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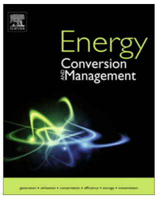

# Influence of geometrical parameters on turbulent flow and heat transfer characteristics in outward helically corrugated tubes

Wei Wang [a], Yaning Zhang [a], Bingxi Li [a,*], Huaizhi Han [b], Xiaoyan Gao [a]

[a] *School of Energy Science and Engineering, Harbin Institute of Technology, Harbin 150001, China*
[b] *College of Power and Energy Engineering, Harbin Engineering University, Harbin 150001, China*

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ABSTRACT

Concerning a novel outward helically corrugated tube manufactured through hydraulic forming under 290 MPa, a numerical study was conducted to investigate the mechanism of turbulent flow dynamics and heat transfer enhancement based on the Reynolds stress model (RSM) using the FLUENT software. A validation of the Reynolds stress model for turbulent flow over a wavy surface was performed, and the results were then compared with the results from a large eddy simulation (LES) model and with experimental measurements. The helically corrugated tubes with different corrugation height-to-diameter ratios and pitch-to-diameter ratios are then evaluated to explore their influence on turbulent flow and heat transfer. It was found that the intensity of swirl flow was enhanced with an increase in the corrugation height, and it increased with a decrease in the corrugation pitch, the intensification of the swirl flow strengthens the heat transfer and resistance characteristics. The intensity of rotational flow was enhanced with an increase in the corrugation height, and increased with an increase in the corrugation pitch; the enhanced rotational flow causes an inhibition effect on heat transfer and resistance. Moreover, the maximum values of the local Nusselt number and the friction factor along the walls were observed at the reattachment point, and their minimum values appeared at the core of the swirl flow. It is therefore reasonable to keep the corrugation height-to-diameter ratios be less than 0.1, and the pitch-to-diameter ratios be less than 2 to ensure that the growth rate of the heat transfer is greater than the growth rate of the flow resistance.

## 1. Introduction

In recent years, numerous experimental and numerical simulation studies have been performed on the heat transfer performance enhancement of corrugated tubes, considering various factors such as different corrugation shapes [1,2], the Reynolds number (*Re*) [3,4], the Prandtl number (*Pr*) [5], the corrugation height, and the corrugation pitch [6–9]. Certain researchers have reported studies on multiphase flow [10] and nano-fluids [11] in corrugated tubes to strengthen the heat transfer performance. Compared with smooth tubes, a corrugated tube has a significant heat transfer enhancement efficiency, which were unanimously confirmed in all the above studies.

Most of the studies on corrugated tubes have focused on the inward concave type [2,4,7,12–16], as shown in Fig. 1a–h, for reasons of ease and simplicity. However, the inward corrugated tubes are not suitable for the cases of high-temperature and high-pressure fluids, such as in nuclear or chemical facilities, because they usually present problems of stress concentration and endoscopy obstruction.

Owing to the fact that the local features of the fluid velocities and temperatures are difficult to obtain through measurement methods, the numerical simulation methods are widely employed to reveal the details of the turbulent flow and the heat transfer mechanisms. Various numerical models such as the standard $k-\varepsilon$ model [17,18], the renormalization group RNG $k-\varepsilon$ model [19,20], and the shear stress transport (SST) $k-\varepsilon$ model [21] are employed to predict the flow and the heat transfer performance in various complex structures. The standard $k-\varepsilon$ model has been validated and successfully applied, however, when employed in the research of rotational flow and curved wall flow it may result in distortion [22]. Although the RNG $k-\varepsilon$ model and the realizable $k-\varepsilon$ model have been improved on the basis of the standard $k-\varepsilon$ model, the physical properties are still assumed isotropic, which may result in low accuracy of the prediction of the turbulent flow details in complex structures [23,24]. The RSM treats the physical properties as anisotropic, it performs well in predicting sudden flow expansion and complex anisotropic flow. In addition, by solving the Reynolds-stresses term $(\overline{u'u'}, \overline{u'v'}, \overline{u'w'})$, it can also predict

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* Corresponding author.
*E-mail address:* libx@hit.edu.cn (B. Li).

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**Nomenclature**

| | |
|---|---|
| $C_1$, $C_2$ | $k$-$\varepsilon$ model constants |
| $D$ | inner diameter of tube (m) |
| $E$ | inner energy (J/kg) |
| $f$ | fanning fraction factor |
| $Hl$ | corrugation height (m) |
| $I$ | turbulent 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*

| | |
|---|---|
| $\rho$ | density of fluid (kg/m$^3$) |
| $\varepsilon$ | turbulence dissipation rate (m$^3$/s$^2$) |
| $\mu$ | dynamic viscosity (kg/m/s) |
| $\Phi$ | scalar quantities |
| $\lambda$ | 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 |

the turbulent pulsating momentum. Many excellent reports also adopt the RSM to study the complex turbulent flow and heat transfer problems [25,26].

In this work, the RSM has been employed as well, to explore the turbulent flow dynamics and the heat transfer performance in a novel outward helically corrugated tube, which has been manufactured through hydraulic forming under 290 MPa, as shown in Fig. 2. The tube is very suitable for high-temperature and high-pressure working fluids such as those in nuclear power stations, in chemical engineering, and in petroleum refining. After processing, the tube does not need further pressure tests, and can be easily subjected to endoscopy. Furthermore, these types of tubes are used in combined-cycle nuclear power plants, which are planned to use the exhaust from the high temperature gas-cooled reactor (HTGR) to reheat the steam from the high-pressure turbine of the advanced pressurized water reactor (APWR).

We intend to investigate the mechanism of turbulent flow and heat transfer in helically corrugated tubes, and the effects of different corrugation height-to-diameter ($Hl/D$ = 0.05, 0.1 and 0.15) and pitch-to-diameter ($pl/D$ = 1, 2 and 3) ratios on the coefficients of flow and heat transfer characteristics, and compare the results with those from the smooth tube with a fixed width-to-diameter ratio ($wl/D$ = 0.5) and $Re$ = 25,500 ($u_{in}$ = 20 m/s). Firstly, the RSM was employed for the modeling of the turbulent flow in undulant wall tubes, the results were then compared with the LES results and the experimental data. Secondly, the mean velocity vectors in longitudinal and cross section, and the components profiles in the streamwise ($u/u_{in}$), the transverse ($v/u_{in}$) and the vertical ($w/u_{in}$) directions are then discussed to describe the details of turbulent flow. Finally, the turbulent kinetic energy ($TKE$) was analyzed to reveal the velocity-fluctuation intensity distribution, and the local Nusselt number ($Nu$) and the friction factor ($f$) along the tube walls were obtained to discuss the relationship among the flow features, heat transfer and flow resistance performance.

## 2. Mathematical approach

### 2.1. Geometry of outward helically corrugated tube and meshing system

The structure of the helically corrugated tube is shown in Fig. 3, including the tube length ($L$ = 200 mm), the inner diameter ($D$ = 20 mm), the tube wall thickness ($tl$ = 2 mm), the corrugation width ($wl$ = 10 mm), the corrugation height ($Hl$), and the corrugation pitch ($pl$). In order to investigate the influence of the corrugation height and pitch on the fluid flow and the heat transfer characteristics, five cases of helically corrugated tube were numerically studied and compared with the results from the smooth tube. The geometrical dimensions are listed in Table 1.

A nonuniform structured grid was used in the geometrical model, with a grid refinement near the interfaces, as shown in Fig. 4. The dimensions of the first cell (0.02 mm) next to the interface was determined by the Re and satisfies the condition of $y^+ \approx 5$, and the growth factor was 1.3 for the near-wall grids [27]. In the transverse direction, the size of final-layer near-wall grids is equal to the dimension of the main flow region grids (0.6 mm); streamwise, the dimension of grids is equal to 1 mm; and the total number of mesh is 28,800, which was decided via the grid independence test in the case 1 tube under the different $Re$ [28].

The numerical simulation was conducted with ANSYS Fluent 14.5, with three-dimensional configurations.

### 2.2. Governing equations

During the simulation of the turbulence fluid flow in the outward helically corrugated tube, the following assumptions were imposed: the property parameters of the working fluid (He) were considered the same as that for an incompressible flow, with constants as listed in Table 2; the gravitational force and the radiation heat transfer were neglected [29,30].

The Reynolds-Averaged Navier-Stokes (RANS) equations in conjunction with the RSM were solved using the chimera RANS method. This mathematical model has been used by Su et al. [31] to compute the flow and heat transfers in rotating rectangular channels. The governing equations are given below, and the validation of this model will be presented in Section 3.1.

The continuity equation:

$$\frac{\partial(\rho u_i)}{\partial x_i} = 0 \tag{1}$$

The momentum equation:

$$\frac{\partial}{\partial t}(\rho u_i) + \frac{\partial}{\partial x_j}(\rho u_i u_j) = -\frac{\partial P}{\partial x_i} + \frac{\partial}{\partial x_j}\left[\mu\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} - \frac{2}{3}\delta_{ij}\frac{\partial u_j}{\partial x_j}\right)\right] + \frac{\partial}{\partial x_j}\left(-\rho\overline{u_i' u_j'}\right) \tag{2}$$