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ORIGINAL ARTICLE

Effect of partial slip on an unsteady MHD mixed convection stagnation-point flow of a micropolar fluid towards a permeable shrinking sheet

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Abstract The objective of the present study was to investigate the partial slip effect on an unsteady two-dimensional mixed convection stagnation point flow towards a permeable shrinking sheet. The governing equations are reduced to a system of non-dimensional partial differential equations using a semi-similarity transformation, before being solved numerically by using Keller-box method. The features of the flow characteristics for different values of the governing parameters are analysed and discussed. The results indicate that the momentum, thermal and concentration boundary layer thicknesses increase with increasing mixed convection parameter for opposing flow, whereas the opposite effect is observed for assisting flow. The results also show that the surface velocity is higher when there is slip at a sheet compared to its absent. Further, the study indicates that the boundary layer thicknesses become thicker and thicker with increasing shrinking parameter, while the opposite effect is observed with increasing Hartmann number. Comparison with previously published work for special cases is performed and found to be in excellent agreement.

1. Introduction

The study of hydromagnetic stagnation point flow of an incompressible viscous fluid has attracted many researchers due to wide applications in industries and engineering. Some of the applications are the aerodynamic extrusion of plastic sheets, geothermal energy extractions, cooling of nuclear reactor, plasma studies, cooling of underground electric cables, geothermal energy extractions, artificial fibres and blood flow problems. Hiemenz [1] was first to investigate the two-dimensional stagnation flow towards a stationary plate. On the other hand, the flow over a linearly stretching plate was first considered by Crane [2]. Chiam [3] combined Hiemenz and Crane's problems by considering the steady two-dimensional stagnation-point flow of an incompressible viscous fluid towards a stretching sheet. Kumari and Nath [4] studied the effect of the magnetic field on the stagnation point flow with heat transfer over a stretching sheet. Mahapatra and Gupta [5] investigated the steady two-dimensional

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stagnation-point flow of an incompressible viscous electrically conducting fluid towards a stretching sheet. Sharma and Singh [6] studied the steady MHD two-dimensional stagnation point flow towards a stretching sheet with variable thermal conductivity. Ashraf and Rashid [7] investigated the radiation effect on MHD two-dimensional stagnation point flow towards a heated shrinking sheet. Mostafa and Shimaa [8] investigated the combined effects of magnetic field and thermal radiation on a steady micropolar fluid near a stagnation point towards a moving surface. Bhattacharyya et al. [9] studied the boundary layer flow near a stagnation point with heat and mass transfer over a shrinking sheet with Soret and Dufour effects. Zeeshan et al. [10] investigated MHD natural convection flow of a water/ethylene glycol nanofluid with inverted cone through a porous medium. Ellahi et al. [11] examined MHD flow of a Jeffrey fluid on a peristaltic flow in a rectangular duct embedded in a porous medium. Khan et al. [12] investigated the peristaltic motion and heat transfer of Oldroyd fluid in a channel with inclined magnetic field. The effect of magnetic field on blood flow of Prandtl fluid in a porous walls through a tapered stenosed artery was investigated by Ellahi et al. [13]. Akbar et al. [14] studied the combined effects of magnetic field and heat flux for two different water based nanoparticles for the peristaltic flow in a symmetric vertical permeable channel. Recently, Kandelousi and Ellahi [15] examined the combined effects of MHD and ferrohydrodynamic on Fe_3O_4-plasma nanofluid flow in a vessel and obtained the results using lattice Boltzmann method.

In recent times, the boundary layer flow due to a shrinking sheet is received considerable attention due to its wide engineering applications. Miklavčič and Wang [16] studied the steady viscous flow over a shrinking sheet for both two-dimensional and axisymmetric cases. The effect of suction on MHD boundary layer flow with heat and mass transfer past a shrinking sheet was examined by Muhaimin et al. [17]. Fang and Zhang [18] obtained an exact solution for steady MHD flow with suction over a shrinking sheet. Since the vorticity (rotation or non-potential) flow over a shrinking sheet is not confined within the boundary layer and the flow is likely to exist, whether an adequate suction on the boundary is imposed or a stagnation point (which contains the vorticity) is considered. The stagnation point flow towards a shrinking sheet for both two-dimensional and axisymmetric cases was first investigated by Wang [19]. He found that solutions do not exist for large shrinking rates and may be non-unique in two-dimensional case. Fang et al. [20] numerically investigated the viscous flow over an unsteady shrinking sheet with mass transfer. Fan et al. [21] extended Wang's problem to unsteady flow. Suali et al. [22] studied heat transfer on an unsteady stagnation point flow with suction over a stretching/shrinking sheet. Recently, Bhattacharyya [23] discussed the unsteady boundary layer flow and heat transfer near a stagnation-point towards a shrinking/stretching sheet.

All of the above mentioned studies are restricted to the flows of Newtonian fluids. These Newtonian fluids cannot describe some engineering and industrial processes which are made up of materials having an internal structure. The micropolar fluids are described as a non-Newtonian fluid consisting of dumb-bell molecule, fluid suspension, polymer fluids, animal blood. The presence of smoke or dust in a gas may also model using micropolar fluid dynamics. The theory of micropolar fluid model introduced by Eringen [24] exhibits the local effects arising from the microstructure and micro motion of the fluid elements. Comprehensive reviews of the subject and its applications can be found in the review articles of Peddieson and McNitt [25], Ariman et al. [26,27] and books by Łukaszewicz [28] and Eringen [29]. Guram and Smith [30] and Gorla [31] investigated the steady micropolar fluid near a stagnation point. Nazar et al. [32] examined the steady two-dimensional stagnation-point flow over a stretching sheet. Ishak et al. [33] studied the two-dimensional mixed convection boundary layer flow of a micropolar fluid near the stagnation point over a stretching sheet. Ishak et al. [34] numerically investigated the steady two-dimensional stagnation-point flow of a micropolar fluid over a shrinking sheet. Ashraf and Bashir [35] numerically investigated the effect of MHD on the steady two-dimensional stagnation-point flow of a micropolar fluid towards a heated shrinking sheet. Aman et al. [36] studied the mixed convection stagnation point flow on a vertical surface in the presence of slip effects. Reddy et al. [37] considered the boundary layer flow near a stagnation point of electrically conducting micropolar fluid over a stretching sheet with viscous dissipation, chemical reaction and heat source/sink. Hayat et al. [38] examined the unsteady stagnation point flow of second grade fluid over a porous stretching sheet. Ellahi et al. [39] investigated the unsteady flow of a micropolar fluid through a composite stenosis in arterial blood flow with slip velocity. In other paper, Ellahi et al. [40] studied micropolar fluid with heat and mass transfer of blood flow in a porous walls through a tapered stenosis arteries. Recently, Aurangzaib and Shafie [41] investigated the unsteady MHD flow near a stagnation-point of a micropolar fluid past a shrinking sheet with thermophoresis and slip effects.

In some practical situations, it is important to replace the no-slip condition by the partial slip condition because when fluid flows in micro electro mechanical system (MEMS), the no-slip boundary condition at the solid-fluid interface is no longer applicable. The non-equilibrium region near the interface is more accurately described by the slip flow model. Wang [42] found closed form solution of two-dimensional viscous flow due to stretching sheet with the effects of slip and suction. Aman and Ishak [43] investigated the effect of partial slip on the steady incompressible flow over shrinking permeable sheet. Das [44] studied the effect of partial slip and temperature dependent fluid properties on steady hydro-magnetic micropolar fluid flow over an inclined permeable plate in the presence of chemical reaction, thermal radiation and heat source/sink. Das [45] investigated the steady MHD mixed convection boundary layer stagnation point flow of a micropolar fluid towards a shrinking sheet in the presence of partial slip. Ellahi and Hameed [46] investigated MHD flow of a second grade fluid with heat transfer in a channel with nonlinear slip effects. Zeeshan and Ellahi [47] obtained the series solution of MHD slip flow and heat transfer of a non-Newtonian third grade fluid in a porous pipe. The mixed convection flow and heat transfer past a porous vertical cylinder were investigated by Ellahi et al. [48]. Recently, Chen [49] considered the unsteady mixed convection stagnation point flow on a stretching sheet with slip effect.

Motivated by the above discussions, the effect of partial slip on an unsteady MHD mixed convection stagnation point flow with heat and mass transfer in a micropolar fluid towards a permeable shrinking sheet is investigated in this paper. The unsteadiness is caused by the impulsive motion of the external