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Heat transfer and friction characteristics of plain fin-and-tube heat exchangers, part II: Correlation

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Abstract

A correlation for fin-and-tube heat exchanger having plain fin geometry is proposed in this study. A total of 74 samples were used to develop the correlation. For practical considerations, the proposed heat transfer correlation had absorbed the contact conductance in the development of correlation. The proposed heat transfer correlation can describe 88.6% of the database within ±15%, while the proposed friction correlation can correlate 85.1% of the database within ±15%. The mean deviation of the heat transfer correlation is 7.51%, while that for the proposed friction correlation is 8.31%.

Keywords: Augmentation; Heat exchangers; Finned surfaces

1. Introduction

Fin-and-tube heat exchangers are employed in a wide variety of engineering applications like air-conditioning apparatus, process gas heater, and cooler. There are many variants of the fin patters such as wavy, louver, and slit. Despite these, enhanced fin surfaces can significantly improve the heat transfer coefficients in comparison with their plain fin counterpart, the plain fin is still by far the most popular fin pattern used in the air-cooled heat exchangers. This is because of its superior reliability under long-term operation and its lower friction characteristics. Many investigations were devoted to the heat transfer and friction characteristics for plain fin geometry during the past years. Wang et al. [1] had summarized the most influential works about the plain fin geometry since 1971.

The first successful heat transfer and friction correlations for plain fin geometry having staggered layout were proposed by McQuiston [2]. However, the predictive ability of the friction factors, as pointed out by Gray and Webb [3], was quite poor. The Gray and Webb [3] correlation had significantly improved the predictive capability of friction factors, and the heat transfer correlation is comparable to that of McQuiston [2]. However, it should be pointed out that the correlation developed by Gray and Webb [3] is more appropriate for larger diameter tube and more number of tube rows owing to its limitation of database. A recent investigation by Wang et al. [4] indicated that the Gray and Webb correlation [3] considerably underpredicts the heat transfer data for those having smaller tube diameter. Actually, the mean deviation of the Gray and Webb correlation in predicting the database of Wang and Chi [1] is over 25%, and the predictive errors to the friction factors are even higher.

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Nomenclature

C_1, C_2, C_3, C_4	correlation parameters (dimensionless)	N	number of tube row
D_c	fin collar outside diameter ($D_o + 2\delta_f$)	NTU	number of transfer unit
D_o	tube outside diameter	ΔP	pressure drop
D_h	hydraulic diameter ($4A_cL/A_o$)	P_l	longitudinal tube pitch
ε	effectiveness	$P_1 \ldots P_7$	correlation parameters (dimensionless)
f	friction factor	Pr	Prandtl number
F_1, F_2, F_3	correlation parameters (dimensional)	P_t	transverse tube pitch
F_p	fin pitch	Re_{D_c}	Reynolds number based on tube collar diameter
h_c	contact conductance	δ_f	fin thickness
h_o	heat transfer coefficient	*Subscripts*	
j	$Nu/RePr^{1/3}$ (the Coburn factor)	exp	experimental value
L	depth of the heat exchanger in airflow direction	cor	value by correlation

As pointed out by Wang et al. [1], the use of smaller diameter tube, smaller longitudinal tube pitch, and smaller transverse tube pitch in plate fin-and-tube heat exchangers are becoming popular since it could significantly improve the thermal/hydraulics characteristics and saving resources. Unfortunately, most of the previous published correlations were based on those larger diameter tube (e.g., $D_o = 9.52$, 12.7 and 15.8 mm). The database containing smaller diameter tubes like 7.94, 7, and 6.35 mm tubes was not available in the development of previous correlations. Notice that the smaller diameter tubes are quite popular in residential application. This is because higher heat transfer coefficients, lower pressure drops, and less refrigerant charge can be achieved by using smaller tubes, and eventually led to much more compact fin-and-tube heat exchangers design (see the test results by Wang et al. [1]). Therefore, it is very crucial to update the existing airside performances using a much larger and reliable database. The objective of the present study is to develop the associated correlations for the plain fin-and-tube heat exchangers based on a much wilder and reliable database.

2. The data bank

An attempt has been made to collect data from a wide range of geometric dimensions. However, the airside performance is generally proprietary and many of the published work did not clearly mention their reduction method. As a result, it is necessary to screen out the published data before the final construction of the correlation. Fig. 1 shows typical reduced heat transfer performance (in terms of the Coburn j factors) by McQuiston, [5], Seshimo and Fujii [6], Kayansayan

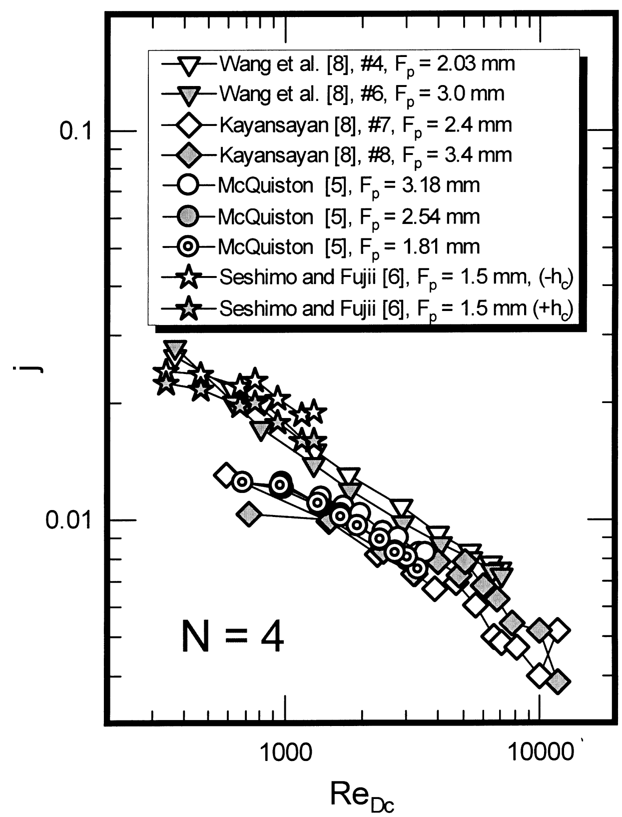


Fig. 1. Comparison of j values between test samples by McQuiston [5], Seshimo and Fujii [6], Kayansayan [7], and Wang et al. [8].

[7], and Wang et al. [8]. Note that the fin patterns tested by these investigators were all plain fins. In addition, the test samples by the above-mentioned investigators consisted of $D_o = 9.52$ mm (before expansion), $P_t = 25.4$ mm, $P_l = 22$ mm, and $N = 4$. Though their fin pitch is not the same, however, as indicated by Wang et al. [8] and Rich [9], the effect of fin pitch on the heat transfer performance is quite small for plain fin-and-tube heat exchangers having four-row configuration. Therefore, it is expected that the heat transfer performance for the preceding samples may be similar. Nonetheless, as shown in the figure, the test results differ as much as 100%. Possible explanations about the deviations in the test results include: (1) contact resistance; (2) data reduction method; and (3) experimental uncertainties.

Most of the investigators claimed a negligible contact resistance and acceptable uncertainties in their investigations. However, their arguments are questionable, being especially doubtful for those samples that were not mechanically expanded. For example, the test results by Kayansayan [7] showed considerable scattering, it is likely to occur without careful control during the hydraulic expansion process.

For similar mechanical expansion production, the test results of Seshimo and Fujii [6] are about 5–8% higher than those of Wang et al. [8]. It should be pointed out that the original heat transfer performance of Seshimo and Fujii [6] was obtained by subtracting the in-tube heat transfer performance and the contact resistance from the overall heat transfer performance. The contact resistance correlation they used was provided by Naito [10]. Seshimo [11] pointed out the values between 10,000–15,000 W m^{-2} K^{-1}. For a similar fin geometry ($P_t = 25.4$ mm, $P_l = 22$ mm, $D = 9.52$ mm, and full fin collar), Sheffield et al. [12] reported that the contact conductance, h_c, ranged from 10,607 to 30,828 W m^{-2} K^{-1}. In practice, it is very hard to accurately predict the contact conductance, and it may be very difficult to differentiate it from the overall conductance. Hence, most of the published works on the airside performance absorbed contact resistance into the airside performance. As a result, as shown in Fig. 1, one can see that if the contact resistance is added back to the original reduced results by Seshimo and Fujii [6], the test results agree favorably with those by Wang et al. [8].

Besides the contact resistance and reduction method, the present authors feel that it is also very important to report the correct circuitry used in the development of correlation. As pointed out by Wang et al. [13], ε–NTU relations depend on the circuitry arrangement, the reduced data are only meaningful if the investigators use correct ε–NTU relations to reduce their test results. Unfortunately, many of the investigators did not mention the details of the relationship they used. In this connection, we did not include the data that did not clearly mention their detailed reduction method.

Therefore, a total of 74 samples are used for the development of correlations after screening. A complete list is shown in Table 1, and the relevant geometric parameters and the data points used for reduction are shown. The data are from Wang [14] (4 samples), Wang et al. [15] (2 samples), Wang et al. [16] (4 samples), Wang et al. [8] (15 samples), Wang and Chi [1] (18 samples), Rich [9] (6 samples), Rich [17] (8 samples), and Seshimo and Fujii [6] (17 samples. The database of Seshimo and Fujii [6] were combined with the contact conductance correlation first [10] before the development of correlation). Figs. 2 and 3 show the airside performances in terms of Coburn j factors and friction factors f for these 74 samples.

3. Results and discussion

It is obvious from the Figs. 2 and 3 that the compli-

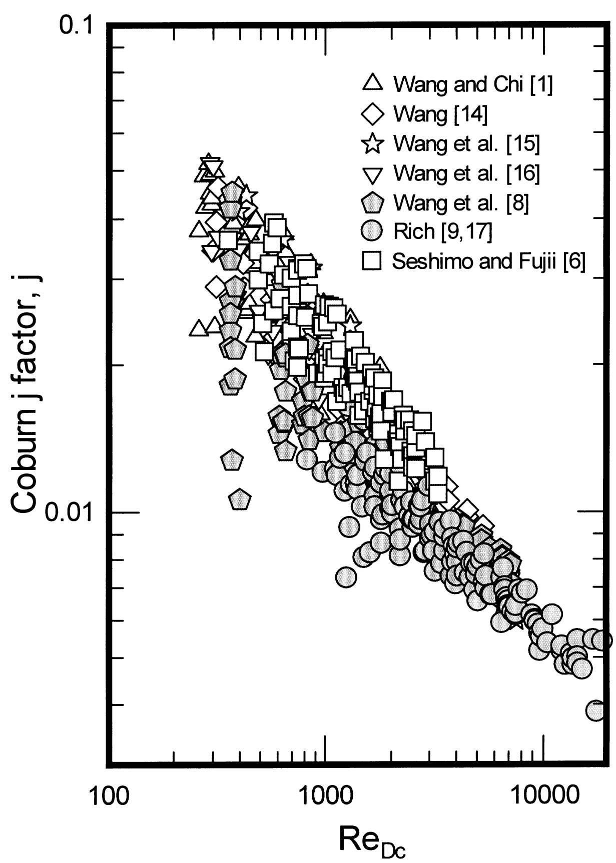


Fig. 2. Database used to develop heat transfer correlation in the present investigation.

Table 1
Geometric dimensions of the sample plate fin-and-tube heat exchangers[a]

No.	References	OD (mm)	N	F_p (mm)	P_l (mm)	P_t (mm)	Data point j value	Data point f value	δ_f (mm)	δ_w (mm)
1	Wang [14]	6.7	1	1.2	13.6	17.7	10	10	0.115	0.27
2	Wang [14]	6.7	1	1.99	13.6	17.7	10	10	0.115	0.27
3	Wang [14]	6.7	2	1.23	13.6	17.7	10	10	0.115	0.27
4	Wang [14]	6.7	2	1.98	13.6	17.7	10	10	0.115	0.27
5	Wang et al. [15]	10.1	1	1.19	22	25.4	10	10	0.115	0.31
6	Wang et al. [15]	10.1	1	2.43	22	25.4	10	10	0.115	0.31
7	Wang et al. [16]	8.38	2	1.7	19.05	25.4	10	10	0.115	0.31
8	Wang et al. [16]	8.38	2	3.13	19.05	25.4	10	10	0.115	0.31
9	Wang et al. [16]	8.38	4	1.7	19.05	25.4	10	10	0.115	0.31
10	Wang et al. [16]	8.38	4	3.13	19.05	25.4	10	10	0.115	0.31
11	Wang et al. [8]	9.97	2	1.82	22	25.4	10	10	0.13	0.35
12	Wang et al. [8]	9.97	2	2.24	22	25.4	10	10	0.13	0.35
13	Wang et al. [8]	9.97	2	3.2	22	25.4	10	10	0.13	0.35
14	Wang et al. [8]	9.97	2	1.77	22	25.4	10	10	0.2	0.35
15	Wang et al. [8]	9.97	2	3.21	22	25.4	9	9	0.2	0.35
16	Wang et al. [8]	9.97	4	2.03	22	25.4	10	10	0.13	0.35
17	Wang et al. [8]	9.97	4	2.23	22	25.4	10	10	0.13	0.35
18	Wang et al. [8]	9.97	4	3	22	25.4	10	10	0.13	0.35
19	Wang et al. [8]	9.97	4	1.77	22	25.4	10	10	0.2	0.35
20	Wang et al. [8]	9.97	4	3.17	22	25.4	10	10	0.2	0.35
21	Wang et al. [8]	9.97	6	1.85	22	25.4	10	10	0.13	0.35
22	Wang et al. [8]	9.97	6	2.21	22	25.4	10	10	0.13	0.35
23	Wang et al. [8]	9.97	6	3.16	22	25.4	10	10	0.13	0.35
24	Wang et al. [8]	9.97	6	1.74	22	25.4	10	10	0.2	0.35
25	Wang et al. [8]	9.97	6	3.16	22	25.4	10	10	0.2	0.35
26	Wang and Chi [1]	7.3	4	1.78	12.4	21	10	10	0.115	0.27
27	Wang and Chi [1]	7.3	4	1.22	12.4	21	10	10	0.115	0.27
28	Wang and Chi [1]	7.3	2	1.78	12.4	21	10	10	0.115	0.27
29	Wang and Chi [1]	7.3	2	1.22	12.4	21	10	10	0.115	0.27
30	Wang and Chi [1]	10	4	1.23	19.05	25.4	10	10	0.115	0.31
31	Wang and Chi [1]	10	2	1.23	19.05	25.4	10	10	0.115	0.31
32	Wang and Chi [1]	10	2	2.23	19.05	25.4	10	10	0.115	0.31
33	Wang and Chi [1]	10	1	2.23	19.05	25.4	10	10	0.115	0.31
34	Wang and Chi [1]	10	4	1.55	19.05	25.4	9	9	0.115	0.31
35	Wang and Chi [1]	10	1	1.23	19.05	25.4	10	10	0.115	0.31
36	Wang and Chi [1]	8.28	4	1.21	19.05	25.4	10	10	0.115	0.31
37	Wang and Chi [1]	8.28	4	2.06	19.05	25.4	10	10	0.115	0.31
38	Wang and Chi [1]	8.28	2	1.23	19.05	25.4	10	10	0.115	0.31
39	Wang and Chi [1]	8.28	2	2.06	19.05	25.4	10	10	0.115	0.31
40	Wang and Chi [1]	8.28	4	1.6	19.05	25.4	10	10	0.115	0.31
41	Wang and Chi [1]	8.28	1	2.04	19.05	25.4	10	10	0.115	0.31
42	Wang and Chi [1]	8.28	1	1.19	19.05	25.4	10	10	0.115	0.31
43	Wang and Chi [1]	10	4	2.31	19.05	25.4	10	10	0.115	0.31
44	Rich [9]	13.233	1	1.75	27.5	31.75	12	–	0.152	0.35
45	Rich [9]	13.233	2	1.75	27.5	31.75	10	–	0.152	0.35
46	Rich [9]	13.233	3	1.75	27.5	31.75	11	–	0.152	0.35
47	Rich [9]	13.233	4	1.75	27.5	31.75	9	–	0.152	0.35
48	Rich [9]	13.233	5	1.75	27.5	31.75	10	–	0.152	0.35
49	Rich [9]	13.233	6	1.75	27.5	31.75	11	–	0.152	0.35
50	Rich [17]	13.335	4	8.7	27.5	31.75	10	10	0.152	0.35
51	Rich [17]	13.335	4	5.75	27.5	31.75	10	10	0.152	0.35
52	Rich [17]	13.335	4	3.81	27.5	31.75	11	11	0.152	0.35
53	Rich [17]	13.335	4	3.31	27.5	31.75	10	10	0.152	0.35
54	Rich [17]	13.335	4	2.77	27.5	31.75	10	10	0.152	0.35
55	Rich [17]	13.335	4	2.17	27.5	31.75	10	10	0.152	0.35

Table 1 (*continued*)

No.	References	OD (mm)	N	F_p (mm)	P_l (mm)	P_t (mm)	Data point j value	Data point f value	δ_f (mm)	δ_w (mm)
56	Rich [17]	13.335	4	1.75	27.5	31.75	9	11	0.152	0.35
57	Rich [17]	13.335	4	1.23	27.5	31.75	8	10	0.152	0.35
58	Seshimo and Fujii [6]	9.996	1	1.5	32	25.4	5	–	0.12	0.312
59	Seshimo and Fujii [6]	9.996	1	1.5	22	25.4	7	–	0.12	0.31
60	Seshimo and Fujii [6]	9.996	1	1.5	20	25.4	5	–	0.12	0.31
61	Seshimo and Fujii [6]	9.996	1	1.5	18	25.4	6	–	0.12	0.31
62	Seshimo and Fujii [6]	9.996	1	2.2	17.7	20.4	6	–	0.12	0.31
63	Seshimo and Fujii [6]	9.996	1	1.8	17.7	20.4	6	–	0.12	0.31
64	Seshimo and Fujii [6]	9.996	1	1.5	17.7	20.4	8	8	0.12	0.31
65	Seshimo and Fujii [6]	9.996	1	1.2	17.7	20.4	7	–	0.12	0.31
66	Seshimo and Fujii [6]	7.94	1	1.5	17.7	20.4	7	7	0.12	0.31
67	Seshimo and Fujii [6]	6.35	1	1.6	17.7	20.4	5	5	0.12	0.31
68	Seshimo and Fujii [6]	9.996	2	1.5	22	25.4	7		0.12	0.31
69	Seshimo and Fujii [6]	9.996	2	1.5	17.7	20.4	7	–	0.12	0.31
70	Seshimo and Fujii [6]	7.94	2	1.5	17.7	20.4	5	–	0.12	0.31
71	Seshimo and Fujii [6]	9.996	3	1.5	17.7	20.4	5	–	0.12	0.31
72	Seshimo and Fujii [6]	7.94	3	1.5	17.7	20.4	7	–	0.12	0.31
73	Seshimo and Fujii [6]	9.996	4	1.5	17.7	20.4	7	–	0.12	0.31
74	Seshimo and Fujii [6]	7.94	4	1.5	17.7	20.4	7	–	0.12	0.31

[a] A total of 676 data points were used to developed j correlation while 530 data points were used to generate the f correlation.

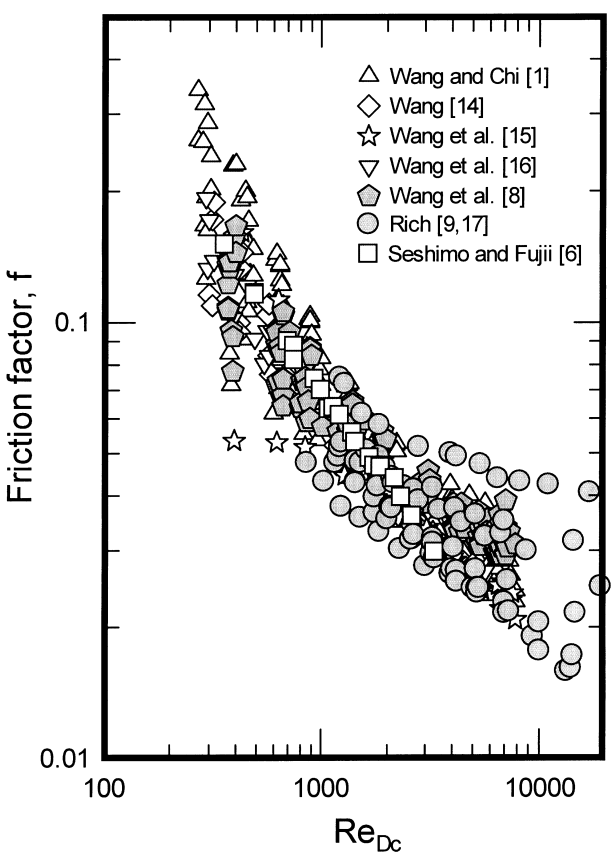


Fig. 3. Database used to develop friction correlation in the present investigation.

cated airside performance cannot be easily correlated. Attempts are made to correlate the database using a multiple regression technique. The basic forms of the correlations are:

$$j = C_1 Re_{D_c}^{C_2} \tag{1}$$

$$f = C_3 Re_{D_c}^{C_4} \tag{2}$$

It is assumed that the parameters of C_1, C_2, C_3, and C_4 depend on the physical dimensions of the heat exchanger. A separate multiple linear regression was carried out to determine the exponents, C_2 and C_4 of the test data. The determinations of C_1 and C_3 are analogous to those of C_2 and C_4. After a detailed evaluation of the database, the final recommended correlations for heat transfer performance are given as follows:

For $N = 1$,

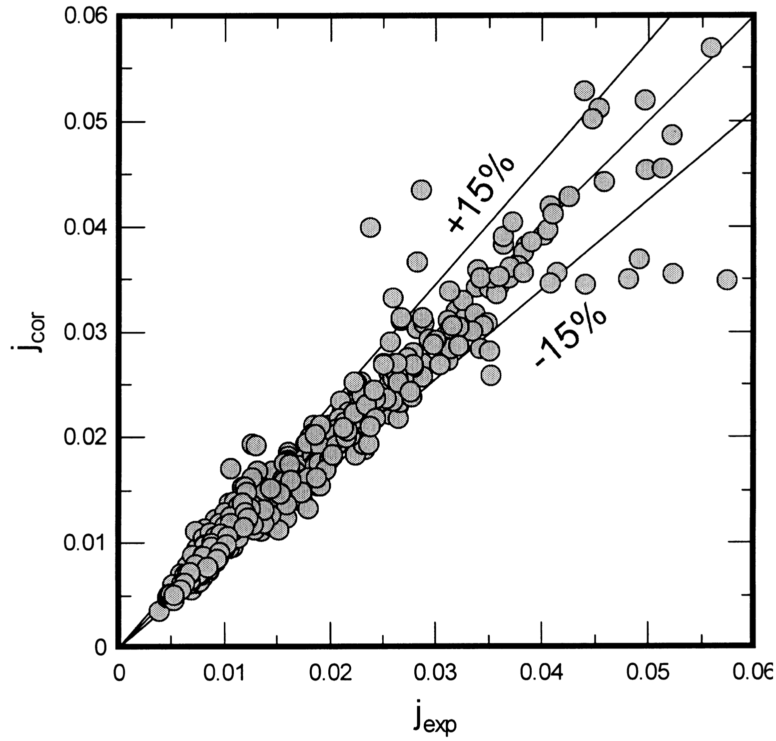
$$j = 0.108 Re_{D_c}^{-0.29} \left(\frac{P_t}{P_l}\right)^{P1} \left(\frac{F_p}{D_c}\right)^{-1.084} \left(\frac{F_p}{D_h}\right)^{-0.786} \left(\frac{F_p}{P_t}\right)^{P2} \tag{3}$$

where

$$P1 = 1.9 - 0.23 \log_e(Re_{D_c}) \tag{4}$$

$$P2 = -0.236 + 0.126 \log_e(Re_{D_c}) \tag{5}$$

For $N \geq 2$,



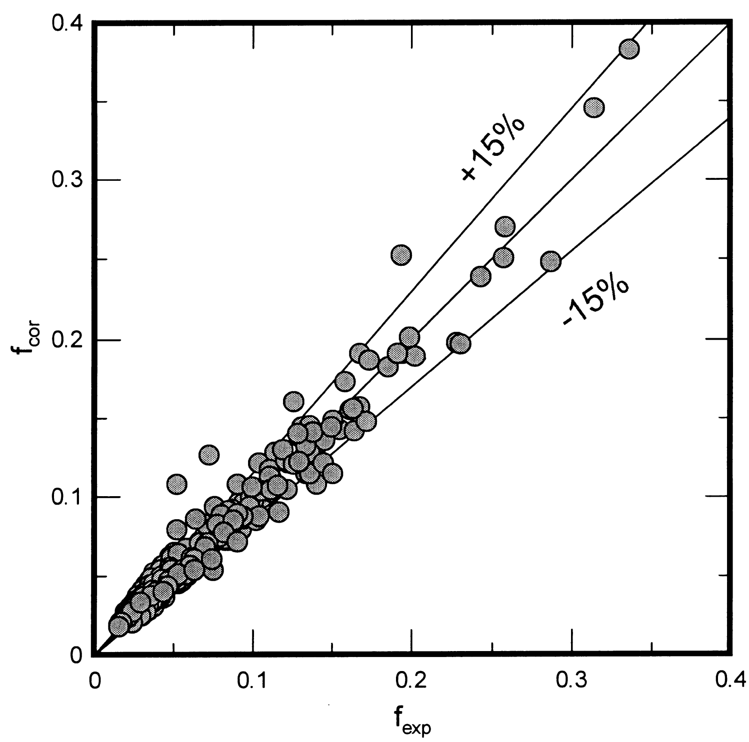


Fig. 4. Comparisons of the present heat transfer and friction correlations with the experimental data.

Table 2
Comparison of the proposed correlation and other correlations

Deviation	Present correlation		McQuiston [2]		Gray and Webb [3]		Seshimo and Fujii [6][a]	
	j	f	j	f	j	f	j	f
±10%	75.6	71.1	34.7	18.7	38.9	22.3	44.3	26.1
±15%	88.6	85.1	46.7	25.8	51.6	33.9	71.7	41.7
±20%	94.3	94.2	56.3	29.2	62.8	45.5	88.6	56.3
Average deviation[b] (%)	0.59	0.76	−20.4	−12.2	−12.4	−20.5	−3.6	18.7
Mean deviation[c] (%)	7.51	8.31	34.4	40.6	15.8	22.4	11.3	23.3

[a] The correlation developed by Seshimo and Fujii is valid for one- and two-row. Comparisons were performed only for one- and two-row database.

[b] Average deviation $= \frac{1}{K}\left(\sum_{1}^{K}\frac{j(f)_{\text{pred}}-j(f)_{\text{exp}}}{j(f)_{\text{exp}}}) \times 100\%\right)$.

[c] Mean deviation $= \frac{1}{K}\left(\sum_{1}^{K}\frac{|j(f)_{\text{pred}}-j(f)_{\text{exp}}|}{j(f)_{\text{exp}}}) \times 100\%\right)$; K = number of data points.

$$j = 0.086 Re_{D_c}^{P3} N^{P4}\left(\frac{F_p}{D_c}\right)^{P5}\left(\frac{F_p}{D_h}\right)^{P6}\left(\frac{F_p}{P_t}\right)^{-0.93} \tag{6}$$

where

$$P3 = -0.361 - \frac{0.042N}{\log_e(Re_{D_c})} + 0.158\log_e\left(N\left(\frac{F_p}{D_c}\right)^{0.41}\right) \tag{7}$$

$$P4 = -1.224 - \frac{0.076\left(\frac{P_l}{D_h}\right)^{1.42}}{\log_e(Re_{D_c})} \tag{8}$$

$$P5 = -0.083 + \frac{0.058N}{\log_e(Re_{D_c})} \tag{9}$$

$$P6 = -5.735 + 1.21\log_e\left(\frac{Re_{D_c}}{N}\right) \tag{10}$$

$$D_h = \frac{4A_cL}{A_o} \tag{11}$$

Notice that the present heat transfer correlation contains the contact conductance in the airside performance, and it is estimated that the percentage of the contact conductance should be less than 7% of the airside performance.The friction factor is given as:

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

where

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

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

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

Fig. 4 shows the comparison of the experimental data with the developed Eqs. (3), (6) and (12). The proposed heat transfer correlation can describe 88.6% of the j factors within 15% and Eq. (12) can correlate 85.1% of the friction factors within 15%. Detailed comparisons of the proposed correlations are tabulated in Table 2. As seen, the present heat transfer correlation gives a mean deviation of 7.53%, whereas the proposed friction correlation shows a 8.31% mean deviation. In addition to the proposed correlation, several correlations were tested against the database. These correlations include the McQuiston [2], Gray and Webb [3], and Seshimo and Fujii [6]. Notice that the correlation by Seshimo and Fujii [6] is valid to one- and two-row in the range of 0.5–2.5 m s^{-1}. The results of the comparison are shown in Table 2. As seen, the mean deviation of heat transfer correlation for the McQuiston correlation, the Gray and Webb correlation, and the Seshimo and Fujii correlation [6] are 34.4, 15.8, and 11.3%, respectively.

4. Conclusions

In this study, a correlation for fin-and-tube heat exchanger having plain fin geometry is proposed. For practical considerations, the proposed heat transfer correlation had absorbed the contact conductance in the development of correlation. The proposed heat transfer correlation can describe 88.6% of the databank within $\pm 15\%$, while the friction correlation can correlate 85.1% of the database within $\pm 15\%$. The mean deviation of the heat transfer correlation is 7.53% and of the friction correlation is 8.31%. Applicability of the geometry ranges as follows:

Fin pattern = plain.
$N = 1–6$.
$D_o = 6.35–12.7$ mm.
$F_p = 1.19–8.7$ mm.
$P_t = 17.7–31.75$ mm.
$P_l = 12.4–27.5$ mm.

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