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Generalized heat-transfer and fluid-flow correlations for corrugated louvered fins

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ABSTRACT

We report heat-transfer and fluid-flow correlations to describe the performance of heat exchangers that use corrugated louvered fins. Friction factor f and Colburn factor j were investigated with respect to the ratio of the fin pitch to the louver pitch (F_p/L_p). Whereas previous correlations cannot be applied for $F_p/L_p > 1$, our f and j correlations can be utilized in a wide range of F_p/L_p which is not only to $F_p/L_p < 1$, but also to $F_p/L_p > 1$, for $100 < \mathrm{Re} < 3000$. We also derived flow efficiency η correlation which is applicable for $0.3 < L_p \sin L_\alpha / F_p < 0.7$, where L_α is the louver angle, in $100 < \mathrm{Re} < 3000$ within an error of ±15%.

1. Introduction

Corrugated louvered fin which is one of the compact heat exchangers induces a large heat-transfer rate due to its repetitive louver geometries. However, louvered fin can result in a relatively large pressure drop. Thus, a number of correlations for the heat-transfer and fluid-flow characteristics of corrugated louvered fin have been reported [1–9]. In particular, the correlations obtained by Wang et al. [7] and Kim and Bullard [9] are widely used. However, these correlations can be applied only when the ratio of the fin pitch (F_p) to the louver pitch (L_p) is less than 1 ($F_p/L_p < 1$). However, according to Shah and Sekulic [10], $F_p/L_p > 1$ is also widely used in the design of corrugated louvered fin. Therefore, general correlations for friction factor and Colburn factor are required for the design of the corrugated louvered-fin heat exchangers.

The friction factor and Colburn factor can be used to describe the pressure-drop and heat-transfer performance of a heat exchanger, respectively. Davenport [1] proposed correlations for j and f for general and Z-type corrugated louvered fins for various fin shapes and flow velocities. Achaichia and Cowell [2] investigated flattening in the low-velocity regime and reported a correlation between the Strouhal number (St) and f; however, those were not general correlations because they contained dimensions. Webb et al. [3–5] proposed j and f correlations and found their results did not match those in Ref. [2]; however, their results did not describe the heat-transfer and fluid-flow characteristics of the entire area of the louvered fins because the authors investigated only specific parts. Wang et al. [6–8] reported general correlations for j and f based on experimental data, as well as data taken from the literature; these are the most widely used correlations. Kim and Bullard [9] investigated heat-transfer and fluid-flow characteristics according to the design parameters used for the louvered fins; their results matched those of Wang et al. for small Reynolds numbers ($100 < \mathrm{Re} < 600$). Kim and Cho [11] reported new j and f correlations based on experimental results obtained for low velocities (<0.3 m/s) and small fin pitches and obtained a configuration with $j = 92\%$ and $f = 94\%$. However, in all the correlations just described, errors occur when the fin pitch is less than the louver pitch.

Webb and Trauger [3] reported a flow efficiency correlation based on experimental investigations with varied fin pitches and louver angles. Sahnoun and Webb [4] improved this correlation, which was discontinuous at the critical Reynolds number. However, in these two studies, the authors considered only high-fluid velocities with $\mathrm{Re} \geqslant 500$ and did not investigate the effects of louver pitch.

In this study, we investigated the effects of the geometric parameters of louvered fins to determine general correlations that predict the heat-transfer rate, pressure drop, and flow efficiency. The proposed correlations describe the heat-transfer and fluid-flow characteristics of the entire area of the louvered fin rather than a

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Nomenclature

A_a	total surface area [mm^2]
A_c	minimum flow area [mm^2]
$C_{1,2}$, C_μ	turbulent constant
c_p	specific heat at constant pressure [J/kg · K]
f	friction factor
F_d	flow depth [mm]
F_l	fin length [mm]
F_p	fin pitch [mm]
F_α	flow angle [°]
G_k	generation of turbulent kinetic energy
h	heat transfer coefficient [W/m^2 K]
j	Colburn factor
k	thermal conductivity [W/m · K]/turbulent kinetic energy [m^2/s^2]
L_l	louver length [mm]
L_p	louver pitch [mm]
L_α	louver angle [°]
Pr	Prandtl number
$\dot{Q}$	heat transfer rate [W]
Re$_{L_p}$	Reynolds number [$=\rho u_c L_p/\mu$]
T	temperature [K or °C]
t	time [s]
u, v, w	velocity [m/s]
x, y, z	Cartesian coordinate
Greek symbols	
η	flow efficiency
δ	fin thickness [mm]
ε	dissipation rate of turbulent kinetic energy [m^2/s^3]
μ	dynamic viscosity [kg/m · s]
θ	angle between fins/polar angle
ρ	density [kg/m^3]
ε	emissivity
Subscripts	
fin	fin
i, j, k	tensor index
in	inlet
out	outlet
Ref.	reference
wall	wall

specific area. The correlations are dimensionless and suitable for a general fin. Furthermore, to simplify the correlations, we removed factors due to small-size effects.

2. Mathematical modeling and experiments

Fig. 1(a) shows a diagram of a corrugated array of louvered fins. The airflow passes through the inlet of the fin array and is discharged at the outlet. Heat transfer occurs between the air and the fins when the air is drawn into the fin array. The array consists of repeated plate fins at regular intervals with a pitch F_p, as shown in Fig. 1(b). Fig. 1(c) shows the design parameters for the louvered fins, including the fin length F_l, flow depth F_d, louver length L_l, louver pitch L_p, fin thickness δ, and louver angle L_α. In this section, we define the corrugated louvered fin problem and validate our mathematical model using data from experiments as well as from previously reported studies.

2.1. Governing equations and boundary conditions

The following assumptions were made in our numerical analysis.

1. The flow is two-dimensional (2D), steady, incompressible, and turbulent.
2. The working fluid is air, and the properties are constant.
3. Natural convection and radiation heat transfer can be neglected.

The flow was 2D and was affected by the louvers between the flat tubes. Accordingly, we modeled this geometry in two dimensions. Because of the size of the louvered fins and the flow velocity, the realizable k–ε model [12] was selected to describe the turbulence. The following general transport equation was used:

$$\frac{\partial}{\partial t}(\rho\phi) + \frac{\partial}{\partial x_i}(\rho u_i \phi) = \frac{\partial}{\partial x_i}\left(\Gamma_\phi \frac{\partial \phi}{\partial x_i}\right) + S_\phi \tag{1}$$

where Γ_ϕ and S_ϕ are arbitrary scalar parameters used to describe continuity, momentum, turbulent kinetic energy, and turbulent kinetic energy dissipation as given in Table 1.

The boundary conditions used to determine the heat-transfer and fluid-flow characteristics around the louvered fins were as follows. At the interface between the fluid and a solid, we have

$$u_{\text{wall}} = v_{\text{wall}} = w_{\text{wall}} = 0 \tag{2}$$

and at the inlet and outlet, we have

$$\dot{m} = \dot{m}_{\text{in}}, \quad T = T_{\text{in}} \tag{3}$$

and

$$\dot{m} = \dot{m}_{\text{out}} = \dot{m}_{\text{in}}, \quad \frac{\partial k}{\partial n} = 0, \quad \frac{\partial \omega}{\partial n} = 0, \quad \frac{\partial p}{\partial n} = 0, \quad \frac{\partial T}{\partial n} = 0 \tag{4}$$

The plane of symmetry was exploited to reduce the computational requirements. Periodic boundary conditions [13,14] were applied to the upper and lower boundaries of the louvered fins, as shown in Fig. 2(a), as follows:

$$p(x,y,z) = -\alpha x + p(x,y,z) \tag{5}$$

$$p(L,y,z) = p(0,y,z) \tag{6}$$

$$v(L,y,z) = v(0,y,z) \tag{7}$$

$$T = \frac{t - t_w}{t_b - t_w} \tag{8}$$

$$\frac{t(L,y,z) - t_w}{t_b(L) - t_w} = \frac{t(0,y,z) - t_w}{t_b(0) - t_w} \tag{9}$$

where 0 and L describe the periodic coordinates at the inlet and outlet.

2.2. Numerical procedure

The semi-implicit method for pressure-linked equations (SIMPLE) algorithm was used to couple the pressure and flow fields. The Quick scheme was used to discretize the governing equations, in particular the convective term in the conservation equation, to obtain an accurate numerical solution for the steady simulations. The coupled equations were solved simultaneously. The solution