Influence of Soret Effect on Mixed Convective Melting From A Vertical Plate Embedded in Non Newtonian Fluid Saturated Non Darcy Porous Media in Presence Magnetic Effect

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Abstract- *The influence of Soret effects on the problem of mixed convective melting process along a vertical plate embedded in a non Darcy porous media saturated with non-Newtonian fluid in presence of the magnetic field are analyzed. The temperature and concentration of the plate and the ambient medium are kept up at steady but different stage in order to establish a boundary layer analysis. In order to describe the behavior of non-Newtonian fluid the Ostwald-de Waele power law model is considered. Similarity variables are developed for solving the partial differential equations into nonlinear ordinary differential equations and the simultaneous development of the problem of boundary layers is obtained numerically by fourth order Runge–Kutta method coupled with shooting techniques. Numerical calculations are performed for the various parameters entering into the problem. The obtained results are ensured against previously published work and are found to be in good agreement. The graphical representation for the dimensionless temperature and concentration are calibrated and conferred.*

Keywords- Melting effect, non-Newtonian fluids, Mixed convection, Soret effect, Magnetic effect.

I. NOMENCLATURE

B_0	Magnetic field strength
Cs	specific heat of solid phase
f	Dimensionless stream function
g	Acceleration due to gravity
h_x	Local heat transfer coefficient
L	Latent heat of melting of solid
K	Permeability of the porous medium
K^*	Modified permeability of porous medium with power law fluid
Mg	the Magnetic parameter
M	Melting parameter
Nu_x	Local Nusselt number
Sh_x	Local Sherwood number
Le	Lewis number
Re	Non-Darcian parameter
Pe	Peclet number
Sr	Soret parameter
n	Power law index
T	Temperature in thermal boundary layer
T_s	Temperature at the solid region
T_m	Melting temperature
C	Concentration
C_w	Concentration of wall
u	Velocity in x-direction
v	Velocity in y- direction
x	Coordinate along the melting plate
y	Coordinate normal to melting plate
η	dimensionless similarity variable

Greek symbols

α	Thermal diffusivity
β_T	Coefficient of thermal expansion
μ^*	Fluid consistency of inelastic non-Newtonian power law fluid
χ	Mixed convection parameter
υ	Kinematic viscosity
ρ	Density

σ	Electrical conductivity
θ	Dimensionless temperature

Subscripts

m	Melting point
∞	Condition at infinity

II. INTRODUCTION

In porous media heat and mass transfer studies by the process of convection has received significant attention accompanied by melting effect years due to significant application in permafrost melting, frozen ground thawing, casting and welding processes. Pozovonkov *et al.* (1970) [1] considered the heat transfer rate of a melting surface using laminar boundary layer in porous medium using Karman-Pohlhausen method. Epstein and Chao (1976) [2] deliberated the melting heat transfer from a flat plate in a steady laminar case using similarity solutions technique, while Kazmierczak et al. (1986,1987) [3, 4] analyzed melting from a vertical flat plate embedded in a porous medium in case of free and forced convection processes. rate by applying finite difference method Sparrow *et al.* (1977) [5] calculated the heat transfer in the melting region of a non- porous medium. In the natural convection process Bakier (1997) [6] obtained the solution by applying analytical homotopy analysis for the case of aiding and opposing flow in a porous medium. He pointed out that in the liquid solid interface the melting phenomenon decreases the local Nusselt number while Gorla et al. (1999) [7] achieved the conclusion about melting process which is equivalent to mass injection or blowing near boundary deducing the information relating to the distribution of temperature, stream function, velocity and heat transfer rate by solving the problem using fourth order Runge-Kutta method on the mixed convection problem on melting from a vertical plate embedded in porous medium. Tashtoush (2005) [8] studied the magnetic and buoyancy effects to investigate the flow, temperature profiles and heat transfer characteristics for melting effect associated with uniform wall temperature based on non-Darcy flow model. The melting phenomena on unsteady and steady mixed convection heat transfer from a vertical plate in a liquid saturated porous medium with aiding and opposing external flows has been deliberated by Cheng and Lin (2006, 2007) [9, 10]. Madhavi et al. (2017) [11] considered the MHD mixed convection flow from a vertical plate embedded in a saturated porous medium with melting and heat source or sink.

In spite of complexity for explaining the rheological performances of non-Newtonian fluids, several investigators used the different types of mathematical models in recent past frequently in mechanical and chemical engineering processes. Considering geothermal and oil reservoir engineering applications Shenoy (1994, 1993) [12, 13] presented numerous interesting applications of non-Newtonian power law fluids with yield stress on convective heat transport in fluid saturated porous media and also presented heat transfer for Non-Darcy natural, forced and mixed convection in non-Newtonian power-law fluid saturated porous media. Poulikakos and Spatz (1988) [14] investigated the melting phenomena on free convection from a vertical front in a non-Newtonian fluid-saturated porous matrix. Nakayama and Shenoy (1992) [15] produced a unified similarity transformation for Darcy and non-Darcy forced, free and mixed convective heat transfer in non-Newtonian inelastic fluid-saturated porous media. by Hooper et al. (1993) [16] surface injection or suction on mixed convection from a vertical plate in a porous medium with surface injection or suction is analyzed. Ibrahim et al. (2000) [17] considered surface mass transfer for the non-Darcy mixed convection flow in case of a vertical plate embedded in a non-Newtonian fluid-saturated porous medium. In the presence of suction or injection and heat generation or absorption effects mixed convection heat and mass transfer of non-Newtonian fluids from permeable surface embedded in a porous medium is presented by Chamkha and Al-Humoud (2007) [18].

In the Dufour or diffusion-thermo effect energy flux caused by a composition gradient and the Soret or thermal-diffusion effect mass fluxes caused by temperature gradients. Postelnicu (2004) [19] has investigated influence of a magnetic field on free convection heat and mass transfer from vertical surfaces in a Darcy porous medium Considering the Soret and Dufour effect. Using integral method Cheng (1993) [20] examined that the Nusselt number and Sherwood number decreases when transverse magnetic field normal to the flow of an electrically conducting fluid in a saturated Darcy porous medium along a vertical surface is applied. Chandrasekhara and Namboodiri (1985) [21] studied the similar problem for mixed convection case in non- Darcy porous medium for discussing the effect of porosity and permeability on the flow field in the case of Newtonian fluids under the influence of magnetic field. The steady MHD free convective heat and mass transfer studies for a semi-infinite vertical porous plate embedded in a porous media is investigated by Alam and Rahman (2005) [22]. Malashetty et al. (2006) [23] studied the double diffusive convection analytically in couple stress liquids with Soret effect. Abdel-Rahman (2008) [24] studied the effect of thermal diffusion and MHD effects on combined, free-forced convection and mass transfer in case of a viscous fluid flow through a porous medium by means of heat generation. For natural convective heat and mass transfer in a non-Newtonian fluid saturated non-Darcy porous medium the effect of melting and thermo-diffusion is explored by Kairi and Murthy (2009) [25]. Shateyi et al.[2010] [26] analyzed the effects of thermal radiation, hall currents, Soret, and Dufour on MHD Flow by mixed convection over a vertical surface in porous media.

The main purpose of the present investigation is to analyze the effect of melting in non-Newtonian fluids on mixed convection in non Darcy porous medium. The effects of Dofour and Soret effect as well as magnetic effect are included. Using Matlab BVP solver bvp4c, which is a finite difference code that implements the 3-stage Lobatto IIIa formula, a numerical solution of the boundary layers equations is achieved.

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III. MATHEMATICAL FORMULATION

Let us consider the mixed convection heat transfer from a vertical flat plate embedded in a non Darcy porous media saturated with non-Newtonian fluid. It is assumed that this plate constitutes the interface between the liquid and solid phases during melting inside the porous matrix. The plate temperature, T_m , is the melting temperature of the material occupying the porous matrix, which is regarded as constant. The temperature of the solid phase far from the interface is T_s and the liquid phase temperature is T_∞ $(T_\infty < T_m)$. The origin of the coordinate system is placed at the leading edge of the interface surface between the solid and liquid phases. x is the coordinate along the surface of the plate measured from the origin, and y is the coordinate normal to the surface. u and v are the components of the non-Darcy velocity in the x and y directions, respectively, is shown in the figure 1.

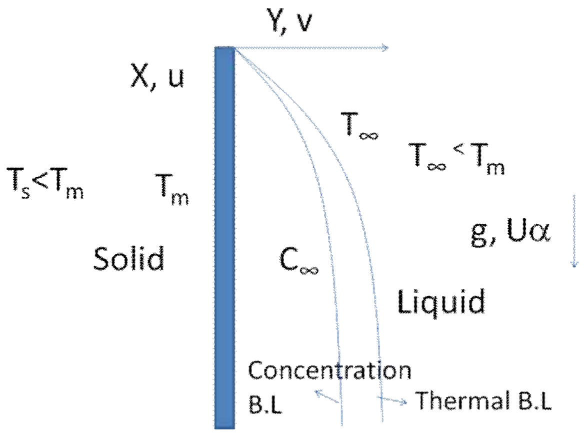

Figure 1. Schematic model and system of coordinates.

A magnetic field of strength B_0 is applied in the y-direction which is normal to the flow direction. The flow is steady, laminar and two dimensional. The fluid and porous medium are in local thermal equilibrium and constant except density. The Boussiensq approximation is valid and the boundary layer approximation is applicable. The governing equation, namely the equation of continuity, momentum equation and energy equation for isotropic and homogeneous porous medium can be written as

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}=0 \quad (1)$$

$$\left(1+\frac{\sigma B_0^2 k}{\rho v}\right)\frac{\partial u^n}{\partial y}+\rho_\infty\frac{bk^*}{\mu^*}\frac{\partial u^2}{\partial y}=-\frac{\rho k^* g}{\mu^*}\left(\beta_T\frac{\partial T}{\partial y}+\beta_C\frac{\partial C}{\partial y}\right) \quad (2)$$

$$u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}=\left(\alpha\frac{\partial^2 T}{\partial y^2}\right) \quad (3)$$

$$u\frac{\partial C}{\partial x}+v\frac{\partial C}{\partial y}=\left(D\frac{\partial^2 C}{\partial y^2}\right)+\frac{D_m K_T}{T_m}\frac{\partial^2 T}{\partial y^2} \quad (4)$$

where *u* and *v* represents the Darcian velocity components along the x- and y-directions, respectively. n represent the power law index and T and C represent the temperature and concentration respectively. ρ_∞ is the reference density, g is the acceleration due to gravity, α and *D* are the constant thermal and molecular diffusivities, respectively. U_∞ is the free stream velocity, b is the empirical constant associated with the Forcheimer porous inertia term and μ^* is the consistency index power law fluid. Following Christopher and Middleman (1965) [30] and Dharmadhikari and Kale (1985) [31], the modified permeability of the flow *k*∗ of the non-Newtonian power law fluid is defined as

$$k^*=\frac{1}{2c_t}\left(\frac{n\epsilon}{3n+1}\right)^2\left(\frac{50K}{3\epsilon}\right)^{(n+1)/2}$$

Where $K = \frac{\epsilon^3 d^2}{150(1-\epsilon)^2}$, ϵ is the porosity of porous medium.

$$c_t = \begin{cases} \frac{25}{12} & \text{Christopher and Middleman [30]} \\ \frac{2}{3}\left(\frac{8n}{9n+3}\right)^n \left(\frac{10n-3}{6n+1}\right)\left(\frac{75}{16}\right)^{3(10n-3)/(10n+11)} & \text{Dharmadhikari and Kale [31]} \end{cases}$$

For n=1, $c_t = 25/12$

The boundary conditions necessary to complete the problem formulation are:

$$v = 0,\ T = T_m,\ C = C_w\ ,\ k\frac{\partial T}{\partial y} = \rho[L + C_s(T_m - T_s)]v \quad \text{at}\ \ y = 0 \tag{5}$$

$$u = U_\infty,\ T \to T_\infty,\quad C \to C_\infty \quad \text{at}\ \ y \to \infty \tag{6}$$

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

The boundary condition (5) indicates that the temperature on the plate is constant and thermal flux of heat conduction to the melting surface is equal to the sum of the melting heat and the heat required for raising the temperature of solid to its melting temperature [Epstein and Cho (1976)] [2].

The stream function $\Psi(x,y)$ is chosen in such a way that the continuity equation automatically satisfied i.e.,

$$u = \frac{\partial \Psi}{\partial y} \quad \text{and} \quad v = -\frac{\partial \Psi}{\partial x} \tag{7}$$

Introducing the following similarity transformation equation, the above system of partial differential equations (1-3) are transferred into the non-linear ordinary differential equations

$$\eta = \frac{y}{x} Pe_x^{\frac{1}{2}} \chi^{-1} \tag{8}$$

$$\Psi = \alpha Pe_x^{\frac{1}{2}} \chi^{-1} f(\eta) \tag{9}$$

$$\theta(\eta) = \frac{T - T_m}{T_\infty - T_m} \tag{10}$$

$$\phi(\eta) = \frac{C - C_w}{C_\infty - C_w} \tag{11}$$

Introducing Eqs. (7), (8), (9) into Eqs. (2) and (3), we obtain the following transformed governing equations:

$$n(1+M_g)f'^{n-1}f'' + 2Re^* f' f'' = -(1-\chi)^{2n}(\theta' + N\phi') \tag{12}$$

$$\theta'' + \frac{1}{2} f\theta' = 0 \tag{13}$$

$$\frac{1}{Le}\phi'' + \frac{1}{2} f\phi' + S_r\theta'' = 0 \tag{14}$$

Where, $\chi^{-1} = 1 + \sqrt{\frac{Ra_x}{Pe_x}}$, $Pe_x = \frac{U_\infty x}{\alpha}$, $Ra_x = \frac{x}{\alpha}\left[\frac{\rho_\infty k^* g \beta_T (T_\infty - T_m)}{\mu^*}\right]^{1/n}$, $M_g = \frac{\sigma B_0^2 k^*}{\rho v}$, Hartmann number, $\chi =$ mixed convection parameter, $M = \frac{C_p(T_\infty - T_m)}{L + C_s(T_m - T_\infty)}$, melting parameter, $Re^* = \frac{\rho_\infty b k^*}{\mu^*}\left(\frac{\alpha}{x}\right)^{2-n}\left(Pe_x^{1/2} + Ra_x^{1/2}\right)^{2(2-n)}$, Reynolds number, $N = \frac{\beta_C(C_w - C_\infty)}{\beta_C(T_w - T_\infty)}$, Buoyancy Parameter, Soret number, $S_r = \frac{D_m k_T (T_w - T_\infty)}{\alpha T_m (C_w - C_\infty)}$, Lewis number, $Le = \frac{\alpha}{D}$

The forms of non linear differential equations are as follows:

$$f' + 2M\theta' = 0,\ \theta = 0,\ \phi = 0 \quad at \quad \eta = 0 \tag{15}$$

And

$$f' \to \chi^2,\ \theta \to 1 \quad \phi \to 1 \qquad at \quad \eta \to \infty \tag{16}$$

Physical quantities are of interest of engineers are the Nusselt number and Sherwood number, which are expressed as

$$\frac{Nu_x}{\chi^{-1} Pe_x^{\frac{1}{2}}} = \theta'(0) \tag{17}$$

$$\frac{Sh_x}{\chi^{-1} Pe_x^{\frac{1}{2}}} = \phi'(0) \tag{18}$$

IV. SOLUTION PROCEDURE

Using boundary conditions (15) and (16), the approximate solution of Eq. (12), Eq. (13) and Eq. (14) are solved numerically by means of the fourth order Runge- Kutta method coupled with a shooting technique and by giving appropriate initial guess values. The solution thus obtained is matched with the given values at $f'(\infty)$ and $\theta'(0)$. The integration length □$_{\infty}$□varies with the parameter values and it has been suitably chosen each time such that the boundary conditions at the outer edge of the boundary layer are satisfied. Accuracy up to 4th decimal place is considered for convergence.

V. RESULTS AND DISCUSSION

The non-dimensional equations eq. (12), eq. (13) and eq. (14) along with boundary conditions (15) and (16) are solved numerically. It can be easily seen from figure 2 that the fluid concentration boundary layer increases for a fixed value of melting parameter (M=1.0) for the increase of Soret parameter and there is a decent in the concentration distribution for dilatants fluid.

Table 1. Comparison of values of $-\theta'(0)$ for free convection along a vertical plate in Newtonian and non-Newtonian fluid saturated porous medium in the absence of parameters with χ=0, Re=0, Le=0, N=0.

Sl. No	Fluid type without melting	Cheng and Minkowycz (1977)	Chen and Chen (1988)	Kairi and RamReddy (2015)	Present Work
1	M=0, n=0.5	....	0.3768	0.37682	0.37681
2	M=0, n=1	0.4440	0.4437	0.44370	0.44370

From figure 3 it can be seen that the temperature distribution decreases uniformly with increasing magnetic parameter so that the thickness of the thermal boundary layer increases for fixed values of melting parameter in case of dilatants fluid. Figure 4 shows the pattern of the concentration distribution for different values of the magnetic parameter. It can be observed that the concentration of the fluid decreases as magnetic parameter increases. The influence of melting parameter on the temperature and concentration profile is presented in figure 5 and figure 6 respectively. A decrease in both the thermal and solutal distributions is observed as increase in the values of the melting parameter for a fixed value of magnetic parameter. Keeping Soret parameter fixed if melting parameter is increased there also seen a decrement of temperature as well as concentration and are shown in the figure 7 and figure 8. From figure 9 and figure 10 it is obvious that mixed convection parameter plays an important role on temperature and concentration profile. It indicates that thermal and concentration boundary layer increases with increase of mixed convection parameter for fixed value of melting parameter.

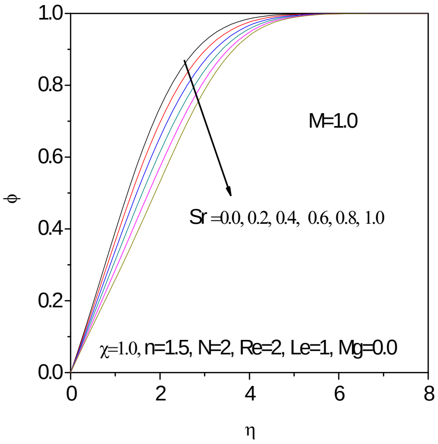

Figure 2. Dimensionless concentration for fixed value of melting parameter on the various values of Soret parameter.

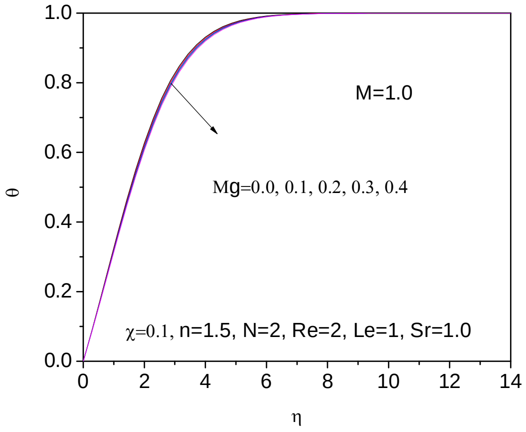

Figure 3. Dimensionless temperature profile for fixed value of melting parameter on the various values of magnetic parameter.

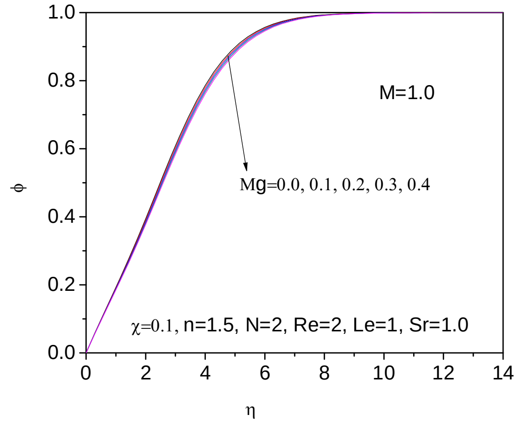

Figure 4. Dimensionless concentration profile for fixed value of melting parameter on the various values of magnetic parameter.

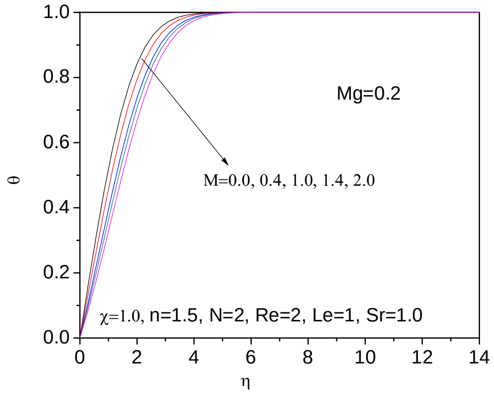

Figure 5. Dimensionless temperature profile for various values of melting parameter on the fixed values of magnetic parameter.

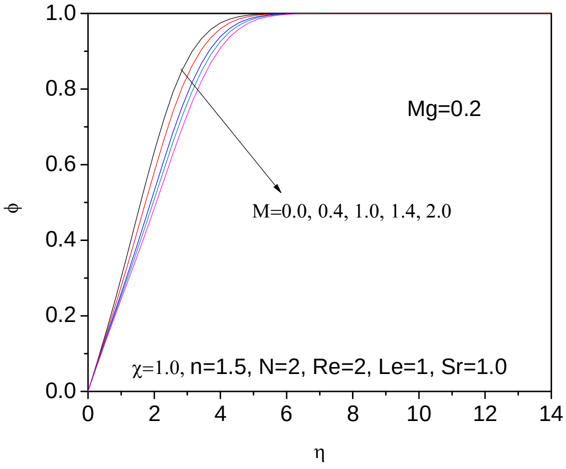

Figure 6. Dimensionless concentration profile for various value of melting parameter on the fixed values of magnetic parameter.

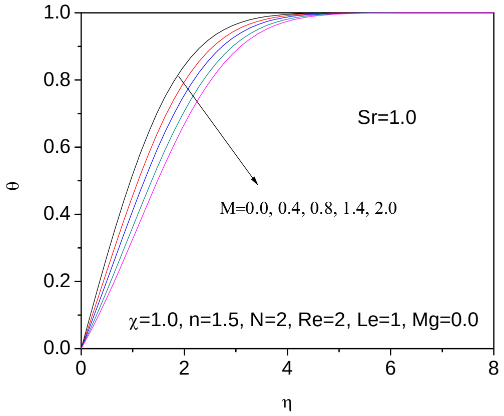

Figure 7. Dimensionless temperature profile for various value of melting parameter on the fixed values of Soret parameter.

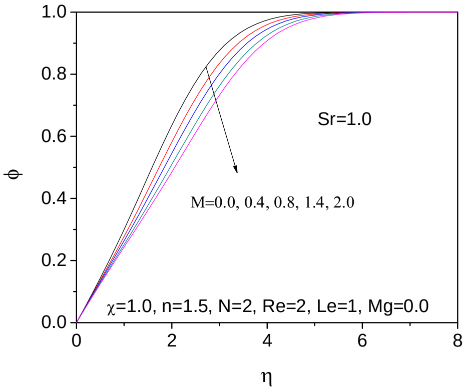

Figure 8. Dimensionless concentration profile for various value of melting parameter on the fixed values of Soret parameter.

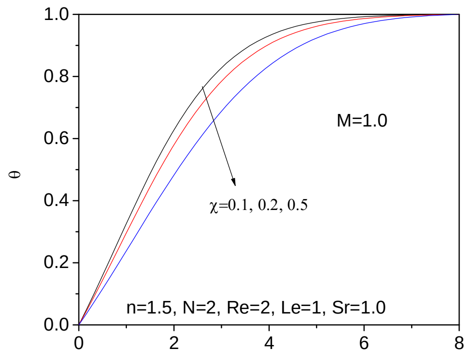

Figure 9. Dimensionless temperature profile for fixed value of melting parameter on the various values of mixed convection parameter.

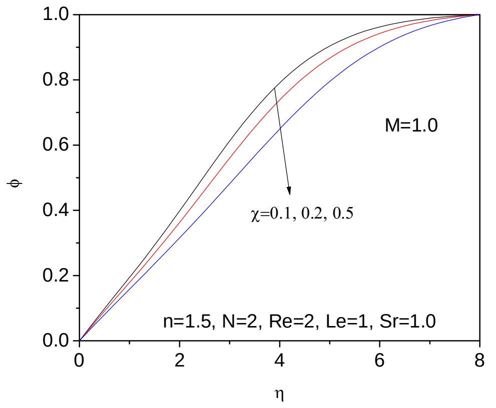

Figure 10. Dimensionless concentration profile for fixed value of melting parameter on the various values of mixed convection parameter.

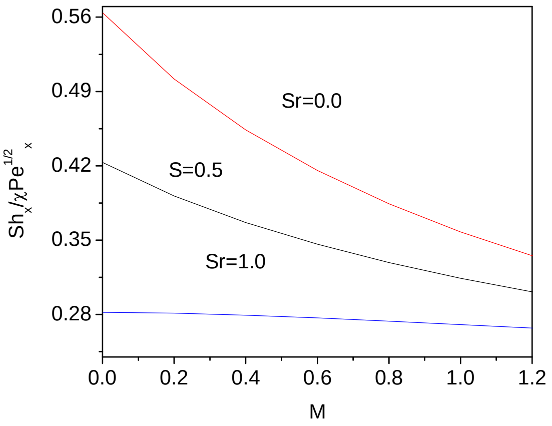

Figure 11. Variation of mass transfer coefficient against *M* for varying *Sr* keeping other parameter fixed.

It is seen from the figure 11 that the variation of mass transfer coefficient against melting parameter for different values of soret parameter. As melting parameter increases a reduction in mass transfer rate is observed with the increment of Soret parameter. Figure 12 shows that a decrement in mass transfer rate is observed in case of dilatants fluid than Newtonian fluid in the absence of magnetic parameter. Also it is noted that the heat transfer rate decreases for the case of dilatants fluid in the presence of Magnetic field with small amount and is shown in the figure 13.

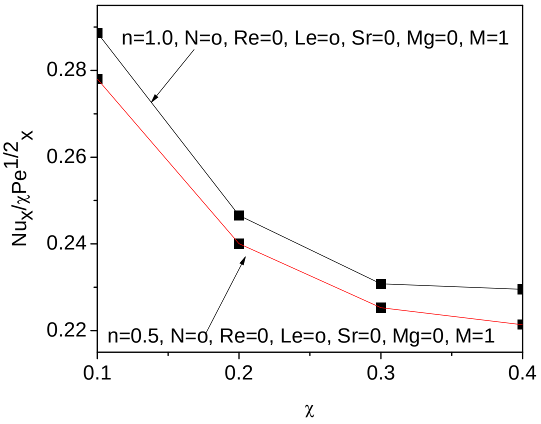

Figure 12. Variation of heat transfer coefficient against χ for Newtonian and pseudoplastic fluid.

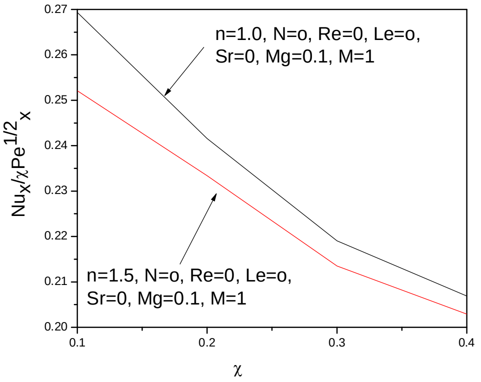

Figure 13. Variation of heat transfer coefficient against χ for Newtonian and dilatants fluid.

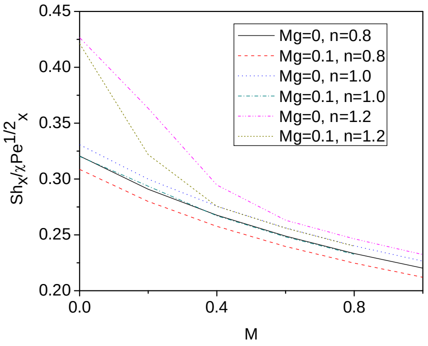

Figure 14. Variation of mass transfer coefficient against *M* for varying *Mg* and *n* keeping other parameter fixed.

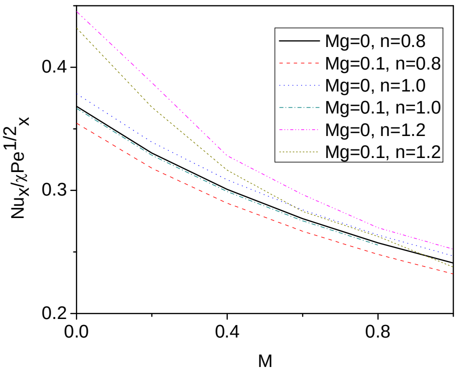

Figure 15. Variation of heat transfer coefficient against *M* for varying *Mg* and *n* keeping other parameter fixed.

Figure 14 shows that Variation of mass transfer coefficient against *M* for varying *Mg* and *n* keeping other parameter fixed. In this case, Sherwood number decreases with increases of melting parameter. It is also observed that Sherwood number decreases with increases of magnetic parameter for the cases of dilatants, Newtonian and pseudoplastic fluid. The variation of heat transfer coefficient against melting parameter for varying magnetic parameter (Mg) and power law index (n) is illustrate in figure 15. It can clear that with increases of melting parameter heat transfer rate decreases. It also noted that heat transfer rate decreases with increases of magnetic field for dilatants, Newtonian and pseudoplastic fluid.

VI. CONCLUSION

The impact of Soret parameter on the mixed convective melting process along a vertical plate embedded in a non Darcy porous media saturated with non-Newtonian fluid in presence of the magnetic field are investigated. The heat transfer rate as well as mass transfer rate decreases with increases of magnetic parameter for dilatants, Newtonian and pseudoplastic fluid.

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