International Journal of Mathematical Archive-12(12), 2021, 1-8
IJMA Available online through www.ijma.info ISSN 2229 – 5046

MHD MIXED CONVECTIVE FLOW IN A POROUS MEDIUM AND CONVECTIVE BOUNDARY CHEMICAL REACTION

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(Received On: 06-12-21; Revised & Accepted On: 31-12-21)

ABSTRACT

The current paper study the effect of thermal radiation on steady MHD mixed convection flow in a porous medium and boundary chemical reaction. The effect of chemical reaction is also taken into account and hence a first-order chemical reaction is considered. Firstly, the governing equations of fluid have been written into a normalized form and then an implicit finite-difference scheme is applied for solving the ordinary differential equations. Illustrative outcomes are obtained to interpret the different physical parameters of interest. The results show that, for the case $B_i = 0$, (biot number) the skin-friction is almost constant for various values of radiation parameter and no change in the Nusselt number takes place. However, for $B_i > 0$, increasing the radiation parameter is leading to an increase in values of skin-friction and reduction in values of Nusselt number.

Keywords: *Radiation effect, MHD flow, convection boundary condition, chemical reaction, Biot number.*

1. INTRODUCTION

The coupled heat and mass transfer convection flows under the influence of magnetic field are found in many applications and engineering processes such as cooling of nuclear reactors, the boundary layer control in aerodynamics, plasma studies and etc. Analysis of free and forced convection flow for electrically conducting fluids in the presence of chemical reaction is of substantial importance in many applications in Science and Technology such as packed-bed catalytic reactors, cooling of nuclear reactors, geothermal reservoirs, thermal insulation and etc. Magnetohydro-dynamic (MHD) flows are also frequently arisen in a porous media in order to controlling transport phenomena such as petroleum reservoirs recovery, radioactive waste disposal and etc.

There has been an interest in analyzing MHD flow under the influence of thermal radiation effects due to the effect of radiation on the performance of many engineering systems applying the electrically conducting fluids. Moreover, by taking into account the radiation heat transfer the operating temperature rises and then the fluid is ionized. Many new engineering processes take place at high temperatures and thus the effect of thermal radiation cannot be ignored. Therefore, having the knowledge of radiation heat transfer is of considerable importance in modeling the engineering issues.

REVIEW OF LITERATE

1. Combined heat and mass transfer by laminar natural convection from a vertical plate were studied by Lin and Wu [1].
2. Hossain and Takhar [2] found the radiation effect on mixed convection along a vertical plate with uniform surface temperature. The effect of free convection on MHD coupled heat and mass transfer of a moving permeable vertical surface was reported by Yih [3].
3. Chamkha and Khaled [4] investigated hydro-magnetic combined heat and mass transfer by natural convection from a permeable surface embedded in a fluid saturated porous medium.
4. Chamkha *et al* [5] investigated the natural convection from an inclined plate embedded in a variable porosity medium due to solar radiation.

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5. Makinde [6] studied the free convection flow with thermal radiation and mass transfer past a moving vertical porous plate.
6. Ramachandra Prasad *et al* [7] considered the radiation and mass transfer effects in two-dimensional flow past an impulsively started iso-thermal vertical plate. The effect of chemical reaction on the mixed MHD flow over a semi-infinite plate in a porous medium was studied by
7. Recently, Makinde and Aziz [9] considered a convective boundary condition in a MHD mixed convection flow over an infinite vertical plate. The effects of permeability, suction and chemical reaction have been investigated in their model. The objective of the present analysis is focused on analyzing the effects of thermal radiation on steady MHD mixed convection flow over an infinite vertical plate considering a convective boundary condition and suction which the plate is embedded in a porous medium. Moreover, a first-order chemical reaction is also considered.

2. PHYSICAL AND MATHEMATICAL MODEL

An infinite vertical plate considered in the present study is shown in Figure 1. The plate is embedded in a saturated porous medium. The Cartesian coordinate system is selected for the problem. The x and y axes are along and perpendicular to the surface, respectively. The cold fluid on the right side of the surface is assumed as viscous, incompressible, Newtonian and electrically conducting. The temperature of the fluid is $T\infty$ where all thermo-physical properties are taken constant and independent of temperature (T) and concentration (C) except for the density (ρ). In the present work, the mixed convection flow is considered laminar, steady and hydro-magnetic. The forced magnetic field of strength B_0 is homogeneous and normal to the plate. Because of the small magnetic Reynolds number for most fluids in engineering problems, the induced magnetic field is considered insignificant. The temperature of the hot fluid with a convective heat transfer coefficient h_f on the left side of the plate is T_f .

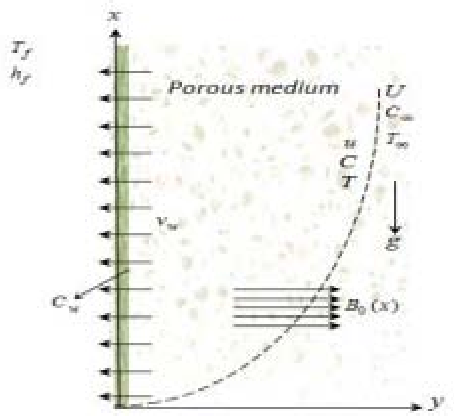

Fig. 1 Schematic of coordinate system.

Under the foregoing conditions and Boussinesq approximation, the system of momentum, energy and concentration equations can be written as follows [9, 10]:

$$\frac{\partial u}{\partial x} + \frac{dv}{dx} = 0 \tag{1}$$

$$\frac{\partial u}{\partial x}u + v\frac{dv}{dx} = \frac{\partial^2 u}{\partial y^2}u + g\beta(T - T_\infty) + g\beta(C - C_\infty) - \left(\frac{\sigma_e\ B_0^2}{\rho} + \frac{\vartheta}{K}\right)(u - U_\infty) + U_\infty\frac{dU_\infty}{dx} \tag{2}$$

$$\frac{\partial T}{\partial x}u + v\frac{dT}{dx} = \alpha\frac{\partial^2 T}{\partial y^2} - \frac{\alpha}{k}\frac{\partial q_r}{\partial y^2} + Q(C - C_\infty) \tag{3}$$

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

The appropriate boundary conditions for this problem may be given by:

$$U = 0,\ v = 0,\ T = T_w,\ C = C_w y = 0 :$$
$$U \to U_\infty = cx,\ T \to T_\infty\ \ C \to C_\infty\ \ as\ \ y \to \infty \tag{5}$$

where u is the velocity component parallel to the x-axis, ν, Cp and k are kinematic viscosity, specific heat at constant pressure and thermal conductivity of the fluid, respectively. β_t and β_m are thermal and concentration expansion coefficients. g, q_r, vm, Cw and U are the gravitational acceleration, radiation heat flux, wall suction velocity, local concentration at plate surface and free stream velocity, respectively. σ is the electrical conductivity and K is the permeability parameter. Subscript ∞ denotes the free stream conditions of temperature and concentration. Furthermore, D is the mass diffusivity, T_m is the mean fluid temperature, kT is the thermal diffusion ratio, C_s is the concentration susceptibility and γ is the reaction rate coefficient.

By taking into account the Rosseland approximation for the radiation term [11] in the equation (2), the convective heat flux, q_r, can be modeled as:

$$q_r = -\frac{4\sigma}{3k}\frac{dT^4}{dy}$$

where k is the Rosseland mean absorption coefficient and σ is the Stefan-Boltzmann constant. The Rosseland approximation is used for an optically thick medium, so the fluid is assumed to be optically thick medium. It seems reasonable to assume that the temperature differences within the flow are sufficiently small so that, T^4 can be stated in a simpler way by using a Taylor series about T∞ and neglecting higher order terms, therefore:

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

By replacing the above expression into equations (6) and (7), the energy equation (2) reduces to the following equation:

$$\eta = y\sqrt{\frac{c}{\vartheta}},\ \ \psi(x,y) = \sqrt{\upsilon c x}\ f(\eta) \tag{8}$$

$$\theta(\eta) = \frac{(T-T_\infty)}{(T_w-T_\infty)}\quad \phi = \frac{(C-C_\infty)}{(C_w-C_\infty)},\ G_T = \frac{g\beta(T_w-T_\infty)x^3}{\upsilon^2},\ G_c = \frac{g\beta(C_w-C_\infty)x^3}{\upsilon^2}$$

$$Ra = \frac{4\sigma T_\infty^3}{kK'},\ Re_x = \frac{U_\infty x}{\upsilon},\ K = \frac{\upsilon}{c\bar{K}},\ P_r = \frac{\upsilon}{\alpha},\ S_c = \frac{\upsilon}{D}\ \ \upsilon = \frac{\mu}{\rho},\ M = \frac{\sigma_e B_0^2}{c\rho},\ S = \frac{Q(C_w-C_\infty)\vartheta}{c\alpha(T_w-T_\infty)}$$

To normalize the equations (1), (3) to (5) and (8), the following normalized quantities are introduced:

where η, Pr, M, Gr, Gc are the normalized coordinate along the y-axis, the Prandtl number, magnetic field parameter, Eckert number, thermal Grashof number and mass transfer Grashof number, respectively. Also κ, Sc and λ are the permeability parameter, Schmidt number and reaction rate parameter, respectively. F is the normalized velocity of free stream and R is the radiation parameter. Furthermore, f, θ and φ are the normalized quantities of velocity, temperature and concentration, respectively.

In this work similar to [9], the calculations of y direction are considered while the variations are neglected in the x direction. Therefore, with help of normalized parameters the ordinary differential equations (1), (3) to (5) and (8) are converted to simplified ordinary differential equations as follows:

$$f''' + ff'' - f'^2 + G_T\theta + G_C\emptyset - (K+M)(f'-1) + 1 = 0 \tag{9}$$

$$(1 + \frac{4}{3}Ra)\theta'' + S\emptyset = 0 \tag{10}$$

$$\theta'' + Scf\emptyset' = 0 \tag{11}$$

R_a is the thermal radiation parameter. where K is the prous medium permeability parameter. f=o, $f' = 0, \theta = 1, \emptyset = 1$, at $\eta = 0$,

$$f' = 0, \theta = 1, \emptyset = 1, \eta \to \infty$$

$$C_f = \frac{2\tau_w}{\rho U_\infty^2},\ N_u = \frac{xq_w}{k(T_w-T_\infty)},\ S_h = \frac{xq_m}{k(C_w-C_\infty)} \tag{12}$$

$$where\ \tau_w = \mu\frac{\partial u}{\partial y}\ |y=o\ \ Q_w = -ik\frac{\partial u}{\partial y}\ |y=o - -\frac{4\sigma}{3k}\frac{dT^4}{dy}\ \ |y=0,\ Q_c = -D\frac{\partial C}{\partial y}\ |y=o$$

$$Rex^{1/2} C_f = f''(0) \tag{13}$$

$$Rex^{1/2} N_u = -(1 + \frac{4Ra}{3})\theta'(0) \tag{14}$$

$$Rex^{1/2} S_h = -\theta'(0) \tag{15}$$

3. NUMERICAL SOLUTION

The normalized equations (9) to (11) that are coupled, with the boundary conditions (12) and (13) are solved numerically using an implicit finite difference scheme of second order. The numbers of grids in numerical domain are chosen 10000 points and the convergence criterion is taken 10- 8. The integration is considered as a region limited to η = 10 which lies very well outside the momentum, energy and concentration boundary layers. More details of the integration scheme can be found in [10]. In order to access the accuracy of the present scheme, the values of the wall shear stress, Nusselt and Sherwood numbers have been compared with those obtained by Makinde and Aziz [9] for a special case, R = 0. It is seen from Table 1 that the computation showing the comparison with [12] for differenent value of S κ, λ, M = R_a $K = 0$, Ec, $G_{T=}$ 1.0, Sc, is 0.5. $G_{c=}$ 0.5

4. RESULT AND DISCUSSION

In order to get a physical insight into the problem, a representative set of numerical results is shown graphically in Figs.1-10, to illustrate the influence of physical parameters viz., magnetic parameter Mp, Prandtl number Pr Eckert number Ec, Unsteadiness parameter and variation (exponent) τ on the velocity f′ and temperature θ. The profiles for velocity and temperature are shown in fig.1 to fig. 10

Effect for velocity profile:

4.1 Effect of the Prandtl number: From the fig.1 it is observed that the velocity f′ (0) decreases as the power -law index of the surface temperature variation (exponent) τ and the magnetic parameter (Mp) increases with Prandtl number Pr = 1
4.2 Effect of the viscosity Parameter. It is seen from fig.1 that the velocity decreases as the power-law index of the surface temperature variation τ and the magnetic parameter (Mp) increases with the variable viscosity parameter θ = 3.0
4.3 Effect of the Eckert number: From the fig.2-3, it is observed that the velocity profiles are almost identical for different values of temperature variation τ and the magnetic parameter (Mp) with Eckert number Ec = 0.0 andEc = 0
4.4 Effect of the Magnetic Parameter: In fig.4 it is observed that the velocity decreases as magnetic parameter (Mp) increases. Effect for temperature profile:
4.5 Effect of variation (exponent): From the fig.5 it is observed that as variation (exponent) τ increases the temperature decreases for fixed value of magnetic parameter (Mp).
4.6 Effect of the Magnetic Parameter: It is seen from fig.6-7 that the temperature decreases as magnetic parameter Mp increases.
4.7 Effect of the Prandtl and Eckert number: From the fig.8 it is observed that the temperature decreases as the magnetic parameter increases with Pr=1, τ = 0.3 and Ec = 0
4.8 Effect of Heat transfer: It is seen from fig.9 that as Mp increases the heat transfer rate - θ ′ (0), decreases but as τ increases the heat transfer rate increases. That is why, the parameters τ and Mp have considerable influence on the heat transfer rate - θ ′ (0).
4.9 Effect of the Unsteadiness Parameter: In the fig.10 (a), it is observed that the velocity profiles are approximately symmetrical for different values of unsteadiness parameter $A1$, temperature variation τ and the magnetic parameter (Mp) with Pr = 0.05, Eckert number Ec = 0.75, $A1$ = 0.5. It is seen from fig.10(b) that as variation (exponent) τ increases the temperature decreases for fixed value of magnetic parameter (Mp) and unsteadiness parameter$A1$with Pr = 1, $A1$ = 0.5 and θ = 3.0

All the figures are obtained from Pr = 0.72 that corresponds to air and Sc = 0.24, 0.62, 0.78 which states the diffusion of hydrogen, water and ammonia in air, respectively. Moreover, F = 0.5 is chosen for all profiles.

Table-1: computations showing the comparison with singh *et al* [12] for different value of S when $G_C = 0.5 \quad P_r = 1.$,

S	$f''(0)$ [12]	$-\theta'(0)$ [12]	$-\phi'(0)$ [12]	$f''(0)$ Present	$-\theta'(0)$ Present	$-\phi'(0)$ Present
−1	1.8444	1.3908	0.4631	1.844462	1.390856	0.463174
0	1.9995	0.6392	0.4789	1.999553	0.639244	0.478964
1	2.1342	−0.0730	0.4917	2.134287	−0.073040	0.491749

Figure 2 computations showing $f''(0)$ - $\theta'(0)$ $-\theta'(0)$

S	K	Pr	G_T	G_C	Sc	M	Ra	$f''(0)$	$-\theta'(0)$	$-\phi'(0)$
0	1	0.1	1	0.5	0.5	0.1	0.1	2.389898	0.236593	0.502813
0.5	1	0.1	1	0.5	0.5	0.1	0.1	2.477113	−0.20393	0.513073
1	3	0.1	1	0.5	0.5	0.1	0.1	2.878166	−0.64378	0.518639
1	5	0.1	1	0.5	0.5	0.1	0.1	3.184808	−0.65098	0.517897
1	1	1	1	0.5	0.5	0.1	0.1	2.370055	−0.04316	0.494804
1	1	10	1	0.5	0.5	0.1	0.1	2.154799	1.073118	0.474395
1	1	0.1	0.5	0.5	0.5	0.1	0.1	2.220679	−0.68158	0.496618
1	1	0.1	0.7	0.5	0.5	0.1	0.1	2.358558	−0.65897	0.507416
1	1	0.1	0.5	1	0.5	0.1	0.1	2.437256	−0.66294	0.507347
1	1	0.1	0.5	2	0.5	0.1	0.1	2.856783	−0.63004	0.526974
1	1	0.1	0.5	0.5	1	0.1	0.1	2.170082	−0.49096	0.653140
1	1	0.1	0.5	0.5	2	0.1	0.1	2.125898	−0.33929	0.851850
1	1	0.1	0.5	0.5	0.5	1	0.1	2.305895	−0.05390	0.859057
1	1	0.1	0.5	0.5	0.5	3	0.1	2.704379	−0.04824	0.879438
1	1	0.1	0.5	0.5	0.5	0.1	1	2.103755	0.006342	0.848097
1	1	0.1	0.5	0.5	0.5	0.1	3	2.104745	0.049987	0.848680

llustrates the effects of the Biot number and magnetic field parameter on the normalized velocity profiles. It is observed that the velocity increases from zero at the boundary to its peak point and then falls to the velocity of free stream with F = 0.5. Figure 2 shows that the values of velocity increase with increasing the Biot number because of a rise in convective heat transfer to the fluid on the right side of the wall and decrease with increasing the magnetic parameter because of exerting a drag force on the fluid by the magnetic field.

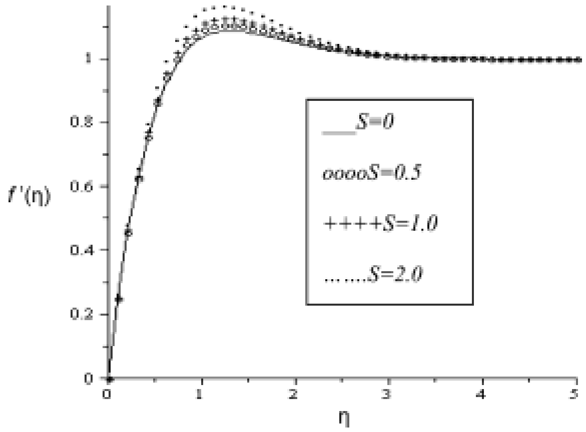

Fig. 2 Velocity profiles for G_T = Gc= K = M = $1 P_r = 1., S_C = 0.62., Ra = 0.1$

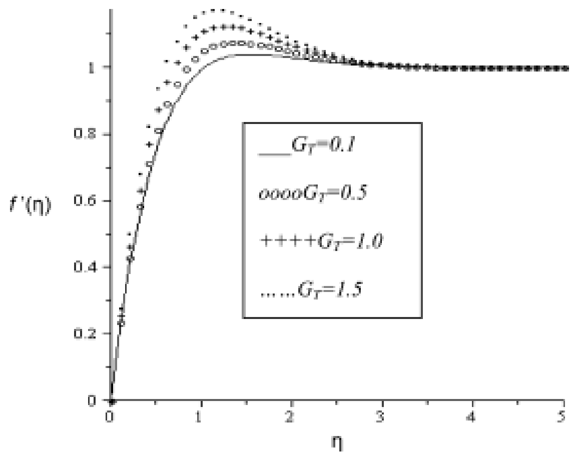

Fig. 3 Velocity profiles for $G_c = K = S = M = 1$, $Sc = 0.62$, $Pr = 0.72$, $Ra = 0.1$

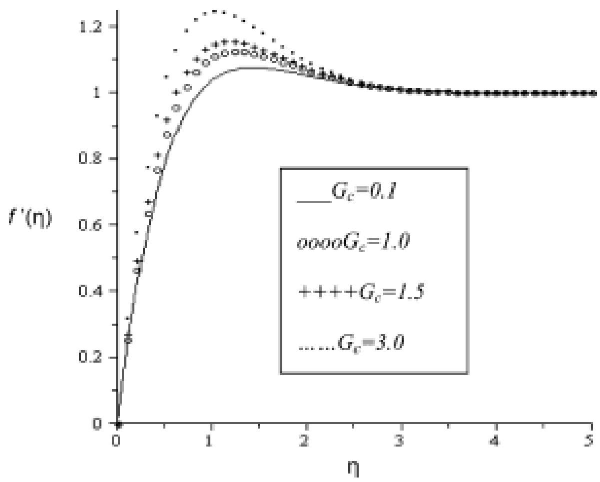

Fig. 4 Velocity profiles for $G_T = K = S = M = 1$, $Sc = 0.62$, $Pr = 0.72$, $Ra = 0.1$

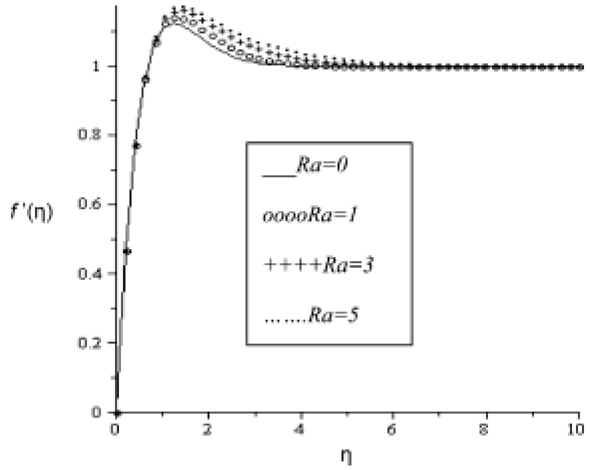

Fig. 5 Velocity profiles for $G_T = G_c = K = S = M = 1$, $Pr = 0.72$, $Sc = 0.62$

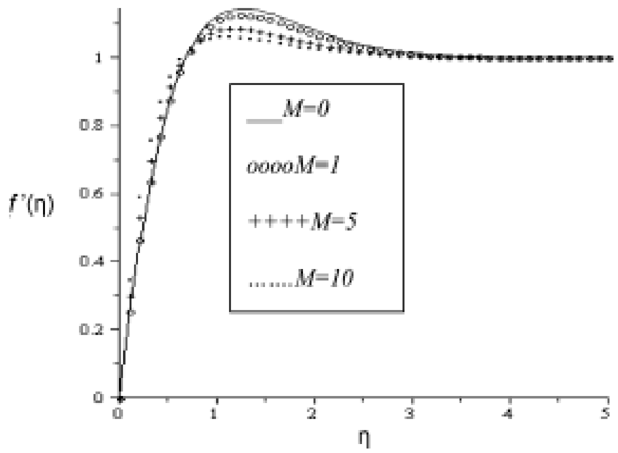

Fig. 6 Velocity profiles for $G_T = G_c = K = S = 1$, $Pr = 0.72$, $Sc = 0.62$, $Ra = 0.1$

5. CONCLUSION

An analysis is carried out to study the effect of radiation on MHD mixed convection over a vertical plate with the convective boundary condition including the effects of chemical reaction, suction and viscous dissipation. An implicit finite difference scheme of the second order has been applied for solving the governing equations. The main outcomes of the paper can be itemized as follows:

- The results demonstrated that the values of velocity and temperature are enhanced with increasing the Biot number.
- The values of concentration are affected by chemical reaction and decrease with increasing the reaction rate parameter.
- Due to the importance of thermal radiation effect, the velocity and temperature increase by increasing the radiation parameter.
- Increasing the values of radiation parameter creates an increase in skin-friction and reduce in Nusselt number.
- Increasing the Biot number tends to increase the skin-friction.
- There is no significant effect on Nusselt number by increasing the Biot number.
- For the case Bi=0, the skin-friction is almost constant for various values of radiation parameter and no change in the Nusselt number takes place.
- Increasing the value of reaction rate parameter yields an increase in the Sherwood number and a decrease in the skin-friction.
- Velocity and temperature in the unsteady case is observed to be lesser than those of the steady case.

- It is observed that an increment in unsteadiness parameter increases the Prandtl number and decreases the Eckert number
- The velocity decreases with the increase of power law index of the surface temperature variation (exponent) and the magnetic parameter.
- The temperature decreases with the increase of the power law index of the surface temperature variation (exponent) and the magnetic parameter .
- The heat transfer rate increases rapidly with the increase of power law index of the surface temperature variation (exponent) whereas when the magnetic parameter increases the heat transfer rate decreases.
- Temperature decreases with an increasing in the value of unsteadiness parameter A1
- Increasing the Prandtl number leads to a decrease in the surface temperature.

6. NOMENCLATURE

B0 Homogeneous magnetic field
Bi Biot number
C Concentration of chemical species
Cp Specific heat at constant pressure
D Mass diffusivity
Ec Eckert number
f Dimensionless velocity
F Dimensionless velocity of free stream
g Gravitational acceleration
Gr Thermal Grashof number
Gc Mass transfer Grashof number
h Convection heat transfer coefficient
k Thermal conductivity of fluid
K Permeability coefficient
K Rosseland mean absorption coefficient
M Magnetic field parameter Subscripts
Pr Prandtl number
q Heat flux f Hot fluid
Sc Schmidt number
T Temperature of fluid
u Velocity component along the

U Free steam velocity
v Velocity component along the y-axis
x Coordinate in horizontal direction
y Coordinate in vertical direction
Greek symbols
β Expansion coefficient
γ Reaction rate coefficient
φ Dimensionless concentration
η Dimensionless coordinate along the y-axis
κ Permeability parameter
λ Reaction rate parameter
ν Kinematic viscosity
ρ Density of fluid
σ Electrical conductivity of fluid
σ Stefan-Boltzmann constant

∞ Free stream
R Radiation parameter m Related to concentration
r Radiation
t Related to temperature
xaxis w wall

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Source of support: Nil, Conflict of interest: None Declared.