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Microstructure and inertial characteristics of a magnetite ferrofluid over a stretching/shrinking sheet using effective thermal conductivity model

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ABSTRACT

Nanofluid is the most promising gift of modern science to improve the heat transfer capabilities of conventional heat transfer fluids. However, one of the most crucial drawbacks for classical nanofluid models is that they cannot describe a class of fluids that have certain microscopic characters arising from the micro-rotation and local structure of the fluid elements. In this work, the innovative micropolar nanofluid model is introduced to study the microstructure and inertial characteristics of the substructure particles. More exactly, the flow and heat transport of micropolar ferrofluid over a stretching/shrinking sheet subjected to suction and injection is studied. Magnetite-Fe_3O_4 (iron oxide) nanoparticles are considered in water taken as conventional base fluid. The mathematical model has been formulated based on Tiwari-Das nanofluid model. Explicit exact solutions of non-linear coupled momentum equations are obtained. The solution of energy equation is obtained in terms of Whittaker function with the help of Maple. The impacts of pertinent parameters on velocity, micro-rotation velocity and temperature are shown graphically for positive and negative mass transfer flow and analyzed in detail. The results show that micro-rotation velocity increases first and then decreases. There is a remarkable change occurs to micro-rotation velocity for positive and negative values of mass transfer parameter. Presence of mass transfer parameter accelerate the profiles near the flow domain and then decelerates it. Further, micropolar ferrofluid have higher velocity than the classical nanofluid. Comparison have been made with published data under special cases and obtained in close agreement.

1. Introduction

Conventional heat transfer fluids such as water, ethylene glycol and engine oil are poor heat transfer fluids because of low thermal conductivity and thus cannot fulfil the high demand of industrial and technological fields. Recent advances in nanotechnology allow to develop a new class of fluids termed nanofluids, which is firstly utilized by Choi [1]. Since then, this research topic has attracted the attention of many researchers worldwide in view of its fascinating thermal characteristics and potential applications in numerous fields such as microelectronics, biomedical and transportation. Pak and Cho [2] performed experiments on the turbulent heat transfer flow of two different types of suspended nanoparticles γ-alumina (Al_2O_3) and titanium dioxide (TiO_2) nanofluid. The experimental data showed that the dispersed nanoparticles enhanced convective heat transfer coefficient of water. Eastman et al. [3] showed with some preliminary experiments with Cu-water suspended nanoparticles and found that the heat transfer coefficient higher than predicted for pure water. Qiang and Yimin [4] also performed an experiment on Cu-water based nanofluid and found better results as compared to the obtained results of Eastman et al. [3]. Other notable experimental work on nanofluids include those by Rashidi and Nezamabad [5]; Mahanta and Abramson [6]; Sun et al. [7] and Walvekar et al. [8].

There are two mathematical models constantly used to study the behaviour of nanofluids, namely, Buongiorno model [9] and Tiwari-Das model [10]. The first model deals with the seven main mechanisms of slip between solid and fluid phases such as inertia, Brownian diffusion, diffusiophoresis, thermophoresis, fluid drainage, Magnus effect and gravity settling. After examining all these mechanisms, he concluded that in the absence of turbulent effects, Brownian diffusion and thermophoresis are two important dominating mechanisms in nanofluids. Buongiorno model ware used in many recent papers by Buongiorno and Hu [11]; Kuznetsov and Nield [12]; Noghrehabadi et al. [13]; Mutuku and Makinde [14]; Xua and Pop [15]; Khan and Makinde [16], among others. Later, this model has been also extensively used in various problems of nanofluid over stretching and shrinking surfaces. For example, Zaimi et al. [17] studied the heat transfer flow of a nanofluid over a stretching/shrinking surface. Khan et al. [18] used finite difference scheme to a convective heat and mass transfer past a convectively-heated stretching sheet using third-grade nanofluids model in the presence of partial slip. Qasim et al. [19]

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investigated heat and mass transfer of a nanofluid thin film past a stretching sheet in the presence of magnetic field. Numerical approach for magneto-nanofluid over a stretching sheet was used by Akbar et al. [20] considering Buongiorno model. Mohyud-Din et al. [21] studied the heat and mass transfer through convergent/divergent channels in a nanofluid. Khan et al. [22] examined the MHD flow of nanofluid over a nonlinearly stretching/shrinking wedge. Recently, the impact of radiation on the melting heat transfer nanofluid over a stretching sheet has been scrutinized by Sheikholeslami and Rokni [23]. Further, few recent studies on Buongiorno model are given in Sheremet and Pop [24]; Sheikholeslami et al. [25]; Sheikholeslami and Ganji [26]; Ahrar and Djavareshkian [27]; Mustafa [28] and Ahmad et al. [29].

The second model is the Tiwari-Das model which considers the volume fraction of nanoparticles instead of the Brownian motion and thermophoresis effects. Later many researchers focused on this model to study the heat transfer characteristics in nanofluids under different physical situations. Yu et al. [30] measured the thermal conductivity of nanofluids containing graphene oxide nanosheets and found that higher enhancement in thermal conductivity compare to the ethylene glycol. Yacob et al. [31] studied the convective flow of Cu-water and Ag-water nanofluids past a stretching/shrinking surface. Vajravelu et al. [32] also used same nanoparticles, and studied free convection flow over a stretching sheet with internal heat generation or absorption. Other representative studies on Tiwari-Das model using different types of nanoparticles can be found in Hamad [33]; Hamad et al. [34]; Sheikholeslami et al. [35]; Sheikholeslami and Ganji [36]. On the other hand, Ebaid and Sharif [37] studied heat transfer flow of CNTs nanofluids under magnetic field. The effect of chemical reaction with water based Cu, Al_2O_3 and SWCNTs nanofluids is studied by Kandasamy et al. [38]. MHD flow of water base nanofluids containing Cu, Al_2O_3 and TiO_2 past an accelerated plate was considered by Hussanan et al. [39]. Saleh et al. [40] have extended the work of Ebaid and Sharif [37] by taking the convective condition effects in both cases of suction and injection flow. Both of these problems have been solved exactly via the application of Laplace transform. Khan et al. [41] presented heat transfer flow of nanofluids contain CNTs in a channel with Navier slip condition. Sheikholeslami [42] studied magnetic field effect on CuO-H_2O nanofluid flow in a porous channel. Impact of Coulomb force and thermal radiation on Fe_3O_4-Ethylene glycol nanofluid heat transfer through porous enclosure is observed by Sheikholeslami and Rokni [43].

Micropolar fluid theory was developed by Eringen [44], deals with a class of fluids that exhibits certain microscopic characters arising from the local structure and microrotation of the fluid elements. These fluids contain dilute suspensions of rigid macromolecules with individual motions that support stress and body moments and are affected by spin inertia. The flow equations of such fluids involve micro-rotation vector and gyration parameter in addition to the velocity vector. Hassanien and Gorla [45] discussed heat transfer in a micropolar fluid from a stretching surface. This problem was extended by Mohammadein and Gorla [46] to include the viscous dissipation and heat generation. Turkyilmazoglu [47] analyzed flow due to a porous stretching sheet. The condition of Newtonian heating on micropolar fluid was applied by Hussanan et al. [48]. Although numerous publications are available, see for example, Hussanan et al. [49]; Waqas et al. [50]; Saleh et al. [51], who considered micropolar model under different effects and geometries. However, micropolar model are not examined under nanoparticles effect. The addition of nanoparticles in a micropolar fluid, make the mixture more complex as compare to conventional nanofluids. This research provides a new dimension for researchers to explore nanofluid characteristics. Das and Duari [52] presented the numerical solution of the flow of a micropolar nanofluid over a stretching sheet in the presence of chemical reaction by using Buongiorno model approach. This problem was extended by Hsiao [53] to include the viscous dissipation and investigated its influence on MHD heat transfer flow in absence of chemical reaction. Recently, the effect of free convection with water, engine oil and kerosene based micropolar nanofluid over a vertical plate is studied by Hussanan et al. [54] by using Tiwari-Das mathematical model.

The present work suggests that micropolar ferrofluid, magnetite Fe_3O_4 nanoparticles suspended in conventional micropolar fluid, provide one of the possible solution to the challenges highlighted above. Keeping in view of thermal physical and magnetic properties of Fe_3O_4 nanoparticles, a mathematical model for the micropolar ferrofluid flow in the presence of thermal radiation over a stretching/shrinking subjected to suction and injection is developed based on Tiwari-Das nanofluid model. Summary of analytical and numerical studies on Buongiorno and Tiwari-Das nanofluid models are given in Tables 1 and 2, respectively. Thermo-physical properties of H_2O and magnetite-Fe_3O_4 are given in Table 3 (Sheikholeslami et al. [55]; Sheikholeslami and Shehzad [56]).

2. Problem formulation

Consider the steady two-dimensional boundary layer flow of a micropolar ferrofluid over a stretching/shrinking sheet. The x-axis is taken along the sheet and y-axis is normal to it. A transverse magnetic field B_0 is applied perpendicular to the sheet and the stretching/shrinking sheet velocity is assumed as $u_w(x) = ax$, where $a < 0$ is a constant for shrinking and $a > 0$ for stretching sheet, as shown in Fig. 1(a) and (b). Under these assumptions, the flow of micropolar ferrofluid governed by the following equations

$$\frac{d}{dt}\left(\rho_{nf}\right) = \nabla\cdot\left(\rho_{nf}\mathbf{V}\right), \tag{1}$$

$$\rho_{nf}\left(\frac{d\mathbf{V}}{dt}\right) = -\nabla p + \left(2\mu_{nf}+\kappa\right)\nabla(\nabla\cdot\mathbf{V}) - \left(\mu_{nf}+\kappa\right)\nabla\times(\nabla\times\mathbf{V}) + \kappa(\nabla\times\mathbf{N}) + \mathbf{J}\times\mathbf{B} + \rho_{nf}\mathbf{g}, \tag{2}$$

$$\rho_{nf} j\left(\frac{d\mathbf{N}}{dt}\right) = \left(\varphi+\lambda+\gamma_{nf}\right)\nabla(\nabla\cdot\mathbf{N}) - \gamma_{nf}\nabla\times(\nabla\times\mathbf{N}) + \kappa(\nabla\times\mathbf{V}) - 2\kappa\mathbf{N} + \rho_{nf}\mathbf{l}. \tag{3}$$

Table 1
Summary of analytical and numerical studies on Buongiorno nanofluid model.

References	Nanoparticles	Geometry	Method
Kuznetsov and Nield [12]		Vertical plate	Analytically
Noghrehabadi et al. [13]		Stretching sheet	Numerically
Mutuku and Makinde [14]		Vertical plate	Numerically
Xua and Pop [15]		Horizontal channel	Analytically
Khan and Makinde [16]		Stretching sheet	Numerically
Zaimi et al. [17]		Stretching/shrinking sheet	Numerically
Khan et al. [18]		Stretching surface	Numerically
Qasim et al. [19]		Stretching sheet	Numerically
Akbar et al. [20]		Stretching surface	Numerically
Sheikholeslami and Rokni [23]		Stretching plate	Numerically
Sheremet and Pop [24]		Horizontal cylindrical	Numerically
Sheikholeslami et al. [25]		Parallel plates	Numerically
Sheikholeslami and Ganji [26]		Parallel vertical permeable sheets	Numerically
Ahrar and Djavareshkian [27]	Al_2O_3	Square cavity	Numerically
Mustafa [28]		Rotating disk	Numerically
Ahmad et al. [29]		Thin needle	Numerically
Mohyud-Din et al. [57]		Rotating plates	Analytically
Khan et al. [58]		Porous wedge	Numerically
Sheikholeslami [59]	CuO	Porous cavity	Numerically