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MIXED CONVECTION MAGNETO HYDRODYNAMIC HEAT AND MASS TRANSFER ON MELTING FROM A VERTICAL PLATE EMBEDDED IN POROUS MEDIUM UNDER THE INFLUENCE OF SORET AND DUFOUR EFFECTS

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ABSTRACT

A mathematical model is developed to examine the combined effects of Soret and Dufour on mixed convection magneto hydrodynamic (MHD) heat and mass transfer on melting from a vertical plate saturated in porous medium. The governing boundary layer equations for momentum, energy and species transfer are transformed to a set of non-linear ordinary differential equations by using similarity solutions which are then solved numerically based on shooting algorithm with Runge–Kutta–Fehlberg integration scheme over the entire range of physical parameters with appropriate boundary conditions. The influence of Soret number and Dufour number and magnetic parameter on velocity, temperature and concentration fields are studied graphically.

Keyword: Liquid phase; Mixed convection; Dufour effect; Soret effect; Melting effect; and Magnetic parameter.

INTRODUCTION

The study of magneto hydrodynamic (MHD) laminar flow through a porous medium has become very important in recent years because of its possible applications in many branches of science and technology, particularly in the field of Agricultural Engineering to study the underground water resources, seepage of water in river beds; in chemical engineering for filtration and purification process, in Petroleum Technology to study the movement of natural gas, oil and water through the oil reservoirs. There has been a renewed interest in MHD flow and heat transfer in porous and clear domains due to the important effect of magnetic field on the boundary layer flow control and on the performance of many systems using electrically conducting fluid such as MHD power generators, the cooling of nuclear reactors, plasma studies, purification of molten metal from non-metallic inclusion, geothermal energy extractions etc. Many problems of MHD Darcian and non- Darcian flow of Newtonian fluid in porous media have been analyzed and reported in the literature. Chamkha (1997) analyzed the hydromagnetic natural convection flow from an isothermal inclined surface adjacent to thermally stratified porous medium. Bian *et al.* (1996) have studied the natural convection in an inclined porous medium with the effect of electromagnetic field. Tashtoush (2005) analyzed the effects of magnetic and buoyancy on melting from a vertical plate embedded in saturated porous media. Afify (2007) analyzed the effects of variable viscosity on non-Darcy MHD free convection along a non-isothermal vertical surface in a thermally stratified porous medium.

Heat transfer accompanied by melting effect has received much attention in recent years because of its important applications in permafrost melting, frozen ground thawing, liquid polymer extrusion, casting and welding processes as well as phase change material (PCM). In manufacturing processes such as hot extrusion, a material such as metals, polymers, ceramics and others is pushed or drawn through a die of the desired cross-section to produce different types of objects. The melting effect is important in hot extrusion or hot working process since it is done above the material's re-crystallization temperature to keep the material from work hardening and to make it easier to push the material through the die. Also, in the permafrost research, the melting effect plays an important role in the problems of permafrost melting and frozen ground thawing. According to the analysis of Walker (2007), the phenomenon of permafrost degradation in Arctic Alaska is very critical due to global warming and this result accelerates the green house effect. Many studies have been reported concerning the melting process by heat convection mechanism. For example, Kazmierczak *et al* (1987) presented similarity solutions to analyze the melting phenomenon from a vertical plate in porous medium induced by forced convection of a dissimilar fluid. Hassanien and Bakier (1991) studied the melting effect in mixed convection flow from a horizontal flat plate embedded in a porous medium. Bakier (1997) studied the melting effect on a plate with aiding and opposing flows for an arbitrary wall temperature. Gorla *et al* (1999) changed the arbitrary wall temperature by a uniform wall temperature at the solid-liquid interface to analyze the velocity and temperature fields for aiding flow conditions. Cheng and Lin (2007) examined the melting effect on mixed convective heat transfer from a porous vertical plate in liquid-saturated porous medium with aiding and opposing external flows. Cheng and Lin (2008) also examined transient mass transfer in mixed convective heat flow with melting effect from a vertical plate in a liquid-saturated porous medium in the presence of aiding external flow. Bakier *et al* (2009) studied hydromagnetic heat transfer by mixed convection from a vertical plate in a liquid saturated porous medium in the presence of melting effect. Recently, Chamkha *et al* (2010) considered the effects of melting and heat generation or absorption on steady mixed convection from a radiate vertical wall embedded in a non- Newtonian power-law fluid-saturated porous medium for aiding and opposing external flows.

Coupled heat and mass transfer by mixed convection over a vertical surface in a porous media has gained much attention from researchers because of its engineering and industrial applications. When heat and mass transfer occur simultaneously in a moving fluid, the relations between the fluxes and the driving potentials are of a more intricate nature. It has been observed that an energy flux can be generated not only by temperature gradients but also by concentration gradients. The energy flux caused by a concentration gradient is termed the diffusion-thermo (Dufour) effect. On the other hand, mass fluxes can also be created by temperature gradients and this embodies the thermal-diffusion (Soret) effect. In most of the studies related to heat and mass transfer process, Soret and Dufour effects are neglected on the basis that they are of a smaller order of magnitude than the effects described by Fourier’s and Fick’s laws. But these effects are considered as second order phenomena and may become significant in areas such as hydrology, petrology, geosciences, etc. The Soret effect, for instance, has been utilized for isotope separation and in mixtures between gases with very light molecular weight and of medium molecular weight. The Dufour effect was recently found to be of an order of considerable magnitude so that it cannot be neglected, Eckert and Drake (1972). Dursunkaya and Worek (1992) studied diffusion-thermo and thermal-diffusion effects in transient and steady natural convection from a vertical surface, whereas Kafoussias and Williams (1995) presented the same effects on mixed convective and mass transfer steady laminar boundary layer flow over a vertical flat plate with temperature dependent viscosity. Postelnicu (2004) studied numerically the influence of a magnetic field on heat and mass transfer by natural convection from vertical surfaces in porous media considering Soret and Dufour effects. Both free and forced convection boundary layer flows with Soret and Dufour effects have been addressed by Abreu *et al.* (2006). Alam and Rahman (2006) have investigated the Dufour and Soret effects on mixed convection flow past a vertical porous flat plate with variable suction. The effect of Soret and Dufour parameters on free convection heat and mass transfers from a vertical surface in a doubly stratified Darcian porous medium has been reported by Lakshmi Narayana and Murthy (2007). Srinivasacharya and Swamy (2012) studied numerically the effects of double diffusive natural convection heat and mass transfer along a vertical plate embedded in power-law fluid saturated porous medium with Soret and Dufour effects. Recently, The Soret and Dufour effects on mixed convection flow due to exponentially stretching surface in a quiescent fluid–saturated non–Darcy porous medium has been reported by Srinivasacharya and RamReddy (2013).

In view of the above discussions, authors envisage to investigate the steady two-dimensional mixed convection and mass transfer flow on melting from a vertical plate embedded in a saturated porous medium taking into account the Soret and Dufour effects in the presence of magnetic parameter. The problem addressed here is a fundamental one that arises in many practical situations such as polymer extrusion process and combined effects of the physical parameters will have large impact on heat and mass transfer characteristics. The accurate estimation of velocity, temperature and concentration at the wall is not possible by neglecting Soret, Dufour and other important physical parameters. The non-linearity of the basic equations and additional mathematical difficulties associated with it, have led to the use of numerical method. The transformed dimensionless governing equations are solved numerically by using sixth-order Runge–Kutta–Fehlberg method with shooting technique.

Mathematical Formulations

Consider steady two-dimensional MHD laminar mixed convection heat and mass transfer flow of a viscous and incompressible fluid over a vertical plate in a saturated porous medium. A uniform transverse magnetic field B_0 is imposed along the y-axis. The induced magnetic field due to the motion of the electrically conducting fluid is negligible. It is assumed that the external electric field is zero and the electric field due to the polarization of charges is negligible. The magnetic Reynolds number is assumed to be small and therefore the induced magnetic field is negligible compared with the applied magnetic field. The applied magnetic field is also taken as being weak so that Hall and ion nip effects may be neglected. The x coordinate is taken along the plate, the y –coordinate is measured normal to the plate, while the origin of the reference system is taken at the leading edge of the plate. We assume that the Dufour effect may be described by a second-order concentration derivative with respect to the transverse coordinate in the energy equation whereas Soret effect is described by the second-order temperature derivative in the mass-diffusion equation. The plate is at a constant temperature T_m at which the material of the porous matrix melts. The liquid phase temperature is T ($> T_m$) and the temperature of the solid far from the interface is T_∞ ($< T_m$). The liquid phase concentration is C ($> C_m$) and the concentration of the solid far from the interface is C_∞ ($< C_m$). The flow is steady, laminar and two dimensional. With the usual boundary layer and linear Boussinesq approximations, the governing equations, namely the equation of continuity, the momentum, the energy equation and the concentration equation for the porous medium may be written as

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0 \tag{1}$$

$$\left(1+\frac{\sigma B_0^2}{\rho \nu}\right)\frac{\partial u}{\partial y} = \frac{-Kg}{\nu}\left(\beta_\gamma \frac{\partial T}{\partial y} + \beta_c \frac{\partial C}{\partial y}\right) \tag{2}$$

$$u\frac{\partial T}{\partial x} + v\frac{\partial T}{\partial y} = \alpha \frac{\partial^2 T}{\partial y^2} + \frac{\sigma B_0^2 u^2}{\rho C_\rho} + D_1 \frac{\partial^2 C}{\partial y^2} \tag{3}$$

$$u\frac{\partial C}{\partial x} + v\frac{\partial C}{\partial y} = D\frac{\partial^2 C}{\partial y^2} + D_2 \frac{\partial^2 T}{\partial y^2} \tag{4}$$

In the above equations, $Ha, K, \alpha, \nu, \beta_\gamma, \beta_C$ *and* g are the magnetic parameter, permeability, equivalent thermal diffusivity, kinematic viscosity, thermal expansion coefficient, concentration expansion coefficient and acceleration due to gravity respectively, D is the effective solutal diffusivities, D_1 quantifies the contribution due to the heat flux caused by concentration gradient (Dufour effect) and D_2 quantifies the contribution due to the mass flux caused by temperature gradients (Soret effect).

The above problem is solved subject to the following boundary conditions.

$$y = 0, \quad T = T_m\,,\; C = C_m,\; k\frac{dT}{dy} = \rho\left[L + C_s\left(T_m - T_s\right)\right]v$$

$$y \to \infty\,,\;\; T \to T_\infty,\;\; u \to U_\infty\;\;, C \to C_\infty \tag{5}$$

Where L and C_s are latent heat of the fluid and specific heat capacity of the solid phase respectively.

The continuity equation is automatically satisfied by defining a stream function

$$u = \frac{\partial \psi}{\partial y} \;\; and \;\; v = -\frac{\partial \psi}{\partial x} \tag{6}$$

By introducing the following similarity transformation

$\eta = Pe_x^{0.5}\frac{y}{x}$, $\psi = \alpha Pe_x^{0.5} f(\eta)$, $\theta(\eta) = \frac{T - T_m}{T_\infty - T_m}$, $\phi(\eta) = \frac{C - C_m}{C_\infty - C_m}$ Where $Pe = \frac{u_\infty x}{\alpha}$ is the Peclet number. Substituting Equation (6) in Equations (2), (3) and (4) we obtain the following transformed governing equations.

$$\left(1 + Ha^2\right) f'' + \frac{Gr}{\mathrm{Re}}\left(\theta' + N\phi'\right) = 0 \tag{7}$$

$$\mathrm{Re}\left(\theta'' + \frac{1}{2} f\theta' + Df\,\phi''\right) + \frac{Ha\ Ec}{Da} f'^2 = 0 \tag{8}$$

$$\frac{1}{Le}\phi'' + \frac{1}{2} f\phi' + Sr\,\theta'' = 0 \tag{9}$$

The boundary conditions are

$$\begin{aligned} &\eta = 0, \theta = 0,\ f(0) + 2M\theta'(0) = 0,\ \phi = 0 \\ &\eta \to \infty, \theta = 1,\ f' = 1,\ \phi = 1 \end{aligned} \tag{10}$$

Where $M = \frac{C_p(T_\infty - T_m)}{1 + C_s(T_m - T_s)}$ is the melting parameter, $\mathrm{Re} = \frac{U_\infty x}{\nu}$ is the Reynolds number, $Gr = \frac{Kg\beta_T(T_\infty - T_m)x}{\nu^2}$ is the Grashof number $Da = \frac{K}{x^2}$ is the Darcy number, $Ha = \sqrt{\frac{\sigma B_0^2}{\rho\nu}}$ is the magnetic parameter, $Ec = \frac{u_0^2}{C_p(T_\infty - T_m)}$ is the Eckert number, $Le = \frac{\alpha}{D}$ is the Lewis number $Df = \frac{D_1\Delta C}{\alpha\Delta T}$ is the Dufour number and $Sr = \frac{D_2\Delta T}{\alpha\Delta C}$ is the Soret number. The buoyancy ratio is $N = \frac{\beta_c\Delta C}{\beta_T\Delta T}$. The parameter N>0 represent the aiding buoyancy and N<0 represent the opposing buoyancy.

The non-dimensional heat and mass transfer coefficients are defined as

$$\frac{Nu}{pe^{0.5}} = \theta'(0) \tag{11}$$

$$\frac{Sh}{pe^{0.5}} = \phi'(0) \tag{12}$$

Numerical Solution

The system of non-linear ordinary differential equations (7) - (9) together with the boundary conditions (10) is solved numerically using the shooting iteration technique together with a sixth order Runge-Kutta integration scheme which were implemented with maple software package. In a shooting method, the missing (unspecified) initial condition at the initial point of the interval is assumed, and the differential equation is then integrated numerically as an initial value problem to the terminal point. The accuracy of the assumed missing initial condition is then checked by comparing the calculated value of the dependent variable at the terminal point with its given value there. If a difference exists, another value of the missing initial condition must be assumed and the process is repeated. This process is continued until the agreement between the calculated and the given condition at the terminal point is within the specified degree of accuracy. For this type of iterative approach one naturally inquires whether or not there is a systematic way of finding each succeeding value. The present results are validated by direct comparison with those obtained by Tashtoush (2005) as shown in Table 1. It seen from this table that both results are in excellent agreement, which gives confidence in the numerical results obtained for the present problem.

Table 1: Values of $\theta'(0)$ and $f(0)$ for $Ha=0, Ec=0, Da=0.1, R=0$, $\mathrm{Re}=1.0, Df=0, Sr=0, Le=1.0$ or different values of mixed convection and melting parameters.

		Tashtoush[4]		Present work	
M	Gr/Re	$\theta'(0)$	$f(0)$	$\theta'(0)$	$f(0)$
0.4	0.0	0.4571	-0.3657	0.4570	-0.3656
	1.4	0.6278	-0.5023	0.6278	-0.5022
	20	1.6866	-1.3493	1.6866	-1.3493
2.0	0.0	0.2743	-1.097	0.2743	-1.097
	1.4	0.3807	-1.5231	0.3808	-1.5232
	3.0	0.4747	-1.8988	0.4747	-1.8988
	8.0	0.6902	-2.7607	0.6902	-2.7607
	10.0	0.7587	-3.0290	0.7593	-3.0375
	20.0	1.0382	-4.1529	1.0382	-4.1529

DISCUSSION OF RESULTS

In the present study we have adopted the following default values for numerical computation: M=0.5, Da=1.0,Ec=0.1, Re=1.0, Df=0.02, Sr=0.2, Le=1.0, N=0.5,Ec=0.1 and Ha=0.2 unless otherwise specified. The Dufour number and Soret number are chosen in such a way that their product is constant according to definition provided that the mean temperature T_m is kept constant, Kafoussias and Williams (1995). For Illustrations of the results, numerical values are plotted in Figs. 1-16. The effect of buoyancy parameter Gr/Re on the fluid velocity distribution is depicted in Fig.1. It is observed from this figure that the values of slip velocity f' increase as the buoyancy parameter Gr/Re increases. On the other hand, the velocity is uniform for the case of zero buoyancy (forced convection flow). As Gr/Re increases, the velocity increases while the thermal and concentration boundary layer thickness decrease accordingly. This results in an increase in temperature and concentration as shown in Figs. 2-3.

Figs. 4-6 present the influence of melting parameter M on velocity, temperature and concentration profiles respectively. It is obvious that increasing the melting parameter M causes higher acceleration to the fluid flow which, in turn, increases its motion and causes decrease in the temperature and concentration profiles. This accompanied by respective increases in the boundary layer thickness of velocity, temperature and concentration. Physically this can be explained as follows: When a cold sheet plunges into a hot water it starts to melt.

Fig. 7 shows the behaviour of velocity profiles for different values of Hartmann number Ha. It is well known that the Hartmann number represents the importance of magnetic field on the flow. It is observed from this figure that the effect of magnetic field is to decrease the velocity profiles, due to the fact that the introduction of transverse magnetic field normal to the flow direction has a tendency to give rise to a resistive-type force called the Lorentz force and hence results in retarding the velocity profile. Thus when the Hartmann number increases the Lorentz force also increases due to which velocity profile decreases. Figs.8 clearly indicates that the fluid temperature increases on increasing the Hartmann number Ha and, as a consequence, thickness of the thermal boundary layer increases. This result qualitatively agrees with the expectations, since magnetic field exerts retarding force on the convection flow and increases its temperature profiles. Fig 9 depicts the effects of Hatmann number Ha on concentration. It is observed that concentration decreases with an increase in Ha, which led to decrease in concentration boundary layer.

The effects of Dufour (Df) and Soret (Sr) numbers on the velocity, temperature and concentration are depicted in Figs. 10-12. The velocity as well as temperature increases but the concentration decreases with an increase in the Dufor number Df (or simultaneous decrease in the Suret number Sr). Thus it is observed from Figures that the velocity, temperature and concentration distributions are affected by the Dufour and Soret effects, especially the thermal boundary layer thickness which increases while concentration boundary layer thickness which decreases with increase in the Dufour number (or simultaneously decrease in the Soret number).

It should be mentioned that the profile of concentration is found to be more prudent to the changes with Dufour number Df and Soret number Sr, respectively. Thus it is evident that the effects are obviously playing an important role under mixed convection flow for molecular diffusion in the presence of Dufour and Soret effects. Therefore, we conclude that the influence of thermal-diffusion as well as the diffusion- thermo effects is greatly effective in the study of mixed convection on melting. Figs. 13-15 show the effect of Eckert number (Ec) on velocity, temperature and concentration profiles in the mixed convection flow. It is seen from the figures that the velocity and concentration curves decrease with the increase of Eckert number. However, with the increase of Eckert number, there is significant increase in heat generation due to fluid motion and this translates to temperature increase as shown in Fig.14. Fig. 16 depicts the effect of buoyancy ratio (N) in velocity distribution. It is observed that increasing the values of (N) have a tendency to increase the slip velocity on the plate for flow.

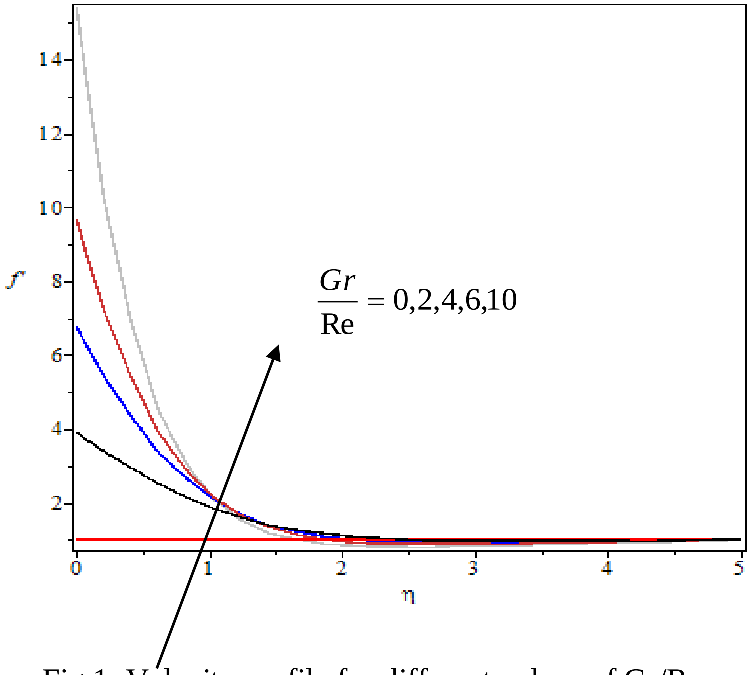

Fig.1: Velocity profile for different values of Gr/Re

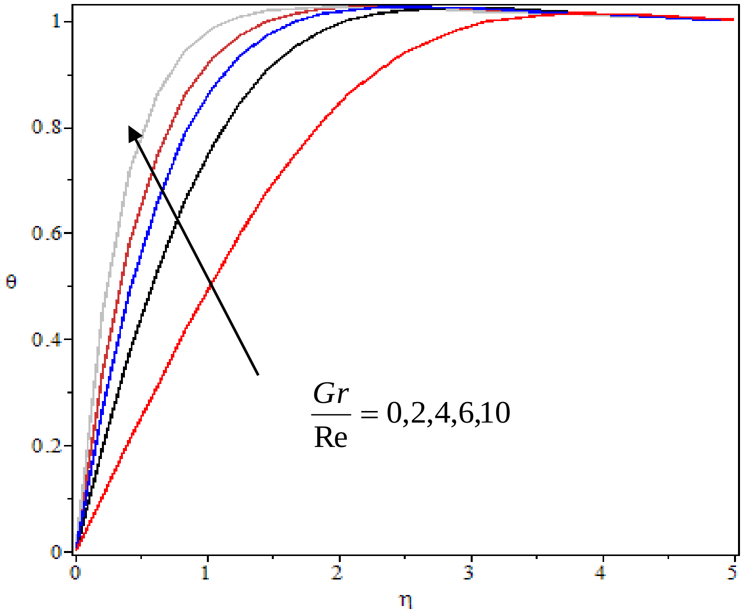

Fig.2: Temperature profile for different values of Gr/Re

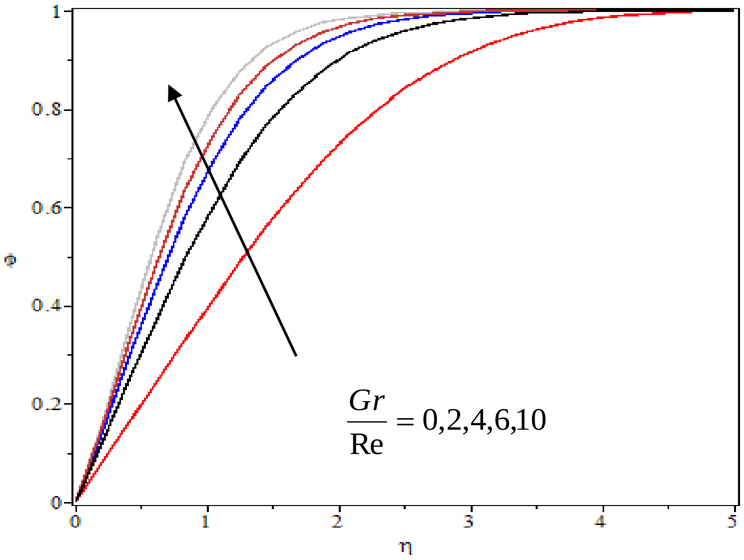

Fig.3: Concentration profile for different values of Gr/Re

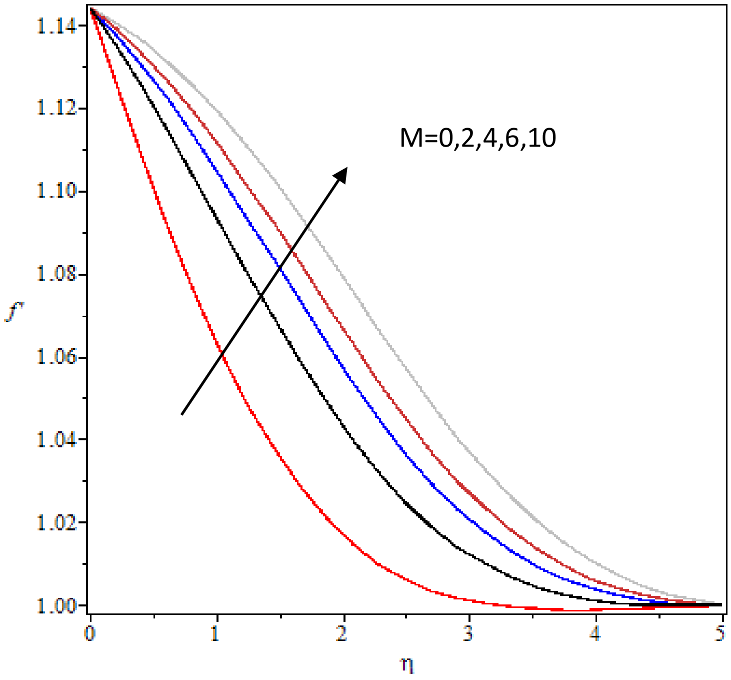

Fig.4: Velocity profile for different values of M

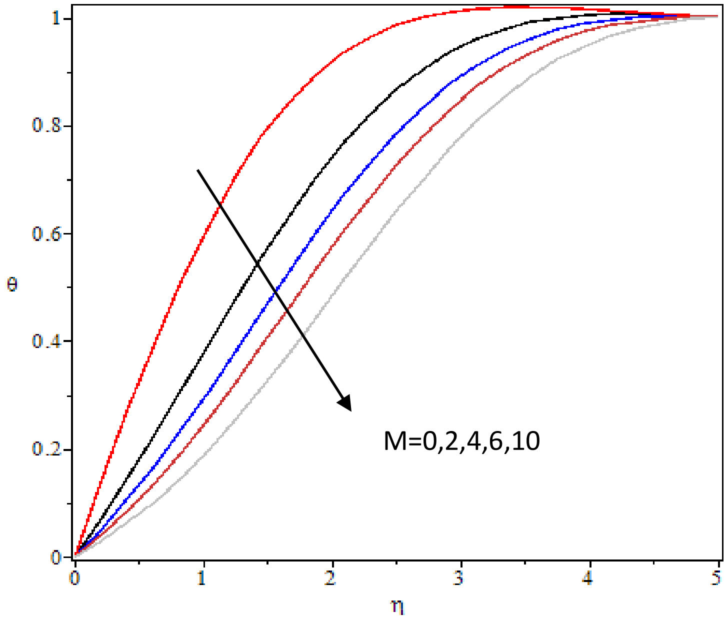

Fig.5: Temperature profile for different values of M

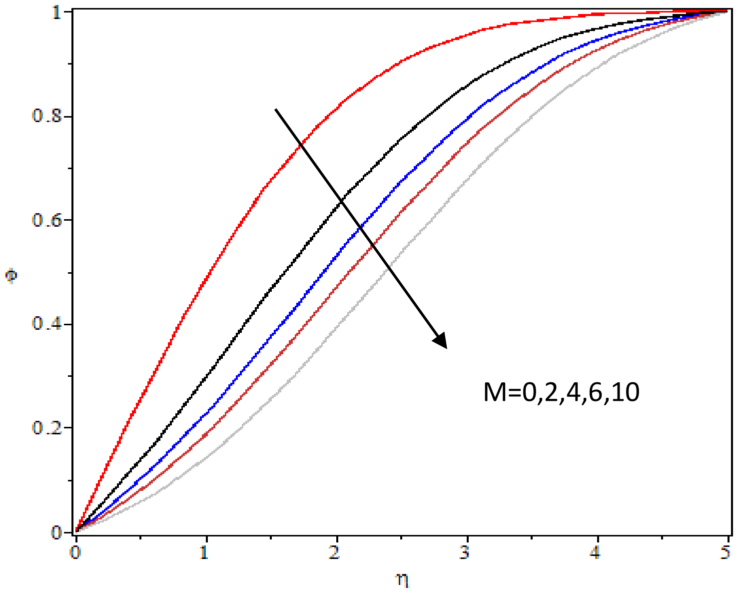

Fig.6: Concentration profile for different values of M

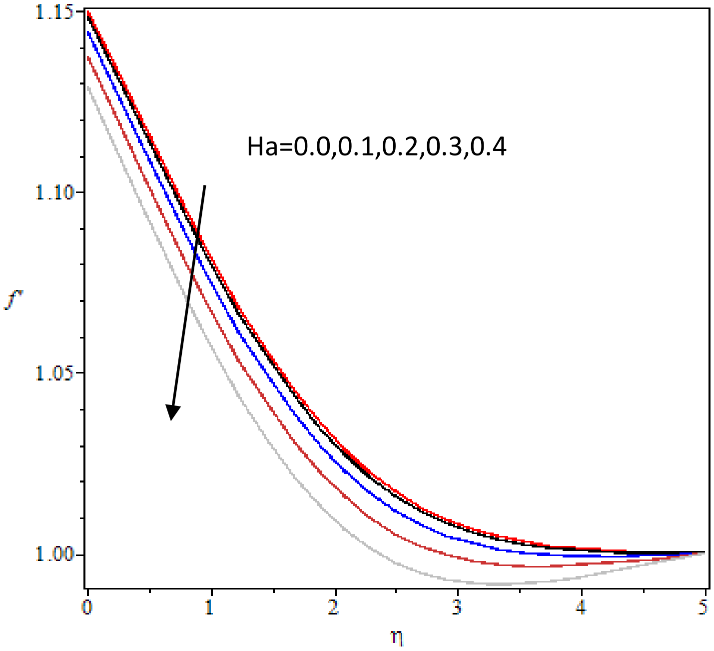

Fig.7: Velocity profile for different values of Ha

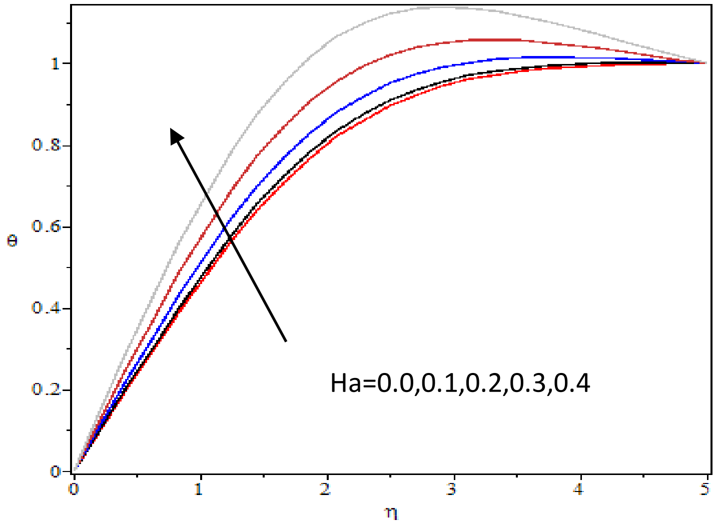

Fig. 8: Temperature profile for different values of Ha

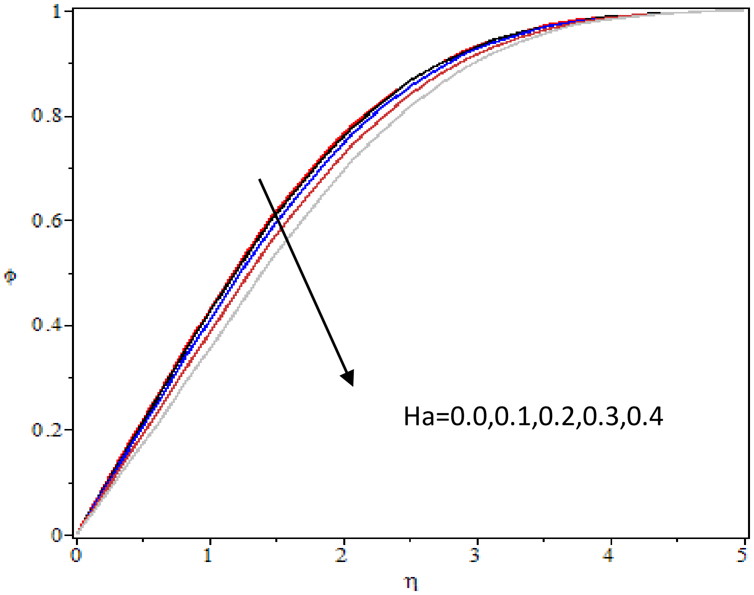

Fig.9: Concentration profile for different values of Ha

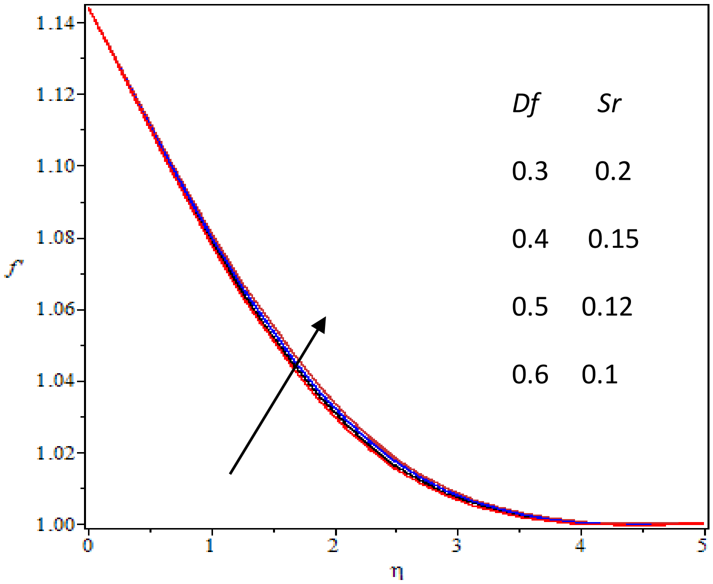

Fig.10: Velocity profile for different values of Df and Sr

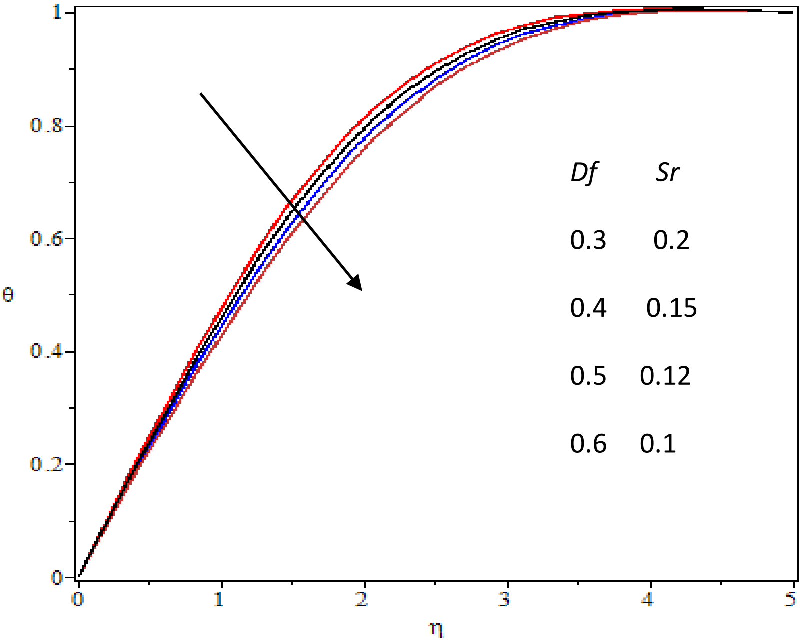

Fig.11: Temperature profile for different values of Df and Sr

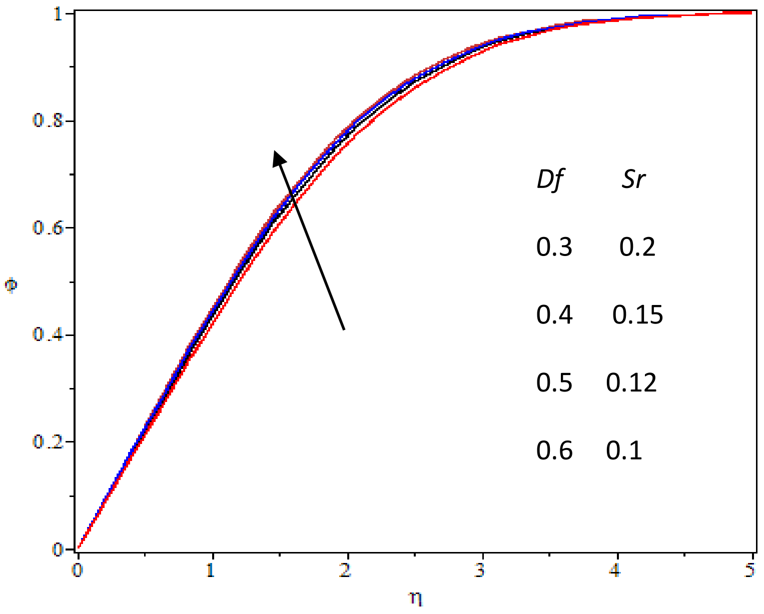

Fig.12: Concentraton profile for different values of Df and Sr

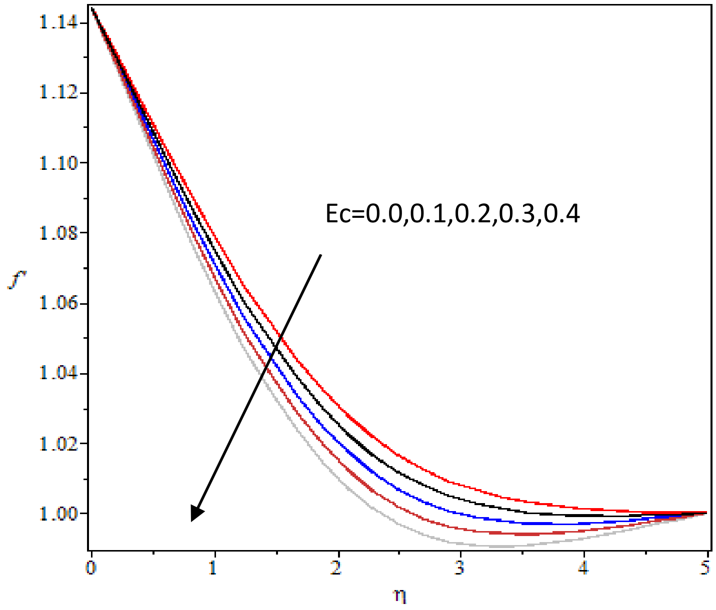

Fig.13 Velocity profile for different values of Ec

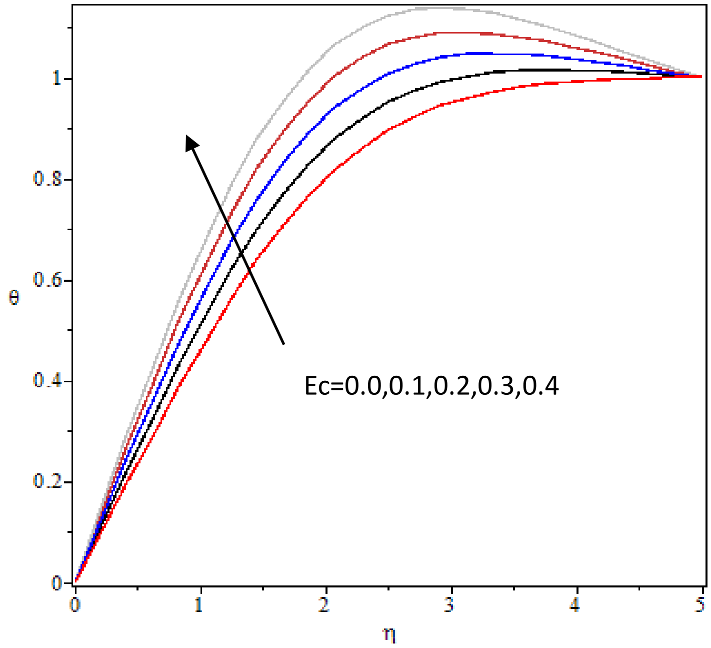

Fig.14: Temperature profile for different values of Ec

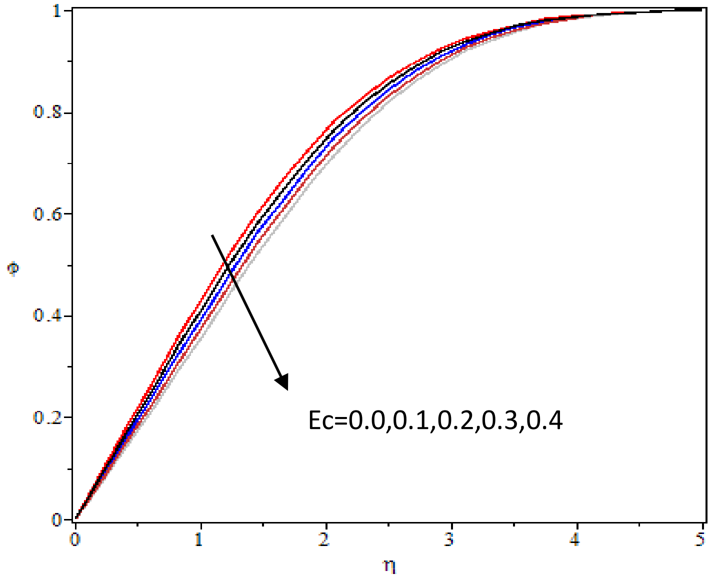

Fig.15: Concentration profile for different values of Ec

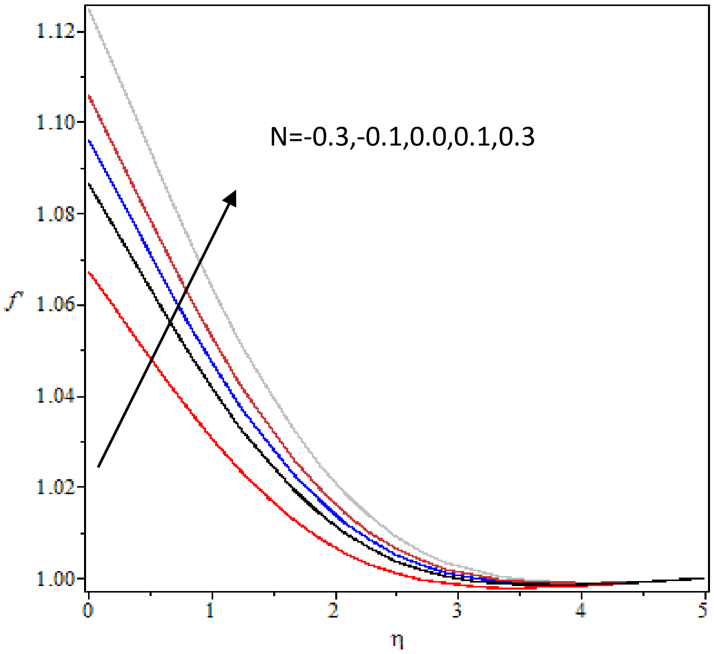

Fig.16: Velocity profile for different values of N

CONCLUSION

In this paper the mathematical model capturing the role of mixed convection on melting from a vertical flat plate embedded in non-Darcy porous medium in presence of thermal diffusion and diffusion thermo effects is developed. The governing equations are derived using the boundary layer and Boussineq approximation. These equations are transformed using a similarity transformation and then solved by six-order Runge-Kutta method. Graphical results for velocity, temperature and concentration as well as the Nusselt number are presented and discussed for different parametric conditions. It is noted that the velocity, temperature and concentration as well as the heat and mass transfer coefficients are significantly affected by the melting phenomena, thermal diffusion and diffusion thermo effects. The heat and mass transfer coefficient are reduced with an increasing value of the melting point.

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