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Optimization of design parameters for nanofluids flowing inside helical coils☆

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ABSTRACT

In this study water/Al_2O_3nanofluid is used in helical tubes. Copper helical tubes are in constant wall temperature and the fluid flow is laminar. Thermophysical properties of Nanofluids are assumed to depend on particles volume fraction and temperature. To analyze the heat transfer rate and pressure drop in helical coils, Nusselt number, friction factor and thermal–hydraulic parameter are used. Numerical simulation and Taguchi method are used to investigate the effect of fluid flow and geometrical parameters on JF factor. After simulations, Taguchi method is used for finding the optimum condition for the desired parameters. Proposed optimum conditions are simulated to insure the obtained results. Results indicate that Nanofluids improve the thermal–hydraulic performance of helical tubes. On the other hand using Nanofluids don't change the optimized shape factors but temperature dependent properties alter the optimum particle volume fraction.

1. Introduction

In industrial applications pipelines and tubes which have different types such as straight, curved and coiled tubes, are widely used. Coiled tubes are used in compact heat exchangers, condensers and evaporators in the food, pharmaceutical, modern energy conversion and power utility systems, heating ventilating and air conditioning (HVAC) engineering and chemical industries [1–3]. In coiled tubes centrifugal force makes a pair of longitudinal vortices and these secondary flow increase the heat transfer coefficient.

Dravid et al. [4] numerically investigated the effect of secondary flow on laminar flow heat transfer in helically coiled tubes both in the fully developed region and in the thermal entrance region. They presented a correlation for the asymptotic Nusselt number. Patankar et al. [5] discussed the effect of the Dean number on friction factor and heat transfer in the developing and fully developed regions of helically coiled pipes. Good agreements were obtained in comparison with the experimental data. Kubiar and Kuloor [6] studied experimentally the heat transfer rate and pressure drop of glycerol flowing inside a vertical helical coil at constant wall temperature. The flow regime is laminar and new correlations were proposed. Rahul et al. [7] presented a correlation for outside Nusselt number of a helical tube. Their results indicated that the pitch of coil significantly affects the outside heat transfer coefficient. Helical and straight tubes were compared by Prabhanjan et al. [8]. The results showed that a helical coil heat exchanger increases the heat transfer coefficient and the temperature rise of fluid depends on the coil geometry and the flow rate. Xin and Ebadian [9] studied the effect of Prandtl number and geometric parameters on Nusselt number. Ko [10] studied numerically the entropy generation in helical coils at constant wall flux. In his analysis of second thermodynamic law, he found that optimum Reynolds number and curvature ratio are related to the amount of wall heat flux. Naphon and Wongwises [11] reviewed the flow and heat transfer characteristics in curved tubes and tabled the proposed correlations at the applicable ranges. Kumar et al. [12] experimentally and numerically studied tube in tube helical heat exchanger in turbulent regime. The predicted Nusselt number and friction factor were compared with relations proposed by other researchers. Although the boundary conditions were different the results were reasonably in good agreement. Salimpour et al. [13,14] used Wilson plot in order to investigate helical coil heat exchangers experimentally. They presented correlations for inner and outer Nusselt numbers. They reported that as the pitches of coils increase, the shell side heat transfer coefficient increases. Shell side Nusselt number for counter flow is higher than parallel flow configurations. They also used oil for the flow in helical coil to derive the correlations for Nusselt number with variable fluid properties.

Thermophysical properties of fluid are essential in many engineering applications. Conventional heat transfer liquids such as water, oil and ethylene glycol have low thermal conductivity. So there exists a strong motivation in order to overcome these disadvantages to develop more compact and high performance heating and cooling systems. One way to overcome this problem is adding solid particles with high thermal conductivity to the base fluid. An innovative technique to improve the heat transfer is using the nano-scale particles in the base fluid. Fluids with nanoparticles suspended in them are called Nanofluids [15]. Nanofluids introduce a unique approach for treating more effective heat removal in thermal–fluid systems. This technology has been widely used in industries since materials with sizes of

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Nomenclature

c_p	Heat capacity, $W/kg.K$
d	Tube diameter, m
D_c	Coil diameter, mm
f	Friction factor, $f = 2d.\Delta p/L.\rho.u^2$
J	Colburn factor, $J = h.pr^{2/3}/\rho.c_p.u$
JF	JF factor, $J/f^{1/3}$
h	Heat transfer coefficient, $W/m^2.K$
L	Tube length
k	Thermal conductivity, $W/m.K$
Nu	Nusselt number, hd/k
$m^{\bullet}$	Mass flow rate, Kg/s
Pc	Coil pitch, mm
pr	Prandtl number, ν/α
p	Pressure, N.m-2
Re	Reynolds number, $4m^{\bullet}/\pi d \mu$
SN	Signal to noise ratio
T	Temperature, °C
u	Velocity, $m.s^{-1}$
x_i	Cartesian coordinates
Y_i	Quality characteristic

Greek symbols

ρ	Density $kg/m.s$
μ	Viscosity $kg.m^{-3}$
φ	Particle volume fraction (%)

Subscripts

w	water
p	nanoparticles
nf	Nanofluids

nanometers possess unique physical and chemical properties. Heat transfer in a straight tube in laminar regime under constant wall heat flux using Al_2O_3/water Nanofluids was studied by We and Ding [16,17]. They reported that as the particle volume fraction and Reynolds number increase, the heat transfer coefficient increases. They mentioned that Brownian motion of nanoparticles is responsible for decreased thermal boundary layer thickness and finally the enhancement in heat transfer rate. Palm et al. [18] and Roy et al. [19] numerically investigated heat transfer rate by Al_2O_3 in ethylene glycol and water, respectively in laminar regime in radial systems and concluded that as the Reynolds number and particle volume fraction increase the wall shear stress increases.

Literature surveys show that heat transfer rate increases by using helical tubes [8]. In this study the effect of adding nanoparticles in thermal–hydraulic performance of helical tubes is investigated. At first by the use of water the simulation procedure is validated. Then the desired design parameters are given to Taguchi method to estimate the number of simulation. At last, according to the results of simulation for water and Al_2O_3/water, Taguchi algorithm predicts the optimum values of design parameters.

2. Numerical simulation

2.1. Physical model

The design parameters in helical coil are mass flow rate, coil diameter and coil pitch. By adding nanoparticles another design parameter which is nanoparticle volume fractions should be included. The geometry of helical tubes is shown in Fig. 1(a). All

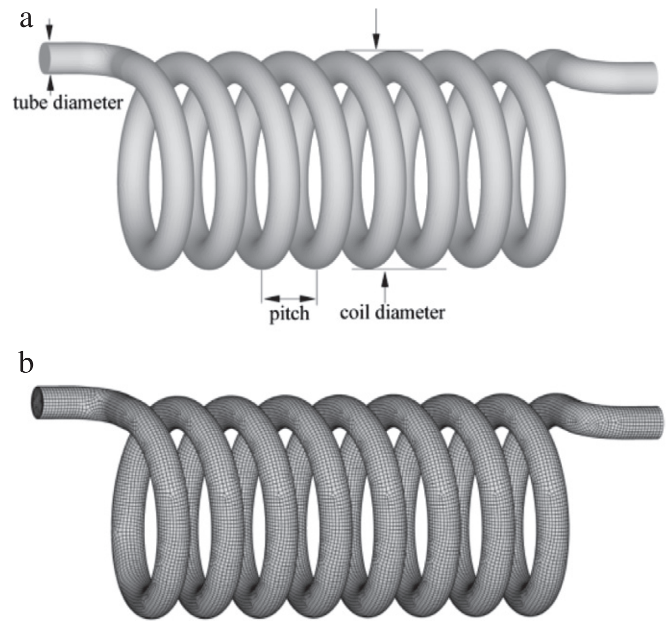

Fig. 1. (a) The geometry and design parameters of helical tubes and (b) the grid system used in simulation.

tubes have the same diameters (12 mm) and occupy the same longitude space. Nanofluids enter the helical tube with uniform velocity and temperature (27 °C) and are affected only by the tube conditions. Nanofluids are incompressible and the flow is laminar. The solid particles in the base fluid are very small so despite the fact that Nanofluids are two phase mixtures, they can be considered a single phase fluid [20]. Therefore it is reasonable to consider Nanofluids with low volume fractions of particles as a single phase flow.

2.2. Thermophysical properties of Nanofluids

Adding nanoparticles to the base fluid change the thermophysical properties of fluid. Measurements show that changes in thermal conductivity and viscosity do not obey the mixture rules. According to the experiments several scientists proposed correlations for predicting the thermophysical properties. But what is evident is that, these proposed correlations do not match and so many parameters such as particle material, size, volume fraction and temperature affect Nanofluids properties. For each case three types of simulation are done according to the fluid flowing inside helical coil, water, Al_2O_3/water with constant properties (thermophysical properties vary only by particle volume fraction) and temperature dependent properties (thermophysical properties vary by particle volume fraction and fluid temperature). The effective properties of the Al_2O_3/water Nanofluids are defined as follow: Density [21]:

$$\rho_{nf} = \varphi \rho_p + (1-\varphi)\rho_w \tag{1}$$

The density of water and alumina are 998.2 and 3880 kg/m3 respectively [22].

Heat capacitance [23]:

$$c_{pnf} = \varphi\left(\rho_p c_{p,s}\right) + (1-\varphi)\left(\rho_p c_{p,s}\right)/\rho_{nf} \tag{2}$$

The heat capacity of water and alumina are 4182 and 729 $W/kg.K$ respectively [22].