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Numerical study of heat transfer on using lobed cross sections in helical coil heat exchangers: Effect of physical and geometrical parameters

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ABSTRACT

In this paper, flow characteristics and heat transfer applications of a helical coil with four different lobed cross sections are investigated numerically. The flow is laminar, Reynolds number changes from 1300 to 2500 and the wall of the helical coil in all the simulations has a constant temperature of 373 K. Effects of cross section lobe number (n) on heat transfer rate and pressure drop are studied. The results show that a coil with n = 6 presents the highest Nusselt number (*Nu*) and the lowest friction factor coefficient (f). In the next step, effects of different geometrical parameters (coil pitch, height, and diameter) and different fluids (Prandtl number) are studied. It is observed that the coil diameter has the greatest effect in comparison to the other geometrical parameters. Last but not the least, the effect of adding Al_2O_3 nanoparticles to water is discussed. It can be observed that upon using Al_2O_3-Water nanofluid, the Nusselt number increased 28 percent compared to water as the working fluid. But, it is seen that the friction factor coefficient does not change considerably. Moreover, it can be seen that the higher volume concentrations result in higher heat transfer rates. Finally, a correlation based on the numerical data for predicting Nusselt number is presented.

1. Introduction

Helical coil tube heat exchangers are a kind of curved tubes which are mostly used in industry and a variety of applications such as heat storage, heat recovery process, air conditioning, and chemical reactors [1]. Moreover, they are used in petroleum units as shell and coil heat exchanger to decrease the temperature of lubricating oil of the pumps and also in double pipe heat exchangers [2–4]. In this kind of heat exchanger, as fluid flows through curved tubes, centrifugal force is generated. A secondary flow induced by the centrifugal force has a significant effect on flow behavior. The phenomenon of secondary flow in curved tubes is more complex than in straight tubes. In addition, the pressure drop for flow in curved tube is higher than that of the straight tube at the same flow rate and tube length. This phenomenon mostly increases heat transfer rate and pressure drop. Based on the previous studies, many investigations have been carried out to increase the efficiency of helical coil heat exchangers.

Jamshidi et al. [5] experimentally studied the heat transfer enhancement in shell and helical coil tube heat exchanger. They studied flow characteristics and geometrical parameters such as coil pitch and coil diameter. The working fluid in all the experiments was water flowing in the laminar regime. Maowed [6] experimentally studied the effect of flow and geometrical parameters on forced convection in helical coils.

Pawar et al. [7] carried out an experimental research to investigate the effects of Newtonian and Non-Newtonian fluids in helical coils under unsteady flow conditions. The working fluids in the experiments were water and also glycerol-water mixture as the Newtonian fluid and dilute aqueous polymer solutions of sodium carboxymethyl cellulose (SCMC), sodium alginate (SA) as non-Newtonian ones.

In another experimental approach, Hardik et al. [8] investigated heat transfer and pressure drop in a helical coil with water as the working fluid by studying the effects of tube curvature and Reynolds number. One of the special things about this paper is measuring the coil's wall temperature by using infrared thermal imaging technique. They found the following correlation for Nusselt number:

$$Nu = 0.0456\left(\frac{D}{d}\right)^{-0.16} Re^{0.8}\mathrm{Pr}^{0.4} \quad (1)$$

Xin and Ebadian [9] carried out an experimental research on the effects of fluid properties (Prandtl number) and geometrical parameters on heat transfer rate of helical pipes. The working fluid of the experiments were air, water, and ethylene glycol which were in laminar regime. They presented a correlation for Nusselt number which is as

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Nomenclature

C_p	thermal capacity, Kj/kg K
D	coil diameter, m
d	tube diameter, m
k	thermal conductivity of fluid, W/mK
L	coil length, m
Re	Reynolds number, $= \frac{uD}{\nu}$
Nu	Nusselt number, hD/k
De	Dean number,= Re $\sqrt{\frac{d_t}{D_c}}$
Pr	Prandtl number,= $\frac{\mu C_p}{k}$
f	friction factor coefficient,= $\frac{2d}{L}\frac{\Delta P}{\rho u^2}$
f_c	friction factor coefficient of helical coil
f_s	friction factor coefficient of smooth tube
d_p	nanoparticle diameter
d_p	temperature, K
u	velocity, m/s
ΔP	pressure difference
N	lobe number

Greek symbols

Φ	volume fraction of nanoarticles
μ	dynamic viscosity, $kg{\cdot}m^{-1}{\cdot}s^{-1}$
ν	kinematic viscosity, $m^2{\cdot}s^{-1}$
ρ	density of the fluid

Subscripts

bf	base fluid
nf	nanofluid
P	nanoparticle
B	brownian
eff	effective

follows (with the range of the present study):

$$Nu = (2.153 + 0.318De^{0.643})\mathrm{Pr}^{0.177}$$
$$0.7 < Pr < 175,\ \ 20 < De < 200,\ \ 0.0267 < D/d < 0.0884, \quad (2)$$

In an experimental analysis, Wang et al. [10] studied the flow characteristics of a newly-designed helical coil heat exchanger. The helical coil consisted of one-round plastic reversed loop after each half-round period which resulted in better distribution of the flow in the helical coil. Moreover, the curvature of the reversed loops was another important factor in enhancing the heat transfer. They showed that the reversed loops enhanced the heat transfer rate by 20 percent with no sensitive pressure drop.

Omara and Abdelatief [11] carried out a detailed and novel study to examine the effects of using elliptic helical coils on heat transfer and pressure drop. In this regard, two different cross sections were used for the tubes which were of circular and rectangular shapes. The results indicated that the rectangular cross section was superior to its circular counterpart on the basis of increasing heat transfer rate. They understood that the overall thermal performance of the case with rectangular cross section was 14 percent higher than the customary helical coils with circular coil and tube.

Compared to the numerous investigations of the heat transfer in single-phase flows, not many works on the heat transfer characteristics in two-phase flows in helically coiled tubes have been reported [12,13]. In the last few years, many researchers have used various methods for increasing the heat transfer rate of heat exchangers [14–17]. One of these methods that has drawn much attention is using nanoparticles (such as typically made of metals, oxides, carbides, or carbon nanotubes) in base fluids (such as water, engine oil, and ethylene glycol) to perform the low thermal conductivity of the fluids [18–23]. One of the other advantages of using nanofluids is more intense effect near the wall and reducing the boundary layer thickness which results in higher heat transfer rate. Recently, many researches on the helical coil heat exchangers with nanofluids as their working fluids have been carried out [24–26].

In an experimental analysis, Fule et al. [27] investigated CuO-Water nanofluid in a helical coil heat exchanger with the working fluid flowing in the laminar regime. They desired to determine the effects of particle loading and flow rate on Nusselt number. They observed that the nanofluid increased the Nusselt number 77.7% than the base fluid for the highest considered volume concentration (5%).

Khosravi-Bizhaem and Abbassi [28] numerically studied the effects of using helical coil along with Al_2O_3-Water nanofluid on heat transfer enhancement and entropy generation. The nanofluid flowing in the laminar regime was modeled using Eulerian two-phase mixture which has recently been very popular among the researchers. It was seen that higher curvature ratio leads to higher heat transfer rates.

Table 1
Thermo-physical properties of base fluid and nanoparticles.

Property	Water	Al_2O_3
ρ (Kg/m^3)	998.2	3590
C_p (KJ/Kg)	4179	780
k (W/mK)	0.6	46
μ (Pa·s)	0.001003	0

Speaking of nanofluids use in helical coils along with changing the cross section of the geometry, Fsadni et al. [29] numerically studied this effect on turbulent heat transfer and pressure drop of the system. The nanoparticle at hand was Al2O3-water and the coil was under constant heat flux boundary condition. It was observed that the nanofluids caused 7–34% increase in heat transfer coefficient.

One of the areas of interest in geometry modifications is using heat exchangers with lobed cross sections which nowadays are highly recommended. Their main advantage is the increase of heat transfer rate due to higher swirl intensity. In recent studies, some researchers applied these lobed tubes on the entrance of a smooth tube which resulted in acceptable and higher performances [30–32]. Moreover, the lobed cross sections have been used as the full lobed tube [33] which all imply the fact that they cause higher overall performance.

The above-mentioned remarks are the core motive of the present study to implement the concept of stronger swirling flows in helical coils. According to the authors' knowledge, numerous studies were carried out regarding the helical coils and the effects of important parameters on heat transfer and pressure drop. We firmly state here that no previous research on the use of lobed cross sections in helical coil heat exchangers has been carried out so far. As a result, in the present paper, it has been tried to use lobed cross sections in helical coil heat exchangers which turns out to yield impressive results in comparison to the other customary heat exchangers. In this regard, we investigated the effect of geometrical parameters such as lobe number, coil diameter and flow parameters such as Prandtl number and finally the effect of nanoparticles on the performance of helical coil heat exchanger.

2. Governing equations

Present study considers fluid flow in a helical coil heat exchanger. In order to solve the problem, some simplifications have been made. It is simply assumed that the flow is in laminar regime, which is due to the range of the considered Reynolds number. In addition, the flow is in