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Research Paper

Numerical investigation of helically coiled tube from the viewpoint of field synergy principle

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HIGHLIGHTS

- Helically coiled tube is numerically investigated in terms of field synergy principle.
- Field synergy principle can describe heat transfer of the tube quantitatively.
- Entransy dissipation augmentation number is proposed as evaluation criterion.
- Field synergy principle and entransy dissipation have a good agreement.

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ABSTRACT

The heat transfer characteristics of helically coiled tube are numerically investigated from the viewpoint of field synergy principle, and the simulation results have a good agreement with experimental results. The heat transfer enhancement of helically coiled tube can be attributed to the improvement of the synergy between the velocity vector and temperature gradient due to secondary flow, and the effects of Reynolds number, curvature ratio, and coil pitch on heat transfer performance can be well described by the field synergy principle. Moreover, the entransy dissipation augmentation number is proposed to evaluate the heat transfer performance of helically coiled tube, which is found to be suitable to evaluate heat transfer augmentation techniques.

1. Introduction

With the sky-rocketing prices of petroleum and coal, to use energy sources efficiently has become one of the most effective ways to reduce the energy demand. Helically coiled tubes are widely employed in many industrial applications due to their higher heat transfer rate and more transfer area per unit volume of space as compared to straight tube [1]. Dean [2,3] was considered the first to report the analytical expression for flow field in a curved pipe with circular cross-section. From then on, a large number of studies on helically coiled tubes have been reported. Liou [4] investigated the flow patterns in helically coiled tubes with various torsion-to-curvature ratios using laser light-sheet flow visualization and LDV measurement, and the results showed that the torsion effect on the secondary flow is not limited to low Reynolds number. Lin and Ebadian [5] conducted a fully elliptic numerical study on three-dimensional turbulent developing convective heat transfer in helically coiled pipes with finite pitches, they investigated the effects of some important parameters on developing temperature field and heat transfer in the helical pipes, and the results showed that the Nusselt number for the helical pipe is oscillatory before the flow is fully developed. Ko and Ting [6] investigated the entropy generation for the fully developed laminar convection in a helically coiled tube under constant wall heat flux condition, and presented the optimal design based on the minimum entropy generation principle. Wu et al. [7] numerically investigated the influences of Reynolds number, curvature ratio, and coil pitch on the average friction factor, Nusselt number and the non-dimensional entropy generation number in a helically coiled tube subjected to uniform wall temperature boundary condition. Shokouhmand and Salimpour [8] analytically investigated the effects of some parameters like Reynolds number, curvature ratio, and coil pith on the entropy generation rate under uniform wall temperature condition, and proposed some optimal Reynolds numbers of laminar flow subjected to uniform wall temperature condition. Cioncolini and Santini [9] carried out an experimental study on the effect of curvature on the laminar to turbulent flow transition in helically coiled tube from direct inspection of the experimental friction factor profiles obtained for the tested tubes. Naphon and Wongwises [10] conducted a literature review on heat transfer and flow characteristics of single-phase and

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two-phase flows in helically coiled tubes, spirally coiled tubes and other coiled tubes. The survey indicated that numerous theoretical and experimental works have been reported on single-phase heat transfer characteristics and flow characteristics for helically coiled tubes.

From the literature review above, it can be seen that most of the previous works are focused on the influences of the design parameters on heat transfer and flow performance of helically coiled tube. Almost all the studies attributed the heat transfer enhancement of helically coiled tube to the secondary flow induced by the centrifugal force, which was not enough in explaining the heat transfer enhancement of helically coiled tube qualitatively and quantitatively. Guo et al. [11,12] proposed the field synergy principle for heat transfer augmentation, which indicated that the heat transfer rate depends not only on the flow and temperature fields but also on their synergy. According to the field synergy principle, the better the synergy of velocity vector and temperature field is, the higher the heat transfer rate of convection. Tao et al. [13] conducted a numerical study on laminar heat transfer and fluid flow characteristics of wavy fin heat exchanger from the viewpoint of field synergy principle. Kuo and Chen [14] conducted a research on the performance of a novel wave-like form gas flow channel in the proton exchanger membrane fuel cells using field synergy principle. Guo et al. [15,16] numerically investigated the circular tube fitted with helical screw-tape inserts and curved micro-channel from the viewpoint of field synergy principle, and they reported that their heat transfer performance could be described well by field synergy principle. Tao et al. [17] demonstrated that the three heat transfer enhancement mechanisms, namely, the decreasing of thermal boundary layer, the increasing of flow interruption and the increasing of velocity gradient near a solid wall, will lead to reduction of the intersection angle between velocity vector and temperature gradient.

The present work not only focuses on the effects of design parameters on heat transfer performance of helically coiled tubes, but also on the physical mechanism for heat transfer enhancement. The influences of curvature ratio, coil pitch and Reynolds number on performance of helically coiled tubes are numerically studied in the present work, and the results would be re-examined from the viewpoint of field synergy principle. The volumetric average intersection angle between the velocity vector and temperature gradient in the computational domain is determined, and the thermal performance of helically coiled tube is further investigated in terms of entransy dissipation.

2. Model description

2.1. Computational domain

Fig. 1 illustrates the sketch of an investigated helically coiled tube. The total length of all investigated tubes is fixed at $L = 0.5$ m, the inner diameter of all tubes is fixed at $d = 0.01$ m. The principal geometric parameters include the inner diameter of the tube, d, the curvature diameter of the coil, D, and the coil pitch, b. The curvature ratio δ is defined as the ratio of tube diameter to the coil diameter, d/D. The dimensionless pitch, λ, is defined as $b/\pi D$. The other important dimensionless parameters are presented as follows:

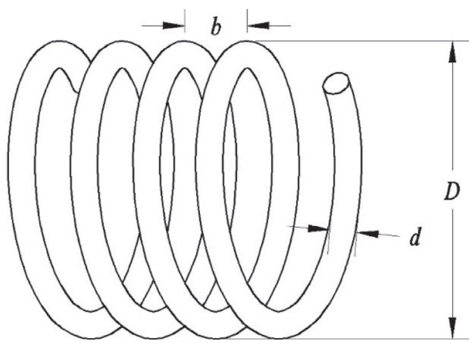

Fig. 1. Geometry of a helically coiled tube.

$$Re = \frac{\rho U d}{\mu}, \quad Nu = \frac{hd}{k}, \quad De = Re\,\delta^{0.5} \tag{1}$$

where U and h are average velocity and convective heat transfer coefficient of coiled tube, respectively.

2.2. Governing equations and grid independence validation

The grid systems are generated using ANSYS ICEM CFD, and imported into ANSYS CFX. Several turbulence models are available, and the K-epsilon model is adopted due to its wide application and reasonable accuracy in engineering applications.

The governing equations for this model are listed as follows [18]:

$$\text{Continuity equation:} \quad \frac{\partial u_i}{\partial x_i} = 0 \tag{2}$$

$$\text{Momentum equation:} \quad \frac{\partial(\rho u_i u_j)}{\partial x_j} = -\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j}\left(\mu \frac{\partial u_i}{\partial x_j} - \rho \overline{u_i' u_j'}\right) \tag{3}$$

The equations for the turbulence kinetic energy K and its dissipation rate ε are written as follows:

$$\rho u_k \frac{\partial \varepsilon}{\partial x_k} = \frac{\partial}{\partial x_k}\left[\left(\mu + \frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial x_k}\right] + \frac{c_1 \varepsilon}{K}\mu_t \frac{\partial u_i}{\partial x_j}\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right) - c_2 \rho \frac{\varepsilon^2}{K} \tag{4}$$

$$\rho u_j \frac{\partial K}{\partial x_j} = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_k}\right)\frac{\partial K}{\partial x_j}\right] + \mu_t \frac{\partial u_i}{\partial x_j}\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right) - \rho \varepsilon \tag{5}$$

Here, μ_t is turbulence viscosity, $c_1 = 1.44$, $c_2 = 1.92$, $\sigma_k = 1.0$, $\sigma_\varepsilon = 1.3$.

$$\text{Energy equation:} \quad \frac{\partial(\rho u_j T)}{\partial x_j} = \frac{\partial}{\partial x_j}\left(\Gamma \frac{\partial T}{\partial x_j} - \rho \overline{u_j' T'}\right) + \Phi \tag{6}$$

where Γ is diffusion coefficient, Φ is source term.

The water whose inlet temperate is fixed at 293.15 K is selected as working fluid, and the wall temperature is fixed at 473.15 K in the present work. The convergence criterion is that the maximum residual is less than 1×10^{-5}. In order to validate the solution independency of the mesh number, different grid systems for two helically coiled tubes are investigated. The predicted average Nu for these grid systems is shown in Fig. 2. It can be seen that the Nusselt number nearly remains constant when the grid number is higher than 700,000. Therefore, the adopted grid number in the computation is around 710,000.

2.3. Model verification

An empirical correlation of Nusselt number in the tube side, whose average error is 0.91%, is presented as follows [19]:

$$Nu = 0.152 De^{0.431} Pr^{1.06} \lambda^{-0.277} \tag{7}$$

In order to validate the computational model and numerical method, the mean Nusselt number obtained by numerical simulation is compared with calculated value using Eq. (7), and the results are shown in Fig. 3. It can be seen that the computational results agree well with the empirical correlation at $\lambda = 0.08$, and the