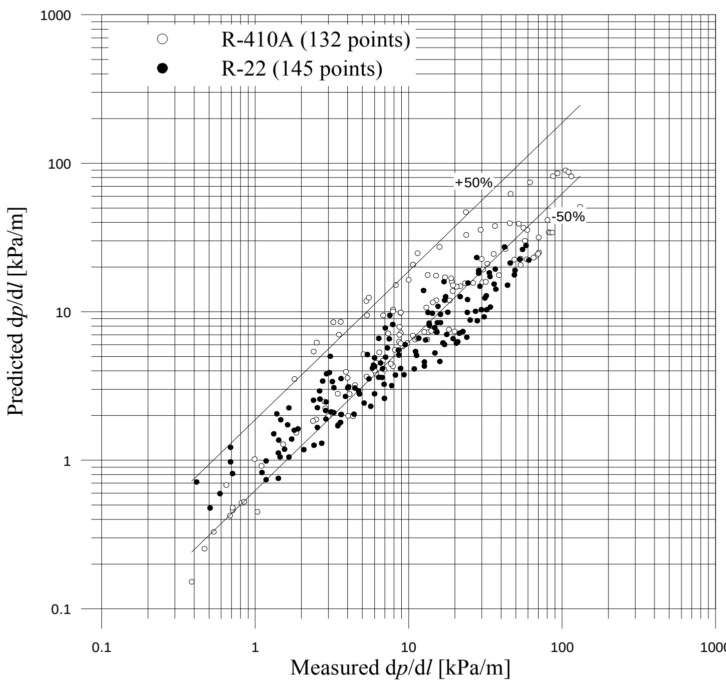

Figure 6. Comparison of R-22 and R-410A measurements with predictions by the Chisholm/Idelshik method.

3. Improved Correlation

We propose a new correlation based on the two-phase pressure drop correlation for straight tubes by Muller-Steinhagen & Heck (1986) and a multiplier which accounts for the bend curvature. This approach differs from that proposed by Chisholm (1983), where a two-phase multiplier was applied to a single-phase correlation for a return bend.

According to Muller-Steinhagen & Heck (1986), the two-phase pressure drop in a straight tube is predicted considering the pressure drops of liquid and vapour phases, which are calculated separately.

$$\left.\frac{\mathrm{d}p}{\mathrm{d}l}\right|_{\mathrm{k}} = 2\frac{f_k}{D}\frac{G^2}{\rho_k} \quad (10)$$

where k stands for l or v, and f_k is given by equation (8) using vapour or liquid properties, as appropriate. The pressure drops computed for each phase are combined by the following equation:

$$\left.\frac{\mathrm{d}p}{\mathrm{d}l}\right|_{s-t} = \left[\left.\frac{\mathrm{d}p}{\mathrm{d}l}\right|_{l} + 2x\left(\left.\frac{\mathrm{d}p}{\mathrm{d}l}\right|_{v} - \left.\frac{\mathrm{d}p}{\mathrm{d}l}\right|_{l}\right)\right](1-x)^{1/3} + \left.\frac{\mathrm{d}p}{\mathrm{d}l}\right|_{v} x^3 \quad (10)$$

where the index *s-t* denotes the straight-tube pressure drop. The pressure drop in the return bend, denoted by the index *r-b*, is then obtained by applying a "curvature" multiplier, Λ, to the straight-tube correlation:

$$\left.\frac{\mathrm{d}p}{\mathrm{d}l}\right|_{\mathrm{r-b}} = \Lambda\left.\frac{\mathrm{d}p}{\mathrm{d}l}\right|_{\mathrm{s-t}} \quad (11)$$

We derived the multiplier Λ via the Buckinham-PI Theorem with the following dimensionless groups: (i) GxD/μ_v; (ii) $1/x$-1; (iii) ρ_l/ρ_v; and (iv) $2R/D$. The first group is the vapour-only Reynolds number to take into account the influence of vapour velocity, Gx/ρ_v, while the second and the third terms are related to mass distribution for each phase. The last term regards the effects of the bend curvature. The resulting PI-equation is given by:

$$\Lambda = \mathrm{a}_0\left(\frac{GxD}{\mu_v}\right)^{\mathrm{a}_1}\left(\frac{1}{x}-1\right)^{\mathrm{a}_2}\left(\frac{\rho_l}{\rho_v}\right)^{\mathrm{a}_3}\left(\frac{2R}{D}\right)^{\mathrm{a}_4} \quad (12)$$

where the coefficients, fitted through the Least Squares Method, are given in Table 2 in column (A).

Figure 7 plots the pressure drop predictions for all the experimental data. While the agreement between the measurements and correlation is good in general, the correlation underpredicts several points for bend #3 from the Chen et al. (2004b) database. The fourteen most underpredicted data points for bend #3 have all stratified-wavy flow. This, however, could not be the only reason for the underprediction since Geary's stratified-wavy data are predicted well.

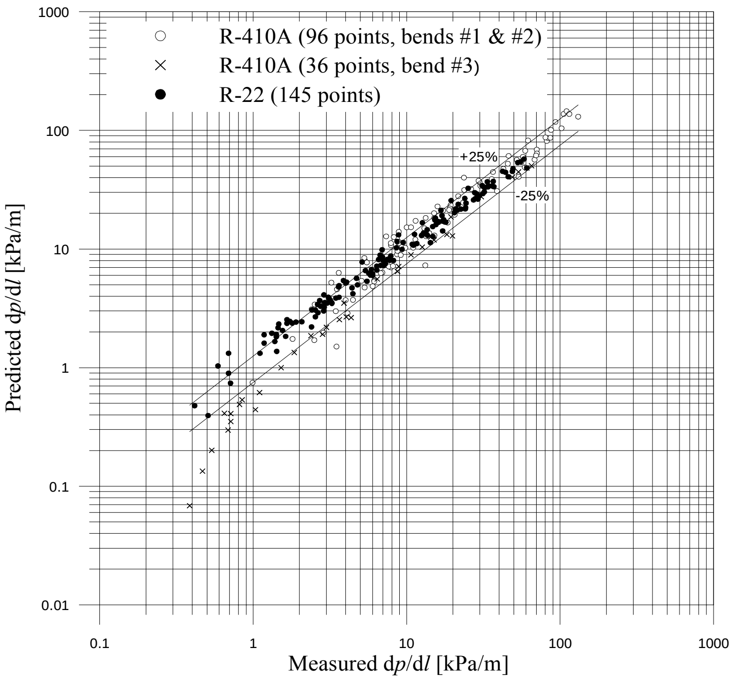

Figure 7. Comparison of all measurements with predictions by the new correlation (A).

Looking further for the reason for underpredictions, we note that in #3 experimental arrangement the straight tubes connecting the subsequent bends had the straight length of approximately four tube diameters, while Hoang & Davis

(1984) suggested that the length equal to nine tube diameters is required to complete the remixing process of the phases after leaving a return bend. It can be then speculated that the connection tubes were too short in #3 configuration to allow the flow to re-establish the straight-tube flow pattern, and this resulted in a larger return-bend pressure drop than would be measured otherwise. The straight-tube lengths for #1 and #2 test arrangements corresponded to approximately eight tube diameters.

Since the heat exchangers used in air conditioning and refrigeration have long tubes (much longer than 9 tube diameters) that allow the refrigerant to re-establish its straight-tube flow pattern after leaving the return bend, we removed bend #3 data from the database and refitted the constants in equation 12. Table 2 includes the new constants in column (B).

Table 2. Fitted coefficients for equation (12).

Coefficient	(A) 277 points - all points	(B) 241 points - all points except bend #3
a_0	$5.2 \cdot 10^{-3}$	$6.5 \cdot 10^{-3}$
a_1	0.59	0.54
a_2	0.22	0.21
a_3	0.27	0.34
a_4	-0.69	-0.67

Figure 8 plots the pressure drop predictions against the reduced 241-point database that includes all R-22 data and the R-410A data for bends #1 and #2. The mean deviation of predictions is 15.7 %, and 75 % of the predictions are within ±25 % error bands. Table 3 provides the statistical information on the goodness of predictions of the reduced 241-point dataset by the four correlations considered in this study.

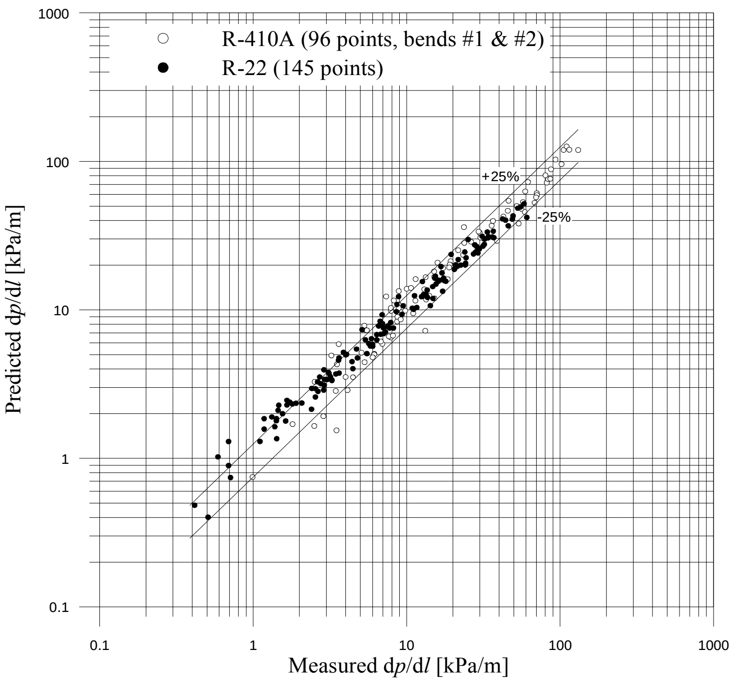

Figure 8. Comparison of 241-point database measurements with predictions by the new correlation (B).

Table 3. Statistical evaluation of predictions for the 241-point database for four studied correlations.

	Geary (1975)	Chen et al. (2004b)	Chisholm (1983)	Proposed (B)
Mean deviation (%)	22.5	22.8	36.5	15.7
Points within 10 %	83	67	21	105
Points within 25 %	153	160	61	180
Points within 50 %	196	207	158	226
Points outside 50 %	45	34	83	15

Figure 9 compares the four correlations for the entire vapour quality range from the saturated liquid to saturated vapour. Starting with the saturated liquid, all correlations show an increase of pressure drop with increasing quality, which can be explained by a decrease of the two-phase density. While the Geary correlation and the Chen et al. correlation continue this trend throughout the two-phase region to the saturated vapor line, the Chisholm/Idelshik predictions flatten at high vapor qualities, and the new correlation predicts a decrease in pressure drop when vapor quality approaches unity. Thus, the predictions by the Chisholm/Idelshik correlation and the new correlation agree with the general trend of pressure drop known in straight tubes. The decrease in the pressure drop at high vapour qualities can be explained by the reduced interference between the phases once the liquid layer on the tube thins and the wall becomes occasionally dry. The proposed correlation has a smooth transition to Muller-Steinhagen & Heck (1986) for qualities lower than 0.2 and greater than 0.8, although it is singular for x=0 and zero for x=1.

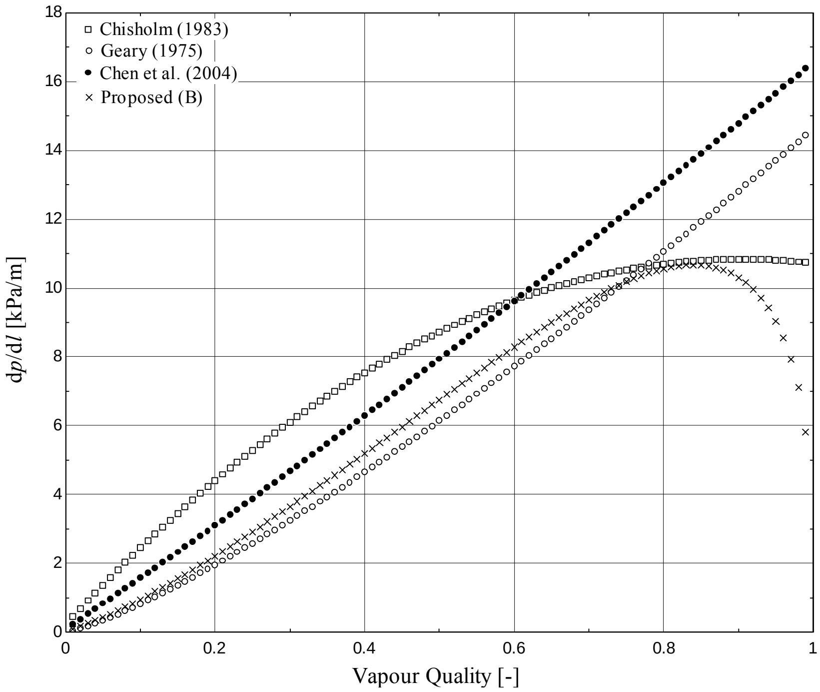

Figure 9. Comparison of return bend pressure drop predictions by the studied correlations (Conditions: refrigerant R-22, D=5.0 mm, R=10.0 mm, T_{sat}=7 °C, and G=200 kg m^{-2}s^{-1})

4. Final Remarks

An improved correlation for pressure drop in return bends was developed using 145 data points for R-22 and 96 points for R-410A. The correlation is based on the Muller-Steinhagen & Heck (1986) pressure drop correlation for straight tubes and a multiplier that accounts for the bend curvature. The Buckinham-PI Theorem was used to formulate the curvature multiplier in terms of refrigerant properties, flow characteristics, and bend geometry. The new correlation predicts 75 % of the experimental data points within the ±25 % error bands with the mean deviation of 15.7 % for all data. Future experimental research on refrigerant flow in return bends is recommended to include the characterization of refrigerant flow pattern and its influence on refrigerant pressure drop.

5. Acknowledgements

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7. Nomenclature

Symbols

B straight-tube length between neighboring tubes
dp/dl pressure gradient, Pa m^{-1}
D inner diameter, m
f friction factor
G refrigerant mass flux, kg s^{-1} m^{-2}
K local pressure loss coefficient
L bend length, m
p pressure, Pa
R bend radius, m
x vapour quality

Greek letters

Φ two-phase multiplier
Λ curvature multiplier
μ absolute viscosity, Pa s
ρ specific mass, kg m^{-3}
σ surface tension, N m^{-1}

Subscripts

l liquid phase
sp single phase
v vapour phase