Hall and ion slip effects on mixed convection flow of nanofluid between two concentric cylinders

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Abstract This article analyzes the effects of Hall and ion-slip parameters on mixed convective electrically conducting nanofluid flow between two parallel concentric cylinders considering magnetic field. The governing equations are non dimensionalized. The resulting system of nonlinear ordinary differential equations is solved utilizing homotopy analysis method. The influence of the magnetic parameter, Hall, ion-slip, Brownian motion and thermophoresis parameters on non-dimensional velocity, temperature and nanoparticle volume fraction is analyzed and represented graphically. It is found that increasing Hall and ion-slip parameters decrease the temperature but increase the velocity and nanoparticle volume fraction and the opposite trend observed when magnetic parameter increased. It is observed that as Brownian motion and thermophoresis parameters increase, the velocity and temperature increase but the nanoparticle volume fraction decreases.

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1. Introduction

The analysis of heat transfer and mixed convection flow in an annular region between two concentric cylinders has been concentrating on vast investigation for many years. This is because of its wide range of applications in the model of cooling devices for microelectronic and electronic equipment, solar energy collection, etc. A number of investigations have been reported on the convective heat transfer flows in the annulus region between two concentric cylinders (See Dawood et al. (2015) for review of such flows). Nanofluids are intermission of nanoparticles in a mixed conventional fluid Choi and Eastman (1995). Nanofluids, first pioneered by Choi and Eastman (1995), consist of uniformly dispersed and suspended nanometer sized particles in a base fluid. It has been established experimentally that these fluids have a thermal conductivity more than the base fluids. Nanofluids have applications in microelectronics, micro fluidics, transportation, biomedical, X-rays, material processing and scientific measurement. Buongiorno proposed an analytical model for convective transport in nanofluids, which incorporate the effects of Brownian diffusion and thermophoresis. Brownian motion and thermophoresis of nanoparticles were considered as the most probable mechanisms. The arbitrary motion of nanoparticles within the base fluid is called Brownian motion and this results from continuous collisions between the nanoparticles and the molecules of the base fluid. Brownian motion of nanoparticles constitutes a key mechanism of the thermal conductivity enhancement with increasing temperature and decreasing nanoparticle size with no effect in heat transfer of nanofluids. The phenomenon in which the particles can diffuse under the

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influence of a temperature gradient is called thermophoresis. The thermophoresis force tends to move the particles in the direction opposite to the temperature gradient, and in contrast, the Brownian motion force tends to move the particles from high concentration to low concentration areas of the fluid. Due to Brownian diffusion and thermophoresis the nanoparticles can move homogeneously with the fluid but they also possess a slip velocity relatively to the fluid. Several investigators analyzed the heat transfer and mixed convection flow of nanofluids in an annular region under various aspects. A numerical study of mixed convection of nanofluid in a concentric annulus with rotating inner cylinder is studied by Sheikhzadeh et al. (2013). Togun et al. (2014) presented a detailed review on convective heat transfer of fluid and nanofluid flow through various annular passage configurations with different boundary conditions for various fluids. Jamshad and Tauseefmohyuddin (2014), Tauseefmohyuddin et al. (2015), Tauseefmohyuddin and Irfanullahkhan (2016) and Zulfiqar et al. Zulfiqar and Tauseefmohyuddin (2016) analyzed heat and mass transfer analysis for the flow of a nanofluid between rotating parallel plates. Kandelousi and Ellahi (2015), Sheikholeslami and Ellahi (2015a,b), Sheikholeslami et al. (2016) studied the influence of induced magnetic field on free and mixed convective heat transfer of nanofluid. Naveed et al. (2016) numerically investigated the flow and heat transfer of nanofluid in an asymmetric channel with expanding and contracting walls suspended by carbon nanotubes. Aggregation effects on water base nanofluid over permeable wedge in mixed convection and the influence of induced magnetic field and heat flux with the suspension of carbon nanotubes for the peristaltic flow in a permeable channel studied by Akbar et al. (2015), Ellahi et al. (2015), Ellahi et al. (2016) Mojtab et al. (2016), Rahman et al. (2016) and Rashidi et al. (2015). Heat transfer effects on carbon nanotubes suspended nanofluid flow in a channel with non-parallel walls under the effect of velocity slip boundary condition is numerically studied by Irfanullahkhan et al. (2015), Umar et al. (2015, 2016).

Convection and heat transfer using nanofluids has acquired considerable attention in present days. It is due to their diverse application in scientific, engineering and industrialized applications such as cooling of nuclear reactor, power generating systems, automobile engines, welding equipment and heat exchanging in electronics devices. The convective heat transfer and fluid flow problems with the interaction of magnetic field have attracted much attention due to several astrophysics and industrial applications. Chamkha et al. (2015) presented a review on various research work done on the MHD convection of nanofluids in various geometries and applications. Mozayyeni and Rahimi (2012) studied the effect of the magnetic field applied in the radial direction on the mixed convective flow in a cylindrical annulus with rotating outer cylinder. Ashorynejad et al. (2013) studied numerically the mixed convective heat transfer in an annuli of horizontal cylinder filled with nanofluid considering constant radial magnetic field on the fluid. Omid et al. (2013) obtained an analytical solution to the influence magnetite field on mixed convective in an annuli. Sheikholeslami and Abelman (2015) studied the heat and mass transfer of nanofluid flow between two coaxial cylinders considering magnetic field. Das et al. (2015) analyzed the mixed convective nanofluids flow in a concentric cylindrical pipes considering a uniform magnetic field.

In the investigations concerned with the MHD convective flows, the Hall current and ion slip terms in Ohm's law were neglected in order to simplify the mathematical analysis of the problem. However, the significance of Hall current and ion slip are essential in the existence of strong magnetic field. Therefore, in several physical situations it is required to include the influence of Hall current and ion slip terms in the MHD equations. The effects of the Hall current on electrically conducting steady viscous fluid in channels was studied by Tani (1962). Srinivasacharya and Kaladhar (2012, 2013) studied the effects of Hall current, the ion slip effect on mixed convective couple stress fluid flow between two circular cylinders. Garget et al. Garg et al. (2014) investigated the impact of Hall parameter on oscillatory convective viscoelastic magnetohydrodynamic flow in a vertical channel. Hayat et al. (2016) addressed the effects of Hall and ion slip, radiation and viscous dissipation on the mixed convective flow of nanofluid in a channel.

The literature survey reveals that the problem on mixed convective heat transfer flow of nanofluid in a concentric cylinders considering the impact of Hall current, ion slip parameter has not been considered. Also, the interaction of Hall current, ion slip influence with magnetite nanoparticles in a mixed convective flow, presents an interesting fluid dynamics problem. Hence, the aim of this paper is finding the impact of the Hall and ion slip parameter on the heat transfer flow of steady mixed convection nanofluid in a concentric cylinders. The homotopy analysis procedure is used to find the solution of ordinary differential equations. The HAM method, developed by Liao (2003), is a powerful technique to solve the various types of strongly non-linear equations. The effect of flow parameters on the velocity, temperature, nanoparticle volume fraction are examined.

2. Formation of the problem

Let the steady, laminar and incompressible nanofluid flow in the annular space between two infinitely long concentric cylinders of radius a and $b(a < b)$ and kept at temperatures T_a and T_b respectively. Choose a cylindrical polar coordinate system (r, φ, z) with z-axis along the common axis of the cylinders (as shown in Fig. 1) and r normal to the z-axis. Assume that the outer cylinder is rotating with a constant angular velocity Ω whereas the inner cylinder is at rest. The flow is generated because of the rotation of the exterior cylinder. Since the flow is fully developed and the cylinders are of infinite length, the flow depends only on r and a strong magnetite field B_0 is imposed in an axial direction. The induced magnetic field is ignored with the presumption of the magnetic Reynolds number is very low. Assume relatively high electron-atom collision frequency so that the impact of Hall, ion slip cannot be omitted. Thermophysical characteristics of the nanofluid are taken as constant except density in the buoyancy term of the momentum equation. The flow is a mixed convection flow taking place under thermal buoyancy and uniform pressure gradient in azimuthal direction. The velocity component along φ direction, temperature and nanoparticle volume fraction are denoted by u, T and ϕ, respectively. With the above assumptions and Boussinesq approximations with energy, the equations governing the steady flow of an incompressible nanofluid Buongiorno (2006) are