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Original Research Paper

Experimental and numerical investigation of nanofluid heat transfer in helically coiled tubes at constant wall heat flux

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ABSTRACT

The current study focuses on numerical and experimental investigation of the laminar, steady state flow in helical tubes with constant wall heat flux boundary condition. Pressure drop and convection heat transfer behavior of water–silver nanofluid in helical coils were evaluated and compared to the pure water. In the numerical part of the study, incompressible Navier–Stokes equations, derived from an orthogonal helical coordinate system were solved by finite difference method with projection algorithm using FORTRAN programming language. Homogeneous model with constant effective properties was used for nanofluid. The Local Nusselt number in the entrance region of the helical tubes and the effects of curvature and torsion ratios and Reynolds number have been discussed. In the experimental part, six helical heat exchangers with different curvature and torsion ratios were designed, capable of providing a constant wall heat flux. Pressure drop measurement and fully developed heat transfer coefficient and Nusselt number calculations were carried out and compared with the numerical results.

The results show that for laminar flow with constant wall heat-flux boundary condition, the helical tubes with larger curvature ratio lead to higher heat transfer enhancement and higher pressure drop increase, when employing the nanofluid instead of the base fluid. Moreover, compared to using metal Ag nanofluid in straight tubes, utilization of base fluid in helical coils with greater curvature increases heat transfer more effectively. Finally, we conclude that since using Ag nanofluid increases the heat transfer of helical heat exchangers about 3.5–3.8%, utilizing this nanofluid could enhance the thermal performance of heat exchangers, which can benefit the industry.

1. Introduction

Energy is one of the most important issues facing human beings in the last 50 years. Among all forms of energy we are using today, over 70% of them are produced in or through the form of heat. In many industrial systems, heat must be transferred either to insert energy into a system or to remove the energy produced in a system [1]. For decades, many efforts have been made to enhance heat transfer of heat exchanger. These efforts commonly include passive and active methods such as creating turbulence, extending the exchange surface or the use of a fluid with higher thermo physical properties [2].

As one of the passive enhanced heat transfer methods Helical tubes have been extensively used as heat exchanger in many fields, for example, chemical industry, power production, food industry, environment engineering, waste heat recovery, air conditioning, and refrigeration. Dean [3] was the first researcher who investigated the flow in curved tube. He introduced a dimensionless parameter named Dean number, which could characterizes the flow in curved tube. Patankar et al. [4] investigated the effect of Dean number on friction coefficient and heat transfer both in the developing and fully developed regions of helically coiled pipes.

In curved tubes, centrifugal force causes secondary fluid which significantly increases heat transfer rates of these tubes [5]. Dravid et al. [5] 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 one. They presented a correlation for the asymptotic Nusselt number. Manlapaz and Churchill [6] proposed two reliable correlations for the friction factor and the Nusselt number for the fully developed laminar convection in the helical coils with the constant heat flux. Liu and Masliyah [7] evaluated Nusselt number in developing region of the helical tube numerically and represented correlations for

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Nomenclature

B	binormal direction
C_p	thermal capacity
d	pipe diameter
h	convection heat transfer coefficient
h_r	radial scale factor
h_s	axial scale factor
h_θ	circumferential scale factor
k	thermal conductivity
N	normal direction
Nu	Nusselt number
p	pressure
P_s	coil pitch
Pr	Prandtl number
q''	heat flux
R	coil radius
r	radial direction
r_i	pipe radius
Re	Reynolds number
s	axial direction
T	temperature
t	time
u	velocity component
V	velocity vector
x	position vector
X^+	$\gamma/2RePr$

Greek symbols

μ	dynamic viscosity
φ	volume fraction of the nano particles
ρ	density
τ	torsion ratio
κ	curvature ratio
θ	circumferential direction
ν	kinematic viscosity
α	thermal diffusivity

Subscripts

ave	average
b	bulk
f	fluid
fd	fully developed
in	inlet of pipe
nf	nanofluid
p	particle
r	radial direction
γ	dimensionless distance from entrance
s	axial direction
θ	circumferential direction

Superscripts

$*$	provisional
$\rightarrow$	vectorial quantity
$'$	dimensional quantity
n	iteration number

thermal entrance length. Hüttl et al. [8] used incompressible Navier–Stokes equations derived in an orthogonal helical coordinate system to investigate the effect of torsion and curvature on axial velocity and secondary laminar flow field.

Kim et al. [9] studied developing flow in helical tube and proposed a new correlation for fully developed angles of laminar flows in helical coil.

Due to the low thermal conductivity of pure fluid, suspension of millimeter or micrometer sized particles is created. Although thermal conductivity is high in this mixture, poor suspension stability, corrosion, channel clogging, and great pressure drop are some of the disadvantages of this system [10]. Adding nano sized particles to fluid was first proposed by Choi [11]. Compared to conventional suspension, nanofluids show better stability and rheological properties, reported higher thermal conductivities, and no penalty in pressure drop [12].

Buongiorno [13] developed a two-component nonhomogeneous equilibrium model for mass, momentum and heat transfer for nanofluids. He claimed that heat transfer enhancement is commonly attributed to nanoparticle dispersion.

Investigations of heat transfer behavior of the two phase mixtures such as nanofluids apply two different methods: Single phase approach and two phase approach. Homogeneous model is one of the single phase approaches based on thermo-physical properties of nanofluid as a homogeneous fluid. There are many studies carried out in literature for modeling thermo physical behavior of nanofluids. All the existing models for heat conduction of nanofluid can be categorized into two general groups: static models and dynamic models [14]. Recent models present combined static and dynamic mechanisms.

Murshed et al. [15] represented a model including the effects of particle size, nanolayer, Brownian motion, particle surface chemistry and interaction potential which are the static and dynamic mechanisms responsible for the enhanced effective thermal conductivity of nanofluids. Corcione [16] presented two empirical correlations for predicting the effective dynamic viscosity and thermal conductivity of nanofluids. They derived their correlations based on a large number of experimental data available in the literature.

Akbarinia and Behzadmehr [17] studied laminar mixed convection of a nanofluid in horizontal curved tubes using homogeneous model and showed that concentration has a positive effect on the heat transfer enhancement. Gabriala Huminic and Angel Huminic [18] performed a numerical investigation on the heat transfer characteristics of double-tube helical heat exchangers using nanofluids under laminar flow conditions. They reported that the convective heat transfer coefficients of the nanofluids and water increase with the increase in the mass flow rate and Dean number.

Hashemi and Akhavan-Behabadi [19] conducted an experimental study on heat transfer and pressure drop characteristics of mixed CuO nanoparticles and oil, as a base fluid flow, inside the horizontal helical tube under constant heat flux boundary condition. They defined new parameter index called performance index to evaluate the overall performance of the two enhanced heat transfer methods.

Akbaridoust et al. [20] investigated Pressure drop and the convective heat transfer behavior of nanofluid in helically coiled tubes under constant wall temperature using both numerical and experimental procedures. They employed both homogeneous and Dispersion models for their numerical approach.

Turbulent forced convection flow of nanofluid inside the helical coils under constant wall temperature was investigated both numerically and experimentally by Rakhsha et al. [21]. They used the single phase approach with effective properties for modeling nanofluid. Bahremand et al. [22] studied the turbulent flow inside the helical coils under constant heat flux both numerically and experimentally. Their results indicate that Eulerian–Lagrangian two phase approach results in a better estimation compared to the single phase approach.