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Hydrodynamically and thermally developing laminar flow in spiral coil tubes

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ABSTRACT

In this study, steady state combined developing flow and heat transfer in spiral tube coils is numerically investigated. The spiral coil is isothermal and the fluid flow is laminar. The spiral coils with four different curvature ratios of defined as the radius of the spiral at the outlet (R_o) to the radius at the inlet (R_i), $R_o/R_i = 2.5$, 5, 7 and 17, are simulated for $Pr = 0.7$ (air) and $Pr = 7$ (water). The cold fluid is assumed to enter the coil from the innermost turn of the spiral tube. The three-dimensional steady-state continuity, Navier–Stokes and energy equations are solved using the commercially available CFD software—Fluent v6.1.22®. The effects of the spiral tube pitch, curvature ratio, the Prandtl and the Dean number on the friction factor and the heat transfer are investigated for combined developing flow. With increasing Reynolds number, the heat transfer is enhanced 2–4 times over straight tubes of the same length due to secondary flow and centrifugal forces. The friction losses also increase to some extent. As the number of turns is increased, the normalized friction factor tends to decline towards the straight tube values. Useful correlations for the normalized apparent friction factor and the mean axial Nusselt number were generated.

1. Introduction

Spiral tubes or spiral coils are widely used in various thermal engineering applications such as heat exchangers, electronic cooling, chemical reactors, etc. They have better heat transfer performance and compactness which result in occupying less space. The heat transfer phenomena occurring in the spiral tubes are more complicated than those in straight ducts. Secondary flows observed in the flow patterns and the curvature of the spiral coils facilitates centrifugal forces which in turn significantly affect the flow field and heat transfer.

In an experimental study on the viscosity of air, Grindley and Gibson [1] were the first who noticed the effect of curvature on the flow through a coiled pipe. Eustice [2,3] experimentally demonstrated the existence of the secondary flow by ink injection to water flowing in a coiled pipe. A mathematical model for the fluid flow in a curved duct of constant radius (or constant curvature) was introduced by Dean [4,5]. His studies revealed that a secondary flow develop in curved tubes when so called the Dean number exceeds a certain critical value. Since then several experimental [6–11] and numerical [12–24] studies have been published which examined the flow and heat transfer phenomena in the spiral tubes.

In the literature, most of the studies on curved tubes are focused on helically coiled tubes. Very little information is available on horizontal spiral coiled tubes (HSCT) and HSCT heat exchangers. Researchers have studied different vertical helical coils. Naphon et al. [13] have reviewed the literature for three main categories of curved tubes: vertical helical coiled tubes, spirally coiled tubes and others curved tube arrangements. Although numerous studies on the hydrodynamic and the heat transfer performance are available in literature, there are very few published studies on the horizontal spiral coils where the curvature ratio variation (D/D_c) is 0.1 and below where D_c is the diameter of curvature. Naphon [14] experimentally studied coils having coil diameter varied from 150 mm to 400 mm and the tube diameter 9.5 mm outer diameter. Coils having curvature ratio (D/D_c) variation of 0.24–0.067 were investigated for the hydrodynamic characteristics and compared with vertical helical coil.

Ho and Wijeysundera [15,16] numerically studied a spiral coil heat exchanger consisting of a number of horizontal layers of spirally wound, finned tubes connected to vertical manifolds at the inner and outermost turns of each coil. Alammar [17] studied turbulent flow and heat transfer. The local skin friction coefficient, the Nusselt number, and the wall temperature along the tube wall were

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Nomenclature

A	surface area [m^2]
b	coil pitch [m]
C_f	apparent friction factor [−]
d	tube diameter [m]
D	coil diameter [m]
De	Dean number [−]
Gz	Graetz number [−]
h	heat transfer coefficient [W/m^2 K]
$\bar{h}_s$	mean local heat transfer coefficient [W/m^2 K]
k	thermal conductivity [W/m K]
L	length of the (spiral) tube [m]
Nu	Nusselt number [−]
P	pressure [N/m^2]
Pr	Prandtl number [−]
R	radius of curvature [m]
Re	Reynolds number [−]
s	axial tube length [m]
T	temperature [K]
u, v, w	velocity components [m/s]
$\mathbf{V}$	fluid velocity [m/s]
x, y, z	cartesian coordinate system [m]
z^+, s^+	dimensionless axial length [−]
Greek symbol	
α	thermal diffusivity [m^2/s]
φ	polar angle [rad]
μ	dynamic viscosity [N s/m^2]
υ	kinematic viscosity [m^2/s]
ρ	density [kg/m^3]
θ	circumferential angle [rad]
Subscripts	
app	apparent
c	curvature
fd	fully developed straight tube
i	inlet
o	outlet
s	spiral coil
st	straight tube
dst	developing straight tube
w	wall

presented. Kurnia et al. [18] investigated the heat transfer performance of various configurations of coils of non-circular tubes. The effects of the Re, Pr numbers and the coil diameter are discussed. Their results have been compared with those of the straight square tube of the same length. Kurnia et al. [19] have also studied three-dimensional laminar flow of a Newtonian fluid in a square cross-section ducts. Naphon [20] numerically and experimentally investigated the heat transfer and flow characteristics of the horizontal spiral-coil tube. It was found that the induced centrifugal force in the spiral-coil tube had a significant effect on the enhancement of heat transfer and the pressure drop increased. Yang and Chiang [21] experimentally investigated the heat transfer for water flowing through a curved pipe with varying-curvature. The results were compared with those of the straight pipe. It was found that the friction coefficient for curved pipe was also increased by less than 40%.

Sasmito et al. [22] conducted a numerical study of laminar flow heat transfer in-plane spiral ducts with rectangular, square, triangular, trapezoidal, circular and half circular cross sections, and compared them to straight ducts of the same cross sections and at the same length as the coiled ducts. It was reported that the in-plane spiral ducts have higher heat transfer performance than straight ducts. Sasmito et al. [23] also studied laminar nanofluid flow and heat transfer enhancement in square cross section horizontal tubes. Shih and Huang [24] studied the thermal design and model analysis of Swiss-roll recuperator. The results showed that the effectiveness of the recuperator increased with the number of turns and number of transfer unit. Yoo et al. [25] numerically studied horizontal spiral coils of six turns in which radius of curvature was increased exponentially with the polar angle. They found that the effect of Re number was stronger than that of the curvature. Bowman and Park [26] using Fluent v6.2 numerically investigated the pressure drop and heat transfer characteristics of coiled systems. They have found that up to 10% of the additional pressure drop and 40% of the enhanced heat transfer characteristics were obtained from the spiral coil system over the toroidal. Using the same CFD software, the same authors [27] numerically studied laminar flow and heat transfer performance of spiral coil tube heat exchangers with coil-to-tube radius ratios (5–45) and spiral pitch. They showed that the local friction factor and heat transfer varied continuously along the tube length.

Even though the interest in spiral coiled systems is on the rise, there are very few published articles on horizontally arranged spiral coil tubes. These articles deal with the laminar fluid flows ($Re < 2100$) and generally with the parabolic velocity BC at the inlet. There is very little information and/or correlations on the friction factor and Nusselt numbers as well. In the absence of appropriate

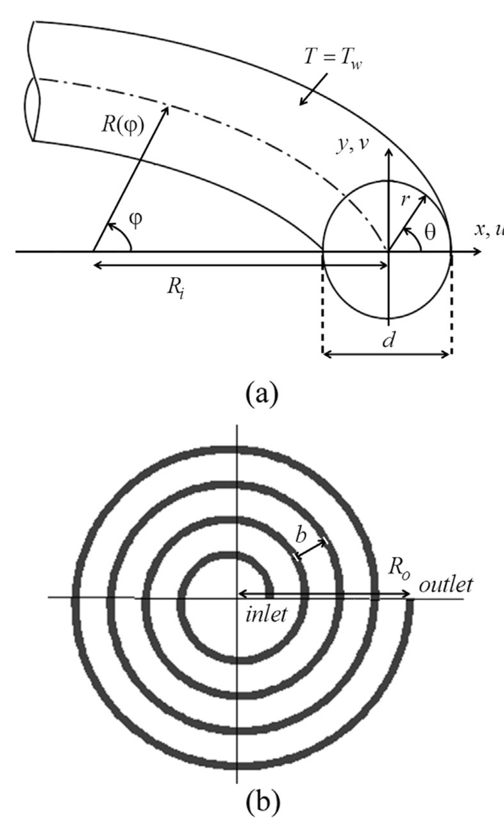

Fig. 1. (a) Geometry and the coordinate system (b) spiral pipe configuration.