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Numerical study of developing laminar forced convection of a nanofluid in an annulus

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ABSTRACT

Laminar forced convection of a nanofluid consisting of Al_2O_3 and water has been studied numerically. Two dimensional elliptical governing equations have been solved to investigate the hydrodynamics and thermal behaviors of the fluid flow throughout an annulus. Single phase approach is used for the nanofluid modeling. The velocity and temperature profiles are presented in the fully developed region. The axial evolution of temperature, convective heat transfer coefficient and the friction coefficient at the inner and outer walls' region are shown and discussed. It is shown that the dimensionless axial velocity profile does not significantly change with the nanoparticle volume fraction. But, the temperature profiles are affected by the nanoparticle concentration. In general convective heat transfer coefficient increases with nanoparticle concentration. However, when the order of magnitude of heating energy is much higher than the momentum energy the friction coefficient depends on the nanoparticle concentration. At higher Reynolds numbers for which the momentum energy increases, this dependency on the nanoparticle volume fraction decreases.

1. Introduction

Nowadays after a century of struggling for enhancing industrial heat transfer by fluid mechanics, the low thermal conductivity of conventional fluids such as water, oil, and Ethylene-Glycol (EG) for transferring the heat has been one of the great challenges on the heat transfer science. One of the ways to overcome this problem is to replace conventional fluids with some advanced fluids with higher thermal conductivities. Maxwell's study in 1873 [1] shows the possibility of increasing the thermal conductivity of a fluid–solid mixture by increasing volume fraction of solid particles. Thus, the particles with micrometer or even millimeter dimensions were used. Those particles caused several problems such as abrasion, clogging and pressure losses.

During the past decade technology to make particles in nanometer dimensions was improved and a new kind of solid–liquid mixture that is called nanofluid, was appeared [2]. The nanofluid is an advance kind of fluid containing small quantity of nanoparticles (usually less than 100 nm) that are uniformly and stably suspended in a liquid. The dispersion of a small amount of solid nanoparticles in conventional fluids such as water or EG changes their thermal conductivity remarkably.

Thermal conductivity of nanofluids has been measured by several authors with different nanoparticle volume fraction, material and dimension in several base fluids and all findings show that thermal conductivity of nanofluid is higher than the base fluids. Among them, Lee et al. [3] demonstrated that oxide ceramic nanofluids consisting of CuO or Al_2O_3 nanoparticles in water or ethylene-glycol exhibit enhanced thermal conductivity. For example, using Al_2O_3 nanoparticles having mean diameter of 13 nm at 4.3% volume fraction increase the thermal conductivity of water under stationary conditions by 30% [4]. On the other hand, larger particles with an average diameter of 40 nm led an increase of less than 10% [3]. Different concepts have been proposed to explain this enhancement in heat transfer. Xuan and Li [5] and Xuan and Roetzel [6] have identified two causes of improved heat transfer by nanofluids: the increased thermal dispersion due to the chaotic movement of nanoparticles that accelerates energy exchanges in the fluid and the enhanced thermal conductivity of nanofluid. On the other hand, Keblinski et al. [7] have studied four possible mechanisms that contribute to the increase in nanofluid heat transfer: Brownian motion of the particles, molecular-level layering of the liquid/particles interface, ballistic heat transfer in the nanoparticles and nanoparticles clustering. Similarly to Wang et al. [8], they showed that the effects of the interface layering of liquid molecules and nanoparticles clustering could provide paths for rapid heat transfer.

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Nomenclature

B_c	Boltzman constant (J/K)
C	Specific heat (J/kg K)
C_f	Area average friction coefficient $(= \tau_i A_i + \tau_o A_o / A_i + A_o / (\rho V_0^2/2))$
d_p	Nanoparticle diameter (nm)
d_f	Molecular diameter of base fluid (nm)
f_p	Friction coefficient
h_i	Inner wall convective heat transfer coefficient (W/m^2 K)
h_o	Outer wall convective heat transfer coefficient (W/m^2 K)
k	Thermal conductivity(W/m K)
L_{Bf}	Mean free path of base fluid (m)
N_i	Inner wall Nusselt number
N_o	Outer wall Nusselt number
P	Pressure (Pa)
Pr	Prandtl number
q_w	Uniform heat flux (W/m^2)
r	Radius (m)
Re	Reynolds number
T	Temperature (K)
V	Velocity (m/s)
x	Axial direction

Greek letter

ϕ	Volume fraction
μ	Dynamic viscosity (N s/m^2)
ρ	Density (kg/m^3)

Subscripts

app	appearance
eff	effective
f	base fluid
i	inlet
m	mixture
mr	mixture in radial direction
mx	mixture in axial direction
o	outlet
p	particle
s	solid
w	wall
wi	inner wall
wo	outer wall

Numerous theoretical and experimental studies have been conducted to determine the effective thermal conductivity of nanofluids. However, studies show that the measured thermal conductivity of nanofluid is much larger than the theoretical predictions [9,10]. Many attempts have been made to formulate efficient theoretical models for the prediction of the effective thermal conductivity [11–15]. Chon et al. [14] reported an experimental correlation for the thermal conductivity of Al_2O_3 as a function of nanoparticle size and fluid temperature. They showed that the Brownian motion of nanoparticle constitutes a key mechanism of the thermal conductivity enhancement with increasing temperature and decreasing nanoparticle size.

Nanoparticle high contact surface in comparison with larger particles, not only causes to improve heat transfer ability but also increases stability [4]. Xuan and Li [5] compared two kinds of nanofluid that one consisted in copper nanoparticles with 100 nm in diameter, and other consisted in copper nanoparticles with 10 nm in diameter. They showed that thermal conductivity of nanofluid, which included smaller particles, is higher than the one, which is made by the larger particles. This is also confirmed with the recent works of Li and Peterson [16] and Mints et al. [17]. They showed that the thermal conductivity enhancement of the two nanofluids demonstrated a nonlinear relationship with respect to temperature, nanoparticle volume fraction, and nanoparticle size. In addition they found the importance of the nanoparticle size on the effective thermal conductivity.

During the past decade many researchers have been started to study the hydrodynamic and thermal behaviors of various nanofluids at different flow conditions and also at different geometrical configurations numerically and experimentally. Among them Pak and Cho [18] and Xuan and Li [5,19] experimentally worked on convective heat transfer for laminar and turbulent flow of a nanofluid inside a tube. They introduced the first empirical correlations for the Nusselt number using nanofluids composed of water/Cu, water/TiO_2 and water/Al_2O_3. Ulzie et al. [20] studied laminar convective heat transfer and viscous pressure loss for alumina-water nanofluid in a vertical heated tube. Li and Kleinstreuer [21] studied the thermal performance of nanofluid flow in a trapezoidal microchannel. They showed that nanofluids do measurably enhance the thermal performance of microchannel mixture flow with a small increase in pumping power. Specifically, the thermal performance increases with volume fraction, but the extra pressure drop, will somewhat decrease the beneficial effects. Santra et al. [22] investigated the effect of copper–water nanofluid as a cooling medium to simulate the behavior of heat transfer due to laminar natural convection in a differentially heated square cavity. They observed that the heat transfer decreases with increase in the nanoparticle volume fraction for a particular Ra, while it increases with Ra for a particular nanoparticle volume fraction. Mirmasoumi and Behzadmehr [23] have studied the effects of nanoparticle mean diameter on the heat transfer and flow behavior into a horizontal tube under laminar mixed convection condition. Their calculated results demonstrate that the convection heat transfer coefficient significantly increases with decreasing the nanoparticles means diameter. However, the hydrodynamics parameters are not significantly changed. They also showed that the non-uniformity of the particles distribution augments when using larger nanoparticles and/or considering relatively high value of the Grashof numbers.

An appraisal of thermal augmentation of thermoelectric module using nanofluid-based heat exchanger is presented by Nnanna et al. [24]. They showed that there exist a lag-time in thermal response between the module and the heat exchanger. This is attributed to thermal contact resistance between the two components.

Numerical calculation of nanofluid convective heat transfer has been done in general with two different approaches; single phase or two-phase approach. The first one assumes that the fluid phase and nanoparticles are in thermal and hydrodynamic equilibrium. This approach is simpler and requires less computational time. Thus, several theoretical studies of convective heat transfer with nanofluids [25–29] used this approach. However, as mentioned by Ding and Wen [30] the distribution of the nanoparticles could only be assumed uniform if the corresponding Peclet numbers is always less than 10.

Annulus appears in many industrial heat exchangers. Therefore, many investigations have been done on the heat transfer mechanisms of an annulus. Among them Srivastava et al. [31] experimentally investigated the effect of an unheated length and the annulus ratio on the variations in heat transfer coefficient in the