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A correlation for heat transfer and flow friction characteristics of the offset strip fin heat exchanger

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ABSTRACT

The correlation for heat transfer and flow friction characteristics of fins is the basis for the optimization of heat exchangers, and it is of great importance to develop generally accurate formulas. To study the hydrodynamics and heat transfer characteristics of offset strip fins, Fluent is adopted to conduct the numerical simulation. Based on the calculation results of empirical correlations, the fluid constitutive model under different Reynolds numbers is determined in order to ensure the prediction efficiency and accuracy of offset strip fins. Good agreements are obtained between the numerical simulation and the Manglik & Bergles correlation, which verifies the validity and reliability of the numerical simulation method. Due to the fact that the traditional empirical formula is not able to cover the general specifications of Chinese domestic offset strip fins, the correlation of flow and heat transfer characteristics is improved based on the numerical simulation results and the industrial standard (Aluminum plate-fin heat exchanger NB/T 47006-2009). By coupling the Manglik & Bergles equation with the ALEX equation, a new relational expression of offset strip fins is proposed.

1. Introduction

Heat exchanger is widely used in the fields of chemical, oil refining, food, pharmaceutical, aviation and other industries. Due to the industrial requirements for compact heat exchangers, the high efficient fins have been studied by researchers for decades [1], such as the offset strip fins, wavy fins and louvered fins. Since the correlation for heat transfer and flow friction characteristics of fins is the basis for the optimization of heat exchangers [2,3], it is of great importance to develop generally accurate formulas, in which case the experimental research and numerical simulation methods are two effective means.

In 1940s, the U.S. Navy Bureau of Ships launched an experimental research on the heat transfer and flow characteristics of the compact surfaces at the Naval Engineering Experiment Station. Based on it, the Office of Naval Research, the Bureau of Ships, the Bureau of Aeronautics and the Atomic Energy Commission drew a systematic plan at Stanford University in 1947. Related research results were collated into the book—Compact heat exchangers [4], including the flow and heat transfer performance of plain fins, offset strip fins, wavy fins, and perforated fins, which has been the fundamental reference for the design and optimization of plate fin heat exchangers.

From 1970s to 90s, scholars have carried out a series of experimental studies on developing the correlations of the flow and heat transfer characteristics of plate fin heat exchangers [5]. Wieting [6] firstly put up with the empirical correlations for heat transfer and flow friction characteristics of rectangular offset fin plate fin heat exchangers, where the Reynolds number and the structural parameters were employed as the independent variables. Based on the experimental data of 21 groups of serrated fins, Joshi and Webb [7] proposed the correlation of heat transfer factor (j) and friction factor (f) under different range of Reynolds number. Mochizuki et al. [8] conducted an experimental study of 18 test cores with different fin geometries in a wind tunnel, then f and j correlation equations were derived for the offset strip fin cores. Shah and Bhatti [1] summarized the expressions of friction factors and Nusselt numbers with different generalized duct geometries. Kurosaki et al. [9] experimentally studied the details of the heat transfer process in louver arrays. Based on systematic experimental investigations, the standard experimental thermos-hydraulic characteristics of interrupted surfaces were obtained by Dubrovsky and Vasiliev [10], as well as the correlations as functions of Re and

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Nomenclature

A_c	the minimum flow area, m^2
A_s	heat transfer surface area, m^2
C_p	specific heat at constant pressure, J/kg K
D_h	hydraulic diameter, m
E	the total energy of fluid, J/kg
f	friction factor
h	enthalpy, J/kg
h_f	fin height, m
I	turbulence intensity
J	diffusion flux
j	heat transfer factor
k	heat transfer coefficient, W/(m^2 K)
L	channel length, m
l_f	offset length of fins, m
m	flow rate, kg/s
N	number
Nu	Nusselt number
p	pressure, Pa
Δp	pressure drop, Pa
Pr	Prandtl number
Q	heat flow, W
Re	Reynolds number
S	source item
St	Stanton number
s	fin spacing, m
T	temperature, K
ΔT_{max}	the maximum temperature difference during heat exchange, K
ΔT_{min}	the minimum temperature difference during heat exchange, K
$\overline{\Delta T}$	mean temperature difference, K
t	time, s
t_f	fin thickness, m
u	velocity, m/s
x	calculation result

Symbols

α	convective heat transfer coefficient, W/m^2 K
ρ	density, kg/m^3
μ	dynamic viscosity, Pa s
λ	heat conductivity coefficient, W/m K
τ	viscous stress, Pa

Subscripts

cor	parameter of the empirical correlation
eff	effective parameter
f	parameter of the fin
in	parameter of the inlet
out	parameter of the outlet
sim	parameter of simulation
w	parameter of the wall
x	parameter along the x direction
y	parameter along the y direction
z	parameter along the z direction

Abbreviations

AD	absolute deviation
AAD	average absolute deviation
RD	relative deviation
ARD	average relative deviation

geometric parameters. Rational design equations for f and j covering the laminar, transition, and turbulent flow regimes were presented by Manglik and Bergles [11]. However, the proposed correlations are restricted to some specific geometry.

Benefit from the developments of computer science and technology, computational fluid dynamics (CFD) has been adopted to study the pressure drop and heat transfer characteristics of plate fin heat exchangers since 2000 [12,13]. Compared with the experimental method, numerical simulation is widely applied with the advantages of intuitive results and low cost. FLUENT is used to predict the fluid distribution in plate-fin heat exchangers [14]. Qu [15] simulated and analyzed the influence of structural parameters on heat transfer and flow resistance at the Reynolds number range of [500, 4500]. Wang et al. [16] presented a numerical model for plate fin heat exchangers with plain fins and serrated fins at the Reynolds number range of [300, 800], which incorporated the characteristics of fluid flow and heat transfer. In comparison with the available correlations in the literature and experimental results, Ismail and Velraj [17] used FLUENT software for the estimation of f and j data of a typical offset fin. Using CFD software, Wen et al. [18] conducted a 3-dimensional numerical simulation of fluid flow and heat transfer characteristics in plain fins.

In addition, different constitutive models have been adopted by scholars to conduct the simulation. The standard k–ε model, RNG k–ε model, Realizable k–ε model and the large eddy simulation (LES) were tested by Ferrouillat et al. [19] at the Reynolds number range of [2000, 8000], who found out that the standard k–ε model did not correctly predict counter-rotating vortices. Tian et al. [20] chose the laminar model, standard k–ε model and RNG k–ε model to investigate the air-side heat transfer and fluid flow characteristics of wavy fin-and-tube heat exchangers with delta winglets at the Reynolds number range of (500, 5000), where the RNG k–ε model showed substantial improvements over the standard model including strong streamline curvature, vortices, and rotation. A standard k–ε model with enhanced wall treatment was used to predict the turbulent flow in the plate-fin heat exchanger as well as in the fin geometry [21]. The low-Re k–ε model was applied to calculate a mixed flow fields of plate finned-tube heat exchangers [22]. The SST k–ε turbulence model [23] was adopted to investigate the thermo-flow characteristics of a heat exchanger with offset-strip fins in the transition and turbulent regimes. Xu et al. [24] adopted the low-Re turbulence model and acquired well results against the experiments. However, the specific fluid constitutive model only makes sense in a limited range of Reynolds number.

This paper adopts Fluent to conduct the numerical simulation for studying the hydrodynamics and heat transfer characteristics of the offset strip fin at the Reynolds number range of [300, 10,000]. In consideration of the prediction efficiency and accuracy, the fluid constitutive model under different Reynolds numbers is determined by comparing the numerical results with the calculation results of empirical correlations. Based on the industrial standard (Aluminum plate-fin heat exchanger NB/T 47006-2009), the correlation of flow and heat transfer characteristics is improved.