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Numerical investigation of tube-side fully developed turbulent flow and heat transfer in outward corrugated tubes

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A B S T R A C T

A numerical study was conducted to investigate the mechanism of turbulent flow dynamics and heat transfer enhancement in novel outward corrugated tubes with a Reynolds number ranging from 3800 to 43,800 and a constant wall temperature condition. Experiments were conducted for one case of a transversely corrugated tube and five cases of a helical corrugated tube to determine the relationship between the geometric structure and flow dynamics, and the effect of the detached vortex and spiral wake on the heat transfer and pressure drop. The results show that the reasons for the heat transfer enhancement are the convective heat transfer into a jet impingement heat transfer at windward side of the corrugation and the severely turbulent fluctuation with the boundary-layer redevelopment. The rotational flow has little effect on the heat transfer enhancement; however, it inhibits the secondary flow and fluid pulsation, thereby reducing flow resistance. Moreover, the maximum values of the average Nusselt number improvement and overall heat transfer performance were 1.77 and 1.40, with $Hl/D = 0.10$, $pl/D = 0.5$ at $Re = 6260$ and $Hl/D = 0.15$, $pl/D = 1.0$ at $Re = 3800$, respectively. With the variation in Re, the performance evaluation criterion presents the interval optimum principle for various structure parameters, which is superior for coarse and dense corrugation under a low Re and more suitable for small and sparse corrugation under a high Re. For the whole range of Re, the cases of $Hl/D = 0.10$, $pl/D = 1.5$ and $Hl/D = 0.1$, $pl/D = 1.0$ are the better design of geometrical parameters.

1. Introduction

Enhanced heat transfer surfaces are routinely employed to improve the heat transfer efficiency and reduce the metal consumption. Most studies focus on the liquid heat transfer process, because of the higher heat transfer coefficients of denser fluids. The gas-gas heat exchangers often cost a lot of metal materials and space due to the low thermal conductivity, few scientists and engineers pay attention on the it. But the gas waste heat takes up more than a half of the industrial waste heat [1], so it is meaningful to employ the passive enhanced heat transfer technology on the gas-gas heat exchangers. Corrugated tubes are widely used in heat exchangers and have several advantages, such as easier fabrication, greater enhancement in thermal performance, and limited increase in flow resistance, over other types of modified surface tubes. The corrugated tubes considered in the majority of the previous studies were of the inward concave type [2–10], which are obtained through extrusion or press forming methods. However, it is difficult to use the inward corrugated tubes for high-temperature and high-pressure working fluids, because of the concentrated stress produced in the extrusion processing.

Recently, several published studies have unanimously confirmed the heat transfer improvement obtained with corrugated tubes with the help of experimental and numerical simulation methods [7–10]. Pethkool et al. [7] extended the experimental analysis to cover the Reynold's number (Re) range of 5500–60,000 in inward helically corrugated tubes with different pitch-to-diameter ratios ($pl/D = 0.18$, 0.22, and 0.27) and height-to-diameter ratios ($Hl/D = 0.02$, 0.04, and 0.06). The experimental results show that the mean increase in heat transfer rate is between 123% and 232% in the test range, and the maximum value is obtained for the case of $pl/D = 0.27$ and $Hl/D = 0.06$ at a low Re. In addition, the average friction factor of the corrugated tube is in the range of 1.46–1.93 times that of the smooth tube. Harleß et al. [8] conducted an experimental study on gas–liquid heat exchangers with cross-corrugated tubes. The greatest heat transfer enhancement was obtained for a corrugation height of 1.86 mm and corrugation angle of 38.4°; the optimal corrugation angle was expected to be between 20° and 30° within the high range of the Nusselt number (Nu) augmentation and for a moderate increase in the friction factor. A numerical work was conducted by

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Nomenclature

C_1, C_2	k–ε model constants
D	inner diameter of tube (m)
E	inner energy (J/kg)
f	fanning fraction factor
Hl	corrugation height (m)
I	turbulence intensity
pl	corrugation pitch (m)
k	turbulent kinetic energy (J/kg)
L	tube length (m)
Nu	Nusselt number
P	pressure (Pa)
Pr	Prandtl number
Re	Reynolds number
tl	tube wall thickness (m)
u	streamwise velocity component (m/s)
v	transverse velocity component (m/s)
V	velocity (m/s)
wl	corrugation width (m)
w	vertical velocity component (m/s)
y^+	dimensionless distance from the cell center to the nearest wall

Greek letters

ρ	density of fluid (kg/m^3)
ε	turbulence dissipation rate (m^3/s^2)
μ	dynamic viscosity (kg/m/s)
Φ	scalar quantities
λ	thermal conductivity (W/m/K)

Subscripts

s_ave	smooth tube average value
in	inlet
i, j, k	direction of coordinate
$local$	local value
out	outlet
s	smooth tube
t	turbulence
$wall$	tube wall

Mohammed et al. [9] to study the effects of various geometrical parameters on the thermal and flow fields through transversely corrugated circular tubes with *Re* in the range of 5000–60,000 and a heat flux of 50 W/cm^2. The *Nu* increased as the roughness height and width and the *Re* increased and as the roughness pitch decreased. The highest performance evaluation criterion was achieved for $Hl/D = 0.025$, pitch-to-tube diameter ratio $pl/D = 0.5$, and height-to-tube diameter ratio $wl/D = 0.2$. Using water as the working fluid, internal transverse corrugated tubes of various corrugation shapes (square, rectangular, triangular, and trapezoidal) and geometrical parameters were numerically analyzed by Manca et al. [10]. The simulations showed that the average *Nu* increases as the *Re* and Hl/D increase, and they are at most equal to 2.6 times that of the smooth tube results.

It is obvious from the above literature review that the vast majority of the extant research provides an average performance on considering various factors such as the geometrical shape and structure parameter of the tube and the *Re*. In addition, there are few studies on the variation of the flow pattern, which is fundamental to the heat transfer and flow resistance performance and has thus motivated the present study.

In this work, a novel outward corrugated tube manufactured using the hydroforming process under 290 MPa and using a thick-walled stainless steel tube (shown in Fig. 1) is studied. In order to explore the mechanism of the fully developed turbulent flow and heat transfer in the outward TCT and helical corrugated tubes (HCTs), a numerical study was performed with various height-to-diameter ratios ($Hl/D = 0.05$, 0.10, and 0.15) and pitch-to-diameter ratios ($pl/D = 0.5$, 1.0, and 1.5) in the *Re* range of 3800–43,800 in order to match the typical design of a gas–liquid heat exchanger. Firstly, the effects of the corrugation height and pitch on the flow pattern, especially on the detached vortex, spiral wake, and turbulent fluctuation. Secondly, through the local *Nu* and friction factor (f) along the tube walls to investigate the relationship among the complex flow regime, heat transfer, and flow dynamics. Finally, the obtained average *Nu*, f, and *PEC* are discussed, and a overall suggestion are concluded for engineering design.

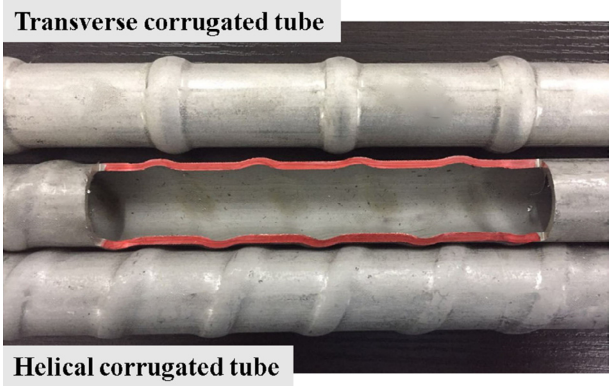

Fig. 1. Outward transverse and helical corrugated tubes.

2. Mathematical approach

2.1. Physical model and assumptions

The computational domain and schematic structure for the model are shown in Fig. 2. The computational domain comprises the inlet fluid section, corrugated tube section, and outlet fluid section. To ensure a fully developed flow at the entrance of the corrugated section, the ratio of the inlet section length to the diameter is set as 60 [11], and to prevent back flow, a length-to-diameter ratio of 10 is set, while considering adiabatic boundary conditions. The structural parameters of the corrugated tube include the tube length ($L = 200$ mm), inner diameter ($D = 20$ mm), tube-wall thickness ($tl = 2$ mm), corrugation width (wl), corrugation height (Hl), and corrugation pitch (pl). In the present study, the geometric parameters of the TCT and HCTs are listed in Table 1.

2.2. Governing equations

A three-dimensional computational fluid dynamics model was developed in this paper to investigate the flow and heat transfer characteristics in corrugated tubes. The Reynolds-averaged Navier–Stokes equations (RANS equations) and Reynolds stress model (RSM), based on Reynolds decomposition, are numerically solved in ANSYS Fluent 14.5. This mathematical model has also