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Evaluation analysis of prediction methods for two-phase flow pressure drop in mini-channels

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A B S T R A C T

Two-thousand and ninety-two data of two-phase flow pressure drop were collected from 18 published papers of which the working fluids include R123, R134a, R22, R236ea, R245fa, R404a, R407C, R410a, R507, CO_2, water and air. The hydraulic diameter ranges from 0.506 to 12 mm; Re_l from 10 to 37,000, and Re_g from 3 to 4×10^5. Eleven correlations and models for calculating the two-phase frictional pressure drop were evaluated based upon these data. The results show that the accuracy of the Lockhart–Martinelli method, Mishima and Hibiki correlation, Zhang and Mishima correlation and Lee and Mudawar correlation in the laminar region is very close to each other, while the Muller-Steinhagen and Heck correlation is the best among the evaluated correlations in the turbulent region. A modified Chisholm correlation was proposed, which is better than all of the evaluated correlations in the turbulent region and its mean relative error is about 29%. For refrigerants only, the new correlation and Muller-Steinhagen and Heck correlation are very close to each other and give better agreement than the other evaluated correlations.

1. Introduction

Pressure drop in two-phase channel flows is an important consideration in the design of heat exchangers. Pressure gradient has been studied extensively because of its importance in many applications. Many models and correlations were proposed to calculate the frictional pressure drop. In what follows, existing correlations picked up for evaluation in this study are described.

1.1. Correlations for common channel

(1) Lockhart and Martinelli correlation (1949)

Based on the separated flow model, Lockhart and Martinelli gave the flowing correlation to calculate the two-phase frictional pressure drop:

$$\left(\frac{dP}{dl}\right)_{TP} = \phi_l^2 \left(\frac{dP}{dl}\right)_l, \tag{1}$$

where Chisholm (1967) gave the following correlation to calculate the two-phase multiplier based on the liquid phase pressure drop:

$$\phi_l^2 = 1 + \frac{C}{X} + \frac{1}{X^2}, \tag{2}$$

The value of C depends on the regimes of the liquid and vapor, and the Martinelli parameter X is given by

$$X^2 = \frac{\left(\frac{dp}{dl}\right)_l}{\left(\frac{dp}{dl}\right)_g} \text{ with } \left(\frac{dp}{dl}\right)_l = f_l \frac{2G^2(1-x)^2}{d\rho_l} \quad \text{and} \quad \left(\frac{dp}{dl}\right)_g = f_g \frac{2G^2x^2}{d}\rho_g \tag{3}$$

where f,ρ,x,G and D are friction factor, density, quality, mass flux and the hydraulic diameter, the subscripts g and l denote the gas phase and the liquid phase, respectively.

(2) Homogeneous model

$$\left(\frac{dp}{dl}\right)_{TP} = \frac{2f_{TP}G^2}{d\rho_{TP}}, \tag{4}$$

$$f_{TP} = \frac{16}{Re_{TP}} \text{ for } Re_{TP} < 2000, \tag{5}$$

$$f_{TP} = 0.079 \times Re_{TP}^{-0.25} \text{ for } Re_{TP} > 2000, \tag{6}$$

where the subscript TP denotes the two-phase and the two-phase density is given by

$$\rho_{TP} = \left(\frac{x}{\rho_g} + \frac{1-x}{\rho_l}\right)^{-1} \tag{7}$$

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(3) Chisholm correlation (1972)

Chisholm transformed the equation to calculate two-phase frictional pressure drop:

$$\frac{\Delta P_{TP}}{\Delta P_{lo}} = 1 + (X^2 - 1)[Bx^{0.875}(1-x)^{0.875} + x^{1.75}], \tag{8}$$

$$X^2 = \frac{\left(\frac{dp}{dl}\right)_{go}}{\left(\frac{dp}{dl}\right)_{lo}}, \tag{9}$$

where the subscripts of go and lo denote that the whole mixture flows as vapor or liquid. Value of B depends on the value of X and mass flux:

If $0 < X < 9.5$,

$$B = \frac{55}{G^{0.5}} \text{ for } G \geqslant 1900 \text{ kg/m}^2\text{ s}, \tag{10}$$

$$B = \frac{2400}{G} \text{ for } 500 < G < 1900 \text{ kg/m}^2\text{ s}, \tag{11}$$

$$\text{and } B = 4.8 \text{ for } G < 500 \text{ kg/m}^2\text{ s} \tag{12}$$

If $9.5 < X < 28$,

$$B = \frac{520}{XG^{0.5}} \text{ for } G \leqslant 600 \text{ kg/m}^2\text{ s}, \tag{13}$$

$$\text{and } B = \frac{21}{X} \text{ for } G > 600 \text{ kg/m}^2\text{ s} \tag{14}$$

If $Y > 28$,

$$B = \frac{15000}{X^2 G^{0.5}}. \tag{15}$$

(4) Friedel correlation (1979)

$$\left(\frac{dp}{dl}\right)_{TP} = \left(\frac{dp}{dl}\right)_{lo}\phi_{lo}^2, \tag{16}$$

$$\phi_{lo}^2 = E + \frac{3.24FX}{F_r^{0.045} We_l^{0.035}}. \tag{17}$$

where

$$F_r = \frac{G^2}{gD\rho_{TP}^2}, \quad F = x^{0.78}(1-x)^{0.224}, \quad We_l = \frac{G^2 D}{\sigma \rho_l}, \tag{18}$$

$$X = \left(\frac{\rho_l}{\rho_g}\right)^{0.91}\left(\frac{\mu_g}{\mu_l}\right)^{0.19}\left(1 - \frac{\mu_g}{\mu_l}\right)^{0.7}, \text{ and} \tag{19}$$

$$E = (1-x)^2 + x^2\frac{\rho_l f_{go}}{\rho_g f_{lo}}. \tag{20}$$

σin Eq. (18) is the surface tension, and μ in Eq. (19) is the dynamic viscosity.

(5) Muller-Steinhagen and Heck correlation (1986)

$$\left(\frac{dp}{dl}\right)_{TP} = F(1-x)^{1/3} + \left(\frac{dp}{dl}\right)_{lo}x^3, \tag{21}$$

$$\text{where } F = \left(\frac{dp}{dl}\right)_{lo} + 2\left[\left(\frac{dp}{dl}\right)_{go} - \left(\frac{dp}{dl}\right)_{lo}\right]x. \tag{22}$$

1.2. Correlations for micro- and mini-channels

There exist many correlations especially for micro- and mini-channels. Following correlations are usually used for calculating the frictional pressure drop in micro- and mini-channels.

(1) Mishima and Hibiki correlation (1996)

Using the Lockhart–Martinelli model, where the constant C in Eq. (2) is modified as follows:

$$C = 21(1 - e^{-319D}). \tag{23}$$

(2) Zhang and Mishima correlation (2006)

In the Zhang and Mishima correlation, the Laplace number instead of the equivalent diameter employed in the Mishima and Hibiki correlation is incorporated as follows:

$$C = 21\left(1 - e^{\frac{-0.358}{La}}\right), \tag{24}$$

$$\text{where } La = \frac{\left(\frac{\sigma}{g(\rho_l - \rho_g)}\right)^{0.5}}{d} \tag{25}$$

(3) Lee and Lee correlation (2001)

The constant C in the Chisholm correlation is calculated by

$$C = A\lambda^q\psi^r Re_{lo}^s, \tag{26}$$

$$\text{where } \lambda = \frac{\mu_l^2}{\rho_l \sigma D} \text{ and } \psi = \frac{\mu_l j}{\sigma}. \tag{27}$$

A, q, r and s are constants which are different in different flow regimes.

(4) Lee and Mudawar correlation (2005)

Two separate correlations were derived for C based on the flow regimes of the liquid and vapor.

For laminar liquid and laminar vapor flows

$$C = 2.16 Re_{lo}^{0.047} We_{lo}^{0.23}. \tag{28}$$

For laminar liquid and turbulent vapor flows

$$C = 1.45 Re_{lo}^{0.25} We_{lo}^{0.23}. \tag{29}$$

(5) Tran et al. correlation (2000)

$$\left(\frac{\Delta p}{\Delta L}\right)_{TP} = \left(\frac{\Delta p}{\Delta L}\right)_{lo}\phi_{lo}^2, \tag{30}$$

where

$$\phi_{lo}^2 = 1 + (4.3X^2 - 1)\lfloor La(1-x)^{0.875} + x^{1.75}\rfloor. \tag{31}$$

(6) Zhang and Webb correlation (2001)

$$\phi_{lo}^2 = (1-x)^2 + 2.87x^2\left(\frac{p}{p_{crit}}\right)^{-1} + 1.68x^{0.25}(1-x)^2\left(\frac{p}{p_{crit}}\right)^{-1.64} \tag{32}$$

2. Database

Two-thousand and ninety-two data points were collected from 18 published papers which are shown in Table 1. Tables 2 and 3 show the ranges of the Reynold number and the proportion of data points which fall in each range. The proportion of the data for both Re_l and Re_g smaller than 2000 is about 15.8%. The database covers the following working fluids and parameter ranges:

Working fluid: R123, R134a, R22, R236ea, R245fa, R404a, R407C, R410a, R507, CO2, water and air;

Hydraulic diameter:	$0.506 \sim 12$ mm;
Range of Re_l:	$10 \sim 37000$;
Range of Re_g:	$3 \sim 4 \times 10^5$.

Table 1
Summary of existing work on two-phase flow pressure drop

Authors [reference] year	Channel size and geometry	Fluid	Parameter range	Data points
Adriana Greco and Giuseppe Peter Vanoli (2004)	Single tube D = 6 mm length 6 m	*R22*	Mass-flux 250–286 kg/m^2 s, heat flux 10.6–17.0 kW/m^2	29
Zhang and Webb (2001)	single tube D = 3.25 mm Length 0.56 m	*R22 R*134a	Mass-flux 400, 600, 1000 kg/m^2 s,	23
Triplett et al. (1999)	Single tube D = 1.1, 1.45 mm, semi-triangular DH = 1.09 mm L = 200 mm	Air and water	Gas 0.02–80 m/s liquid 0.02–8 m/s	127
Lee and Lee (2001)	Rectangular Dh = 3.64, 0.978 mm	Water and air	Re_{lo} = 175–17700	33
Cavallini et al. (2005)	Multi-port channel dH = 1.4 mm	R134a, R236ea	Mass-flux 200–400 kg/m^2 s	21
Agostini and Bontemps (2005)	Multi-port channel DH = 2.01 mm	R134a	Mass-flux 90–295 kg/m^2 s	61
Revellin and Thome (2007)	D = 0.509, 0.79 mm	*R*134a *R*245fa	Mass-flux 350–2000 kg/m^2 s	219
Yi Yie Yan and Tsing Fa Lin (1998)	D = 2.0 mm L = 200 mm	*R*134a	Mass-flux 50,100 kg/m^2 s, Ts = 5,15,31 °C	113
Greco and Vanoli (2006)	D = 6 mm, L = 6 m	*R*22, *R*134a, *R*404a, *R*410a, *R*407 c, *R*507, *R22*	Mass-flux 280–1080 kg/m^2 s	2 6 6
Ekberg et al. (1999)	Annulus, Dh = 2.03, 2.03 mm	Water air	j_g = 0.2–57 m/s j_l = 0.1–6.1 m/s	139
Jassim and Newell (2006)	six micro-channel D_H = 1.54 mm,	*R*410a, *R*134a water and air	Mass-flux 50–300 kg/m^2 s	253
Ould Didi et al. (2002)	D = 10.92 mm, D = 12 mm	*R*134a, *R*123 *R*404a,	Mass-flux 100–500 kg/m^2 s	48
Wang and Chiang (1997)	D = 6.5 mm, L = 1.3 m	*R*407 C, *R22*	Mass-flux 100–700 kg/m^2 s	54
Park and Hrnjak (2007)	D = 6.1 mm, L = 0.15 m	CO_2, *R*410a *R*22	Mass-flux 100–400 kg/m^2 s	54
Srinivas Garimella et al. (2005)	D = 0.506, 0.761,0.52, 3.05, 4.93 mm L/d = 800	R134a	Mass-flux 150–750 kg/m^2 s	291
Yun et al. (2006)	Dh = 1.44, 5 mm	R410a	Mass-flux 200–500 kg/m^2 s	43
Ewelina Sobierska et al. (2006)	DH = 1.2 mm	Water	Mass-flux 50–700 kg/m^2 s	45
Wongwises and Pipathattakul (2006)	DH = 4.5 mm L = 0.42 m	Air and water	j_g = 0.0218–65.4 m/s j_l = 0.069–6.02 m/s	160
Wambsganss et al. (1992)	DH = 5.45 mm	Air and water	Mass-flux 50–500 kg/m^2 s	113

Table 2
Range and proportion of Re_l

Range of Re_{lo}	<10^3	$10^3 \sim 2 \times 10^3$	$2 \times 10^3 \sim 5 \times 10^3$	$5 \times 10^3 \sim 10^4$	$10^4 \sim 4 \times 10^4$
Data number	748	378	467	229	270
Proportion	35.8	18.1	22.3	10.9	12.9

Table 3
Range and proportion of Re_g

Range of Re_o	$0 \sim 2 \times 10^3$	$2 \times 10^3 \sim 10^4$	$10^4 \sim 3 \times 10^4$	$3 \times 10^4 \sim 10^5$	$10^5 \sim 4 \times 10^5$
Data number	516	482	468	351	275
Proportion (%)	24.7	23.0	22.4	16.8	13.1

3. Evaluation of two-phase pressure drop correlations against the database

Figs. 1–6 present the comparison of frictional pressure drop calculated by the evaluated correlations with the experimental data. The abscissa denotes measured pressure drop, while the ordinate does the predicted one. The error band of ±30% is also shown by the solid lines in these figures. Tables 4 and 5 present the evaluation results. The mean error and the fractions of data points which fall within the relative error of ±30% and ±50% are shown in the two tables. Table 4 includes all the data, while Table 5 includes those data for refrigerants only. The results illustrate that the Muller-Steinhagen and Heck correlation gives the best predictions, as pointed out by Ribatski et al. (2006), followed by the homogeneous model, the Mishima–Hibiki correlation and the Zhang–Mishima correlation. The Zhang–Webb correlation, Friedel correlation and Tran et al. correlation do not work very well. The Zhang–Webb correlation is developed based on experimental data for refrigerants, therefore it may work for refrigerants, but not for other fluids. Table 5 shows the comparison between the calculated results and data for refrigerants. The mean relative error of the prediction by the Zhang–Webb correlation is 55.8% and the proportion of data points which fall within the error of ±30% is about 60.3% for the data of refrigerants, but for all of the data, the mean relative error is as large as 1863.7%. In the same way, the mean relative error of the Friedel correlation is 418.8% for all of the data while 124.6% for the data of refrigerants only. Therefore, it could be concluded that the Friedel

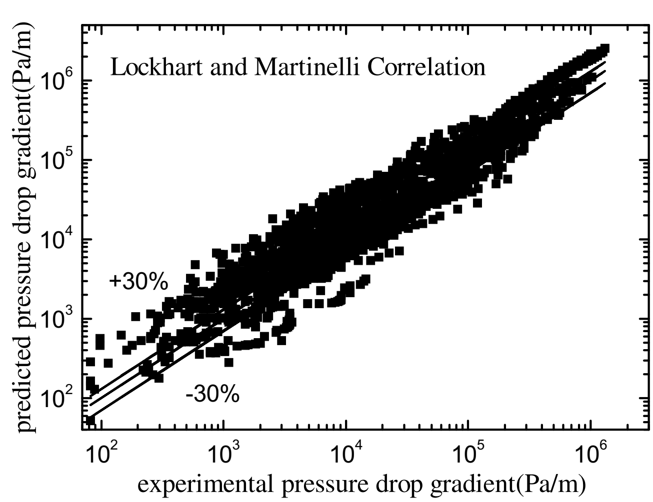

Fig. 1. Comparison between the Lockhart–Martinelli Correlation and the database.

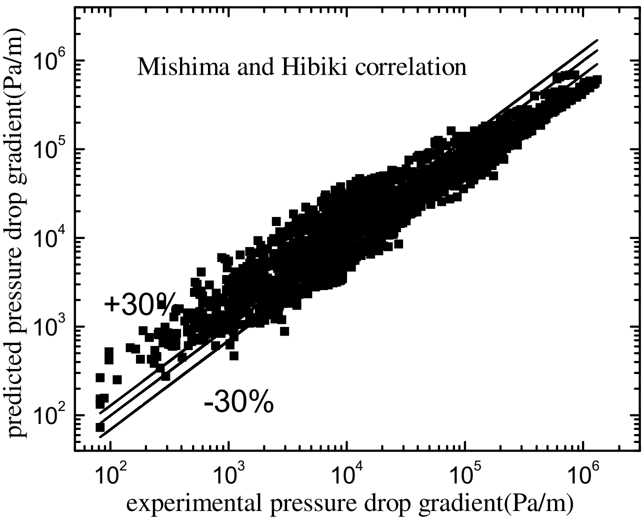

Fig. 2. Comparison between Mishima and Hibiki correlation and database.

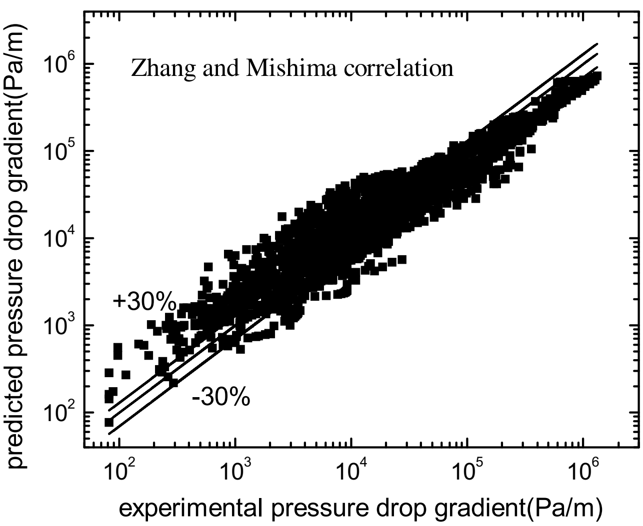

Fig. 3. Comparison between Zhang and Mishima correlation and database.

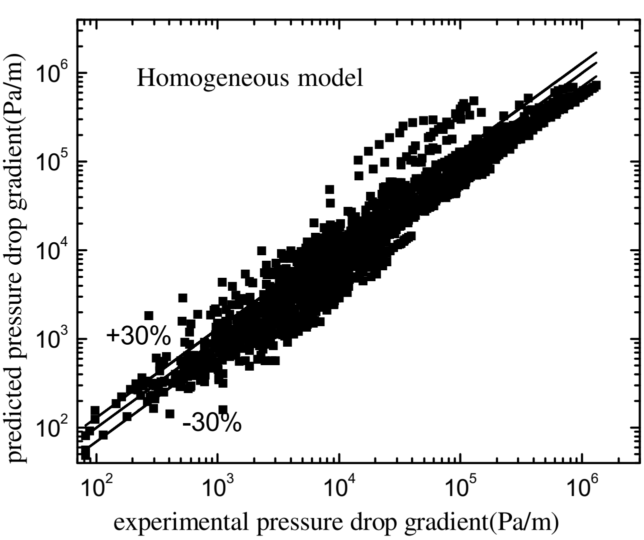

Fig. 4. Comparison between Homogeneous model and database.

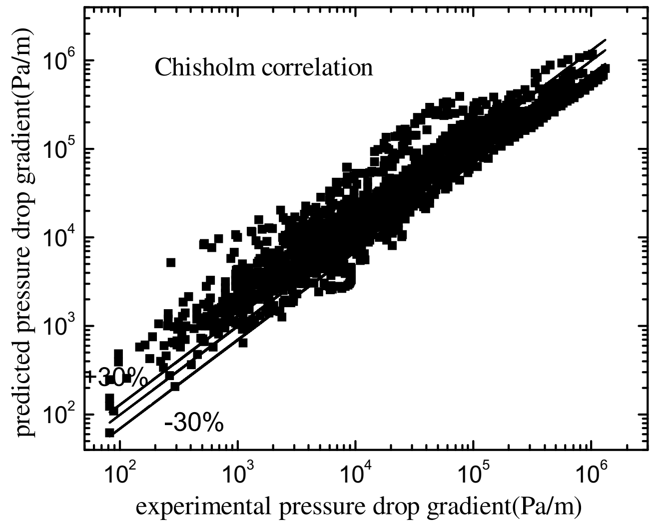

Fig. 5. Comparison between the Chisholm correlation and the database.

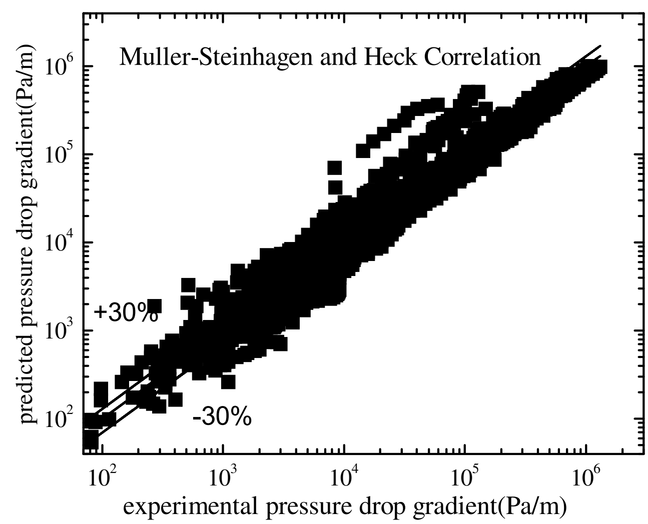

Fig. 6. Comparison between the Muller-Steinhagen and Heck correlation and the database.

correlation and Zhang and Webb correlation is much more suitable for refrigerants than for other fluids.

4. New correlation

4.1. New correlation

Different constant values were given for the parameter C in the Chisholm correlation for different flow regimes, but the parameter C should be a variable affected by some flow conditions. Chisholm (1967) gave the following equation in calculating two-phase pressure drop:

$$\frac{\Delta P_{\mathrm{TP}}}{\Delta P_{\mathrm{l}}} = \frac{1}{\alpha}\frac{f_{\mathrm{l}}}{f_{\mathrm{lo}}}\left(1+\frac{A_{\mathrm{g}}}{A_{\mathrm{l}}}\right)\left(\frac{A_{\mathrm{g}}}{A_{\mathrm{l}}Z^2}+1\right) = \frac{1}{\alpha^{1+n}}\left(1+\frac{A_{\mathrm{g}}}{A_{\mathrm{l}}}\right)^{1-n}\left(\frac{A_{\mathrm{g}}}{A_{\mathrm{l}}Z^2}+1\right) \tag{33}$$

where α is the ratio of hydraulic diameter of liquid in the two-phase flow to that in the single-phase flow; A_{g} and A_{l} are the cross-sectional area of pipe occupied by liquid or vapor; f_{l} is the friction factor for liquid phase in the two-phase flow and f_{lo} is the friction

Table 4
Statistics of the evaluated correlations for all the data

Prediction method	Fraction of data pints within the relative error of ±30% (%)	Fraction of data pints within the relative error of ±50% (%)	Mean relative error (%)
Lockhart and Martinelli	31.9	53.6	78.0
Mishima and Hibiki	41.9	64.5	59.0
Zhang and Mishima	34.8	64.5	64.5
Homogeneous model	45.5	79.3	41.4
Friedel	24.7	34.7	418.8
Chisholm (1972)	35.2	53.0	88.1
Muller-Steinhagen–Heck	59.8	81.1	38.6
Lee–Lee	23.8	40.4	122.0
Lee–Mudawar	29.5	45.7	85.9
Zhang–Webb	41.2	49.1	1863.5
Tran et al.	17.1	25.4	201.7

Table 5
Statistics of the evaluated correlations for data of refrigerants

Prediction method	Fraction of relative error within ±30% (%)	Fraction of relative error within ±50% (%)	Mean relative error (%)
Lockhart–Martinelli	23.1	43.1	95.7
Mishima–Hibiki	34.9	58.8	68.0
Zhang–Mishima	32.4	58.8	77.2
Homogeneous model	41.8	82.8	33.9
Friedel	23.0	33.4	124.6
Chisholm (1972)	28.7	49.4	72.9
Muller-Steinhagen–Heck	63.1	86.0	28.1
Lee–Lee	16.4	29.7	158.0
Lee–Mudawar	15.9	30.1	110.8
Zhang–Webb	60.3	71.4	55.8
Tran et al.	19.1	27.4	119.6

factor for the liquid flowing alone. Under the assumption that there is no local slip ($u_g/u_l = 1$) and for rough tubes, it is concluded that $\alpha = 1$, $n = 0$ and

$$\frac{A_l}{A_g} = \frac{X}{Z} \tag{34}$$

Hence the following correlation is obtained

$$\phi_l^2 = 1 + \frac{C}{X} + \frac{1}{X^2}, \quad C = Z + \frac{1}{Z} \tag{35}$$

$$Z = \left(\frac{\rho_g}{\rho_l}\right)^{0.5} \tag{36}$$

Therefore the constant C is not constant, but a parameter that is affected by flow conditions. For mini- and micro-channels, because of large effect of surface tension and gap size, Zhang (2006) found that C depends on the Laplace number and was correlated in Eq. (22). Based on the database, it is found that C is strongly affected not only by La but also by Re_l in the laminar flow region. So the following expression is obtained for C in the laminar flow region:

$$C = 26\left(1 + \frac{Re_l}{1000}\right)\left[1 - \exp\left(\frac{-0.153}{0.27 \times La + 0.8}\right)\right] \tag{37}$$

Statistical analysis results show that the value of C changes with the Reynolds number. Furthermore, C/X in the Chisholm correlation strongly depends on the ratio of Re_g to Re_l, especially when Re_l or Re_g is over 2000, which is clearly shown in Fig. 7(a–c). It can be found also that the data points become more scattered with the increase of the ratio of Re_g to Re_l. Based on the statistical analysis, the Chisholm correlation is modified as follows:

$$\phi_l^2 = 1 + \frac{C\left(\frac{Re_g}{Re_l}, \frac{1-x}{x}\right)}{X^n} + \frac{1}{X^2} \tag{38}$$

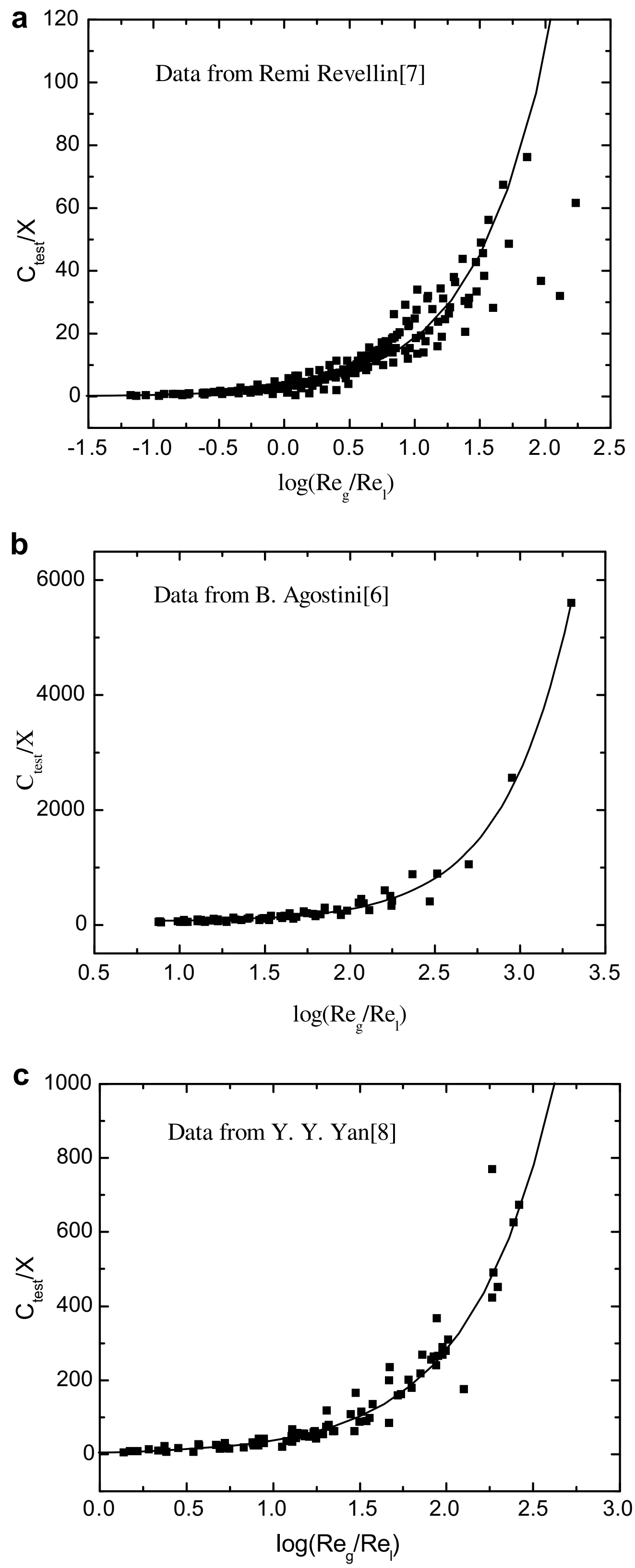

Fig. 7. Relationship between C/X and $\log(R_g/R_l)$.

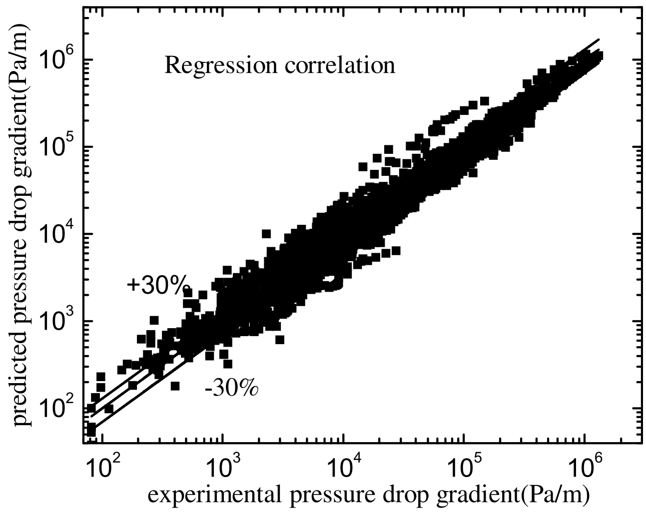

Fig. 8. Comparison of regression correlation to experimental data.

where $n = 1.19$ and

$$C = 1.79\left(\frac{Re_g}{Re_l}\right)^{0.4}\left(\frac{1-x}{x}\right)^{0.5} \tag{39}$$

It should be pointed out that the value of C calculated by Eq. (39) will not sharply change while x goes to 1 or 0, because Re_l or Re_g changes inversely with x and $1-x$ respectively. Particularly for the database, x ranges from 1.5×10^{-5} to 0.98, while the calculated value of C is from 29.9 to 3.2 accordingly.

4.2. Comparison between the new correlation and other correlations against the database

Fig. 8 shows the comparison between the predicted frictional pressure drop and experimental data. Tables 6 and 7 show the statistical analysis results of the predicted frictional pressure drop calculated by the new correlation and the evaluated correlations in comparison with the database. Especially, Table 7 shows the statistical results for data of refrigerants only. Obviously, the best one is the new correlation in all of the correlations, the next one is the Muller-Steinhagen and Heck correlation. For refrigerants, the new correlation and the Muller-Steinhagen and Heck correlation are almost same and better than other correlations. The second better is the homogeneous model.

Table 8 shows the statistical results of predicted pressure drop for laminar flow, i.e. for the condition that both Re_l and Re_g are less than 2000. Although the statistics of those correlations are very close, the Zhang and Mishima correlation and Mishima and Hibiki correlation are a little better than the other existing correlations. The Muller-Steinhagen and Heck correlation does not work so well as in the turbulence region. The new correlation is better than any other correlations. The statistics for the mean relative error and the proportions of datum points which fall in relative errors within ±30 and ±50% are better than other correlations. Table 9 shows the evaluated results under the condition that Re_l or Re_g is over 2000. The mean error of the new correlation is 29.4% which is less than 34.8% of the Muller-Steinhagen and Heck correlation. On the whole, the new correlation gives the best prediction among these evaluated correlations.

4.3. Comparison between the new correlation and other correlation based on independent experimental data

The predictions by the new correlation and other correlations are also compared based on some additional experimental data that are not included in the previous database. There are 371 data points in total. Table 10 shows the results of comparison. For these data, the mean relative error of the Muller-Steinhagen and Heck correlation is only about 17.8% and is lowest among all of these correlations including the new correlations. And the mean relative error of the new correlation is about 22.21%, which is better than other correlations except the Muller-Steinhagen and Heck correlation. The Mishima–Hibiki correlation and the Zhang–Mishima correlation are better for the experimental data for small hydraulic diameter. The Zhang–Webb correlation is better for refrigerants, but not for air and water.

Table 6
Comparison of regression correlation to other correlations

Prediction method	Fraction of relative error within ±30% (%)	Fraction of relative error within ±50% (%)	Mean relative error (%)
New correlation	62.2	83.9	30.6
Muller-Steinhagen–Heck	59.8	81.1	38.6
Homogeneous model	45.5	79.3	41.4
Mishima–Hibiki	41.9	64.5	59.0

Table 7
Comparison of regression correlation to other correlations (for refrigerants)

Prediction method	Fraction of relative error within ±30% (%)	Fraction of relative error within ±50% (%)	Mean relative error (%)
New correlation	64.2	85.0	27.3
Muller-Steinhagen–Heck	63.1	86.0	28.1
Homogeneous model	41.8	82.8	33.8
Zhang–Webb	60.3	71.4	55.8

Table 8
Statistical analysis of data ($Re_l < 2000$& $Re_g < 2000$, 309data)

Prediction method	Fraction of relative error within ±30%	Fraction of relative error within ±50%	Mean relative error (%)
Lockhart–Martinelli	37.2	63.8	42.7
Mishima–Hibiki	43.7	68.3	45.9
Zhang–Mishima	38.5	68.3	42.8
Homogeneous model	43.4	65.0	62.2
Muller-Steinhagen–Heck	36.8	66.0	60.1
Lee–Lee	16.5	40.1	65.8
Lee–Mudawar	41.1	60.5	44.8
New correlation	50.5	71.8	37.9

Table 9
Statistical analysis of data ($Re_l > 2000$ or $Re_g > 2000$)

Prediction method	Fraction of relative error within ±30%	Fraction of relative error within ±50%	Mean relative error (%)
Lockhart–Martinelli	31.0	51.9	84.1
Mishima–Hibiki	41.6	63.9	61.2
Zhang–Mishima	34.2	63.8	68.2
Homogeneous model	45.8	81.2	37.8
Chisholm (1972)	35.9	54.3	79.2
Muller-Steinhagen–Heck	63.7	83.7	34.8
Lee–Lee	25.1	40.5	131.8
Lee–Mudawar	27.5	43.1	93.0
New correlation	64.3	86.0	29.4

Table 10
Comparison between the new correlation and other correlation based on independent experimental data (MRE = mean relative error)

Authors		Ekberg et al. (1999)	Shin et al. (2004)	Saisorn and Wongwises (2008)	Quiben and Thome (2007)	Average MRE
Hydraulic diameter (mm)		2.03	0.691	0.53	8, 13	
Fluids		Air and water	R134a	Air and water	R410A, R22	
Data points		67	75	47	182	**371**
MRE	New correlation	23.2%	12.3%	32.1%	23.4%	**22.2**%
	Lockhart-Mart inelli	26.6%	56.1%	21.1%	76.5%	**56.3**%
	Mishima–Hibiki	26.2%	23.7%	20.5%	78.8%	**50.8**%
	Zhang–Mishima	39.9%	15.4%	37.6%	80.6%	54.6%
	Homogeneous model	18.2%	40.1%	60.3%	33.5%	**35.5**%
	Fridel	83.7%	165.3%	/	101.1%	/
	Chisholm	26.2%	46.1%	83.0%	79.6%	**63.6**%
	Muller-Steinhagen–Heck	19.2%	12.0%	22.5%	18.3%	**17.8**%
	Lee–Lee	32.0%	47.8%	56.8%	169.5%	**105.8**%
	Lee–Mudawar	23.4%	75.9%	42.4%	78.3%	**63.3**%
	Zhang–Webb	/	31.0%	/	29.8%	/
	Tran.	193.1%	157.7%	673.3%	63.4%	**183.2**%

5. Conclusion

Based on 2092 data points collected from 18 published papers, 11 existing correlations to predict two-phase pressure drop were evaluated and a new correlation was proposed. Following conclusions were drawn.

1. The constant C in the Chisholm correlation is a variable which affected by many factors. In laminar region, it depends on Re_l and the Laplace number, and C/X is greatly affected by the ratio of Re_g to Re_l in the turbulent flow region. Based on the statistical results, a new correlation was proposed based on the Chisholm correlation.
2. Generally speaking, among the 12 correlations for predicting the pressure drop in micro- and mini-channels including the newly proposed correlation, the latter is the best for all of the experimental data. The Muller-Steinhagen and Heck correlation is close to the newly proposed correlation in the turbulent flow region. In the laminar flow region, the Muller-Steinhagen and Heck correlation is not as well as that in the turbulence flow region.
3. The Friedel correlation and the Zhang–Webb correlation are not very good for air and water, and the Zhang–Webb correlation gives good results for refrigerants.
4. When both Re_g and Re_l is below 2000, several correlations including the Mishima–Hibiki correlation and the Zhang–Mishima correlation are close and can well predict the pressure drop in micro- and mini-channels. The Mishima–Hibiki correlation is a little better on the whole.
5. Based on additional experimental data, the new correlation is compared with other correlations, both the Muller-Steinhagen and Heck correlation as well as the new correlation can well predict the experimental data, but the former is better than the new correlation.

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