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Numerical investigations of laminar flow in coiled pipes

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Abstract

Numerical investigations were done to understand forced laminar fluid flow in rectangular coiled pipes with circular cross-section and characterized by pipe straightness, curvature and torsion. The focus was addressed on exploring the flow pattern and temperature distribution through the pipe. Computer simulations were performed for four rectangular coiled pipes with different angles of the straight tube inclination (9°, 15°, 30° and 45°) at different inlet velocities. The shape of the secondary motions was found to be strongly associated with the axial momentum which depends in turn on the geometric configuration of the pipe. The results show remarkable effects of the straight-tubes inclination on the flow behavior and better heat transfer performance is observed for the coil with smaller angle of straight tube inclination. The results and observations are in a good agreement with the available numerical and experimental works on laminar flow in helical coil pipes.

Keywords: Laminar flow; Rectangular coil pipe; Curvature; Torsion; Inclination angle

1. Introduction

Pipelines or tubes are widely used in industrial applications for transporting gases and liquids. Typical conduits are found among several types: straight, curved and coiled pipes with curvature and torsion. Extensive numerical and experimental investigations are available for both laminar and turbulent flow in straight tubes. However, flow through coiled pipes with curvature and torsion is still under exploration. Coiled pipes are used as compact heat exchangers, condensers and evaporators in the food, pharmaceutical, modern energy conversion and power utility systems, HVACR engineering, and chemical industries, and show high heat transfer performance in these applications. The main characteristics of coiled pipes are the compactness and the high heat transfer performance.

Investigation of flow through pipes with curvature and torsion (both laminar and turbulent flows) is of recent origin [1]. Curvature alone is sufficient to create mean secondary motions of fluid inside tubes. These secondary motions are due to the difference in axial momentum between fluids particles in the core and the wall regions. The core fluid experiences a higher centrifugal force than the fluid near the outer wall which is pushed towards the inner wall in two different streams. Huttl and Friedrich [1,2] performed several DNS (direct numerical simulation) of fully developed flow through toroidal and helical pipes and showed the turbulence structure appearing in instantaneous velocity fields. They found that the pipe curvature which induces a secondary flow has a strong effect on the flow quantities and the turbulence is significantly inhibited by streamline curvature. The torsion effect is weaker than the curvature effect. Dong and Ebadian [3] presented computer simulation of laminar flow ($Re = 1000$) and turbulent flow ($Re = 2.5 \times 10^4$) in helicoidal pipe with thermal properties that are independent of temperature. They presented the velocities (axial and secondary), temperature distribution, friction factor and Nusselt number in both laminar and turbulent flow. Yamamoto et al. [4] considered the flow through a helical pipe and investigated the behavior of the fluid particle trajectory affected by curvature as well as torsion of the helical pipe. They calculated the particle directory numerically and validated the results by an

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Nomenclature

a	tube radius (m)
Cp	specific heat (kJ/kg °C)
d	tube diameter (m)
De	dean number
Gn	Germano number
y	pitch (m)
r	bends curvature (m)
Re	Reynolds number
S	dimensionless axial distance
s	axial distance (m)
T	temperature (K)
U	dimensionless velocity
u	velocity (m/s)

Subscripts

0	inlet condition
r	radial
s	axial
scd	secondary motions
t	tangential
w	wall condition

Greek symbols

α	inclination angle(°)
ρ	density (kg/m^3)
μ	coefficient of viscosity (kg/ms)
δ	curvature ratio
δ_{ij}	Delta function
Γ	thermal conductivity (W/m k)
τ	torsion ratio

experimental visualization. Yang et al. [5] presented numerical investigation of fully developed laminar convective heat transfer in a helicoidal pipe with a finite pitch coiled pipe. Their results indicated that torsion will increase the temperature gradient on one side of the pipe wall and decrease the temperature gradient on the other side. In the case of small Prandtl number fluid, the Nusselt number declines slightly as torsion increases. All these numerical and experimental investigations presented above concern with helically coiled pipes.

In the purpose of designing coiled pipe heat exchanger illustrated in Fig. 1a, numerical investigations were performed on laminar forced convection in pipes composed with two straight tubes and three toroidal bends. The numerical method consisted with three-dimensional laminar flow of incompressible Newtonian fluid using CFD software Fluent V6.0. Also, the effects of the straight tubes inclination on the flow behavior and heat transfer in rectangular coiled pipes were studied for four cases of 9°, 15°, 30° and 45°.

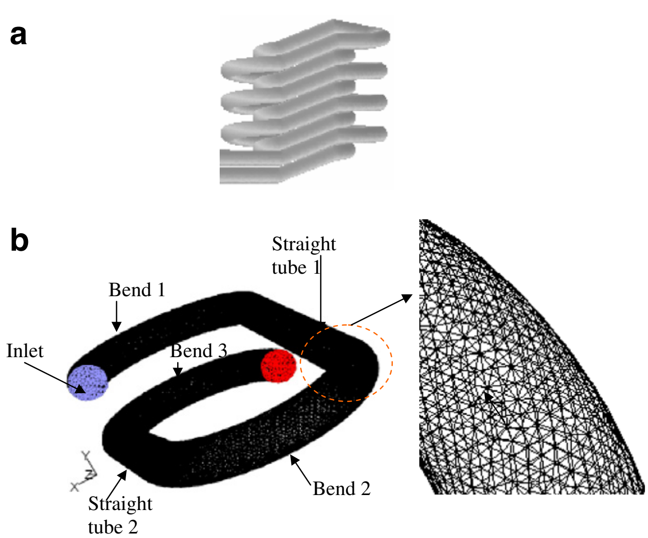

Fig. 1. Compact rectangular coils heat exchanger geometrical configuration: (a) heat exchanger and (b) computational grid.

2. Problem description

2.1. Geometric configuration and governing equations

Fig. 1a illustrates the investigated compact rectangular coils heat exchanger and Fig. 1b presents the schematic of a rectangularly coiled pipe with circular cross-section of inner diameter d, and the investigated pipe includes two straight parts and three smooth bends. In this paper the pitch y is the distance between two adjacent pipe bends and the length of a single straight tube is $l = 2r$. The axial distance from the inlet is represented by S.

The momentum and energy equations for three-dimensional laminar flow in tube with curvature and torsion are [3,7–9]:

$$\frac{\partial}{\partial x_j}\left[\mu\left(\frac{\partial u_i}{\partial x_j}+\frac{\partial u_j}{\partial x_i}-\delta_{ij}\frac{2}{3}\frac{\partial u_k}{\partial x_k}\right)-\rho u_j u_i-\delta_{ij}p\right]=0 \tag{1}$$

$$\frac{\partial}{\partial x_j}\left[\Gamma\frac{\partial T}{\partial x_j}-\rho u_j C_{\mathrm{p}} T\right]+\mu\Phi_v=0 \tag{2}$$

$$\text{where}\quad \Phi_v=\frac{\partial u_i}{\partial x_j}\left(\frac{\partial u_i}{\partial x_j}+\frac{\partial u_j}{\partial x_i}-\frac{2}{3}\frac{\partial u_k}{\partial x_k}\delta_{ij}\right) \tag{3}$$

The equations were previously derived for the velocity components of particle flows in pipe induced by curvature and torsion [4].

2.2. Parameters definitions

The following dimensionless parameters are used to present the results [1–4,10,11].