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Research Paper

Optimization of micro-finned tubes in double pipe heat exchangers using particle swarm algorithm

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ABSTRACT

In this study, a particle swarm optimization approach is employed to determine the optimal micro-fin geometry which maximizes the thermal efficiency of micro-finned tubes in the double pipe heat exchangers. The considered decision variables of the micro-finned tubes are the number of micro-fins which various from 10 to 60, the micro-fin height varying from 0.0 to 0.5 mm, and the micro-fin helix angle which is between 5 and 30°. The study is conducted for the Reynolds number ranging from 3×10^3 to 10^5 and for the inner diameter of the tube equal to 5, 10, 15 mm. The governing equations for the turbulent fluid flow are solved numerically employing the commercial software package ANSYS CFX v.15. The numerical procedure is validated by comparing the simulation results for the non-isothermal flow of water through a micro-finned tube with the experimental results from the literature. The simulation results are then employed in the particle swarm optimization algorithm to optimize the micro-fin geometry. The results indicate that the optimum micro-fin height increases with increasing the Reynolds number. However, the opposite trend is observed for the optimal helix angle.

1. Introduction

Designing highly efficient compact heat exchangers has been an engaging area of heat transfer research in recent years. Extending the heat transfer surface and making the flow field turbulent are common means to enhance the heat transfer in such devices. Employing helically micro-finned tubes, which increases the heat transfer surface and enhances the mixing between fluid layers without affecting the overall size of the heat transfer device significantly, is a prevalent approach to improve the heat transfer performance in such cases. Commercial applications of the internally enhanced tubes to optimize the heat transfer have increased substantially in recent years. For example, the refrigeration industry benefits from the tube roughness on the water-side of large refrigeration evaporators and condensers.

A number of recent experimental studies have been conducted on the single-phase fluid flow through micro-finned tubes. Copetti et al. [1] studied the heat transfer and pressure drop characteristics for water flowing in micro-finned tubes experimentally. As far as comparisons with the results of the corresponding smooth tube are concerned, they observed up to 190% increase of the heat transfer coefficient for the micro-finned tubes in the turbulent flow regime. However, they concluded that, in the laminar flow regime, the heat transfer coefficient increased only about 20% over that of the corresponding smooth tube. In another experimental study, Han and Lee [2] investigated the single-phase heat transfer and fluid flow characteristics of the micro-finned tubes. To evaluate the enhancement of the heat transfer performance, they introduced an efficiency index. They observed that the tubes with a larger relative roughness and a smaller spiral angle demonstrated better heat transfer performance compared to the tubes with a larger spiral angle and a smaller relative roughness. Naphon and Sriromruln [3] investigated the heat transfer characteristics and the pressure drop of a horizontal double-pipe heat exchanger with and without a coiled wire insert. They observed that the coiled wire insert had a significant effect on the enhancement of the heat transfer. However, the friction factor of the tube with the coiled wire insert increased simultaneously. Li et al. [4] measured the pressure drop and the heat transfer of oil and water flowing through a micro-finned tube experimentally. Their results showed that there was a critical Reynolds number, Re_{cr}, for the heat transfer enhancement. For $Re < Re_{cr}$, the heat transfer in the micro-finned tube was the same as that in the corresponding smooth tube; however, for the Reynolds numbers larger than Re_{cr}, the heat transfer in the micro-finned tube gradually improved compared that of the corresponding smooth tube with increasing the Reynolds number. Afroz and Miyara [5] measured the pressure drop

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Nomenclature

c_1	cognitive coefficient
c_2	social learning coefficient
c_p	specific heat, J/kg K
d	inner tube diameter, m
e	fin height, m
f	Darcy's friction factor
g	gravitational acceleration, m/s^2
h	heat transfer coefficient, W/m^2 K
k	thermal conductivity, W/m K
L	tube length, m
$\dot{m}$	mass flow rate, kg/s
N	number of micro-fins
N_P	number of particles
Nu	Nusselt number
p	pressure, Pa
P	fin pitch, m
Re	Reynolds number
t	fin width, m
T	temperature, K
U	overall heat transfer coefficient, W/m^2 K
V	velocity of particles
X	position of particles

Greek symbols

α	helix angle
β	apex angle
μ	dynamic viscosity, N s/m^2
ρ	density, kg/m^3

Subscripts

b	bulk
f	fluid
h	hydraulic
i	inlet
o	outlet, outer
opt	optimum
p	particles

of a single-phase turbulent fluid flow inside herringbone micro-finned tubes for different fin dimensions experimentally in order to develop a general correlation for the single-phase fluid flow friction factor for such cases. Their results showed that larger helix angle and fin height resulted in a greater pressure drop inside the herringbone micro-finned tubes. Furthermore, depending on the fin geometric parameters and the mass velocity of the working fluid, the pressure drop of the herringbone tube could be significantly higher than those of the helical micro-finned and smooth tubes. Zdaniuk et al. [6] determined the heat transfer coefficient and the friction factor for eight different micro-finned tubes as well as for one smooth tube experimentally. Their results indicated that a micro-finned tube with a helix angles of 48°, e/d of 0.0244, and 48 micro-fins could be recommended for the heat exchanger applications irrespective of the value of the Reynolds number. Siddique and Alhazmy [7] investigated the single-phase heat transfer and pressure drop characteristics for the turbulent fluid flow inside a double-pipe heat exchanger with micro-finned tubes experimentally. They correlated the heat transfer and the pressure drop data by the Dittus–Boelter and Blasius type relations, respectively. They concluded that the microfins had a significant effect on both the heat transfer rate and the pressure drop in such tubes. Bharadwaj et al. [8] studied the pressure drop and the heat transfer characteristics of water flowing in a micro-finned tube with a twisted tape insert experimentally. They considered a wide range of fluid flow regimes from Laminar to fully turbulent. For a constant pumping power, their results showed that the grooved tube without a twisted tape yielded the maximum heat transfer enhancements of 400% in the laminar regime and 140% in the turbulent regime compared to the heat transfers of the corresponding smooth tube. Similar comparisons for the spirally grooved tube with a twisted tape showed the maximum enhancements of 600% in the laminar regime and 140% in the turbulent regime compared to the values for the corresponding smooth tube without a twisted tap. Celen et al. [9] investigated the single phase pressure drop characteristics of the smooth and micro-finned tubes experimentally. They employed a horizontal counter-flow, double-tube heat exchanger as their test section. Their measurements showed that the friction factor and the pressure drop for the micro-finned tube were generally higher than the corresponding values for the smooth tube, implying that the micro-finned tube generated more flow disturbances as a result of the swirl and the recirculation caused by the fins. Recently, Akhavan-Behabadi et al. [10] investigated the laminar convective heat transfer of the oil-copper oxide nanofluid flowing through horizontal smooth and micro-finned tubes for the constant wall temperature boundary condition experimentally. Based on their results, a combined use of the nanofluid and the micro-finned tube led to the heat transfer enhancement up to 230% in comparison with that of the base fluid flowing in the smooth tube. Furthermore, they observed that the Nusselt number for the base fluid flowing in the micro-finned tube increased 56% compared to that of the base fluid flowing through the smooth tube. Derakhshan et al. [11] investigated the mixed convection heat transfer characteristics of the MWCNT-oil nanofluid flowing through the smooth and micro-finned tubes experimentally for the uniform wall heat flux boundary condition. Their results showed that using the nanofluid instead of the pure fluid was a more effective way to enhance the convective heat transfer coefficient compared to employing the micro-finned tube.

There are a few numerical studies devoted to the non-isothermal fluid flow through micro-finned tubes. Kim et al. [12] employed a stabilized finite element solver to simulate the turbulent fluid flow and heat transfer in a micro-finned tube numerically. They assumed that, under the fully developed conditions, the velocity components become periodic in a helical coordinate system. Evaluating the performance of selected turbulence models, they concluded that, the Goldberg model performed the best. Recently, Ağra et al. [13] investigated the pressure drop and heat transfer characteristics of five different micro-finned tubes for the turbulent flow regime numerically. They compared their simulation results with the existing experimental data and the results obtained using the Blasius equation. Their results showed better agreements with the experimental data rather than with the results of the Blasius equation. Celen et al. [14] investigated the pressure drop of the TiO_2–water nanofluid flowing through the plain and enhanced pipes. They provided the comparisons of the pressure drop characteristics for various nanoparticle concentrations and different tube types. Very recently Pirbastami et al. [15] conducted a numerical study of the heat transfer enhancement of the fluid flow through four helically grooved tubes with different pitches, and compared the results with those of the corresponding smooth tube. They observed that the optimum heat