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Original Research Paper

Numerical study on heat transfer and entropy generation of developing laminar nanofluid flow in helical tube using two-phase mixture model

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ABSTRACT

Nanofluids and helical tubes are among the best methods for heat transfer enhancement. In the present study, laminar, developing nanofluid flow in helical tube at constant wall temperature is investigated. The numerical simulation of Al_2O_3-water nanofluid with temperature dependent properties is performed using the two-phase mixture model by control volume method in order to study convective heat transfer and entropy generation. The numerical results is compared with three test cases including nanofluid forced convection in straight tube, velocity profile in curved tube and Nusselt number in helical tubes that good agreement for all cases is observed. Heat transfer coefficient in developing region inside a straight tube using mixture model shows a better prediction compared to the homogenous model. The effect of Reynolds number and nanoparticle volume fraction on flow and temperature fields, local and overall heat transfer coefficient, local entropy generation due to viscous dissipation and heat transfer, and the Bejan number is discussed in detail and compared with the base fluid. The results show that the nanofluid and the base fluid have almost the same axial velocity profile, but their temperature profile has significant difference in developing and fully developed region. Entropy generation ratio by nanofluid to the base fluid in each axial location along the coil length showed that the entropy generation is reduced by using nanofluid in at most length of the helical tube. Also, better heat transfer enhancement and entropy generation reduction can be achieved at low Reynolds number.

1. Introduction

The heat transfer enhancement is one of the most important technical purposes for industries and research. In general, there are two techniques to enhance the heat transfer rate that are passive and active methods. Active methods are based on external power input such as magnetic stirring, ultrasonic effects, surface vibration, electrostatic and magnetic fields. These techniques are not easy to incorporate with other components and also increase the cost of systems [1,2]. The other method, passive techniques, used fluid, surface or geometrical modifications to the fluid flow such as swirl flow devices, extended surfaces, coiled tubes, surface tension devices and additives for fluids [3]. In these techniques, heat transfer rate is improved due to the boundary layer disturbance, but pressure drop is also increased. Therefore, their effectiveness depends on the balance between the heat transfer enhancement and pressure drop penalty [1].

Helical coil tubes are widely used in various industrial devices due to the complex motion induced by the curvature and torsion effects. A secondary flow induced by centrifugal force has significant ability to improve the heat transfer rate. Major advantage of helical coils is that, it provides more surface area for a fixed volume. Also, thermal expansion in a straight tube creates some mechanical problems which can be minimized by using helical tubes [4].

Heat transfer characteristic in helical coil tubes have been widely investigated by researchers both experimentally and numerically. Circumferential variation in the wall temperature and heat flux creates complexity in measurement of heat transfer coefficient [4].

Since pioneer study performed by Dean [5,6], a vast number of researches had been conducted on fluid flow and heat transfer in curved and helical tubes. Mori and Nakayama [7] analyzed the flow field and temperature field in a curved pipe with constant heat flux by theory and experiment in a range of very large Dean number. They observed as Dean number and Prandtl number increases, the effect of curvature on flow resistance and heat transfer increases. Patankar et al. [8] investigated the effect of Dean 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	diameter of nanoparticle (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 (=VD/v_m)
S'''	volumetric entropy generation rate (W/m^3 K)
t	time (s)
T	temperature (K)
U	mean velocity (m/s)
V	velocity (m/s)

Greek symbol

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

Subscripts

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

on friction factor and heat transfer in developing and fully developed regions of helical tubes. Their results show satisfactory agreement with available experimental data and theoretical solutions.

Hardik et al. [4] studied the effect of curvature and Reynolds number on local heat transfer coefficient of water in helical tube experimentally. New correlations were suggested for overall averaged and local circumferentially averaged Nusselt number. Jayakumar et al. [9] conducted numerical study on characteristics of heat transfer under turbulent flow of water in helical coils. They investigated the variations of local Nusselt number along the length and circumference at the wall of a helical tube. They found that the Nusselt number on the outer side of the coil has the highest value among all other points at a specified cross-section. Correlation for prediction of local Nusselt number as a function of angular location of the point was presented.

Conventional heat transfer liquids such as water, oil and ethylene glycol have low thermal conductivity. An innovative technique to improve the thermal conductivity of such fluid was introduced by Choi (1995) by dispersing nano-scale particles in the base fluid. The addition of small amount of solid nanoparticles with high thermal conductivity increase their thermal conductivity remarkably. Nanofluids have attracted attention in many industrial applications such as heat exchangers, automotive cooling applications, cooling of electronic devices, etc [10].

Rahimi-Gorji et al. [11] performed a thermal and flow analysis of an unsteady squeezing nanofluid flow in presence of variable magnetic field. They found that the value of Nusselt number and skin friction coefficient for CuO is better than Al_2O_3's. Also, increase in Hartman number results in an enhancement in velocity and temperature profiles.

Turkyilmazoglu [12] investigated the nanofluid flow of condensation film on a vertical wall theoretically using two different model with five types of nanoparticles. The condensate film thickness is found to reduce with heat transfer enhancement as more volume fraction of nanoparticle is added.

Huminic and Huminic [13] studied the heat transfer and entropy generation inside a helical coiled tube-in-tube heat exchanger in laminar flow regime. Heat transfer coefficient, effectiveness, Nusselt number, and entropy generation were investigated considering the nanoparticle concentration between 0 and 2 vol%. They reported that the maximum effectiveness was 91% for 2% CuO and 80% for 2% of TiO_2 nanoparticles. Also, the increase of nanoparticles leads to the Nusselt number increase and the reduction of entropy generation due heat transfer. They showed that the fluid friction have a negligible effect on entropy generation.

Akbaridoust et al. [14] studied pressure drop and heat transfer of laminar nanofluid flow in helical tubes at a constant wall temperature numerically and experimentally. They used homogenous model and dispersion model for their simulations and observed dispersion model have a better agreement with experimental measurements. Utilization of base fluid in a helical tube enhanced the heat transfer more efficiently compared to the use of a nanofluid in a straight tube.

Rakhsha et al. [15] studied turbulent forced convection of CuO-water nanofluid in helical tubes with constant wall temperature, both numerically and experimentally. Their results show that the maximum circumferential Nusselt number tend to reach the outer wall due to geometry of helical tubes and existence of centrifugal force. The inconsistency between the numerical and experimental results was attributed to single phase modeling of nanofluid.

Mirfendereski et al. [16] performed a numerical and experimental investigation of laminar Ag-water nanofluid in helical tubes with constant wall heat flux. Homogenous model with constant effective properties was used for nanofluid in their numerical simulations. The helical tubes with larger curvature ratio lead to higher heat transfer enhancement and higher pressure drop.

Bahremand et al. [17] studied turbulent Ag-water nanofluid flow in helical tubes with constant wall heat flux, both numerically and experimentally. They observed that the nanofluid modeling by the two phase approach predicted more accurate results than the