International Journal of Mechanical Sciences 130 (2017) 350–359

Contents lists available at ScienceDirect

International Journal of Mechanical Sciences

journal homepage: www.elsevier.com/locate/ijmecsci

Thermophoretic particle deposition on magnetohydrodynamic flow of micropolar fluid due to a rotating disk

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ARTICLE INFO

Keywords:
Thermophoresis
Rotating disk
MHD
Micropolar Fluid
Forced convection
Heat and Mass transfer

ABSTRACT

An investigation is made to study the micropolar fluid flow of transient thermophoretic particle deposition of forced convective unsteady heat and mass transfer flow due to a rotating disk in the presence of uniform magnetic field. The governing nonlinear partial differential equations are transformed using similarity transformation and the numerical methods are discussed using Nachtsheim-Swigert shooting iteration technique along with sixth-order Runge-Kutta integration scheme. The obtained results show that the Nusselt number increases with an increase in the unsteadiness parameter. The results also show that micro-rotational tangential velocity decreases with the increase of the magnetic parameter.

1. Introduction

The theory of micropolar has received great attention during the recent years, because of traditional Newtonian fluids can't precisely describe the characteristic of fluid with suspended particles. Physically, micropolar fluids may present the non-Newtonian fluids consisting of dumb-bell molecules or short rigid cylindrical elements, polymer fluids, fluid suspensions and animal blood. The presence of dust or smoke particular of a gas may also be modeled using micropolar fluid dynamics. Eringen [1] first derived the theory of micropolar fluids, which describes the microrotation effects to the microstructures. Since, Navier-Stokes theory does not describe previously the physical properties of polar fluids, colloidal solutions, suspension solutions, liquid crystals and fluid containing small additives. Eringen [2] extended the theory of thermomicropolar fluids and derived the constitutive laws for fluids with micro structure which has opened up a new area in research in the field of fluid flow. The boundary layer growth of this fluid is discussed by Chawla [3]. He found that the characteristics of two modes of propagation waves, during the initial and final stages of the boundary layer growth. A review of many researchers work in simple problems on the flow of micropolar fluid is given by Ariman et al. [4] which indicate an importance of research work in this field. Recently, Chen et al. [5] briefly introduced the fundamentals of micropolar fluid dynamics (MFD), and proposed a numerical scheme using integrating Chorin's projection method and time centered split method (TCSM) for solving unsteady forms of MFD equations.

Flow due to a rotating disk is encountered in many industrial, geothermal, geophysical, technological and engineering applications. A few of them are rotating heat exchangers, rotating disk reactors for bio-fuels production, computer disk drives and gas or marine turbines. Von Karman [6] studied the fluid flow due to an infinite rotating disk by introducing famous differential equations into ordinary differential equations. Ariman et al. [7] discussed the concept of micropolar fluid flow between two concentric cylinders. Then micropolar flow due to a rotating disc with suction and injection was carried out by Guram and Anwar [8]. The boundary layer flow of micro-polar fluid on rotating axisymmetric surfaces with a concentrated heat source was discussed by Gorla and Takhar [9]. The flow of two dimensional can be converted into three dimensional for a specified condition was proposed by Erdogan [10]. The problem of steady axisymmetric flow and heat transfer in an incompressible micropolar fluid between two porous discs was analysed by Takhar et al. [11]. The quasisteady two dimensional micropolar fluid flow between two coaxial cylinders was studied by Sherief et al. [12]. Hartmann et al. [13] was the first person to investigate the case of the laminar flow of an electrically conductive liquid in a homogeneous magnetic field. Hayat et al. [14] investigated the squeezing flow of an incompressible micropolar fluid between two parallel infinite disks in the presence of a magnetic field. In the case of suction, the angular velocity decreases in the vicinity of a lower disk while its magnitude increases in the vicinity of the upper disk when Hartman number is increased and the opposite trend is observed in the case of blowing. Ashraf and Batool [15] numerically studied an axisymmetric steady laminar incompressible flow of an electrically conducting micropolar fluid over a stretchable disk. It resulted that the shear stress factor is lower for micropolar fluids as compared to Newtonian fluids, which may be beneficial in flow and heat control of polymeric processing. Turkyilma-

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http://dx.doi.org/10.1016/j.ijmecsci.2017.06.029
Received 21 April 2017; Received in revised form 2 June 2017; Accepted 18 June 2017
Available online 20 June 2017
0020-7403/

zoglu and Senel [16] developed the effects of heat and mass transfer phenomenon in rotating flow of viscous incompressible fluid due to a porous disk. Rashidi et al. [17] presented the hydromagnetic flow of viscous fluid due to a rotating disk under different properties. In this investigation, they also analyzed the effect of entropy generation in the considered flow problem. Different researchers analyzed the magnetic flow with and without rotating disk models in disparate conditions and media [18–25]. Khan et al. [26] studied the Bodewadt flow of water based nanofluid over a deformable disk. They computed the numerical solutions of considered flow problem.

When a temperature gradient exists, the suspended particle will tend to move from regions of high temperature to low. The force which produces this effect is called the thermophoretic force. The phenomenon of thermophoresis plays a vital role in the mass transfer mechanism of several devices involving small micron sized particles and large temperature gradients in the fields. Evolution of thermophoresis concept was slowly developed from the theoretical problem of the thermophoresis of aerosol particles in the laminar compressible boundary layer on a flat plate which was considered by Goren [27]. Further, this theory was moved to heated boundary layer by Talbot et al. [28]. They formulated a fitting formula for thermophoretic force useful over the entire range of Knudsen numbers. Then deposition of thermophoretic particles in gas flowing was studied by Batchelor and Shen [29]. They raised the possibility of devising an approximate universal relation between concentration and temperature. Sub-micron deposition from a laminar forced convection boundary layer developing on a heated isothermal vertical cylinder has been investigated by Chiou and Cleaver [30]. They experimently observed that for the heated wall of the heated cylinder resulted in a non-uniform temperature distribution along the cylinder. Due to the developments of this field the last few decades created more attention towards the applications of this field for various physical situations. As this way, a simple approach for evaluating the effect of wall suction and thermophoresis on aerosol particle deposition from a laminar flow over a flat plate is proposed by Tsai [31]. Alam et al. [32] studied thermophoretic particle deposition on two dimensional MHD heat and mass transfer flow over a semi-infinite permeable inclined flat plate with various flow conditions. The thermophoresis particle deposition on transient forced convective heat and mass transfer flow along a wedge with variable viscosity and variable Prandtl number is considered by Rahman et al. [33]. The thermophoresis particle deposition on transient forced convective flow due to a rotating disk is discussed by Alam et al. [34]. The magnetohydrodynamic flow of nanofluid due to a rotating disk with slip effect is studied numerically by Hayat et al. [35]. They found that a reduction in the concentration distribution and related thickness of concentration layer with an increase of Lewis number.

The present work investigates the effects of the thermophoretic particle deposition of forced convective unsteady heat and mass transfer flow of micropolar fluid due to a rotating disk in the uniform electromagnetic field. Using the similarity transformations the governing equations are transformed into a system of ordinary differential equations. They are solved numerically using Nachtsheim-Swigert shooting iteration technique along with sixth-order Runge-Kutta integration scheme. These results are discussed with graphs and tables to illustrate the influence of various parameters on flow, heat and mass transfer characteristics.

2. Mathematical formulations

Let us consider a rotating disk with constant angular velocity Ω about the z axis in a non-rotating cylindrical polar frame of reference (r, φ, z), where z is the vertical axis in the cylindrical coordinates system with r and u as the radial and tangential axes respectively. At $z = 0$, the disk is placed and a unsteady, axially symmetric flow of viscous incompressible electrically conducting non-Newtonian(micropolar fluid) fluid occupies the region $z > 0$. The flow configurations and coordinate system is shown in Fig. 1. The components of the flow velocity q are (u, v, w) and micro-rotational velocity ν are (ν_1, ν_2, ν_3) in the direction of increasing (r, φ, z) respectively. A magnetic field $B = B_0 + b$ is applied perpendicular to the plane of disk. As the magnetic Reynolds number is small due to the induced magnetic field b which is negligible as compared with the imposed field, and hence b is neglected. Uniform temperature T_w and species concentration C_w is maintained at the surface of the rotating disk which is far away from the wall, and the free stream temperature is T_∞($> T_w$) and the ambient fluid is assumed to be C_∞.

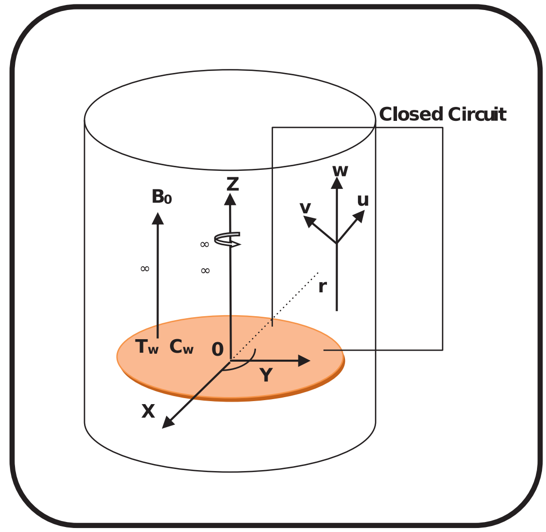

Fig. 1. Schematic diagram.

Following the assumptions stated above, conservation of the mass, momentum with MHD, micro-rotation momentum, energy and particle concentration equations can be written as

$$\frac{\partial u}{\partial r} + \frac{u}{r} + \frac{\partial w}{\partial z} = 0 \tag{1}$$

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial r} - \frac{v^2}{r} + w\frac{\partial u}{\partial z} = -\frac{1}{\rho}\frac{\partial p}{\partial r} + \frac{\mu + k}{\rho}\left(\frac{\partial^2 u}{\partial r^2} + \frac{1}{r}\frac{\partial u}{\partial r} - \frac{u}{r^2} + \frac{\partial^2 u}{\partial z^2}\right) - \frac{k}{\rho}\frac{\partial \nu_2}{\partial z} - \frac{\sigma B_0^2 u}{\rho} \tag{2}$$

$$\frac{\partial v}{\partial t} + u\frac{\partial v}{\partial r} - \frac{uv}{r} + w\frac{\partial v}{\partial z} = \frac{\mu + k}{\rho}\left(\frac{\partial^2 v}{\partial r^2} + \frac{1}{r}\frac{\partial v}{\partial r} - \frac{v}{r^2} + \frac{\partial^2 v}{\partial z^2}\right) + \frac{k}{\rho}\left(\frac{\partial \nu_1}{\partial z} - \frac{\partial \nu_3}{\partial r}\right) - \frac{\sigma B_0^2 v}{\rho} \tag{3}$$

$$\frac{\partial w}{\partial t} + u\frac{\partial w}{\partial r} + w\frac{\partial w}{\partial z} = -\frac{1}{\rho}\frac{\partial p}{\partial z} + \frac{\mu + k}{\rho}\left(\frac{\partial^2 w}{\partial r^2} + \frac{1}{r}\frac{\partial w}{\partial r} + \frac{\partial^2 w}{\partial z^2}\right) + \frac{k}{\rho}\left(\frac{\partial \nu_2}{\partial r} + \frac{\nu_2}{r}\right) \tag{4}$$

$$\frac{\partial \nu_1}{\partial t} + u\frac{\partial \nu_1}{\partial r} - \frac{v\nu_2}{r} + w\frac{\partial \nu_1}{\partial z} = \frac{\gamma}{\rho j}\left(\frac{\partial^2 \nu_1}{\partial r^2} + \frac{1}{r}\frac{\partial \nu_1}{\partial r} - \frac{\nu_1}{r^2} + \frac{\partial^2 \nu_1}{\partial z^2}\right) - \frac{k}{\rho j}\left(\frac{\partial v}{\partial z} + 2\nu_1\right) \tag{5}$$

$$\frac{\partial \nu_2}{\partial t} + u\frac{\partial \nu_2}{\partial r} + \frac{v\nu_1}{r} + w\frac{\partial \nu_2}{\partial z} = \frac{\gamma}{\rho j}\left(\frac{\partial^2 \nu_2}{\partial r^2} + \frac{1}{r}\frac{\partial \nu_2}{\partial r} - \frac{\nu_2}{r^2} + \frac{\partial^2 \nu_2}{\partial z^2}\right) + \frac{k}{\rho j}\left(\frac{\partial u}{\partial z} - \frac{\partial w}{\partial r} - 2\nu_2\right) \tag{6}$$