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# Numerical investigation of flow and heat transfer performances of horizontal spiral-coil pipes*

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**Abstract:** The flow and heat transfer performances of horizontal spiral-coil pipes of circular and elliptical cross-sections are studied. The numerical results are compared with the experimental data, to verify the numerical method. The effects of the inlet water mass flow rate, the structural parameters, the helical pitch and the radius ratio on the heat transfer performances are investigated. Performances of the secondary fluid flow with different radius ratios are also investigated. Numerical results demonstrate that the heat transfer coefficient and the Nusselt number increase with the increase of the water mass flow rate or the helical pitch. The maximum heat transfer coefficient and the maximum Nusselt number are obtained when the radius ratio is equal to 1.00. In addition, the fluid particle moves spirally along the pipe and the velocity changes periodically. The particle flow intensity and the spiral movement frequency decrease significantly with the increase of the radius ratio. Besides, the secondary flow profile in the horizontal spiral-coil pipe contains two oppositely rotating eddies, and the eddy intensity decreases significantly along the pipe owing to the change of curvature. The decreasing tendency of the eddy intensity along the pipe increases with the increase of the radius ratio.

**Key words:** heat exchanger, horizontal spiral-coil pipe, heat transfer performance, flow performance, secondary fluid flow

## Introduction

The spiral-coil pipes are most widely applied in several heat transfer fields, such as refrigeration systems, chemical reactors and heat exchangers. This type of pipes can induce the generation of the centrifugal force, which is beneficial to the production of a secondary flow, to affect the flow field and the heat transfer significantly[1-3]. Dean (1928) proposed a mathematical model for the fluid flow in a curved pipe with a constant radius. It was revealed that the secondary flow could be developed in coiled pipes when a parameter (Dean number) was larger than a certain critical value. In order to investigate the flow and heat transfer performances in spiral-coil pipes, numerous numerical[4-7] and experimental[8-13] studies were carried out. However, most of the studies of spiral-coil pipes focused on dimensional spiral-coil pipes and dimensional spiral-coil pipe heat exchangers.

There are only a few studies of the flow and heat transfer performances of the horizontal spiral-coil pipes. Kurnia et al.[14] studied the flow and heat transfer performances of three types of spiral-coil square pipes with laminar non-Newtonian fluids in them. The results indicate that the horizontal spiral-coil pipes enjoy a good performance as compared with conical spiral-coil pipes and other spiral-coil pipes. Naphon and Suwagrai[15,16] investigated the heat transfer performances of the horizontal spiral-coil pipes with different curvature ratios. The results reveal that the performances of the heat transfer are influenced by the centrifugal force significantly. In addition, the heat transfer coefficient obtained from the horizontal spiral-coil pipes is higher than that obtained from the straight pipe of an equivalent pipe length. Altaç and Altun[17] investigated the effects of the Prandtl number, the Dean number, the curvature ratio and the helical

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pitch on the heat transfer and the friction factor of the horizontal spiral-coil pipes. The results indicate that the heat transfer is increased about 2-4 times with the increase of the Reynolds number due to the secondary flow and the centrifugal forces. Furthermore, Naphon and Wongwises[18-21] investigated the heat transfer characteristics of the horizontal spirally coiled heat exchanger and the horizontal spirally coiled finned-tube heat exchanger under different conditions. Air and water were used as working fluids in the shell-side and the tube-side. The results reveal that the heat transfer rate is directly related to the inlet mass flow rate of the shell-side and tube-side fluids, and the inlet temperatures of the shell-side and tube-side fluids.

Compared with dimensional spiral-coil pipes, the horizontal spiral-coil pipes have a more compact structure and occupy less space in heat exchangers. In addition, the compact structure has important implications for improving the heat transfer efficiency per unit space in heat exchangers. The present work is to investigate the flow and heat transfer performances of the horizontal spiral-coil pipes of circular and elliptical cross-sections using a numerical method. The research can help the study of the mechanism of the heat transfer enhancement, the optimization of the pipe structure and the improvement of the exchanger.

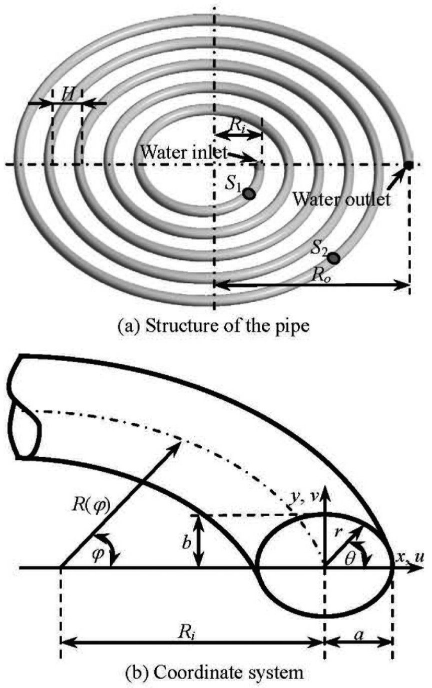


Fig.1 The geometry and coordinate system of the horizontal spiral-coil pipe

## 1. Mathematical model

Figure 1 shows the structure and the coordinate system of a horizontal spiral-coil pipe, where $R_o$ and $R_i$ are the outermost and innermost spiral-coil pipe radii, respectively, $H$ is the helical pitch, $\varphi$ is the polar angle, $\theta$ is the circumferential angle, and $a$ and $b$ are the horizontal and vertical radii of the elliptical pipe cross-section, respectively. The horizontal spiral-coil pipe is described by the polar equation $R(\varphi) = R_i + H\varphi/(2\pi)$ . $S_1$ and $S_2$ are two cross-sections of the pipe between the water inlet and the water outlet.

In our study, the outermost radius $R_o$ and the pipe cross-section area $A$ are constant parameters, and the radius ratio $b/a$ and the helical pitch $H$ are variable parameters. Table 1 shows the structural parameters of the horizontal spiral-coil pipes in the study.

**Table 1 Structural parameters of the horizontal spirally coiled tubes**

| Parameters | Dimensions |
|---|---|
| Outermost radius $R_o$ / m | 0.203 |
| Tube cross-section area $A$ / m$^2$ | $50.3\times10^{-6}$ |
| Helical pitch $H$ / m | 0.01360-0.03000 |
| Radius ratio $b/a$ | 0.50-2.00 |
| Number of coil turns | 5 |

The steady-state equations of the Newtonian fluids can be expressed as

Continuity equation

$$\nabla \cdot \boldsymbol{V} = 0 \tag{1}$$

Momentum equation

$$(\boldsymbol{V} \cdot \nabla)\boldsymbol{V} = -\frac{1}{\rho}\nabla p + \nu \nabla^2 \boldsymbol{V} \tag{2}$$

Energy equation

$$(\boldsymbol{V} \cdot \nabla)T = \alpha \nabla^2 T \tag{3}$$

where $V$ is the fluid velocity, $p$ is the pressure, $T$ is the temperature, $\nu$ is the kinematic viscosity of the fluid, and $\alpha$ is the thermal diffusivity.

Based on the critical Reynolds number of the helical pipe[3], the standard $k$ - $\varepsilon$ turbulence model is used to simulate the flow and heat transfer performances, focusing on the geometry and the physics. The turbulent kinetic energy equation and the turbulent kinetic energy dissipation equation are expressed as

$$\frac{\mathrm{D}k}{\mathrm{D}t} = \frac{1}{\rho}\frac{\partial}{\partial y}\left[\left(\frac{\mu_t}{\sigma_k} + \mu_l\right)\frac{\partial k}{\partial y}\right] + \frac{\mu_t}{\rho}\left(\frac{\partial u}{\partial y} + \frac{\partial v}{\partial x}\right)\frac{\partial u}{\partial y} - \varepsilon \tag{4}$$