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EVALUATION OF PREDICTION METHODS FOR HEAT TRANSFER AND PRESSURE DROP IN PLAIN FIN AND TUBE HEAT EXCHANGERS

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Abstract. *This work aims to verify the performance of three Colburn factor and four fanning friction factor correlations for the air side of plain fin-and-tube heat exchangers when calculated for a wide range of experimental data. The database in this work was acquired from open literature with 361 points to j factor and 186 points to f factor where collar diameter ranges between 5.3 to 10.34 mm; longitudinal tube pitch between 11.2 to 22.0 mm; transverse tube pitch between 19.5 to 25.4 mm; fin pitch between 1.1 to 3.21 mm; fin thickness between 0.115 to 0.2 mm and number of rows between 1 to 6. The correlations were compared to referred experimental database in order to evaluate their accuracy. It is possible to conclude that Colburn correlations predicted the data better than friction factors correlations and the best one presented mean absolute error of 13.3% and 19.5%, respectively.*

Keywords: *Colburn factor, friction factor, compact heat exchangers*

1. INTRODUCTION

Heat exchangers plays a key role in air-conditioning industry (Wang *et al.*, 1997). Various geometries and types of fins exist nowadays, but plain fin are a simple popular geometry (Wang and Chi, 1998a). Most designer of heat exchangers rely on correlation for heat and friction information as well as geometric parameters (Gray and Webb, 1986).

The plain geometry for heat exchanger have been largely studied (Kim, 2015) and a considerable amount of correlations have been developed along the years (Wang *et al.*, 1997; Gray and Webb, 1986; Pirompugd *et al.*, 2006; Kim, 2015). However as related by Tang *et al.* (2009), most correlations have a restrict data-base upon they are built, which cause deviation to raise for different parameters and a soar for smaller diameters. It can be observed that most correlation on literature present higher deviation if confronted with a larger data-base.

This work presents the comparison of proposed correlation to an independent analysis with distinct data-bases in order to evaluate their effectiveness.

2. REVIEW

In the early 20th century some studies regard plain fin with round tubes started to propose correlation for the fanning factor of friction (f) and the Colburn factor (j). Many studies have presented experimental data and correlations for plain fin along the years (Gray and Webb, 1986; Wang *et al.*, 1996; Wang and Chi, 1998a), however most data-base used are limited to few points.

Gray and Webb (1986) applying a multiple regression technique on adimensional equations for j and f developed, by trial and error, one equation for each factor reducing RMS error. The heat transfer and friction equations are limited to number of rows (N) $\geq$ 4; 500 $\leq$ Reynolds number based on external diameter (Re_{D_o}) $\leq$ 24,700; 1.97 $\leq P_t/D_o \leq$ 2.55, where P_t and D_o stands for transverse tube pitch and outside tube diameter, respectively; 1.70 $\leq P_l/D_o \leq$ 2.58, where P_l stands for longitudinal tube pitch; 0.08 $\leq S_p/D_o \leq$ 0.64, where S_p stands for space between fins. Then, using a data-base from Rich (1973), the author proposed another heat transfer equation for any number of rows.

Later, Kayansayan (1992) carried out a numerous experiment with 10 different coil types. His work evaluated geometric parameters ranging from 9.52 $mm \leq D_o \leq$ 16.3 mm; 25.4 $mm \leq P_t \leq$ 40 mm; 22 $mm \leq P_l \leq$ 34.67 mm; 238 $m^{-1} \leq S_p \leq$ 454 m^{-1} and N=4. Refining his data to 110 points, applying a leasts square curve fit the author suggested a correlation for j factor in which 500 $\leq Re_{D_o} \leq$ 30,000.This correlation was plotted in comparison to others equations and showed better precision for his data.

Four years later, firstly, Wang *et al.* (1996) gathered data for plain-fin plate heat exchangers. His experimental data consisted of 15 different geometries for fixed D_c = 10.23 mm, where D_c stands for collar diameter; P_t = 25.4 mm; P_l = 22 mm and 0.13 $mm \leq t \leq$ 0.2 mm, where t stands for fin thickness; 1.74 $mm \leq F_p \leq$ 3.21 mm, where F_p stands for fin pitch; 2 $\leq N \leq$ 6. The authors have done a deep analysis about most correlations up that date and compare them. Also, applying a multiple linear regression technique for experimental Reynolds based on collar diameter (Re_{D_c}) from 800 to 7500, they proposed two equations for j and f factors, respectively. Next year, Wang *et al.* (1997) did another experimental work for plain-fins plate heat exchangers only this time accounting dehumidifying conditions. For fixed values of t = 0.13 mm; D_c = 10.23 mm; P_t = 25.4 mm; P_l = 22 mm and 1.82 $mm \leq F_p \leq$ 3.20 mm; 2 $\leq N \leq$ 6. The analysis was conducted with the same approach of previously paper and resulted in 2 correlation for f and j factor within 300 $\leq Re_{D_c} \leq$ 5500. Later in the following year, Wang and Chi (1998a) published new experimental data for plain fin-and-tube heat exchangers. This work do not mention dehumidifying condition and added great amount of data including a review of experimental data from past investigators. Wang and Chi inspected 7.53 $mm \leq D_c \leq$ 10.23 mm; 1.22 $mm \leq F_p \leq$ 2.31 mm; 21 $mm \leq P_t \leq$ 25.4 mm; 12.7 $mm \leq P_l \leq$ 19.05 mm and 1 $\leq N \leq$ 4.

One year forward Wang and Chi, Kim *et al.* (1999) build a data-base for experimental data regard plain fin-and-tube heat exchangers and correlation for j and f factor. The data comprehend works back from 1971 and up to 1998 for geometries ranging from 20.32 $mm \leq P_t \leq$ 50.80 mm; 17.58 $mm \leq P_l \leq$ 43.99 mm; 7.30 $mm \leq D_c \leq$ 19.51 mm; 0.990 $mm \leq S_p \leq$ 8.547 mm; 0.110 $mm \leq t \leq$ 0.406 mm and 1 $\leq N \leq$ 8. Analysing those experimental points by trial and error with dimensionless equations, the author, obtained 2 correlation for j where N = 1,2 and N = 3. They reported choosing the equations by observing the largest R-square value. This work also present a equation for f factor which was reported to come from a multiple regression applied in Zukauskas and Ulinskas correlation.

Pirompugd *et al.* (2006) studied dehumidifying condition for plain fin-and-tube heat exchanger for 18 geometries with P_t = 25.4 mm and 1.19 $\leq F_p \leq$ 3.16 mm; 0.115 $mm \leq t \leq$ 0.130 mm; 1.075 $mm \leq S_p \leq$ 3.070 mm; 8.51 $mm \leq D_c \leq$ 10.34 mm; 19.1 $mm \leq P_l \leq$ 22.0 mm and 1 $\leq N \leq$ 6. Using their own experimental data 300 $\leq Re_{D_c} \leq$ 5000 and a multiple linear regression technique, the author proposed 8 correlation for heat equation and mass transfer equation. Those equation were sorted by number of row and tube wet condition. The next year, Pirompugd *et al.* (2007) brought 36 new geometries and, following the same logic, suggested new correlations for mass and heat transfer under partially wet and fully wet condition.

Forward to 2009, Tang *et al.* (2009) did an experimental and numerical investigation in fin-and-tube heat exchangers with various fin geometries. Their work focused on other types of fins, however their few experimental data regard plain fin compose the general data-base.

In 2015, Wang *et al.* (2015) published an experimental study for fin-and-tube heat exchanger having diversified fin types. Their work presented 18 geometries from which 6 were plain fin. Data regard plain fin is given as follow 1.6 $mm \leq F_p \leq$ 2.0 mm and 1 $\leq N \leq$ 2.

Also that year, Kim (2015) investigated smaller tube diameters and the accuracy of the correlations given by the literature. Kim tested 9 geometries for plain fin-and-tube with D_c = 5.3 mm; 1.1 $mm \leq F_p \leq$ 1.3 mm and 1 $\leq N \leq$ 3. The author reported poor prediction from Wang *et al.* (1997) j factor correlation due to lack of data variety in their method.

Recently, Qasem and Zubair (2018) did a major review related to heat exchangers with many types of fins and geometries. Even though, a substantially number of correlation regard f and j factor were suggested there is few record for a diverse data base.

3. MATERIALS AND METHODS

3.1 Correlations

For the proposal of this work, it was necessary to choose correlations for analysis. From Qasem and Zubair (2018) review, seven different correlations were chosen in order to verify their error for a data-base. The criteria for a correlation should be as follow: Correlations must have tubes of circular section; the error reported by their author may not be greater than 20% and all geometric data have to have only plain fins.

The correlations were verified for own author's data to eliminate any possible algorithm error. After this step, the equation were implemented in Engineer Equation Solver (EES) with the data-base built. The results were then ploted by Origin software in a easy reading and comparable way.

For accuracy measurement, mean absolute error (MAE) was chosen for individual analysis of ones equation and fraction of the results within 30% deviation ($\lambda(30\%)$) due to variability of the data-base and a large deviation was expected.

3.1.1 j Correlations

Gray and Webb (1986) developed this j-correlation assuming a general equation in form of:

$$j = cF(x_i)Re_{D_o}^m \tag{1}$$

Where $F(x_i)$ represents the dimensionless geometric parameters in the following form:

$$F(x_i) = (x_1)^{n_1}(x_2)^{n_2}...(x_j)^{n_j} \tag{2}$$

Using some mathematics manipulation and MINITAB statistical package, the authors developed their equations. R-square method was used to evaluate the accuracy.

The first correlation used data from Rich (1973) and McQuiston (1978) for N $\geq$ 4 and adjusted data of McQuiston and Tree (1971) and Kays and London (1984). The follow equation showed the highest R-square number:

$$j_4 = 0.14Re^{-0.328}\left(\frac{P_t}{P_l}\right)^{-0.502}\left(\frac{S_p}{D_o}\right)^{0.0312} \tag{3}$$

Equation (3) is valid for N $\geq$ 4; 500 $\leq Re_{D_o} \leq$ 24,700; 1.97 $\leq P_t/D_o \leq$ 2.55; 1.70 $\leq P_l/D_o \leq$ 2.58; 0.08 $\leq S_p/D_o$ $\leq$ 0.64 and has a rms error of 7.3%.

The follow correlation was proposed for N $\leq$4 using Rich's data as a correction for N$\leq$4.

$$\frac{j_N}{j_4} = 0.991\left[2.24Re^{-0.092}\left(\frac{N}{4}\right)^{-0.031}\right]^{0.607(4-N)} \tag{4}$$

Wang *et al.* (1996) reported using their own data and a multiple linear regression technique for a data range of D_c = 10.23 mm; P_t = 25.4 mm; P_l = 22 mm and 0.13 $mm \leq t \leq$ 0.2 mm; 1.74 $mm \leq F_p \leq$ 3.21 mm; 2 $\leq N \leq$ 6. The author then presented the current equation:

$$j = 0.394Re_dc^{-0.392}\left(\frac{t}{D_c}\right)^{-0.0449}N^{-0.0897}\left(\frac{F_p}{D_c}\right)^{-0.197} \tag{5}$$

Equation (5) was reported to describe 97% of author's data with in 10% devition and 4.1% of RMS error.

Kim *et al.* (1999) collected the most varied data analysed by this work. The authors suggest two equations based on R-square method and multiple linear regression. Their data range from 20.32 $mm \leq P_t \leq$ 50.80 mm; 17.58 $mm \leq P_l \leq$ 43.99 mm; 7.30 $mm \leq D_c \leq$ 19.51 mm; 0.990 $mm \leq S_p \leq$ 8.547 mm; 0.110 $mm \leq t \leq$ 0.406 mm and 1 $\leq N \leq$ 8. Equation (6) was establish for three rows and then Eq. (7) was presented for corrected number of rows.

$$j_{N=3} = 0.163Re_{D_c}^{-0.369}\left(\frac{P_t}{P_l}\right)^{0.106}\left(\frac{S_p}{D_c}\right)^{0.0138}\left(\frac{P_t}{D_c}\right)^{0.13} \tag{6}$$

$$\frac{j_{n=1,2}}{j_{N=3}} = 1.043\left[Re_{D_c}^{-0.14}\left(\frac{P_t}{P_l}\right)^{-0.564}\left(\frac{S_p}{D_c}\right)^{-0.123}\left(\frac{P_t}{D_c}\right)^{1.17}\right]^{(3-N)} \tag{7}$$

Pirompugd *et al.* (2006) analysed data for dehumidifying conditions. Based on their data, the authors concluded that no one curve could replicate the experimental data. Using a multiple linear regression method, the authors developed twelve equations for mass and heat transfer under full wet and partially wet conditions. The follow equation were developed for fully wet conditions.

$$j_{h,1} = 0.6189\left(\frac{S_p}{D_c}\right)^{-0.4176}\left(\frac{P_l}{D_c}\right)^{-0.7834}\left(\frac{P_t}{D_c}\right)^{0.9802}Re^{\left(0.3232\frac{S_p}{D_c}+0.04332\frac{P_t}{D_c}-0.07983\frac{P_t}{D_c}-0.6125\right)} \tag{8}$$

$$j_{h,N} = 0.3301j_{h,1}\left(\frac{S_p}{D_c}\right)^{0.4683}\left(\frac{P_l}{D_c}\right)^{0.3549}\left(\frac{P_t}{D_c}\right)^{0.8906}Re^{\left(-0.3611\frac{S_p}{D_c}-0.01713\frac{P_t}{D_c}-0.01710\frac{P_t}{D_c}+0.2514\right)} \tag{9}$$

3.1.2 f Correlations

Similar method was used to 1 and 2. Gray and Webb (1986) proposed Eq. (10) based on same data for previous equations.

$$f = 0.558Re_{D_o}^{-0.521}\left(\frac{P_t}{D_o}\right)^{1.318} \tag{10}$$

Wang *et al.* (1996) equation for friction followed the same method as heat transfer equation and is presented a presented in Eq. (11).

$$f = 1.039Re_{D_c}^{-0.418}\left(\frac{t}{D_c}\right)^{-0.104}N^{-0.0935}\left(\frac{F_p}{D_c}\right)^{-0.197} \tag{11}$$

This equation has 6.5% of RMS error and represents 88% authors data with in 10% deviation.

For the next correlation, Wang and Chi (1998b) discussed the methodology and results of the various authors who presented geometrical data ranging from 6.7 $mm \leq D_o \leq$ 13.233 mm; $1 \leq N \leq 6$; 1.19 $mm \leq F_p \leq$ 8.7 mm; 13.6 mm $\leq P_l \leq$ 27.5 mm; 17.7 $mm \leq P_t \leq$ 31.75 mm and 0.115 $mm \leq t \leq$ 0.2 mm.

For the data mentioned above, Wang and Chi (1998b) developed the following equations:

$$f = 0.0267 Re_{D_c}^{F1} \left(\frac{P_t}{P_l}\right)^{F2} \left(\frac{F_p}{D_c}\right)^{F3} \tag{12}$$

Where:

$$F1 = -0.764 + 0.739\frac{P_t}{P_l} + 0.177\frac{F_p}{D_c} - \frac{0.00758}{N} \tag{13}$$

$$F2 = -15.689 + \frac{64.021}{log_e(Re_{D_c})} \tag{14}$$

$$F3 = 1.696 - \frac{15.695}{log_e(Re_{D_c})} \tag{15}$$

For Kim *et al.* (1999), following steps in j factors, the next equation is presented.

$$f = 1.455 Re_{D_c}^{-0.656} \left(\frac{P_t}{P_l}\right)^{-0.347} \left(\frac{S_p}{D_c}\right)^{-0.134} \left(\frac{P_t}{D_c}\right)^{1.23} \tag{16}$$

3.2 Database

The data-base was acquired from the available literature where papers with plain fins with experimental data were consulted. The geometric parameter were then organized in Table 1.

It is possible to observe that all data range from 5.3 $mm \leq D_c \leq$ 10.34 mm; 11.2 $mm \leq P_l \leq$ 22.0 mm; 19.5 mm $\leq P_t \leq$ 25.4 mm; 0.98 $mm \leq S_p \leq$ 3.07 mm; 1.1 $mm \leq F_p \leq$ 3.21 mm; 0.115 $mm \leq t \leq$ 0.2 mm; $1 \leq N \leq 6$ and 233.6 $\leq Re_{D_c} \leq$ 7861.5. A total of 547 points of data were analysed where 186 points are for f factor and 361 points to j factor.

The data was acquired in tables and figures of cited author. In order to avoid error propagation, points were taken from original publication and only clear data was accounted in our calculation. The information was organized in D_o, D_c, P_l, P_t, S_p, F_p, t, N, Re_{D_o} and Re_{D_c} and if one o those information could not be found, the point was not used.

Table 1. Experimental data range.

$D_c(mm)$	$P_l(mm)$	$P_t(mm)$	$F_p(mm)$	$t(mm)$	N	Ref:
10.23	22.00	25.40	1.74-3.21	0.13-0.20	2-6	(Wang *et al.*, 1996)
10.23	22.00	25.40	1.82-3.16	0.13	2-6	(Wang *et al.*, 1997)
7.53-10.23	12.70-19.05	21.00-25.40	1.22-2.31	0.115	1-4	(Wang and Chi, 1998a)
8.51-10.34	19.10-22.00	19.10-22.00	1.19-3.20	0.115-0.13	1-6	(Pirompugd *et al.*, 2006)
8.51-10.34	19.10-22.00	25.4	1.19-3.00	0.115-0.13	1-4	(Pirompugd *et al.*, 2007)
5.30	11.20	19.50	1.10-1.30	0.12	1-3	(Kim, 2015)

4. ANALYSIS

4.1 Wang's data

Figure 1 present Wang *et al.* (1996) experimental data for Colburn and friction factor. It is possible to see that Wang's own correlation fails to predict his own data for f factor and high Reynolds number increases deviation. For Colburn factor, all equations studied in this work underpredict the data.

Figure 2 present Wang *et al.* (1997) experimental data for both factors. Wang *et al.* (1996) exhibits the best accuracy for friction factor and the others correlations underpredict the data. Even though, Wang and Chi (1998a) correlation exceeds the other in predicts data at low Reynolds number, every equations shows good overall prediction.

Figure 3 shows Wang and Chi (1998a) experimental data for both factors. For f factor every equation underpredict the data for low Reynolds number. after Re_{D_c} > 600, Eq. (5) overestimate the results and rise the deviation with higher Reynolds number. Equation (12) predicts his own data with extreme precision. For j factor, every equation underpredicts the data, Wang and Chi (1998a) data included. It can be seen that equations presents higher prediction rate for higher Re_{D_c}.

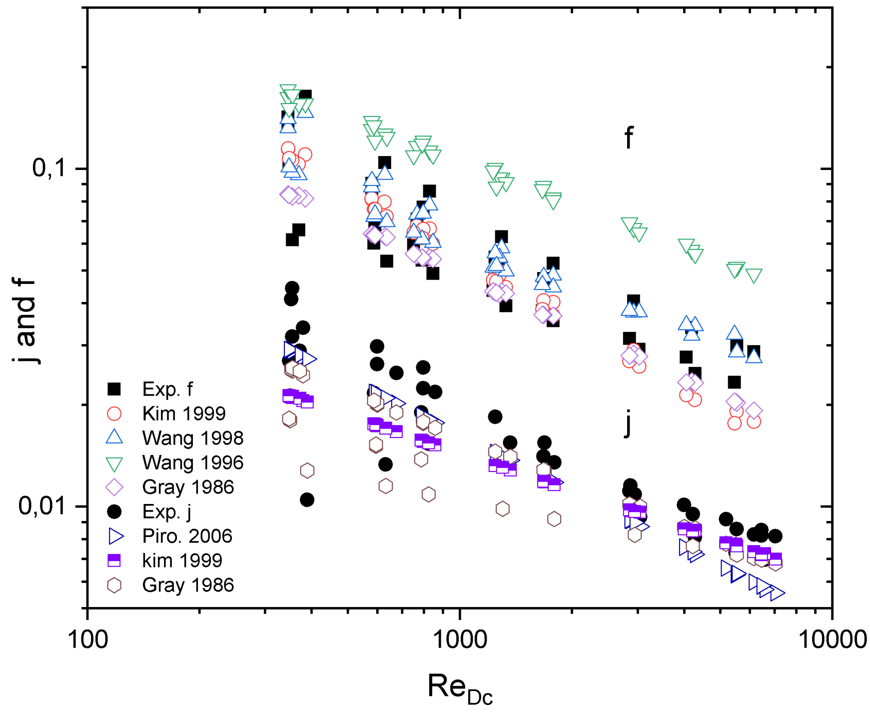


Figure 1. Wang *et al.* (1996) data analysed by various correlations.

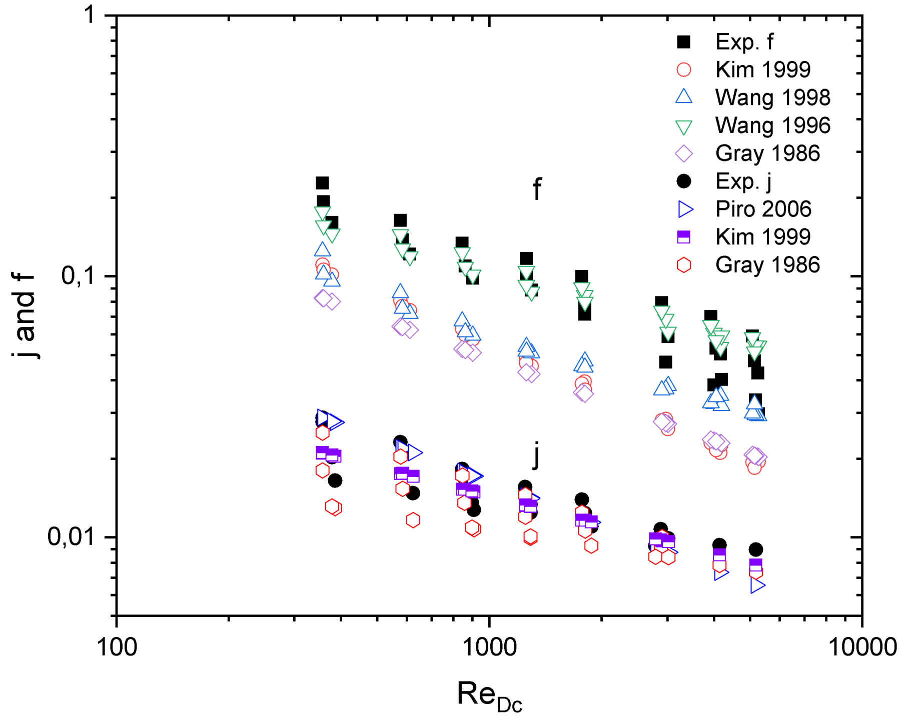


Figure 2. Wang *et al.* (1997) data analysed by various correlations.

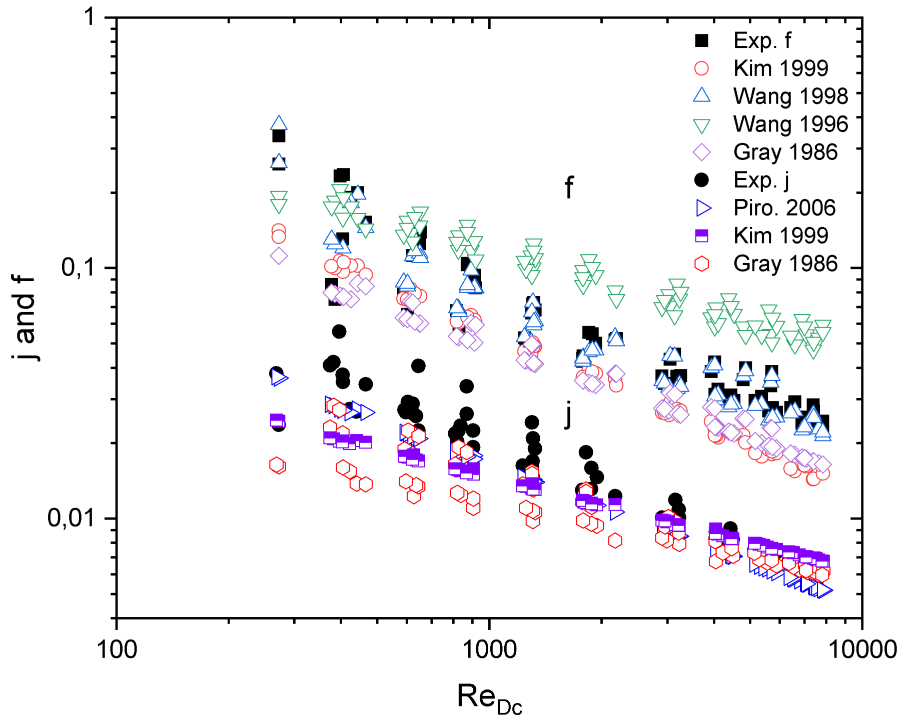


Figure 3. Wang and Chi (1998a) data analysed by various correlations.

4.2 Pirompudg 2006 and 2007 data

Figure 4a shows Pirompugd *et al.* (2006, 2007) experimental data for friction and Colburn factor. For j factor, similar to Wang and Chi (1998a) data, every equation underpredicts the data and Eq. (5) overpredicts after Re_{D_c} > 600. Equation (12) exhibits low error for f data. In general, every equation underpredicts j data showing similar behaviour as for Wang and Chi (1998a) data. The figure also shows a rise in precision for higher Re_{D_c} as also observed in Wang and Chi (1998a) data.

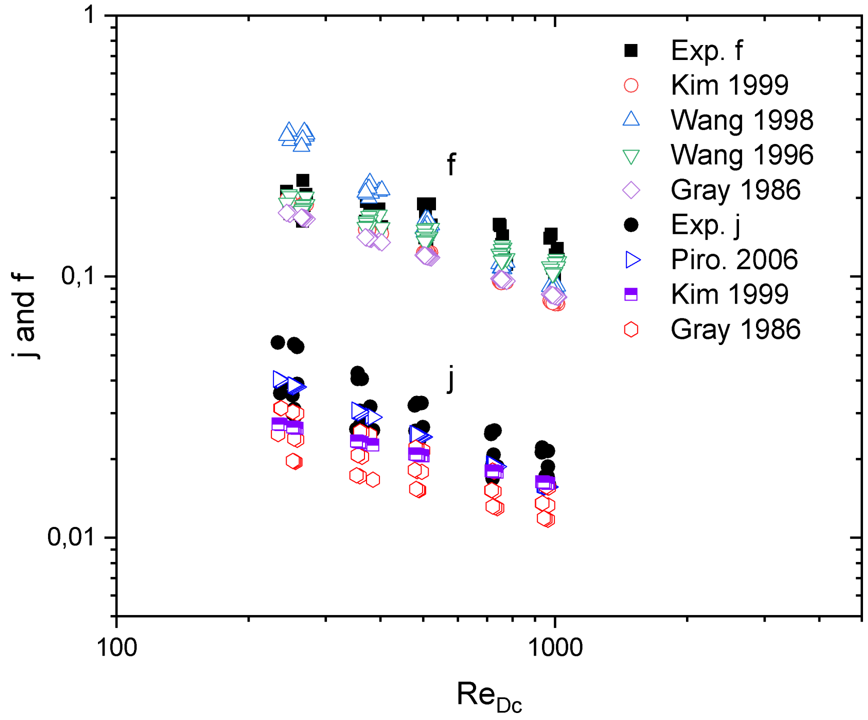
4.3 Kim 2015 data

For friction factor, Eq. (12) shows overprediction for lower Re_{D_c} number while other equations show underpredict results. For higher Re_{D_c} number every correlation underpredict the results while Eq. (5) presents higher precision. In general, for j factor, every correlation underpredict the experimental data and Eq. (9) has slight better accuracy as shown in Fig. 4a.

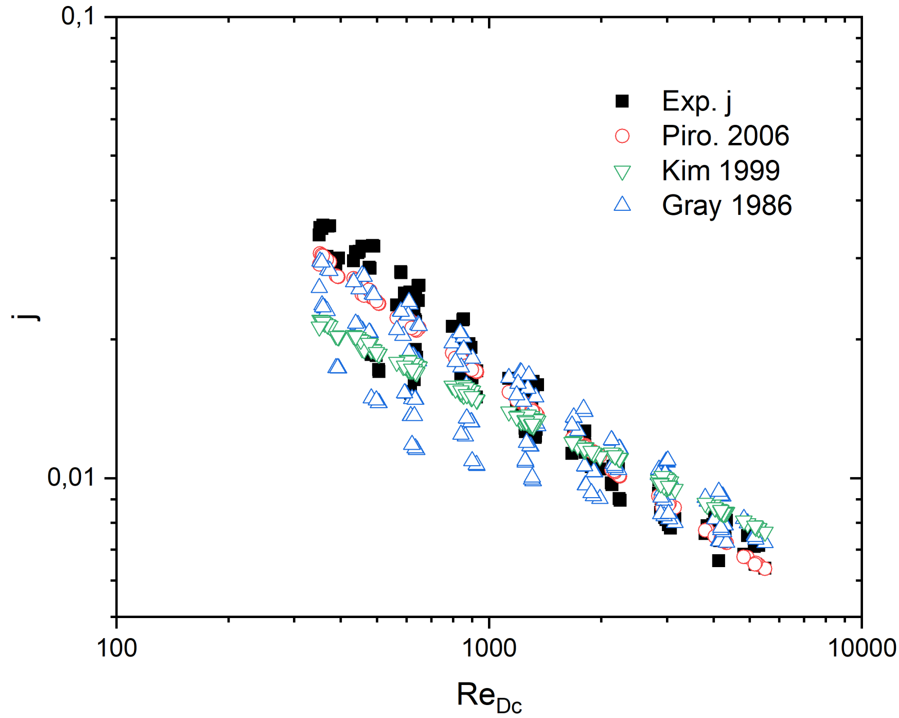
4.4 Error analysis

After evaluating all equations for j factor it can be seen in Tab. 2, that most correlations studied in this work had overall good accuracy with Pirompugd *et al.* (2006) equation showing the best performance with mean absolute error of 13.3% and 98.1% of the data represented within 30% deviation. It can be observed that even relative old equation, as is Gray and Webb (1986) equation, showed fair accuracy with 92.0% of data represented within 30% deviation for newer experimental data.

On the other hand for f factor correlations, Tab. 3 shows higher overall deviation for the correlation chosen. Gray and Webb (1986) equation showed mean absolute error of 30.9% and only 51.1% of the data-base was predicted within 30% of deviation. However, Wang and Chi (1998b) equation presented better performance than the other correlation, showing 19.5% mean absolute error and 75.8% data coverage within 30% deviation. Figure 5 ilustrate how Wang and Chi (1998b) equation and Pirompugd *et al.* (2006) equation behave within all data. Figure 5a presents predicted x experimental data distribuition within 30% of deviaton for f factor data points. Similar to f factor, Fig. 5b also presents predicted x experimental data destribution within the same deviation only this time to j factor.

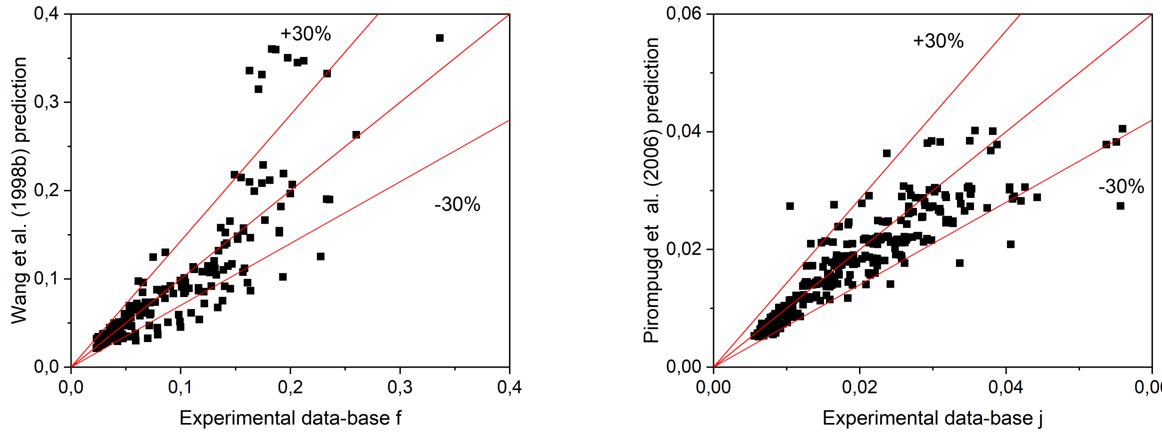


(a) Kim (2015) data.



(b) Pirompugd *et al.* (2006, 2007) data.

Figure 4. Kim and Pirompugd data analysed by various correlations.



(a) All the data for f factor within 30% deviation analysed by Eq. (12). (b) All the data for j factor within 30% deviation analysed by Eq. (9).

Figure 5. Graphical analysis for f and j factor within 30% deviation.

Table 2. j factor data-base and correlation data.

Data-base	Number of data points		Correlation		
			Gray and Webb (1986)	Kim *et al.* (1999)	Pirompugd *et al.* (2006)
Wang *et al.* (1996)	41	MAE	19.6	17.0	22.7
		$\lambda(30\%)$	85.4	75.6	85.4
Wang *et al.* (1997)	24	MAE	17.0	12.0	15.4
		$\lambda(30\%)$	91.7	100.0	83.3
Wang and Chi (1998a)	75	MAE	24.7	19.9	18.1
		$\lambda(30\%)$	57.3	69.3	86.7
Pirompugd *et al.* (2006)	65	MAE	16.3	17.2	9.8
		$\lambda(30\%)$	89.2	80.0	95.4
Pirompugd *et al.* (2007)	110	MAE	15.5	15.0	7.7
		$\lambda(30\%)$	89.1	84.6	97.3
Kim (2015)	46	MAE	29.6	20.9	14.4
		$\lambda(30\%)$	41.3	76.1	95.7
Total	361	MAE	19.9	17.7	13.3
		$\lambda(30\%)$	92.0	90.1	98.1

Table 3. f factor data-base and correlation data.

Data-base	Number of data points		Correlation			
			Gray and Webb (1986)	Wang *et al.* (1996)	Wang and Chi (1998b)	Kim *et al.* (1999)
Wang *et al.* (1996)	37	MAE	20.6	85.8	14.9	19.6
		$\lambda(30\%)$	64.9	10.8	86.5	81.1
Wang *et al.* (1997)	28	MAE	53.6	17.7	38.1	50.5
		$\lambda(30\%)$	0.0	82.1	17.9	0.0
Wang and Chi (1998a)	77	MAE	32.9	78.5	8.2	32.1
		$\lambda(30\%)$	46.8	16.9	97.4	41.6
Kim (2015)	44	MAE	21.8	8.7	31.3	20.9
		$\lambda(30\%)$	75.0	100.0	65.9	75.0
Total	186	MAE	30.9	54.3	19.5	29.7
		$\lambda(30\%)$	51.1	45.2	75.8	40.3

5. CONCLUSION

A data-base of 547 points was acquired from open literature for plain fin heat exchanger and compared with j and f correlations, where 361 points were used to j factor correlations and 186 were used to f factor correlation.

- The best prevision of Colburn factor was given by Pirompugd *et al.* (2006) correlation with a mean absolute error of 13.3%.
- The best prevision of Fanning friction factor was given by Wang and Chi (1998b) correlation with a mean absolute error of 19.5%.

- This work shows that these correlations can be used for the design of plain fin-and-tube heat exchangers, but there is still space for improvement of their performance.

6. ACKNOWLEDGEMENTS

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