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Original Research Paper

Effects of curvature ratio on forced convection and entropy generation of nanofluid in helical coil using two-phase approach

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ABSTRACT

Applying nanofluid and helical coils are two effective methods for thermal performance enhancement. Combination of these techniques could improve the energy efficiency of thermal equipment dramatically. In this study, a numerical analysis of nanofluid flowing in helical coil with constant wall temperature boundary condition was performed to evaluate nanofluid superiority over the base fluid. Forced convective heat transfer and entropy generation of aqueous Al_2O_3 nanofluid with temperature dependent properties were investigated. Eulerian two-phase mixture model was employed for nanofluid modeling and governing mass, momentum, energy, and volume fraction equations were solved using finite volume method. Simulations covered a range of nanoparticle volume fraction of 1–3%, Reynolds number from 200 to 2000, and curvature ratio of 0.05–0.2. In order to evaluate the heat transfer performance, a parameter referred as thermo-hydrodynamic performance index was applied. Also, entropy generation analysis was performed to examine the efficiency of the helical coil and nanofluid. The results demonstrate that performance index enhances by decreasing the Reynolds number and the increasing nanoparticle concentration. The best thermo-hydrodynamic performance can be obtained at low Reynolds number, high nanoparticle volume fraction, and large curvature ratio. Increasing curvature ratio decreases the ratio of local entropy generation by nanofluid to the base fluid. So, utilization of water based Al_2O_3 nanofluid in higher curvature ratio is more efficient from irreversibility point of view.

1. Introduction

Helical coils are widely used in many industrial applications such as food industry, air conditioning, thermal recovery, heat exchangers, etc. One of the best advantages of helical coils is that it provides more surface area in a constant volume. Applying straight pipe in heat transfer equipment creates some mechanical difficulties due to thermal expansion which using of helical coils can minimize it. The heat transfer coefficient and pressure drop in helical coils are higher than straight tubes due to secondary flow which induced by coil curvature and centrifugal force [1,2].

Concerning with fully developed flow, Dean [3,4] performed a theoretical study in a curved pipe and showed that the flow can be characterized by a dimensionless parameter which is named Dean number. Truesdell and Adler [5] investigated the flow in helical coils numerically and found that the effect of pitch on the flow can be offset by replacing the coil radius by the modified coil radius in the case of a small pitch. Vashisth et al. [6] carried out a detailed review on fluid flow and heat transfer in curved pipes with their applications in process industries. De Amicis et al. [7] experimentally and numerically investigated the adiabatic laminar flow in helical coils and found that Ito's correlation shows the best prediction for friction factor.

Relating to developing flow, Dravid et al. [8] numerically and experimentally studied the development of temperature field in helical coil. Patankar et al. [9] numerically investigated the flow and temperature field development in a helical coil of a small pitch. Lin et al. [10] performed a numerical study on the flow and temperature field development simultaneously in a helical coil of a large pitch. Saffari et al. [11] carried out an experimental and numerical study in helical coil in the single phase and two-phase bubbly flow. They proposed a correlation for entrance length in a helical coil based on Reynolds number, Dean number, curvature ratio, and volume fraction. Hardik et al. [2] performed an experimental study on local heat transfer coefficient using infrared thermal imaging technique and proposed overall averaged and local circumferentially averaged Nusselt number.

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Nomenclature

A_c	cross section area (m^2)
Be	Bejan number
c_p	specific heat (J/kg K)
d_p	nanoparticle diameter (m)
d	tube diameter (m)
D	coil diameter (m)
De	Dean number (=$Re\ \delta^{0.5}$)
f_d	drag function
g	gravitational acceleration (m/s^2)
h	local heat transfer coefficient (W/m^2 K)
k	thermal conductivity (W/m K)
Nu	Nusselt number (= hD/k)
p	pressure (*Pa*)
P	coil pitch (*m*)
Pr	Prandtl number (=$c_p k/\mu$)
Q	total heat transfer rate (W)
q''	heat flux (W/m^2)
Re	Reynolds number (=$\rho Vd/\mu$)
S	entropy generation rate (W/K)
S'''	volumetric entropy generation rate (W/m^3 K)
t	time (s)
T	temperature (K)
U	mean velocity (m/s)
V	velocity (m/s)
$\forall$	volume (m^3)

Greek symbol

α	thermal diffusivity (=$k/\rho c_p$)
δ	curvature ratio (=d/D)
κ	Boltzmann constant (=1.3807×10^{-23} J/K)
λ	non-dimensional pitch (=$P/2\pi D$)
μ	dynamic viscosity (N s/m^2)
ν	kinematic viscosity (m^2/s)
ρ	density (kg/m^3)
φ	nanoparticles volume fraction

Subscripts

bf	base fluid
dr	drift
f	fluid
g	global
i	inlet condition
i	indices
j	indices
l	local
m	mixture
nf	nanofluid
o	outlet condition
p	nanoparticle phase
r	radial direction
s	axial direction
w	wall
θ	circumferential direction

The inherently low thermal conductivity of conventional fluids such as water, ethylene glycol, and engine oil limits the heat transfer rate. In order to overcome this problem, Choi [12] invented a new class of fluids which is called nanofluid, by dispersing nanoparticles (average size below 100 nm) in the base fluid. Recent researches indicate that presence of nanoparticles in the fluid at low concentration can enhance the thermal conductivity and heat transfer rate. Hence, nanofluids have attracted researchers' attentions as a new generation of fluids in many industrial applications such as automotive cooling system, technological plants, and heat exchangers.

Akbaridoust et al. [13] numerically and experimentally studied the pressure drop and heat transfer of CuO-water nanofluid flow in helical coils at a constant wall temperature. It is found dispersion model shows a better agreement with experimental data comparing with single phase model. Rakhsha et al. [14] investigated turbulent forced convection of CuO-water nanofluid in helical tubes. They demonstrated inconsistency between experimental and numerical results was attributed to single phase modeling of nanofluid. Mirfendereski et al. [15] performed a numerical and experimental study of laminar Ag-water nanofluid in helical coils with constant wall heat flux. It was revealed that helical coils with greater curvature ratio lead to heat transfer augmentation and pressure drop increment. Bahremand et al. [16] numerically and experimentally studied turbulent Ag-water nanofluid flow in helical tubes with constant wall heat flux. They reported nanoparticles did not significantly affect the axial velocity and turbulent kinetic energy. Bagherzadeh et al. [17] performed a numerical analysis on heat transfer of nanofluid in helical tubes using four-equation model. Their results indicated a better agreement of this model with experiments in comparison with the homogenous model. Khosravi Bizhaem and Abbassi [18] numerically investigated convective heat transfer and entropy generation of nanofluid flow through helical coil in developing and fully developed regions using two-phase mixture model. It is found that applying nanofluid can provide better thermal performance in fully developed region and low Reynolds number.

Almost all of heat transfer enhancement techniques have an expense of friction loss increment, which makes the design of thermal systems as a critical challenge. From the viewpoint of thermodynamic second law, optimum design can be obtained through the effective use of exergy and minimization of entropy generation [19,20]. Ko [21] numerically investigated the entropy generation in a helical coil for both entrance and fully developed region. He found that an optimal Reynolds number exists which produces minimum entropy generation for a specified wall heat flux. Shokouhmand and Salimpour [22,23] analytically studied fully developed laminar flow in helical coils. It was revealed that the optimum Reynolds number decreases when the curvature ratio increases. Amani and Nobari [24] numerically analyzed the developing flow in the curved pipes and showed that the analytical calculations of fully developed flow indicate an acceptable approximations for curved and helical tubes design. Ahadi and Abbassi [25] analyzed the combined effects of length and heat flux on entropy generation and optimal operation of helical coil. The results indicate that optimal values of inlet Reynolds number increases with increase in the inlet temperature and decreases by increasing the combined length and heat flux characteristic.

Nanofluid flow can be modeled via various approaches such as single phase and two phase model. Although two phase models such as Eulerian-Lagrangian or mixture model can predict more accurate results, they require longer computational time instead. In two phase models, base fluid and nanoparticles are considered as distinct phases, which the momentum and heat transfer between phases are modeled using different methods [26,27]. Rostami and Abbassi [28] simulated Al_2O_3-water nanofluid as