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Research Article

Effects of Magnetic Field and Viscous Dissipation on Oberbeck Convection in a Chiral Fluid and Mass Transfer Flow through Porous Media

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Abstract

A chiral molecule is a type of molecule that lacks an internal plane of symmetry and thus has a non-superposable mirror image of a molecule. Chiral fluid is a fluid which has molecules and exhibits the chirality. The influence of viscous dissipation on convective flow, heat transfer, and mass transfer through viscous incompressible chiral fluid through a vertical porous layer immersed in porous medium in the presence of a uniform magnetic field is investigated. The coupled non-linear equations governing the motion are solved analytically using the regular perturbation method with Eckert number E_c as perturbation parameter. The effect of magnetochiral number M, porous parameter σ, Grashof number G_r, Eckert number E, and Schmidt number Sc on velocity, temperature distribution, mass flow rate, skin friction and rate of heat transfer are depicted graphically and some important conclusions are drawn.

Keywords: *Oberbeck convection, chiral fluid and porous medium*.

1. Introduction

Coupled heat and mass transfer driven by buoyancy due to temperature and concentration variations in a saturated porous medium, has several important applications in geothermal and geophysical such as the migration of moisture through the air contained in the fibrous insulation, the extraction of geothermal energy and so on (Sharma et. al, 2011). The fluid flow and heat transfer in a porous medium is still a topic of current research interest due to its numerous industrial and environmental applications. Several comprehensive works published in this field (see, e.g., Rudraiah etal 1980, effect Nield and Bejan, 2006, Vafai, 2005, Bejan 2004, Pop, 2001,Sharma et, al., 2011, Barletta et. al., 2007, Ahmed, 2008,2009, Sahin et. al., 2011,)give a convincing evidence of this development. Special attention has been given to the internal flows in ducts and channels filled with porous media, with a broad application in building physics, mechanical, electrical, chemical, energy and environmental engineering. The thermally developing forced convection flow in a parallel-plate channel or circular tube filled by a saturated porous medium with walls at uniform temperature or uniform heat flux, with axial conduction and viscous dissipation, has been investigated by an extended Graetz method in a series of papers by Nield *et al*. (2003,2004) and Kuznetsov *et al*. (2003).

In spite of some similarities compared to the viscous flow of clear fluids, the internal (forced, free and mixed) convection in saturated porous media shows also essential differences. Nevertheless, the vast literature accumulated along the decades in the latter field (see, e.g., the comprehensive overviews by Shah and London ,1978 and Kakac and Yener, 1995) offers a solid orientation and help in the investigation of analogous problems in porous media. Thus, Storesletten and Pop (1996) have extended the problem of buoyancy–driven viscous flow in a vertical parallel plane channel posed by Banks and Zaturska (1991) to the case of a vertical porous layer with non-uniform wall temperature. The effect of viscous dissipation has been included in the study of the combined free and forced convection in a porous medium between two vertical walls by Ingham *et al*. (1990). Al-Hadhrami *et al*. (2003) proposed a new model for viscous dissipation in porous media across a range of permeability values, while Umavathi *et al*. (2005) presented a numerical and analytical study of the mixed convection in a vertical porous channel using the Brinkman-Forchheimer model with various combinations of boundary conditions and with viscous dissipation effects included. More recent contributions to the effect of viscous dissipation in addition to the buoyancy effects have been published by Nield (2000), (2004) and by Magyari *et al*. (2005).Chamka (2004) studied the unsteady MHD convective heat and mass transfer past a semi-infinite vertical permeable moving plate wi h heat absorption. Combined heat and

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mass transfer in MHD free convection from a vertical surface with Ohmic heating and viscous dissipation was presented by Chien (2004). The study of vertical channel flow bounded by a wavy wall and a vertical flat plate filled with a porous medium was presented by Ahmed (2008). Later on Ahmed (2009) also investigated the effects of free convection heat transfer on three-dimensional channel flow through a porous medium with periodic injection velocity. Fasogbon (2010) studied the simultaneous buoyancy force effects of thermal and species diffusion through a vertical irregular channel by using the parameter perturbation technique.

The problem that we consider in the present paper is to find the influence of viscous dissipation and magnetic field on Oberbeck convection in a chiral fluid with saturated porous media. A chiral material characterized by either left handed or right handed, is a type of molecule that lacks an internal plane of symmetry and has a non-super-imposable with its mirror image by any amount of rotation and translation (see Rudraiah et.al 2010). It is noticed that, the cause for chirality in molecules, is the presence of an asymmetric carbon atom. The term chiral, in general, is used to describe an object that is non-superposable on its mirror image. Human palms are the most universally recognized example of chirality because the left or right palm is non-superposable with its mirror image. A mathematical approach in chirality is the concept of "handedness" either left handed or right handed. Although the origin of chirality in life is still obscure, it is the source of diverse phenomena at the macromolecular and molecular level, governing our environment and the existence of living organisms. Considerable amount of work has been done during the last three decades on scattering from chiral objects (Lakthakia *et al*, 1988, 1994). More recently, Rudraiah et.al (2013) have studied the effects of variation of viscosity and viscous dissipation on Oberbeck magnetoconvection in a chiral fluid and also, the effects of variation of viscosity and viscous dissipation on Oberbeck magnetoconvection in a chiral fluid. Also, they have, studied double diffusive Oberbeck Convection in a chiral fluid in the presence of chemical reaction and thermal radiation and the effects of temperature dependent viscosity and coriolis force on Oberbeck convection in a chiral fluid in the presence of a uniform transverse magnetic field has not been given much attention.

The objective of the present study is therefore to investigate the effects of viscous dissipation and magnetic field on Oberbeck convection in a chiral fluid with saturated porous media in the presence of a uniform transverse magnetic field. The required basic equations along with the Maxwell equations, continuity of charges and the constitutive equations for chirality are given in section 2. Details of the non dimensional procedure and parameters are described in this section only. The equations for skin friction, heat transfer and Sherwood number are derived in section 2.1. Analytical solutions of the coupled linear momentum, energy and concentration of species equations are obtained. The velocity, temperature, skin friction, rate of heat transfer and Sherwood number are computed and the results obtained are depicted graphically, for different values of controlling parameters influencing the flow characteristics to reveal the underlying physics.

2. Mathematical Formulation

We consider a physical configuration as shown in Fig. 1 which consists of an incompressible Boussinesq chiral fluid saturating an infinite vertical sparsely packed porous layer of width h.The temperature and concentration differences across the boundaries are ΔT and ΔC respectively. A Cartesian frame of reference is chosen with x and y axes in the vertical and horizontal directions respectively. A uniform magnetic field B_0 is applied in the z direction which is perpendicular to both x and y axes and also a uniform suction/injection velocity v_0 is applied in the y direction. The flow in the porous medium is governed by the Darcy-Brinkman equation with fluid viscosity different from effective viscosity.

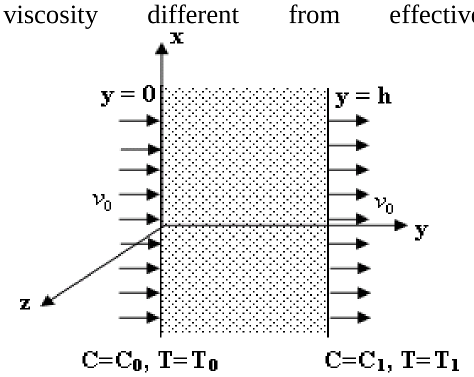

Fig.1 Physical configuration

The governing equations describing chiral fluid flow are Conservation of mass for incompressible fluid:

$$\nabla \cdot \vec{q} = 0, \tag{1}$$

Conservation of momentum:

$$\rho_0 \left[\frac{\partial \vec{q}}{\partial t} + (\vec{q}\cdot\nabla)\vec{q} \right] = -\nabla p + \rho\,\vec{g} + \mu\nabla^2\vec{q} + \vec{J}\times\vec{B} - \frac{\mu}{k'}\vec{q}, \tag{2}$$

Conservation of energy:

$$\rho_0\, c_p \left[\frac{\partial T}{\partial t} + (\vec{q}\cdot\nabla)T \right] = k\nabla^2 T + \phi, \tag{3}$$

where $\phi = 2\mu \left[\begin{array}{l} \left(\frac{\partial u}{\partial x}\right)^2 + \left(\frac{\partial v}{\partial x}\right)^2 + \left(\frac{\partial w}{\partial x}\right)^2 + \frac{1}{2}\left(\frac{\partial u}{\partial y} + \frac{\partial v}{\partial x}\right)^2 + \\ \frac{1}{2}\left(\frac{\partial v}{\partial z} + \frac{\partial w}{\partial y}\right)^2 + \frac{1}{2}\left(\frac{\partial w}{\partial x} + \frac{\partial u}{\partial z}\right)^2 \end{array} \right]$

Conservation of Species:

$$\frac{\partial C}{\partial t} + (\vec{q}\cdot\nabla)C = D\nabla^2 C, \tag{4}$$

Conservation of charges

$$\frac{\partial \rho_e}{\partial t} + \nabla \cdot \vec{J} = 0, \quad (5)$$

where $\vec{J} = \rho_e \vec{q}$ (since the displacement current is negligible compared to convective current).

We assumes the flow is fully developed, steady and unidirectional. Therefore, all the physical quantities vary only with respect to y except the pressure. For a state of equilibrium, we have

$$-\frac{\partial p}{\partial y} = \rho_0 \vec{g} \quad (5a)$$

Equation of state for an incompressible Boussinesq chiral fluid is

$$\rho = \rho_0 \left(1 - \beta\left(T - T_0\right) + \beta^*\left(c - c_0\right)\right). \quad (6)$$

The constitutive equations for chiral fluids [Rudraiah et. al,2010, Lakhtakia, 1988] are:

$$\vec{D} = \varepsilon \vec{E} + i\gamma \vec{B}, \quad (7)$$

$$\vec{B} = \mu \vec{H} - i\mu\gamma \vec{E}, \quad (8)$$

Under these assumptions, equations (1), (2), (3), (4) and (5) take the form:

$$\frac{\partial v}{\partial y} = 0, \quad (9)$$

$$\nu \frac{d^2 u}{dy^2} - v_0 \frac{du}{dy} - \frac{\nu}{\kappa'} u + \beta\left(T - T_0\right) g - \beta^*\left(C - C_0\right) g + \frac{\rho_e v_0 B_0}{\rho_0} = 0, \quad (10)$$

$$k \frac{d^2 T}{dy^2} - \rho_0 c_p v_0 \frac{dT}{dy} + \mu \left(\frac{du}{dy}\right)^2 = 0, \quad (11)$$

$$D \frac{\partial^2 C}{\partial y^2} - v_0 \frac{\partial C}{\partial y} = 0, \quad (12)$$

ρ_e =*constant.* (13)

We make these equations (9) to (13) dimensionless using the quantities:

$$y^* = \frac{v_0}{\nu} y,\ u^* = \frac{u}{v_0} u,\ \rho_e^* = \frac{\rho_e}{\left(\varepsilon^2 E_0^2 + \gamma^2 B_0^2 / h\right)},$$
$$\theta = \frac{\left(T - T_0\right) v_0 k}{q'\nu}, C = \frac{\left(c - c_0\right) v_0 D}{m\nu}. \quad (14)$$

Using eqn (14), eqns (10), (11) and (12) neglecting the asterisks (*) for simplicity, become

$$\frac{d^2 u}{dy^2} - \frac{du}{dy} + Gr\,\theta - Gm\,C + \frac{M}{\mathrm{Re}^2} - \frac{\sigma^2}{\mathrm{Re}^2} u = 0, \quad (15)$$

$$\frac{d^2 \theta}{dy^2} - Pe \frac{d\theta}{dy} + Ec\,\mathrm{Pr} \left(\frac{du}{dy}\right)^2 = 0, \quad (16)$$

$$\frac{d^2 C}{dy^2} - Sc \frac{dC}{dy} = 0. \quad (17)$$

where

$M = \dfrac{\rho_e \left(\varepsilon^e E_0^2 + \gamma^2 B_0^2\right) B_0}{h}$ Magnetochiral number,

$R_e = \dfrac{v_0 h}{\nu}$ Reynolds number, $\sigma = \dfrac{h}{\sqrt{k}}$ Porous parameter,

$G_r = \dfrac{g\beta q \nu^2}{v_0^4 k}$ Grashof number for heat

$G_m = \dfrac{g\beta^* m \nu^2}{v_0^4 k}$ Grashof number for mass,

$E_c = \dfrac{K v_0^3}{q'\nu C_p}$ Eckert number

$P_r = \dfrac{\mu C_p}{K}$ Prandtl number, $S_c = \dfrac{\nu}{D}$ Schmidt number.

We solve the equations (12) to (14) analytically using the following boundary conditions on velocity and isothermal conditions on temperature in dimensionless form are

$$u = 0 \text{ at } y = 0,\ u = 0 \text{ at } y = 1 \quad (18a)$$

$$\theta = -1 \text{ at } y = 0,\ \theta = 0 \text{ at } y = 1 \quad (18b)$$

$$C = 1 \text{ at } y = 0,\ C = 0 \text{ at } y = 1 \quad (18c)$$

3. Analytical Solution

Equations (15) and (16) are the coupled non-linear differential equations whose analytical solutions are obtained using a Regular perturbation technique with Eckert number Ec as a perturbation parameter. In this technique we express u and θ in the series form as

$$u = u_0 + Ec\,u_1 + Ec^2 u_2 + \ldots\ldots\ldots \quad (19a)$$

$$\theta = \theta_0 + Ec\,\theta_1 + Ec^2 \theta_2 + \ldots\ldots\ldots \quad (19b)$$

satisfying the boundary conditions (18a,b,c). Substituting the equations (19a) and (19b) into the eqns (15) and (16) and equating to the like powers of E_c, E_c^2, we get the following boundary value problems. Since we assumed that $E_c \ll 1$, we restricted our solution only up to order 1.

Zeroth order equations:

$$\frac{d^2 \theta_0}{dy^2} - Pe \frac{d\theta_0}{dy} = 0, \quad (20)$$

$$\frac{d^2 u_0}{dy^2} - \mathrm{Re} \frac{du_0}{dy} - \frac{\sigma^2}{\mathrm{Re}^2} u_0 = -Gm\,C - Gr\,\theta_0 - \frac{M}{\mathrm{Re}^2}. \quad (21)$$

First order equations:

$$\frac{d^2 \theta_1}{dy^2} - \mathrm{Pr} \frac{d\theta_1}{dy} = -\mathrm{Pr} \left(\frac{du_0}{dy}\right)^2, \quad (22)$$

$$\frac{d^2 u_1}{dy^2} - \frac{du_1}{dy} - \frac{\sigma^2}{\mathrm{Re}^2} u_1 = -Gr\,\theta_1. \quad (23)$$

The solution for eqns. (17), (20), (21), (22) and (23) are

$$C = \frac{e^{Sc} - e^{Sc\,y}}{e^{Sc} - 1}, \theta_0 = \frac{e^{\mathrm{Pr}\,y} - 1}{e^{\mathrm{Pr}} - 1}, \quad (24),\&(25)$$

$$u_0 = a_0 + a_1 e^{m_1 y} + a_2 e^{m_2 y} + a_3 e^{\mathrm{Pr}\,y} + a_4 e^{Sc\,y}, \quad (26)$$

$$\theta_1 = a_8 + a_9\, e^{\Pr y} + a_{10}\, e^{2m_1 y} + a_{11}\, e^{2m_2 y} + a_{12}\, e^{2\Pr y} + a_{13}\, e^{2Sc\, y} + a_{14}\, e^{(m_1+m_2)y} + a_{15}\, e^{(m_1+\Pr)} + a_{16}\, e^{(m_2+\Pr)y} + a_{17}\, e^{(m_1+Sc)y} + a_{18}\, e^{(m_2+Sc)y} + a_{19}\, e^{(\Pr+Sc)y}, \tag{27}$$

$$u_1 = Gr + a_{20}\, e^{m_1 y} + a_{21}\, e^{m_2 y} - a_{22}\, e^{2m_1 y} - a_{23}\, e^{2m_2 y} - a_{24}\, e^{\Pr y} - a_{25}\, e^{2\Pr y} - a_{26}\, e^{2Sc\, y} - a_{27}\, e^{(m_1+m_2)y} - a_{28}\, e^{(m_1+\Pr)y} - a_{29} e^{(m_2+\Pr)y} - a_{30}\, e^{(m_1+Sc)y} - a_{31}\, e^{(m_2+sc)y} - a_{32}\, e^{(pr+Sc)}. \tag{28}$$

4. Skin-friction and Nusselt numbers

The equations defining the wall skin-friction *(τ)* and Local Nusselt number *(N_u)* are given by

$$\tau = -\mu\left(\frac{\partial u}{\partial y}\right)_{y=0}, \quad and \quad Nu = -\left(\frac{\partial \theta}{\partial y}\right)_{y=0} \qquad \text{(29a,b}$$

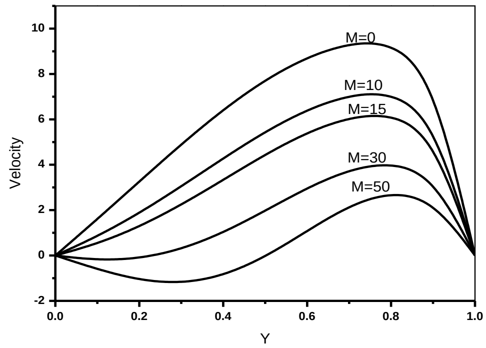

Fig. 2 Velocity profiles for different values of *M* when *E=0.1, Pr=5,R_e=1,σ=0.01 S_c=0.22,G_m=0.5,* and *G_r=0.5*

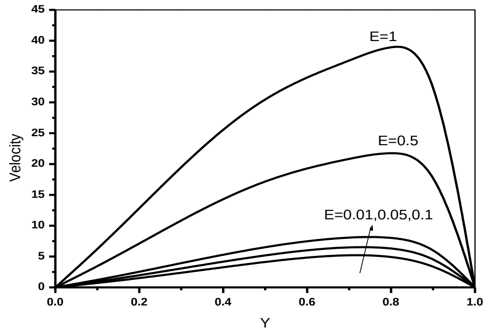

Fig. 3 Velocity profiles for different values of *E* when *M=5, Pr=5,R_e=1,σ=0.01 S_c=0.22,G_m=0.5, and G_r=0.5*

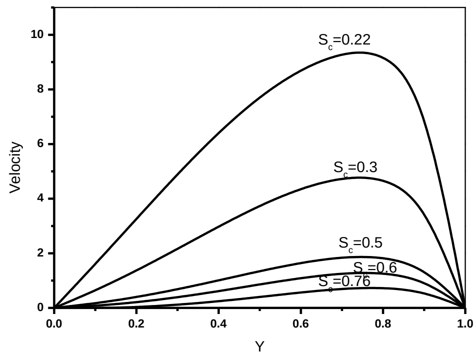

Fig. 4 Velocity profiles for different values of S_c when *M=5, E=0.1,Pr=5,R_e=1,σ=0.01,G_m=0.5, and G_r=0.5*

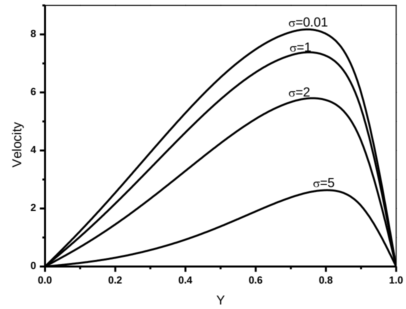

Fig. 5 Velocity profiles for different values of *σ* when *M=5, E=0.1, Pr=5, R_e=1, S_c =0.22, G_m=0.5, and G_r=0.5*

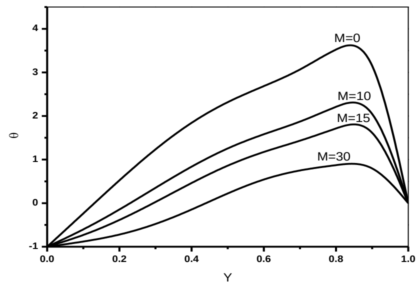

Fig. 6 Temperature profiles for different values of *M* when *E=0.1,Pr=5,R_e=1, S_c =0.22, σ =0.01,G_m=0.5, and G_r=0.5*

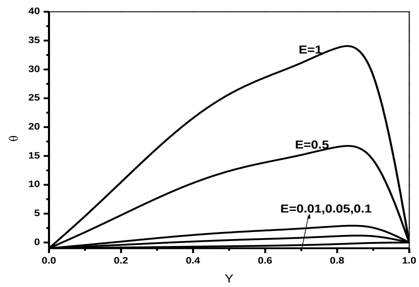

Fig. 7 Temperature profiles for different values of *E* when *M=5, Pr=5, R_e=1, S_c =0.22, σ =0.01,G_m=0.5, and G_r=0.5*

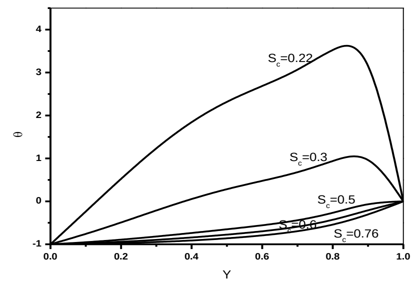

Fig. 8 Temperature profiles for different values of S_c when *M=5, E=0.1,Pr=5,R_e=1,σ=0.01,G_m=0.5, and G_r=0.5*

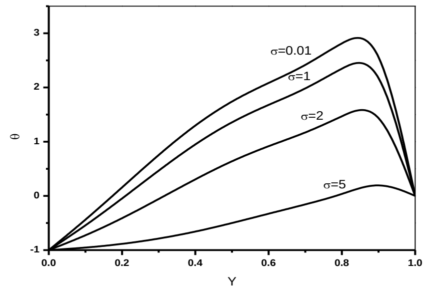

Fig. 9 Temperature profiles for different values of σ when M=5, E=0.1, Pr=5, R_e=1, S_c =0.22, G_m=0.5, and G_r=0.5

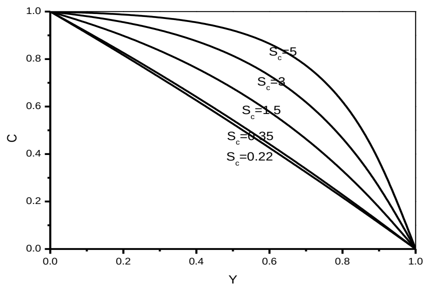

Fig. 10 Concentration profiles for different values of S_c when M=5, E=0.1,Pr=5,R_e=1,σ=0.01,G_m=0.5, and G_r=0.5

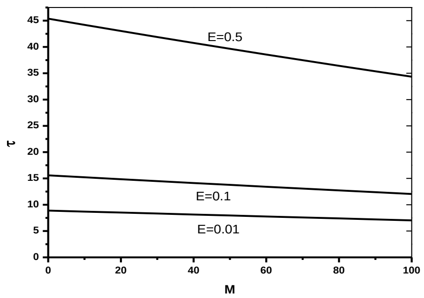

Fig. 11: Skin friction versus Magnetochiral number at y=0 for different values of E when Pr=5, R_e=1,σ=0.01,G_m=0.5, and G_r=0.5

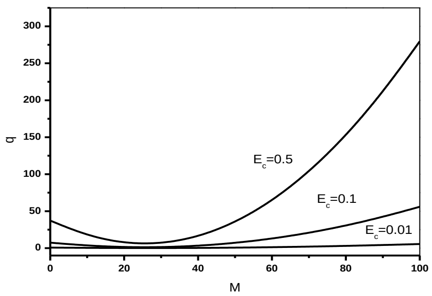

Fig.12: Heat transfer versus Magnetochiral number for different values of for different values of E when Pr=5, R_e=1,σ=0.01,G_m=0.5, and G_r=0.5

Table 1 Comparison of variation of skin friction coefficient at the plate with magnetochiral number M, where *P_r=0.71, S_c0.22, G_m=2.0,G_r=2.0.σ=1.0,E=0.02* and *R_e=5.0.*

M	Acharya et. Al (ordinary fluid)	Present study for chiral fluid
0.5	4.1612	12.9705
1.0	3.3964	12.762
2.0	2.6556	12.3456
3.0	2.3278	11.9299
4.0	2.1406	11.5151
6.0	1.9167	10.6876
7.0	1.8385	10.2751
8.0	1.7725	9.86333

5. Results and Discussion

Analytical solutions for effects of magnetic field and viscous dissipation on double diffusive Oberbeck convection in a chiral fluid saturated porous medium are reported. The results are presented graphically in Fig. 2 to 12 and conclusions are drawn for flow field and other physical quantities of interest that have significant effects.

From Fig. 2 and 6 depicts variation of velocity and temperature profiles, respectively, for different values of *M* when *E_c=0.1, Pr=0.1, Re=5, σ=0.01, Sc=0.22, Gm=0.5, and G_r=0.5.* Fig. 2 shows that the velocity is considerably reduced with the increase in the value of M, because the transverse magnetic field opposes the transport phenomena due to the fact that the presence of a magnetic field produces a Lorentz force which acts in the opposite direction to the fluid motion which results in decreasing the fluid velocity and also decrease the fluid temperature with increase in the magnetic field (see in Fig.6). In addition, the momentum boundary layer thickness decreases with increases in the value of *M* while the same trend is observed for thermal boundary layer thickness as shown in Fig. 2 and 6.

Fig. 3 and 7 shows the effect of Eckert number on velocity and temperature distribution profile. The *E* is varied from 0.01 to 1.0 velocity of fluid and thickness of the thermal boundary layer increases. When *E* is less than 1 the energy dissipation is low. The higher the *E*, the larger the temperature rises due to viscous dissipation. It is witnessed by a sudden increase in the fluid velocity near hot plate before satisfying boundary conditions.

The fluid velocity and temperature variations for various values of Schmidt number S_c in depicted in Fig. 4 and 8. It is observed that increase in S_c there is a reduction in velocity for the fluid both in magnitude and extent and thinning of thermal boundary layer occurs.

Fig. 5 and 9 depicts the effect of porous parameter on velocity and temperature distribution. Velocity and temperature decreases both in magnitude and extent with increase in porous parameter.

Fig. 10 is the plot of concentration profiles against y for different values of Sc. It is observed that as the Schmidt number Sc increases the value of C increases everywhere within the boundary layer.

The Skin friction and the rate of heat transfer are computed for different values of *E* and the results are presented in Fig. 11 and 12. These physical parameters increase with increase in I. The skin friction decreases with increase in *M* and the rate of heat transfer increases with increase in *M*.

Finally, we have compared present work with Acharya's (2000) work. Analysis of the tabular data from table 1 shows that the values that are obtained for chiral fluid are not in good agreement. From this we can predict that the higher values are obtaining for chiral fluids due to chirality in the fluid particles. From Table 1, it is clear that skin-friction values are decreases for both ordinary and chiral fluids but the values are not at all matching with those compared work.

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Nomenclature

ν - *kinematic viscosity*
D - *mass diffusion coefficient*
ε - *dielectric constant*
K - *thermal diffusivity*
k - *thermal conductivity*
k' - *permeability of porous layer*
C_p - *specific heat at constant pressure*
β - *thermal expansion coefficient*
ρ_0 - *reference density*
C_0 - *species concentration at* $y = 0$
β^* - *solutal expansion coefficient*
T_0 - *fluid temperature at* $y = 0$
C - *species concentration*
T - *temperature of the fluid*
γ - *chirality factor*
ρ_e - *distribution of charge density*
v_0 - *suction/ injection velocity*
$\vec{H}$ -*magnetic induction*
$\vec{D}$ - *dielectric field*
h - *width of the channel*
μ_f - *viscosity of the fluid*
ρ - *density of the fluid*
σ - *porous parameter*
θ - *dimensionless temperature*
m -*mass flux per unit area*
q' - *heat flux per unit area*
μ - *magnetic permeability*
$\vec{J}$ -*current density*
$\vec{g}$ - *gravitational field intensity*
$\vec{E}$ - *electric intensity*
$\vec{B}$ - *magnetic Induction*
u, v - *Velocity components in x and y directions respectively*