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Anomalous heat transfer enhancement by slip due to nanofluids in circular concentric pipes

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ABSTRACT

Convective heat transfer of nanofluids in circular concentric pipes under the influence of partial velocity slips on the surfaces and the resulting anomalous heat transfer enhancement are investigated in the present paper. Single phase nanofluid model is employed to get fully developed exact laminar flow and temperature fields accounting for the thermal boundary conditions of both the heated outer wall with the inner wall insulated and the heated inner wall with the outer wall insulated. The presented closed-form solutions of velocity and temperature fields as well as the Nusselt number derivation are able to explain the slip effects on different nanofluids and their contribution to anomaly level of enhancement in the rate of heat transfer, which is the main interest of the recent literature. Results clearly indicate that the anomalous heat transfer enhancement as observed in the experiments and numerical solutions of nanofluid flows occurring in the circular concentric shapes is mainly due to the velocity slip mechanism.

1. Introduction

The circular concentric pipes are recently receiving great attention to explore their hydrodynamical and thermal features, particularly their contribution to heat transfer design. They have various real life applications such as vehicle thermal management [21], heat exchangers [11], solar energy collectors [15,18], thermal storage systems [4], cooling of electronics [8], advanced nuclear systems [5] and microelectromechanical systems in science [7]. The present research is devoted to the single phase nanofluids phenomenon concerning the convective heat transfer within circular concentric pipes taking into account slip velocity effects under heated or adiabatic thermal boundary conditions.

The past two decades witnessed intensive theoretical, numerical and experimental efforts to highlight unique properties of nanofluids with a particular concern of heat transfer enhancement in several engineering applications. Heat transfer characteristics of natural convection in the annulus between horizontal concentric cylinders using different types of nanofluids were investigated numerically in [1]. The nanofluids as compared to the common base fluids including water, ethylene glycol and oil [2] exhibit enhanced thermal conductivity and the convective heat transfer coefficient [10]. Flow and convective heat transfer characteristics of water-based Al2O3 nanofluids in fully developed laminar flow regime were experimentally investigated in [9]. The experimental results showed that the convective heat transfer coefficient enhancement exceeds, by a large margin, the thermal conductivity enhancement. The convective heat transfer coefficient of the nanofluids increases by up to 8% at a concentration of 0.3 vol% compared with that of pure water and it was conjectured that the flattening of velocity profile is a possible mechanism for the convective heat transfer coefficient enhancement exceeding the thermal conductivity enhancement. Exact analytical solutions for heat and mass transfer of MHD slip flow in nanofluids were computed in [19]. A dozen of engineering applications were reviewed in [6]. In [17], a comprehensive review of previous efforts is presented for different convective flow regimes and heat transfer through microtubes and microchannels exposed to velocity slips. In [3], forced convection Al_2O_3-water nanofluid flows in two-dimensional rectangular microchannels were investigated to study heat transfer enhancement due to addition of the nanoparticles to the base fluid especially in microchannels at low Reynolds numbers.

It is now well-known that either single-phase (homogeneous) or two-phase approaches are adopted in the experimental or numerical modeling of heat transfer analysis of nanofluids. In a recent study by Yang et al. [20], Buongiorno's model [4] was modified to investigate the nanofluid flow and heat transfer in a concentric annulus. They found anomalous heat transfer enhancement in the presence of nanofluids when the inner wall of the pipe is insulated. Particularly, the level of anomaly was shown to be

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largely changing relying upon the ratio of diameter of inner to outer pipe. Pursuing this regulated model of [20,12], presented a numerical study of fully developed convective heat transfer of alumina/water nanofluid inside a circular microchannel in the presence of a uniform magnetic field and slip velocity at the walls. In [13], the modified Buongiorno's model of [20], was used to study the fully developed mixed convective heat transfer in a vertical pipe annulus where the flow meets the Navier's slip condition instead of a conventional no-slip condition at the pipe walls. It was concluded that increasing the strength of mixed convection enhances the concentration, velocity and temperature closer to the heated wall surface, leading to both increase in heat transfer and pressure gradients. Moreover, it was concluded that nanofluids can transfer heat more efficiently in a slip condition than in a no-slip condition. Moshizi et al. [14], recently studied Al_2O_3-water nanofluids in a concentric annulus within the perspective of convective heat transfer in the presence of heat generation or absorption by modifying Buongiorno's model and using that of [20], taking into account the slip velocity and showed that heat generation or absorption greatly alters behavior of the flow and thermal layers in nanofluids.

The motivation for the current research is threefold. The first is to employ the single phase model of nanofluids to cover the effects of velocity slip on the fully developed circular concentric pipes flow and heat transfer by extending the pure rarefied slip gas flow study of [7]. In contrast to the conclusions of [7], it is shown that the velocity slip mechanism greatly enhances the rate of heat transfer, an outcome that is also in complete parallel to the aforementioned recent publications. The second goal is to mathematically support the numerical findings of [20], from the framework of single nanofluid flow model with slip. It is indeed shown that anomalous heat transfer enhancement occurs particularly for the heated outer wall with the inner wall insulated, whose level is higher when the inner to outer diameter ratio is smaller, modifying the configuration towards a single circular pipe. And finally, it is aimed at explaining the outcome of the experiment of Hwang et al. [9] from the viewpoint of slip again. Indeed, slightly increasing the slip results in very much enhanced transfer of heat adhering the flattening property of velocity profiles in absolute compliance with the evidences of experimental and numerical conducts of Hwang et al. [9]. The flattening feature on the velocity and the consequent anomalous heat transfer enhancement of both slip and concentration of suspended nanoparticles in different nanofluids are also consistent with the recent numerical findings of [12–14].

2. Mathematical formulation and solution

Let us consider the hydrodynamically and thermally fully developed water-based flow of nanofluids flowing through circular concentric pipes, whose physical setup is displayed in Fig. 1. According to the figure, the r-axis is normal to the pipe walls and the x-axis is aligned horizontally, the inner and outer pipe radii correspond to r_i and r_o, and the walls of the pipe are permitted to carry equal but opposite slip velocities of nanofluids and they are either preserved at constant heat flux q of outer wall with the inner wall insulated, or the outer wall at adiabatic wall condition while inner wall subjected to a constant wall heat flux q. The motion is due to a constant pressure gradient with respect to x-coordinate. Since the fully developed flow and thermal conditions in the long tube are presumed, the variations along x-axis are dropped except the temperature gradient.

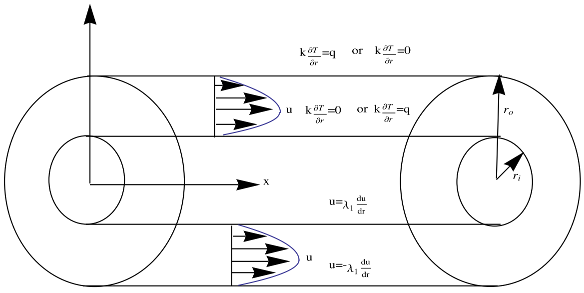

Fig. 1. Basic nanofluid flow configuration in a circular concentric pipe.

Table 1
Thermo-physical properties of water and nanoparticles [16].

	ρ (kg/m^3)	C_p (J/kg K)	k (W/mK)	$\beta \times 10^5$ (K^{-1})
Pure water	997.1	4179	0.613	21
Copper (Cu)	8933	385	401	1.67
Copper oxide (CuO)	6320	531.8	76.5	1.80
Silver (Ag)	10500	235	429	1.89
Alumina (Al_2O_3)	3970	765	40	0.85
Titanium oxide (TiO_2)	4250	686.2	8.9538	0.9

We assume that the nanofluid layer is developed in accordance with a single phase mode in the presence of equally distributed nanoparticles concentration. The fluid is a water based nanofluid containing five distinct types of nanoparticles: Ag, Cu, Cuo, Al_2O_3 and TiO_2, whose thermo physical properties are outlined in Table 1. Together with the energy equation, the full mathematical model including the boundary conditions is given in the motion through the annulus by the single phase system

$$
\begin{aligned}
&\frac{1}{r}\frac{d}{dr}\left(r\mu_{nf}\frac{du}{dr}\right)=p_x,\\
&(\rho c_p)_{nf}u\frac{\partial T}{\partial x}=\frac{1}{r}\frac{d}{dr}\left(rk_{nf}\frac{\partial T}{\partial r}\right),\\
&u=\lambda_1\frac{du}{dr}\quad \text{at } r=r_i,\quad u=-\lambda_1\frac{du}{dr}\quad \text{at } r=r_o,\\
&\frac{\partial T}{\partial r}=0\quad \left(\text{or } k_{nf}\frac{\partial T}{\partial r}=q\right)\quad \text{at } r=r_i,\\
&k_{nf}\frac{\partial T}{\partial r}=q\quad \left(\text{or } \frac{\partial T}{\partial r}=0\right)\quad \text{at } r=r_o,
\end{aligned}
\tag{1}
$$

where u is the velocity along the r-direction, T is the local temperature and p is the pressure. λ_1 is the slip velocity factor, the subscript nf stands for the nanofluid property, and additionally the nanofluid properties appearing in (1) are respectively,

$$
\begin{aligned}
&\mu_{nf}=(1-\varphi)^{-2.5}\mu_f,\\
&\rho_{nf}=(1-\varphi)\rho_f+\varphi\rho_s,\\
&k_{nf}=k_f\frac{k_s+2k_f-2\varphi(k_f-k_s)}{k_s+2k_f+\varphi(k_f-k_s)}
\end{aligned}
\tag{2}
$$

with φ the solid volume fraction or concentration, ρ_f and ρ_s the densities of the pure fluid and nanoparticle, k_f and k_s are the thermal conductivities of the base fluid and nanoparticle, respectively, and c_p is the heat capacitance. It should be reminded that the effective thermal conductivity of the nanofluid k_{nf} approximated as above is due to Maxwell–Garnett [16]. It is also noted that the velocity slip given in (1) is due to both the base fluid and the nanoparticle, which was already adopted in the works of [7,14]. Such a slip mechanism is necessary to explain findings of the recent experimental and numerical studies on the topic as fully discussed in the coming sections.

Defining the mean velocity as

$$u_m=\int_{r_i}^{r_o} ru\,dr$$