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General prediction of the thermal hydraulic performance for plate-fin heat exchanger with offset strip fins

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ABSTRACT

The heat transfer and flow friction coefficients for offset strip fins (OSF) used in plate-fin heat exchangers are numerically investigated with well validated 3D models. The effect of the geometrical three-dimensionality is analyzed in a distinctive way to understand the general behavior of the thermal hydraulic performance. Based on the analysis of a large amount of numerical data by CFD techniques for OSF fins, a couple of new correlations for general prediction of the *j* and *f* factors are developed, which excellently correlate a variety of geometrical parameters with blockage ratio ranging from 10% to 60%. Moreover, 252 experimental data-points for *j* and 290 experimental data-points for *f* covering 24 OSF fins are collected from literatures to examine the predicting abilities of the proposed correlations. The comparisons show that the proposed correlations can present the basic behavior of experimental data with nice accuracy. Further comparisons with the previous correlations from literatures have been done with regards to the same experimental data, which reflect that the proposed ones provide well-adapted predictions for OSF fins with different fin thickness covering a broad range of blockage ratio, while the previous correlations express growing prediction deviations as the blockage ratio increases. On the whole, the proposed correlation predicts 92.5% of the *j* data and 90.3% of the *f* data within 20%, with the RMS errors of less than 15%. The present work might be very helpful to guide the optimum design of plate-fin heat exchangers and also evaluate the performance of heat transfer enhancement in the OSF fin channels.

1. Introduction

Plate-fin heat exchanges, which play an important role in saving energy and resources, are extensively applied to aerospace, electronics, automobile, gases, cryogenic and chemical industries, etc. Depending on the diverse applications, various extended surfaces are developed, such as plain fins, wavy fins, offset strip fins, perforated fins and louvered fins. Among these enhanced fin geometries, offset strip fin (OSF) is widely used. This type of device is characterized by higher degree of surface compactness and substantial heat transfer enhancement due to the laminar boundary layer re-starting. On the other hand, the interrupted arrays also cause a large pressure drop result from the increased skin friction and form drag considered the finite thicknesses of the fin. For these special fin arrays, the range of design configuration is considerably wide. Therefore capturing the general behavior of the overall heat transfer coefficients and friction factors is very important, regardless to optimal design of plate-fin heat exchangers and performance evaluation of the enhanced heat transfer fin-surfaces.

Many researches have been carried out for OSF fin in various ways. Kays and London [1] have provided relatively old but comprehensive experimental data for actual fin cores. From studies in recent years, Dong et al. [2] and Peng and Ling [3–5] have conducted experiments with different OSF fin geometries. But only a few available data has been appeared in these open literatures. Although the experimental results are limit, there has been considerable effort to predict the thermal hydraulic performance in OSF fin cores. Joshi and Webb [6] have presented an analytical model based on numerical analysis in laminar region, and a semi-empirical method used in turbulent region. Muzychka and Yovanovich [7] have developed a predicted model by combining the theoretical models for flat plate and rectangular duct. When determining the predicted equations, they have performed regression analysis of the experimental data from Kays and London [1]. In addition to these analytical models, empirical correlation is perhaps a more popular and practical prediction method. And different predicted correlations have been reported by Joshi and Webb [6], Wieting [8], Mochizuki et al. [9], Manglik and Bergles [10] and Maiti [11]. Because these analytical models or correlations are based on limited experimental data, their predictive abilities are dependent largely upon the number of tested fin geometries. Some previous

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Nomenclature

A	total heat transfer area (m^2)
A_c	free flow area (m^2)
A_{ffe}	area of the front fin end in a unit cell of OSF fin (mm^2)
C_p	specific heat at a constant pressure ($J\,kg^{-1}\,K^{-1}$)
D_h	hydraulic diameter of fin channel (mm)
D_e	equivalent diameter of fin cross-section (mm)
h	height of the offset strip fin (mm)/heat transfer coefficient ($W\,m^{-2}\,K^{-1}$)
l	length of the offset strip fin in a unit cell (mm)
j	Colburn factor, $\frac{\mathrm{Nu}}{\mathrm{RePr}^{1/3}}$
k	turbulent kinetic energy ($m^2\,s^{-2}$)
f	Fanning friction factor, $\frac{2\Delta p}{\rho u^2}\left(\frac{D_h}{4L}\right)$
Nu	Nusselt number, $\frac{hD_h}{\lambda}$
p	pressure (Pa)
Pr	Prandtl number, $\frac{\mu C_p}{\lambda}$
r	coefficient of determination
Re	Reynolds number, $\frac{D_h u\rho}{\mu}$
S_ϕ	source term of ϕ
S	spacing of the offset strip fin (mm)
T	temperature (K)
t	thickness of the offset strip fin (mm)
u, v, w	velocity ($m\,s^{-1}$)
y_P^+	non-dimensional distance
x, y, z	Cartesian coordinates

Greek symbols

α	t/h
β	blockage ratio from literature [19]
γ	t/s
δ	t/l
Γ_ϕ	diffusivity variable
ε	dissipation rate of turbulent kinetic energy ($m^2\,s^{-3}$)
λ	thermal conductivity ($W\,m^{-1}\,K^{-1}$)
μ	dynamic viscosity ($kg\,m^{-1}\,s^{-1}$)
ρ	density ($kg\,m^{-3}$)
ω	blockage ratio
Φ	combined non-dimensional parameter
ϕ	general-dependent variable

Subscripts

t	turbulence

studies [12,13] have also used numerical simulation to investigate the thermal hydraulic behavior of OSF fin. Owing to computational limitations, the numerical models have often been associated with two-dimensional fin-channel geometries. But according to Zhang [14–16], it is found that using 2D computation is inaccurate to predict the overall j and f factors and hence the 3D computation is necessary.

With the rapid growth of computational capabilities, recent studies [5,17–21] have commonly used 3D simulation for OSF fin. Some studies [19,20] have even employed numerical models for generating the design data, which help to reduce the experimental work to some extent. Kim et al. [19] have numerically investigated the thermo-flow characteristics of OSF fin with laminar and SST k–ω turbulence model, and have derived performance correlations. To obtain these correlations, they divided the geometrical range by blockage ratio and conducted sub-regional multiple regressions with numerical results.

Despite these efforts, reliable prediction of the thermal hydraulic performance for OSF fins in a wide range remains a difficulty. Most previous correlations are obtained by regression analysis of experimental data. However the number of the tested fin geometries is not sufficient to achieve the general prediction. Even those numerical studies which involve various fin geometries often fail to exactly verify the validity of the numerical model with experimental data, and much less carefully examine the predicting abilities of their performance correlations. Furthermore, most researches perform inadequate identification of the feature of the fin geometry. The traditional understanding of the geometrical effects mainly rests on the early flow visualization experiments [22–25] which usually provide an essentially two-dimensional flow. The effects of three-dimensionality of the fin geometries appear to be rarely touched upon, but such consideration will facilitate the general prediction of the heat transfer and pressure drop in actual OSF fin cores.

In the present work, the thermal hydraulic performance for OSF fin is numerically investigated. The numerical models are well validated by experimental data in both laminar and turbulent region. Then according to the analysis of the effects of the geometrical three-dimensionality, new performance correlations predicting the heat transfer and friction coefficients are proposed. Finally, the predicting abilities of the proposed j and f correlations are verified by comparing with the available experimental data.

2. Model

2.1. Physical model

The geometry of a typical OSF fin is shown as in Fig. 1. The structural parameters include fin height h, fin spacing s, interrupted length l and fin thickness t. Usually, the fin-channel is assumed to be rectangular, and the fin offset is uniform and equal to half-fin spacing [10]. Therefore the hydraulic diameter for OSF fins is defined as follows:

$$D_h = \frac{4lA_c}{A} = \frac{4l(h-t)(s-t)}{2(l(h-t)+l(s-t)+t(h-t))+t(s-2t)} \tag{1}$$

where the free flow area is taken as $A_c = (h-t)(s-t)$, and the total heat transfer area A includes the fin ends contacted with fluid as well as the channel surface.

Various D_h expressions for OSF fin in previous studies are summarized in Table 1. The conversion between the Reynolds numbers with different D_h is necessary for the present study.

Fig. 2 shows the 3D computational domain for OSF fin. The entrance part, exit part and cover plates are considered here in

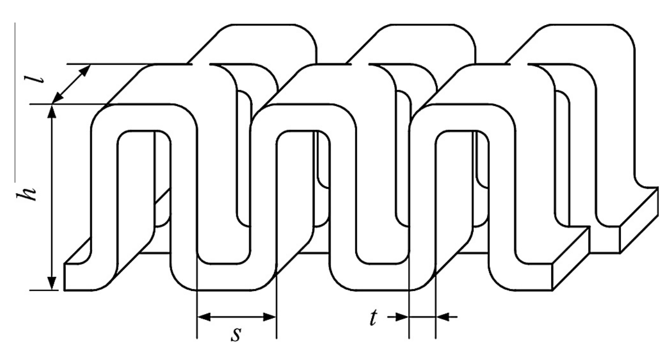

Fig. 1. The geometry and structure parameters of OSFs.