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Experimental and numerical investigations of turbulent forced convection flow of nano-fluid in helical coiled tubes at constant surface temperature

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ABSTRACT

In the present research, steady state turbulent forced convection developing flow of a CuO nano-fluid inside helically coiled tubes at constant wall surface temperature was investigated both numerically and experimentally. Both the pressure drop and convective heat transfer behaviors of the nano-fluid were investigated in detail and compared with the results for pure water. In the experimental section, a heat exchanger was designed to provide different helically coiled tubes with constant wall temperature. Based on the temperature and pressure drop measurement at the inlet and outlet of the pipes, the friction factor and Nusselt number were experimentally obtained for both water and the CuO nano-fluid flow. In the numerical part, the governing equations were solved by virtue of finite volume method in OpenFOAM. The buoyant_Boussinesq_SimpleFoam solver with the assumption of single-phase flow and constant effective thermo-physical properties, computed at mean bulk temperature, was employed. The numerical results respectively demonstrate a 6–7% and a 9–10% increase in the convective heat transfer and pressure drop of the applied CuO nano-fluid over pure water, whereas experimental results show a 16–17% increase in the heat transfer coefficient and a 14–16% increase in the pressure drop for different tube geometries and different Re numbers. Furthermore, the results show that both the pressure drop and heat transfer coefficient increase as the curvature ratio and Re number increase. Finally, using the numerical and the experimental results, correlations are proposed to model the friction factor coefficient and the Nusselt number.

1. Introduction

The field of heat transfer is considered as one of the most important active fields in today's world. Many engineering researches and studies look for special techniques to improve the heat transfer rate. The methods to improve heat transfer rate are mainly classified into passive methods and active methods [1]. In the former no energy input is required while a source of energy is needed in the later. Using mechanical mixing, rotation and vibration could be named as examples of the active techniques. While these techniques are considered very effective in increasing the heat transfer rate, they are generally expensive in compact systems resulting in them not being considered as viable options in many situations in industrial applications. On the other hand, passive methods benefit from the change in geometrical and physical properties of the system. For instance, changing the flow regime from laminar to turbulent, modifying the thermo-physical properties of the working fluid and also altering the geometry of the system can all be mentioned as passive techniques since they do not require an external energy source [1]. In this study, the effects of all the three mentioned passive methods are considered.

Modifying the thermo-physical properties of the working fluid can be achieved through different methods one of which is adding solid particles to the fluid. By adding a solid phase to the liquid phase effective thermal conductivity of working fluid will increase and the larger the effective thermal conductivity, the higher the heat transfer rate. To this end, in the past, micro-fluids were used, yet due to the problem associated with the micron size particles, using nano-meter particles seems to be a superior alternative to this goal. Working with nano-fluids instead of micro-fluids provides numerous advantages including the improvement of the heat transfer rate together with an increment in stability, cooling of the micro-channel without clogging and reducing the pumping power [2].

Changing the geometry of the system is another passive method to intensify the heat transfer rate. Using helically coiled tubes instead of

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straight pipes, one can get a higher heat transfer rate as well as a higher pressure drop. Many investigations have been performed in the helically coiled tube field first of which dates back to 1927, the research conducted by Dean who introduced the dimensionless number (D_e) to characterize the flow [3]. Lin and Ebadian investigated the Nu number in the thermally developing region of helical pipes and reported that the local average Nu number oscillates before reaching a constant number at the thermally fully developed section especially for large curvature ratios [4]. Based on their numerical and experimental studies, Jayakumar et al. proposed a correlation for the inner Nu number of turbulent flow inside helical coils [5]. Jayakumar et al. also took the effect of temperature dependency of the thermo-physical properties of the fluid into account. Moreover, they showed that the pitch of the helical coil in the range of their study has little effect on the fully developed Nu number [6].

The research conducted to take the effect of both of the aforementioned methods, changing the geometry of the system and changing the thermo-physical properties of the system, into account is relatively fewer in numbers. A single-phase numerical study carried out by Akbarinia and Behzadmehr [7] shows that increasing the concentration of the particles increases the heat transfer rate and pressure drop for laminar mixed convection flow of nano-fluid in the horizontal curved pipe. Akbarinia and Laur [8] using a 2-phase approach numerically investigated the effect of the particle diameter on the flow and heat transfer. They stated that increasing the diameter of nano-particles decreases the Nu number, and for nanoscale particles increasing the particle diameter does not change the flow pattern. Hashemi and Akhavan-Behabadi [9] investigated the heat transfer and pressure drop of CuO nano-particles and oil based fluid inside vertical helical coils for different Reynolds and Dean numbers in different nano-fluid concentrations. They concluded that the combined use of nano-fluid and helical coil will noticeably increase the Nu number. Akbaridoust et al. [10] conducted an experimental and numerical investigation of CuO nano-fluid inside helical coils at constant temperature surface. Using the single-phase homogeneous approach and effective properties in this study resulted in a numerical estimation underestimating the experimental results. By using the dispersion model developed by Mokmeli and Saffar-Avval [11] for nano-fluids, Akbaridoust et al. were able to estimate the experimental results more accurately. Recently, Bahremand et al. [12] conducted a numerical and experimental study of silver-water nano-fluid inside helical tubes under constant heat flux. They showed that the single phase approach under-predicts the experimental results but a Eulerian–Lagrangian two phase approach which takes the Brownian motion of nano-particles into account leads to a better estimation. Their results indicate that the use of helical coils is a more effective choice for increasing the heat transfer than use of nano-fluids.

Since turbulent flows are involved in many industrial applications such as the heat exchanger industry, studying them is of great importance. Therefore, in this study the experimental and numerical investigations of turbulent flow of CuO–Water nano-fluid were carried out which can be regarded as the continuation of the study performed by Akbaridoust et al. [10].

In this article, the experimental procedures used to obtain the experimental data are explained in Section 2. Details of the experimental device, coils and nano-fluid are presented. Second, the governing equations and the RANS approach to resolve the turbulent flow are explained in Section 3. Third, the numerical approach to solve the governing equations is explained in Section 4. Fourth, the numerical and experimental results are presented in Section 5. Validation of the numerical results are demonstrated for a single phase flow. The numerical results are presented for both water and the nano-fluid and the results are compared to the experimental results. Finally, the reasons justifying the discrepancy between the numerical and the experimental results are explained in Section 6.

Nomenclature			
c_p	specific heat capacity	*Subscripts*	
D	diameter of the pipe	b	bulk
D_e	Dean number	d	diameter
f	friction factor	eff	effective
I	turbulence intensity	fd	fully developed condition
L	length of the pipe	fr	freezing point
n	normal direction	f	fluid
Nu	Nusselt number	m	mass flow average
p	pressure	ml	turbulent mixing length
p	pitch of helical pipe	P	particle
Pr	Prandtl number	bf	base fluid
q''	wall heat flux	st	straight pipe
r	radius of the pipe	s	axial direction
R_c	radius of helical pipe	w	wall condition
Re	Re number based on the average axial flow velocity	*Greek symbols*	
S_{ij}	strain rate tensor	δ	curvature ratio, r/R_c
T_{ij}	viscose stress tensor	ϵ	turbulent dissipation rate
T	Temperature	φ	circumferential angle
k	conductivity, turbulence kinematic energy	Φ	concentration of nano-fluid
u, v, w	components of velocity in x,y,z direction	λ	dimensionless pitch, $p/2\pi R_c$
y^+	non-dimensional wall distance $u^* y/\nu$	μ	viscosity of fluid
y_*	friction velocity $\sqrt{\frac{\tau_w}{\rho}}$	μ_t	turbulence viscosity
Superscripts		θ	angle of section with respect to the inlet
$'$	fluctuation	ρ	density of fluid
$-$	average value	τ_w	wall shear stress
$*$	enhancement technique		

2. Experiments and measurements

2.1. Experimental setup

To carry out the experimental investigation for the turbulent flow of nano-fluids inside a horizontal coiled tube (Fig. 1), the apparatus which its schematic is shown in Fig. 2 was designed. The apparatus has 3 main sections first of which is the reservoir where the nano-fluid flows to the heating section and returns from the cooling section. The heating tank is a 40 $*$ 60 $*$ 40 cm cubic chamber made of a 2 mm stainless steel plate. Heaters were placed at the bottom of the chamber to provide the heat

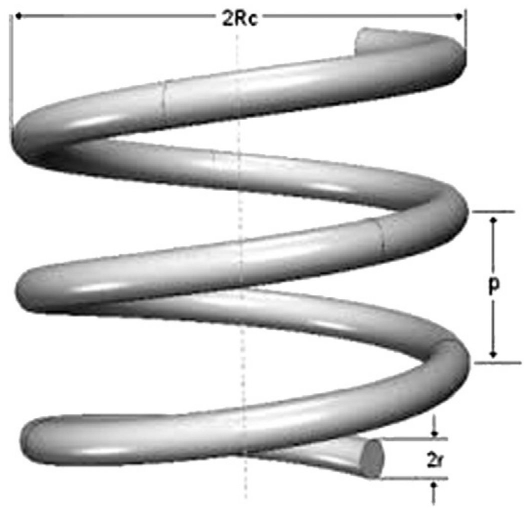

Fig. 1. Schematic of helical tubes.