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Technical Note

# An airside correlation for plain fin-and-tube heat exchangers in wet conditions

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## 1. Introduction

Finned tube heat exchangers are widely used in a variety of applications in the air-conditioning, refrigeration, and process industry. The application may involve condensation of humid air on the heat transfer surfaces when the surface temperature is below the corresponding dew point temperatures. Thus simultaneous heat and mass transfer occurs during the dehumidifying process. The presence of water condensate makes the heat/mass transfer process even complicated since it may bridge the fin spacing and change the airside characteristics of the fin-and-tube heat exchangers.

The most common fin pattern for fin-and-tube heat exchangers is plain fin. In 1978, McQuiston [1] proposed the first general correlation for plain fin pattern based on his test results of five test samples. Recently, Wang et al. [2] proposed a correlation based on test results of nine samples. These correlations provided valuable design information of fin-and-tube heat exchanger in wet conditions. However, these correlation were developed based on test results of one fin configuration ($P_t$ and $P_l$ are the same). Therefore extrapolation of the correlation are seriously questionable. As a result, the objective of the present study is to propose the airside correlation for plain fin geometry in wet conditions based on a much wider and consistent database.

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## 2. The data bank

The database for the present study are taken from [2–4] and those newly tested samples by the present authors. A total of 31 samples are used for the development of correlations. Detailed geometry for the test samples is tabulated in Table 1.

## 3. Data reduction of heat transfer coefficient and friction factors

Basically, the present reduction method is analogous to Threlkeld's approach [5]. Details of the reduction process can be found from the previous studies by Wang et al. [2] and Wang and Chang [6]. Notice that the Threlkeld method is an enthalpy-based reduction method. A brief description of the reduction of heat and mass transfer is given as follows.

The overall heat transfer coefficient is related to the individual heat transfer resistance [7] as follows:

$$\frac{1}{U_{o,w}} = \frac{b'_r A_o}{h_i A_{p,i}} + \frac{b'_p x_p A_o}{k_p A_{p,m}} + \frac{1}{h_{o,w}\left(\dfrac{A_{p,o}}{b'_{w,p} A_o} + \dfrac{A_f \eta_{f,wet}}{b'_{w,m} A_o}\right)} \quad (1)$$

where


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**Nomenclature**

$A_c$ minimum flow area [m$^2$]
$A_o$ total surface area [m$^2$]
$A_{p,i}$ inside surface area of tubes [m$^2$]
$A_f$ fin surface area [m$^2$]
$A_{p,m}$ mean heat transfer area of tubes [m$^2$]
$A_{p,o}$ outer surface area of tubes [m$^2$]
$b'_p$ slope of a straight line between the outside and inside tube wall temperatures [J kg$^{-1}$ K$^{-1}$]
$b'_r$ slope of the air saturation curved at the mean coolant temperature [J kg$^{-1}$ K$^{-1}$]
$b'_{w,m}$ slope of the air saturation curve at the mean water film temperature of the external surface [J kg$^{-1}$ K$^{-1}$]
$b'_{w,p}$ slope of the air saturation curve at the mean water film temperature of the primary surface [J kg$^{-1}$ K$^{-1}$]
$C_{p,a}$ moist air specific heat at constant pressure [J kg$^{-1}$ K$^{-1}$]
$C_1$, $C_2$, $C_3$ and $C_4$ correlation parameters
$D_c$ tube outside diameter, include collar thickness [m]
$D_h$ hydraulic diameter, $4A_cL/A_o$ [m]
$f$ friction factor
$G_c$ mass flux evaluated at the minimum flow are [kg s$^{-1}$ m$^{-2}$]
$F_p$ fin pitch [mm]
$h_{c,o}$ sensible heat transfer coefficient for wet coils [W m$^2$ K$^{-1}$]
$h_d$ mass transfer coefficient [kg m$^{-2}$ s$^{-1}$]
$h_{o,w}$ total heat transfer coefficient for wet external surface [W m$^{-2}$ K$^{-1}$]
$i$ air enthalpy [kJ kg$^{-1}$]
$i_{g,t}$ enthalpy of saturated water vapor evaluated at mean air temperature [kJ kg$^{-1}$]
$j$ the Colburn factor
$j1, f1, f2, f3, f4$ correlation parameters
$k_p$ thermal conductivity of tube wall [W m$^{-1}$ K$^{-1}$]
$L$ depth of heat exchanger [m]
$\dot{m}_c$ mass flowrate of water condensate [kg s$^{-1}$]
$N$ the number of tube row
$\Delta P$ pressure drop [Pa]
$P_l$ longitudinal tube pitch [mm]
$Pr$ the Prandtl number of air
$P_t$ transverse tube pitch [mm]
$Re_{Dc}$ Reynolds number based on $D_c$, $G_cD_c/\mu_a$
$Re_{film}$ mean condensate film Reynolds number, $2\Gamma/\mu$
$U_{o,w}$ wet surface overall heat transfer coefficient, based on enthalpy difference [kg m$^{-2}$ s$^{-1}$]
$W$ humidity ratio [kg kg$^{-1}$ dry air]
$W_{s,w}$ humidity ratio of saturated moist air evaluated at condensate temperature [kg kg$^{-1}$ dry air]
$\delta_f$ fin thickness [m]
$\delta_w$ tube wall thickness [m]
$\eta_{f,wet}$ wet fin efficiency
$\mu$ dynamic viscosity of water [N s m$^{-2}$]
$\mu_a$ dynamic viscosity of air [N s m$^{-2}$]
$\rho_i$ inlet air density [kg m$^{-3}$]
$\rho_m$ mean air density [kg m$^{-3}$]
$\rho_i$ outlet air density [kg m$^{-3}$]
$\sigma$ contraction ratio
$\Gamma$ mass flow rate per unit width of the tube, $\dot{m}_c/N\cdot W$ [kg s$^{-1}$ m$^{-1}$]

$$h_{o,w}=\frac{1}{\dfrac{C_{p,a}}{b'_{w,m}h_{c,o}}}. \tag{2}$$

The four quantities ($b'_{w,m}$, $b'_{w,p}$, $b'_p$, and $b'_r$) in Eq. (1) involve enthalpy-temperature ratios that must be evaluated. Detailed evaluation of these four terms can be found from Wang et al. [2]. The heat transfer performance is in terms of the Coburn $j$ factor, i.e.

$$j=\frac{h_{c,o}}{G_cC_{p,a}}Pr^{2/3}. \tag{3}$$

The determination of the mass transfer coefficient can be obtained from the process line [5]. Namely,

$$\frac{di}{dW}=Le\frac{i-i_W}{W-W_{S,W}}+(i_{g,t}-2500.9\times Le) \tag{4}$$

where the parameter, $Le$, is given as

$$Le=\frac{h_{c,o}}{h_dC_{p,a}}. \tag{5}$$

Detailed integration of Eq. (4) can be found from Myers [7]. The reduction of the friction factor of the heat exchanger is evaluated from the pressure drop equation proposed by Kays and London [8] as

$$f=\frac{A_c\rho_m}{A_o\rho_1}\left[\frac{2\Delta P\rho_1}{G_c^2}+(1-\sigma^2)\left(\frac{\rho_1}{\rho_2}-1\right)\right] \tag{6}$$

Table 1
Detailed geometry used for developed correlation[a]

| No. | References | $D_c$ (mm) | $N$ | $F_p$ (mm) | $P_l$ (mm) | $P_t$ (mm) | $\delta_f$ (mm) | $\delta_w$ (mm) |
|---|---|---|---|---|---|---|---|---|
| 1 | Wang et al. [2] | 10.34 | 2 | 1.82 | 22 | 25.4 | 0.13 | 0.35 |
| 2 | Wang et al. [2] | 10.34 | 2 | 2.24 | 22 | 25.4 | 0.13 | 0.35 |
| 3 | Wang et al. [2] | 10.34 | 2 | 3.2 | 22 | 25.4 | 0.13 | 0.35 |
| 4 | Wang et al. [2] | 10.34 | 4 | 2.03 | 22 | 25.4 | 0.13 | 0.35 |
| 5 | Wang et al. [2] | 10.34 | 4 | 2.23 | 22 | 25.4 | 0.13 | 0.35 |
| 6 | Wang et al. [2] | 10.34 | 4 | 3 | 22 | 25.4 | 0.13 | 0.35 |
| 7 | Wang et al. [2] | 10.34 | 6 | 1.85 | 22 | 25.4 | 0.13 | 0.35 |
| 8 | Wang et al. [2] | 10.34 | 6 | 2.21 | 22 | 25.4 | 0.13 | 0.35 |
| 9 | Wang et al. [2] | 10.34 | 6 | 3.16 | 22 | 25.4 | 0.13 | 0.35 |
| 10 | Wang et al. [3] | 7.53 | 4 | 1.78 | 12.4 | 21 | 0.115 | 0.27 |
| 11 | Wang et al. [3] | 7.53 | 4 | 1.22 | 12.4 | 21 | 0.115 | 0.27 |
| 12 | Wang et al. [3] | 7.53 | 2 | 1.78 | 12.4 | 21 | 0.115 | 0.27 |
| 13 | Wang et al. [3] | 7.53 | 2 | 1.22 | 12.4 | 21 | 0.115 | 0.27 |
| 14 | Wang et al. [4] | 8.62 | 2 | 1.7 | 19.05 | 25.4 | 0.12 | 0.31 |
| 15 | Wang et al. [4] | 8.62 | 2 | 3.11 | 19.05 | 25.4 | 0.12 | 0.31 |
| 16 | Wang et al. [4] | 8.62 | 4 | 1.7 | 19.05 | 25.4 | 0.12 | 0.31 |
| 17 | Wang et al. [4] | 8.62 | 4 | 3.11 | 19.05 | 25.4 | 0.12 | 0.31 |
| 18 | Present study | 10.3 | 4 | 1.23 | 19.05 | 25.4 | 0.115 | 0.31 |
| 19 | Present study | 10.3 | 2 | 1.23 | 19.05 | 25.4 | 0.115 | 0.31 |
| 20 | Present study | 10.3 | 2 | 2.23 | 19.05 | 25.4 | 0.115 | 0.31 |
| 21 | Present study | 10.3 | 1 | 2.23 | 19.05 | 25.4 | 0.115 | 0.31 |
| 22 | Present study | 10.3 | 4 | 1.55 | 19.05 | 25.4 | 0.115 | 0.31 |
| 23 | Present study | 10.3 | 1 | 1.23 | 19.05 | 25.4 | 0.115 | 0.31 |
| 24 | Present study | 8.58 | 4 | 1.21 | 19.05 | 25.4 | 0.115 | 0.31 |
| 25 | Present study | 8.58 | 4 | 2.06 | 19.05 | 25.4 | 0.115 | 0.31 |
| 26 | Present study | 8.58 | 2 | 1.23 | 19.05 | 25.4 | 0.115 | 0.31 |
| 27 | Present study | 8.58 | 2 | 2.06 | 19.05 | 25.4 | 0.115 | 0.31 |
| 28 | Present study | 8.58 | 4 | 1.6 | 19.05 | 25.4 | 0.115 | 0.31 |
| 29 | Present study | 8.58 | 1 | 2.04 | 19.05 | 25.4 | 0.115 | 0.31 |
| 30 | Present study | 8.58 | 1 | 1.19 | 19.05 | 25.4 | 0.115 | 0.31 |
| 31 | Present study | 10.3 | 4 | 2.31 | 19.05 | 25.4 | 0.115 | 0.31 |

[a] All the fin surfaces are not hydrophilically coated.

where entrance and exit losses of the core were included in the friction factor.

## 4. Construction of the correlation

Attempts are made to correlate the present test results by using a multiple regression technique. The basic forms of the correlations are:

$$j = C_1 Re_{\mathrm{Dc}}^{C_2} \tag{7}$$

$$f = C_3 Re_{\mathrm{Dc}}^{C_4}. \tag{8}$$

It is assumed that $C_1$, $C_2$, $C_3$, and $C_4$ are dependent on the physical dimensions of the heat exchanger. A separate multiple linear regression was proceeded to determine the exponents, $C_2$ and $C_4$, of the heat exchangers. The determinations of $C_1$ and $C_3$ are analogous to $C_2$ and $C_4$. As pointed out by Wang et al. [2], the Colburn $j$ factor is relatively insensitive to change of inlet relative humidity, thus the effect of inlet conditions were not included in the development of the $j$ correlation. However, converse to the heat transfer performance, the friction factors were affected by the inlet conditions [3,4] at small fin pitch owing to the presence of water condensate. In this connection, the effect of inlet humidity were included implicitly in the development of friction correlation using the condensate film Reynolds number, $Re_{\mathrm{film}}$ $(=2\Gamma/\mu)$. After a trial and error process, the final equation forms for the Colburn $j$ factor and Fanning friction factor $f$ are given as follows ($300 < Re_{\mathrm{Dc}} < 5000$):

$$j = 19.36 Re_{\mathrm{DC}}^{j1}\left(\frac{F_p}{D_c}\right)^{1.352}\left(\frac{P_l}{P_t}\right)^{0.6795} N^{-1.291} \tag{9}$$

where

Table 2
Comparison of the proposed correlation with the experimental data

| Deviation | ±10% | ±15% | ±20% | ±25% | Mean deviation[a] |
|---|---|---|---|---|---|
| $j$ | 76.2% | 93.4% | 98.3% | 99.4% | 6.33% |
| $f$ | 65.1% | 83.5% | 90.6% | 94.2% | 9.51% |
| $h_{c,o}/h_d C_{p,a}$ | 61.3% | 81.4% | 91.6% | 94.5% | 9.01% |

[a] Mean deviation $= \frac{1}{M}\left(\sum_1^M \frac{|\text{Correlation}-\text{Data}|}{\text{Data}}\right) \times 100\%$; $M$: number of data point.

$$j1 = 0.3745 - 1.554\left(\frac{F_p}{D_c}\right)^{0.24}\left(\frac{P_l}{P_t}\right)^{0.12} N^{-0.19} \tag{10}$$

and

$$f = 16.55 Re_{DC}^{f1}(10 \times Re_{film})^{f2} \times \left(\frac{A_o}{A_{p,o}}\right)^{f3}\left(\frac{P_l}{P_t}\right)^{f4}\left(\frac{F_p}{D_h}\right)^{-0.5827}\left(e^{D_h/D_c}\right)^{-1.117} \tag{11}$$

where

$$f1 = -0.7339 + 7.187\left(\frac{F_p}{P_l}\right)^{2.5}(\log_e(9 \times Re_{film})) \tag{12}$$

$$f2 = -0.5417 \log_e\left(\frac{A_o}{A_{p.o}}\right)\left(\frac{F_p}{D_c}\right)^{0.9} \tag{13}$$

$$f3 = 0.02722 \log_e(6 \times Re_{film})\left(\frac{P_l}{P_t}\right)^{3.2}\log_e(Re_{Dc}) \tag{14}$$

$$f4 = 0.2973 \log_e\left(\frac{A_o}{A_{p,o}}\right)\log_e\left(\frac{D_h}{D_c}\right) \tag{15}$$

and

$$\frac{h_{c,o}}{h_d C_{p,a}} = 0.372 Re_{D_c}^{0.1147}\left(0.6 + 0.6246 Re_{film}^{-0.08899\cdot \exp(F_p/D_c)}\left(\frac{F_p}{P_l}\right)^{0.08833} N^{-0.285}\right). \tag{16}$$

The proposed sensible $j$ factor (Eq. 9), gives a mean deviation of 6.33% while the predictions by friction factors (Eq. 11) shows a mean deviation of 9.51%. Detailed comparisons between the proposed correlations of $j$, $f$ and $h_{c,o}/h_d C_{p,a}$ and the experimental data are depicted in Table 2.

## 5. Conclusions

A generalized heat transfer and friction correlation for plain fin-and-tube heat exchangers in wet conditions are reported in the present study. A total of 31 samples of fin-and-tube heat exchangers are used to develop the correlation. The proposed heat transfer correlation can describe 93.4% of the test data within ±15% with a mean deviation of 6.33% while the proposed friction correlation can describe 83.5% of the results within ±15% with a mean deviation of 9.51%.

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