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Effect of Radiation on MHD Mixed Convection Flow from a Vertical Plate Embedded in a Saturated Porous Media with Melting

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Abstract

The effect of radiation on a steady two-dimension magneto-hydrodynamic mixed convection flow from a vertical plate embedded in a saturated porous media with melting is analyzed.The non-linear partial differential equations, governing the flow field under consideration, have been transformed by a similarity transformation into a system of non-linear ordinary differential equations and then solved numerically by applying Nachtsheim-swigert shooting iteration technique together with sixth order Runge-Kutta integration schemes. Resulting non-dimensional velocity and temperature profiles are then presented graphically for different values of the parameters of physical and engineering interest. It is observed that the nusselt number decreases with increase in melting parameter, while it increases with increase in radiation parameter.

Keywords: *Liquid phase, Mixed convection, Magnetic effect, Radiations effect, Melting effect and porous medium.*

1 Introduction

Convective heat transfers with thermal radiation are very important in the process involving high temperature such as gas turbines, nuclear power plant and thermal energy storage etc. in light of these various applications, Hossain and Takhar [1] studied the effect of thermal radiation using Rosseland diffusion approximation on mixed convection along a vertical plate with uniform free stream velocity and surface temperature. Furthermore Hossain et al. [2, 3] studied the thermalradiation of a grey fluid which is emitting and absorbing radiation in a non-scattering medium. Olanrewaju et al. [4] studied the radiation and viscous dissipation effects on the laminar boundary layer about a flat-plate in a uniform stream fluid (Blassius flow) and about a moving plate in a quiescent ambient fluid (Sakiadis flow) both under convective boundary condition. Samad and Rahman [5] investigated the thermal radiation interaction with unsteady MHD boundary layer flow past a continuous moving vertical porous plate immerse in a porous medium with time dependent suction and temperature, in presence of magnetic field with radiation. In analyzing the problem they consider a Darcy-Forchheimer’s model and the corresponding momentum and energy equations, which they solved numerically, for cooling and heating of the plate by employing Nachtsheim-Swigert iteration technique along with the sixth-order Runge Kutta integration scheme. From the numerical computations, the skin friction coefficient (viscous drag) and the rate of heat transfer (Nusselt number), were sorted out and they concluded that, the suction stabilizes the boundary layer growth and also the velocity profiles increases, while the temperature profiles decreases with an increase of the free convection currents. An analysis to study the MHD flow of an electrically conducting, incompressible, viscous fluid past a semi-infinite vertical plate with mass transfer, under the action of transversely applied magnetic field was carried out by Palani and Srikanth [6]. They assumed that, the heat due to viscous dissipation and the induce magnetic field are negligible. An implicit finite difference schemes of Crank-Nicolson type was used to solve the non-dimensional governing equations which are unsteady, two-dimensional coupled non-linear partial differential equations. Their results show that, the transient velocity, temperature and concentration profiles all reach maximum values before decreasing slightly to their respective steady-state values. They also observed that the contribution of mass diffusion to the buoyancy force increases the maximum velocity significantly and local shear stress gets reduced by the increasing value of magnetic field parameter.

Convective heat transfer in porous media in the presence of melting effect has received some attention in recent years. This stems from the fact that this topic has significant direct application in permafrost melting, frozen ground thawing, casting and bending processes as well as phase change metal. Kazmierczak et al. [7] examined the velocity, temperature and Nusselt number in the melting region from a flat plate in the presence of steady natural convection. Bakier [8] studied the melting effect on mixed convection from a vertical plate of arbitrary temperature both aiding and opposing flow in a fluid saturated porous medium. It was observed that, the melting phenomenon decreases the local Nusselt number at solid-liquid interface. Mixed convection in melting from a vertical plate of uniform temperature in a saturatedporous medium has been extensively studied by Gorla et al. [9]. In their results, it was observed that, the melting process decreases the local Nusselt number at solid-liquid interface. Tashtoush [10] analyzed the magnetic and buoyancy effects on melting from a vertical plate by considering Forchheimer's extension. Cheng and Lin [11] studied melting effect on mixed convective heat transfer with aiding and opposing external flow from the vertical plate in a liquid saturated porous medium by using Runge-Kutta-Gill method and Newton's iteration for similarity solutions. Effect of melting and thermo-diffusion on natural convection heat and mass transfer in a non-Newtonian fluid saturated non-Darcy porous medium was studied by Kairi and Murthy [12]. It was observed that the velocity, temperature and concentration profiles as well as the heat and mass transfer coefficients are significantly affectedby the melting phenomena and thermal-diffusion in the medium. Prasad and Hemalatha [13] studied non-Darcy mixed convection with thermal dispersion-radiation in a saturated porous medium using Forchheimer extension for the flow equations in steady state. It was observed that, the Nusselt number decreases with increase in melting parameter and increases in the combined effect of thermal dispersion and radiation. Recently, Prasad et al. [14] analyzed the problem of mixed convection along a vertical plate in a non Newtonian fluid saturated non-Darcy porous medium in the presence of melting, thermal dispersion-radiationandheat absorbing or generation effects for aiding and opposing external flows.

Of interest, among the reviewed articles in this work is Toshtash [10], in which the combined effect of magnetic and buoyancy influences is considered on melting from a vertical plate. However, several fluids of interest exist with radiating properties for which results in [10] are not applicable. The present article therefore is aimed at addressing the limitation and extends its results to fluids with radiating properties.

2 Mathematical Formulation

A steady two dimension MHD mixed convection laminar boundary layer flow of viscous incompressible and electrically conducting fluid along a vertical plate under the influence of thermal radiation is considered. It is assumed that this plate constitutes the interface between the liquid and solid phases during melting process inside the porous matrix. The plate is maintained at constant melting temperature T_m, of the materials occupying the porous matrix. The liquid phase temperature T_∞, and the temperature of the solid far from the interface is T_s. Figure 1 shows the flow model and coordinate system. The fluid is considered to be grey, absorbing/emitting radiation and Rosseland approximation is used to describe the radioactive heat flux in the energy equation. The radioactive heat flux in the x- direction is considered negligible in comparison to the y-direction, also the fluid is considered to be electrically conducting so that the induced magnetic field is negligible. Hence, only the applied magnetic field B_0 plays a role which gives rise to magnetic forces.

Taking into account the thermal radiation term in the energy equation, the governing equation for steady laminar non-Darcy flow and heat transfer in a porous medium can be written as follows [10]:

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

$$\left(1+\frac{\sigma B_0^2}{\rho v}+\frac{2F\sqrt{K}}{v}u\right)\frac{\partial u}{\partial y}=\frac{-Kg\beta}{v}\frac{\partial T}{\partial y} \tag{2}$$

$$u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}=\frac{k}{\rho C_p}\frac{\partial^2 T}{\partial y^2}+\frac{\sigma B_0^2 u^2}{\rho C_p}-\frac{1}{\rho C_p}\frac{\partial q_r}{\partial y} \tag{3}$$

The boundary conditions are:

$$y=0,\quad T=T_m,\ k\frac{dT}{dy}=\rho\left[L+C_s\left(T_m-T_s\right)\right]v \tag{4}$$

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

where u and v are the velocity component along and normal to the flow direction, F is the inertia coefficient, K is the permeability, k is the liquid thermal conductivity, ρ is the liquid density, σ is the electric conductivity, v is the kinematic viscosity, β is the thermal expansion coefficient, g is the acceleration due to gravity, T is temperature of fluid inside the thermal boundary layer, C_ρ is the liquid specific heat, q_r is the radioactive heat flux in the y –direction, U_∞ is a constant free stream velocity, L is the plate length and C_s is the specific heat capacity of the solid phase.

Using the Rosseland approximation for radiation for an optically thick boundary layer (i.e., intensive absorption) [15-19], the radiation flux is simplified as

$$q_r=-\frac{4\sigma^*}{3k^*}\frac{\partial T^4}{\partial y} \tag{6}$$

where σ^* and k^* are Stefan-Boltzmann and the Rosseland mean absorption coefficient, respectively. Following Chamkha [20] we assume that the temperature differences within the flow such as that the term T^4 can be expressed as a linear function of temperature. Hence, expanding T^4 in a Taylor series about T_∞ (the fluid temperature in the free stream) and neglecting higher-order terms we get

$$T^4 = 4T_\infty^3 T - 3T_\infty^4 \tag{7}$$

In view of Eqs. (6) and (7), Eq (3) reduces to

$$u\frac{\partial T}{\partial x} + v\frac{\partial T}{\partial y} = \frac{\sigma B_0^2 u^2}{\rho C_p} + \left(\alpha + \frac{16\sigma^* T_\infty^3}{3\rho C_\rho k^*}\right)\frac{\partial^2 T}{\partial y^2} \tag{8}$$

Where $\alpha = \dfrac{k}{\rho C_\rho}$ is the thermal diffusivity.

From the above equation it is seen that the effect of radiation is to enhance the thermal diffusivity.

If we take $R = \dfrac{kk^*}{4\sigma^* T_\infty^3}$ as the radiation parameter, (8) becomes

$$u\frac{\partial T}{\partial x} + v\frac{\partial T}{\partial y} = \frac{\sigma B_0^2 u^2}{\rho C_p} + \frac{\alpha}{k_0}\frac{\partial^2 T}{\partial y^2} \tag{9}$$

Where $k_0 = \dfrac{3R}{3R+4}$. It worth citing here that the classical solution for the energy equation, Eq. (9), without radiation influences can be obtained from the above equation, see Tashtoush [10] as $R \to \infty (ie., k \to 1)$

By introducing the following similarity variables

$$\eta = Pe_x^{0.5}\frac{y}{x} \quad \psi = \alpha Pe_x^{0.5} f(\eta), \quad \theta(\eta) = \frac{T - T_m}{T_\infty - T_m} \tag{10}$$

Where Pe is the peclet number, substituting equation (10) into equation (2) and (9), we obtain the following transformed governing equations:

$$\left(1+Ha^{2}+2\Lambda f'\right)f''+\frac{Gr}{\mathrm{Re}}\theta'=0 \tag{11}$$

$$\mathrm{Re}\,\theta''+\left(\frac{3R}{3R+4}\right)\frac{\mathrm{Re}}{2}f\theta'+\left(\frac{3R}{3R+4}\right)\frac{Ha^{2}Ec}{Da}f'^{2}=0 \tag{12}$$

The boundary conditions are

$$\eta=0,\theta=0,\ f(0)+2M\theta'(0)=0$$

$$\eta\to\infty,\theta=1,\ f'=1 \tag{13}$$

Where $M=\dfrac{C_p\left(T_\infty-T_m\right)}{1+C_s\left(T_m-T_s\right)}$ is the melting parameter, $\mathrm{Re}=\dfrac{U_\infty x}{\nu}$ is the Reynolds number, $\Lambda=\mathrm{Re}\,F\sqrt{Da}$ is the inertia parameter, $Gr=\dfrac{Kg\beta_T\left(T_\infty-T_m\right)x}{\nu^{2}}$ is the Grashof number, $Ec=\dfrac{u_0^2}{C_p\left(T_\infty-T_m\right)}$ is the Eckert number, $Da=\dfrac{K}{x^2}$ is the Darcy number and $Ha=\sqrt{\dfrac{\sigma B_0^2}{\rho\nu}}$ is the Hartman number.

The quantity $\dfrac{Gr}{\mathrm{Re}}$ in equation (11) is a measure of the relative importance of free and force convection and is the controlling parameter for the present problem.

The heat transfer rate along the surface of the plate q_w can be computed from the Fourier heat conduction law.

$$q_w=-k\left.\frac{\partial T}{\partial y}\right|_{y=0} \tag{14}$$

The heat transfer results can be represented by the local Nusselt number Nu, which is defined as $Nu=\dfrac{hx}{k}=\dfrac{q_w x}{k\left(T_m-T_\infty\right)}$ (15)

Where h denotes the local heat transfer coefficient and k represent the liquid phase thermal conductivity. Substituting equation (10) and (14) into equation (15) and noticing that $T_\infty \succ T_m$ we obtain

$$\frac{Nu}{Pe^{0.5}} = \theta'(0)\left(\frac{3R+4}{3R}\right) \tag{16}$$

3 Numerical Methods

The dimensionless equations (11)-(12) together with the boundary condition (13) are solved numerically by means of sixth order Runge-kutta methods coupled with shooting technique. The solution thus obtained is matched with the given values of $f'(\infty)\ and\ \theta(0)$. In addition, the boundary condition $\eta \to \infty$ is approximated by $\eta_{\max} = 4$ which is found sufficiently large for the velocity and temperature to approach the relevant free stream properties.

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

		Tashtoush (2005)		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

Table 2: Values of $\theta'(0)$ and $f(0)$ for $\Lambda = 0.5, Ec = 0.1, Da = 0.1,\ R = 2.0,\ Ha = 1.0\ and\ \mathrm{Re} = 1.0$ for different values of mixed convection and melting parameters

Gr/Re	M	$f(0)$	$\theta'(0)$
0.1	0.0	0	1.5895
	0.2	- 0.56263	1.4066
	0.4	- 1.0139	1.2674
	0.6	- 1.3895	1.1579
	0.8	- 1.7110	1.0694
	1.0	- 1.9924	0.9962
1.0	0.0	0	1.6123

0.2	- 0.5819	1.4547
0.4	- 1.06550	1.3319
0.6	- 1.4798	1.2331
0.8	- 1.8429	1.1518
1.0	- 2.1669	1.0835

Table 3: Values of $\theta'(0)$ for $\frac{Gr}{\mathrm{Re}}=0.1, \Lambda=0.5, Ec=0.1, Da=0.1, \ Ha=1.0 \ and \ \mathrm{Re}=1.0$for different values of mixed convection and melting parameters

M	R	$\theta'(0)$
0.0	0.0	0.2500
	0.2	0.8921
	0.4	1.2349
	0.6	1.4463
	0.8	1.5895
	1.0	1.7710
2.0	0.0	0.2500
	0.2	0.6287
	0.4	0.7147
	0.6	0.7459
	0.8	0.7608
	1.0	0.7740

4 Result and Discussion

Numerical computations are carried out for a range of values of the buoyancy parameter Gr/Re, melting parameter M, radiation parameter R, dimensionless inertia parameter Λ and Hartman number Ha on the dimensionless stream function f and θ' at the plate and the results are presented in Tables 1-3. In order to test the accuracy of our results, we have compared our results with those of Toushtash [10] without the radiation effect. The obtained values are found to be in excellent agreement, as presented in Table 1. Numerical results are presented graphically for the mixed convection ranging from 0.0 to 10.0, melting parameter ranging from 0.0 to 2.0, magnetic field ranging from 0.0 to 2.0, dimensionless inertia parameter Λ ranging from 0 to 1.0 and radiation parameter ranging from 0.0 to 2.0. The effects of thermal radiation parameter (R) on the velocity profile and temperature distribution are plotted in figures 2 and 3. It is evident from these figures that, the presence of thermal radiation affect the activity of the fluid or liquid velocity inversely. This can be seen clearly from the velocity curves which decreases as radiation parameter R increases while increasing the values of radiation parameter leads to an increase in liquid temperature distributions, respectively. Figures 4 and 5 depict the effect of mixed convection parameter (Gr/Re) in velocity and temperature distribution respectively. It is observed that increases in the values of Gr/Re have a tendency to increase the buoyancy effect due to temperature differences and this leads to increase in slip velocity on the plate. However, the thermal boundary layer thickness decreases with increase in Gr/Re and it results to increase in the fluid temperature as shown in Figure 5.

Figures 6 and 7 present the influence of melting parameter (M) on velocity and temperature profiles respectively. It is obvious that increasing the melting parameter causes higher acceleration to the fluid flow which in turn, increases its motion and causes decrease in temperature. This is established by respective increases in the boundary layer thickness of velocity and temperature.

The effect of flow inertia (Λ) on the velocity profiles is shown in figure 8. It can be seen that as Λ increases the velocity of the slip on the plate decreases, this decrease in slip velocity is observed to cause an increase in the thermal boundary layer thickness which consequently lead to a decrease in the temperature as shown in figure 9.

Figures 10 and 11 depict the effect of magnetic parameter (Ha) on the dimensionless velocity and temperature distribution, respectively. It can be seen that application of magnetic field normal to the flow of an electrically conducting fluid gives rise to a resistive force that acts in the direction opposite to that of flow. Thus, thermal boundary layer thickness is significantly increased. These behaviors are depicted in the respective decrease in velocity as well as an increase in the temperature as the magnetic parameter Ha is increased.

Figure 12 shows the local Nusselt number varying with the radiation parameter and the different melting parameter. Increasing the values of radiation parameter led to increase in average heat transfer rate, although in the absent of Radiation parameter that is R=0, the heat transfer coefficient is constant with increase in melting parameter while increase in melting parameter led to decrease in average heat transfer rate. This is physically true since fluid temperature decreases with growing M and the temperature gradient on the plate decreases with it.

Figures

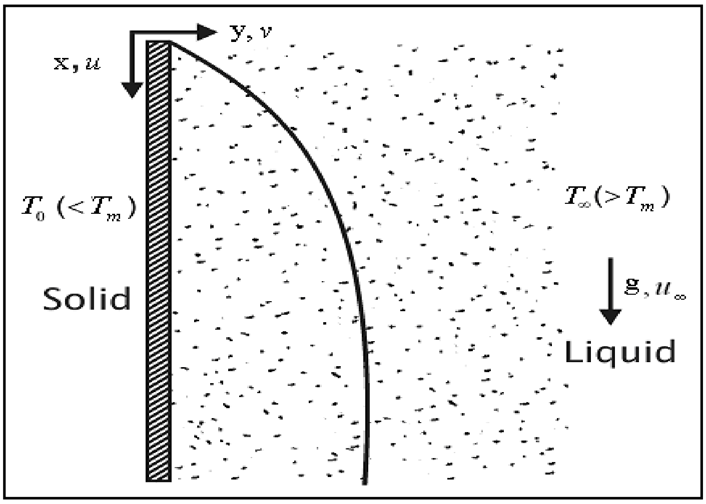

Figure 1: The investigated physical model

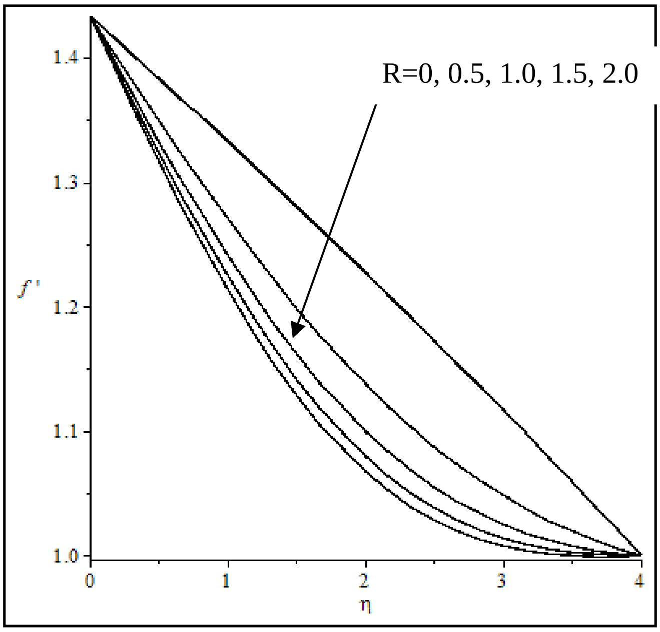

Figure 2: Dimensionless Velocity profiles for different radiation parameters with Gr/Re =1, Re=1.0, Λ=0.5, Ec=0.1, Da=0.1, M=0.2 and Ha=1.0

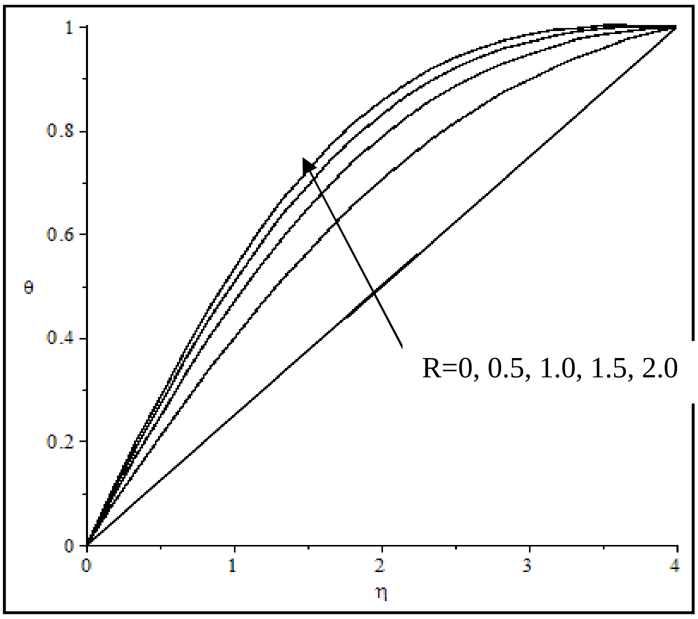

Figure 3: Dimensionless temperature profiles for different radiation parameters with Gr/Re =1, Re=1.0, Λ=0.5, Ec=0.1, Da=0.1, M=0.2 and Ha=1.0

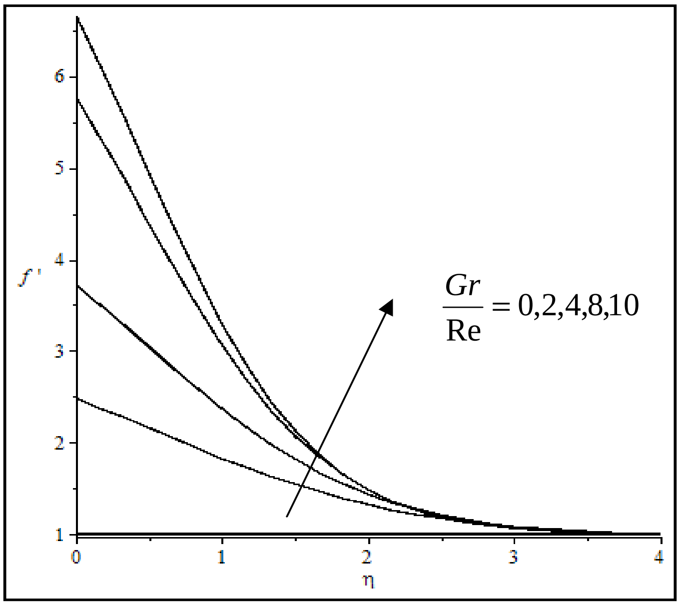

Figure 4: Dimensionless Velocity profiles for different Gr/Re parameters with R=2,Re=1.0, Λ=0.1, Ec=0.1, Da=0.1, M=1.0 and Ha=0

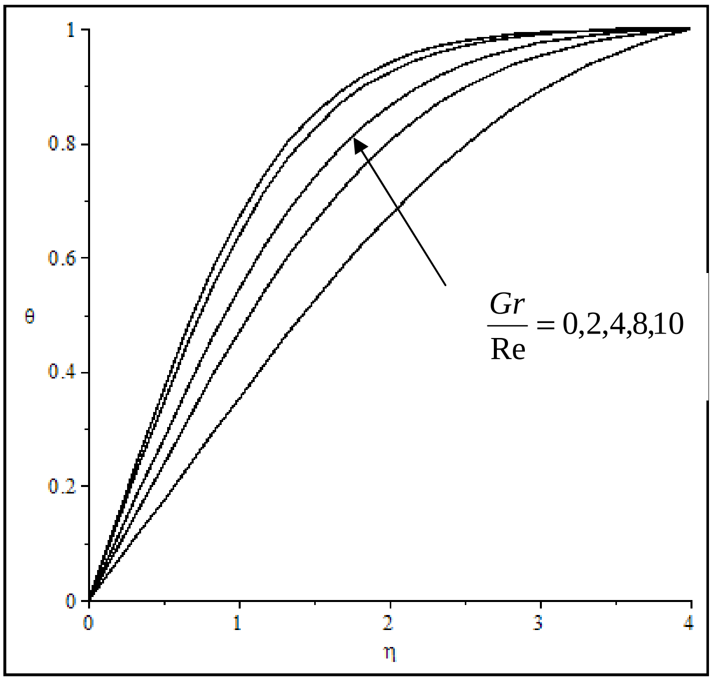

Figure 5: Dimensionless temperature profiles for different Gr/Re parameters with R=2, Re=1.0, Λ=0.1, Ec=0.1, Da=0.1, M=1.0 and Ha=0

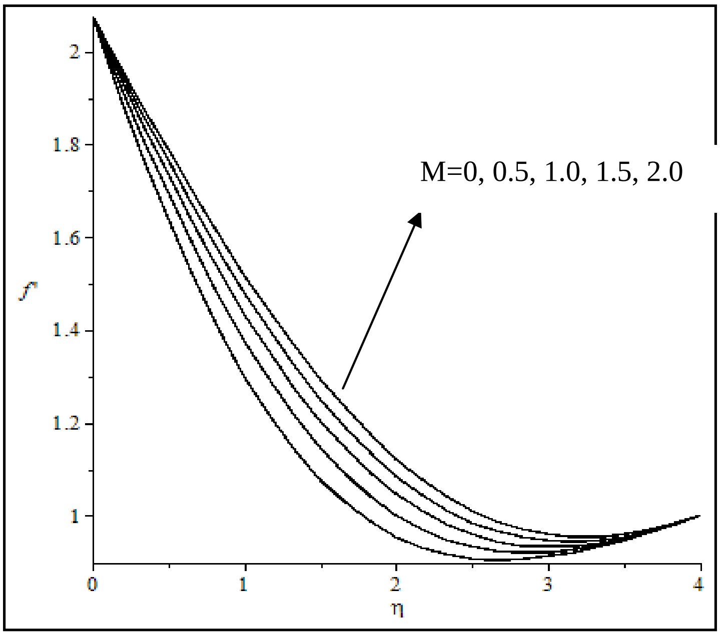

Figure 6: Dimensionless Velocity profiles for different Melting parameters with R=2, Gr/Re =3, Re=1.0, Λ=0.5, Ec=0.1, Da=0.1, M=0.2 and Ha=0.5

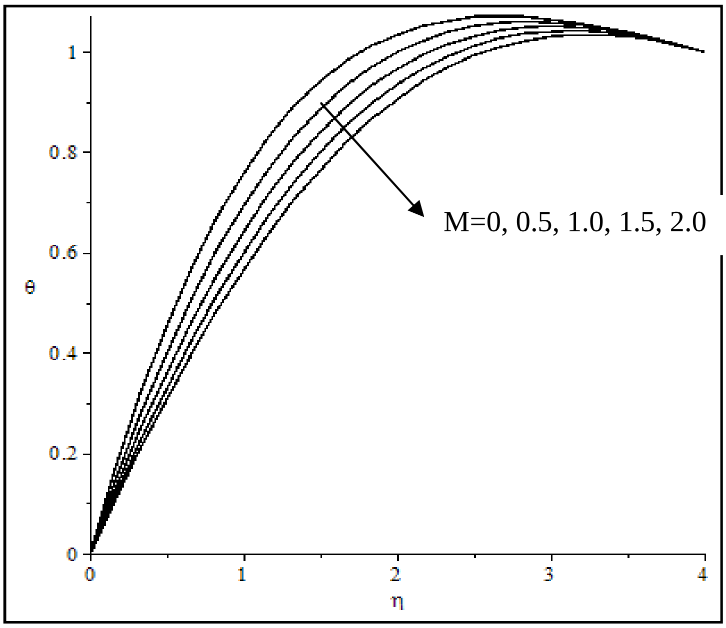

Figure 7: Dimensionless temperature profiles for different Melting parameters with R=2.0 Gr/Re =3, Re=1.0, Λ=0.5, Ec=0.1, Da=0.1, M=0.2 and Ha=0.5

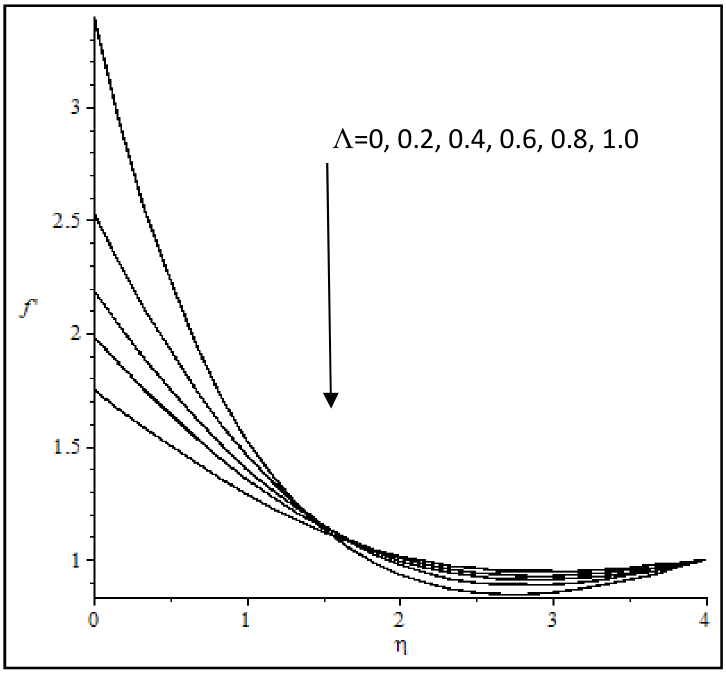

Figure 8: Dimensionless Velocity profiles for different inertia parameters with R=2.0, Gr/Re =3, Re=1.0, Ec=0.1, Da=0.1, M=0.5 and Ha=0.5

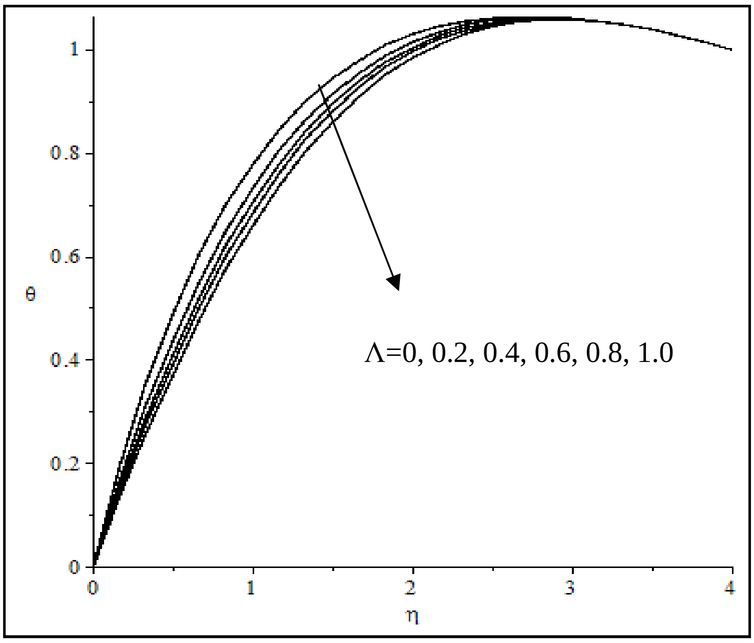

Figure 9: Dimensionless temperature profiles for different inertia parameters with R=2.0, Gr/Re =3, Re=1.0, Ec=0.1, Da=0.1, M=0.5 and Ha=0.5

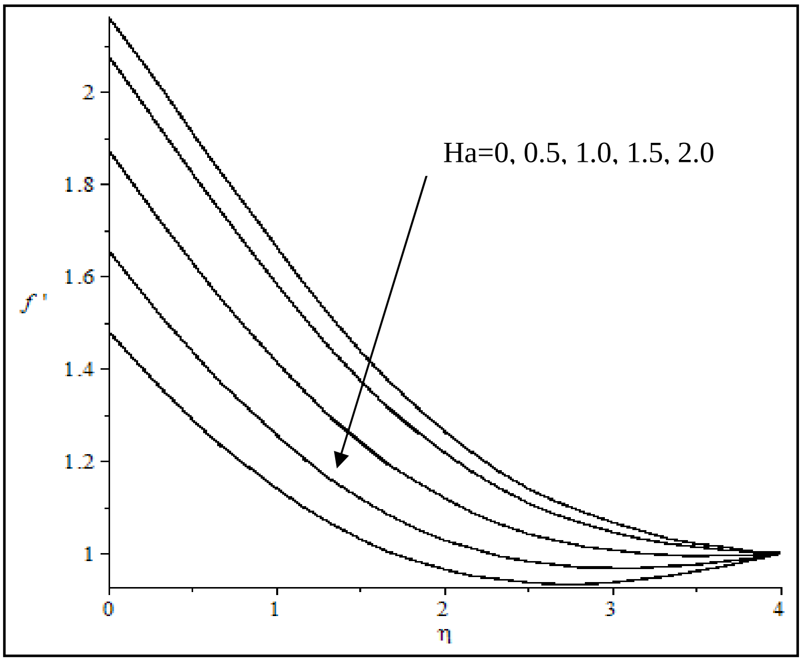

Figure 10: Dimensionless Velocity profiles for different Magnetic parameters with R=2.0 Gr/Re =3, Re=1.0, Ec=0.01, Da=0.1 and M=0.5

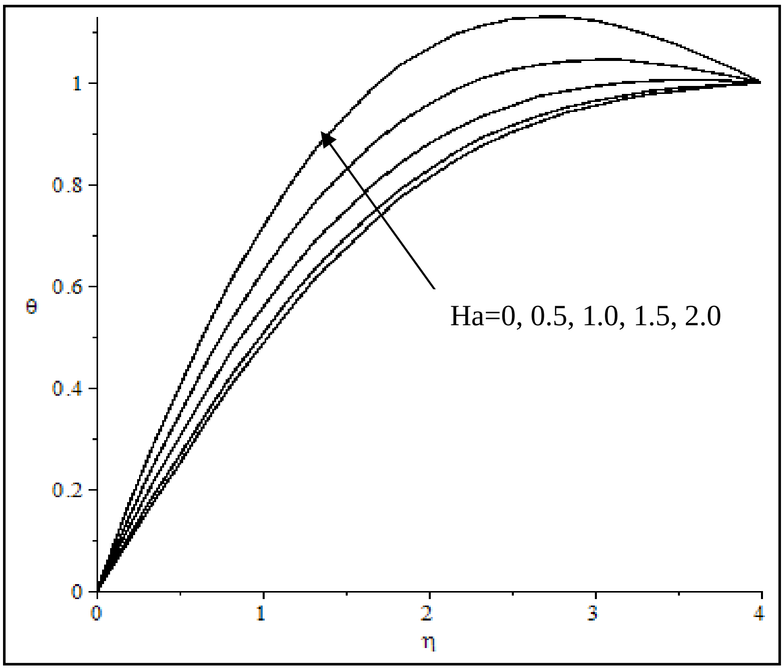

Figure 11: Dimensionless Temperature profiles for different Magnetic parameters with R=2.0, Gr/Re =3, Re=1.0, Ec=0.01, Da=0.1 and M=0.5

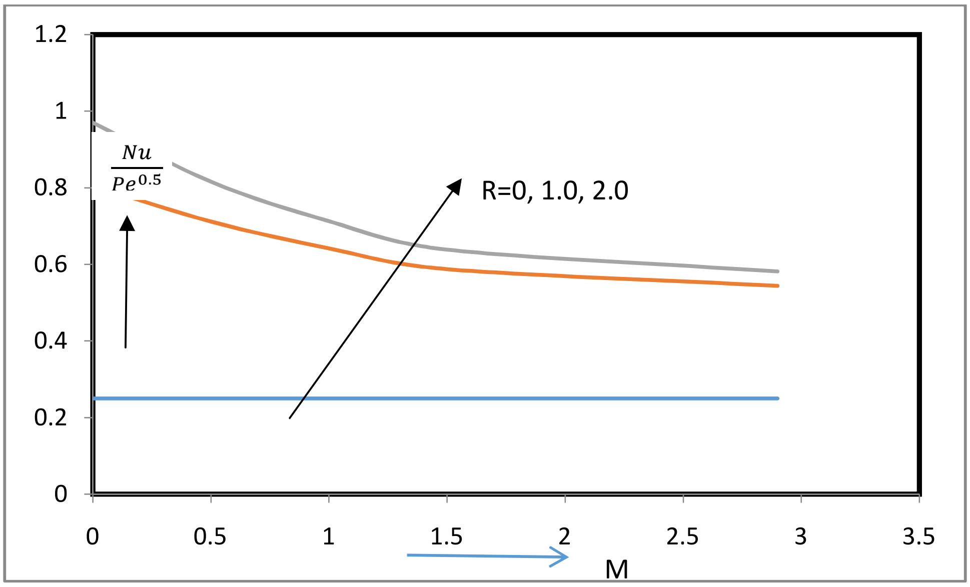

Figure 12: Nusselt number variation with melting parameter for different radiation parameter

5 Conclusion

In this study, effect of radiation on MHD mixed convection flow from a vertical plate embedded in a saturated porous media with melting is analyzed. The heat transfer coefficients were obtained for various values of flow influencing parameters. It is noted that the velocity and temperature profiles as well as the heat transfer coefficients are significantly affected by the radiation parameter in the medium. The major conclusion is that the heat transfer coefficients are reduced with increasing melting parameter and grows with increasing radiation parameter as shown in figure 12 and Table 3. The results obtained in the present work have been validated by works in existing literature and an excellent agreement is found.

Nomenclature

B_0 Magnetic flux density [T]

C_ρ Liquid specific heat capacity [J/kg K]

C_s Solid specific heat capacity [J/kg K]

Da Darcy number, $\frac{K}{x^2}$

Λ Inertia parameter $\mathrm{Re}\, F\sqrt{Da}$

f Dimensionless stream function

G_r Grashof number $\frac{Kg\beta_T\left(T_\infty - T_m\right)x}{\nu^2}$

h Heat transfer coefficient [W/m^2 K]

Ha Hartman number, $\sqrt{\frac{\sigma B_0^2 K}{\rho\nu}}$

Ec Eckert Number $\frac{u_0^2}{C_p\left(T_\infty - T_m\right)}$

K Permeability of porous media [m^2]

k Thermal conductivity [W/m K]

L Plate length [m]

M Melting parameter, $\frac{C_p(T_\infty - T_m)}{1 + C_s(T_m - T_s)}$

Nu Nusselt number $\frac{hx}{k}$

q_w Heat flux [W/m^2]

Re Reynolds number $\frac{U_\infty x}{\nu}$

T Temperature [K]

T_m Melting Temperature [K]

T_s Solid temperature [K]

T_∞ Liquid temperature [K]

q_r Radiation heat flux

u_∞ External flow velocity [m/s]

U, V Velocity in x and y direction [m/s]

x, y Coordinate axes along and perpendicular to plate [m]

R radiation parameter

Greeks

α Thermal diffusivity [m^2/s]

β Coefficient of kinematic viscosity [m^2/s]

η Dimensionless similarity variable

ρ Liquid density [kg/m^3]

ν Kinematic viscosity [m^2/s]

σ Electrical conductivity of fluid [mho m^{-1}]

θ Dimensionless Temperature, $\frac{T - T_m}{T_\infty - T_m}$

ψ Dimensionless stream function [m^2/s]

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