Effects of Radiation and Heat Dissipation on Free Convective Heat and Mass Transfer Flow through a Porous Medium

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ABSTRACT

This paper investigates the effects of radiation and heat dissipation on free convective heat and mass transfer flow through a porous medium. Solutions of time dependent energy, momentum and concentration equations under the relevant initial and boundary conditions were derived using perturbation technique. Selected set of line graph representing the effect of controlling parameters embedded in the problem are discussed during the course of numerical computation. It is observed that, an increase in Gr and Gm results in the thickening of the thermal boundary layer, which leads to an increase in the velocity layer. However, increase of variable parameter Prandtl number, results in the increase in temperature and decrease with radiation.

Keywords: *Radiation, Heat dissipation, Free convective heat, Porous medium*

Nomenclature	U' Dimensional velocity of the fluid
U Dimensionless velocity of the fluid	g Acceleration due to gravity
$\Pr$ Prandtl number	t' Dimensional time
C' Dimensional concentration of the fluid	C Dimensionless concentration
y' Dimensional co-ordinate perpendicular to the plate	y Dimensionless co-ordinate perpendicular to the plate
S Dimensionless heat sink parameter	T_∞ Initial temperature
Q Dimensional heat sink parameter	Gr Thermal Grashof number
K Permeability parameter	Sc Schmidt number
C_∞ Concentration of the fluid far away from the fluid	C'_w Constant concentration at the plate
γ Suction	E ratio of kinetic energy
T_∞ Temperature of the fluid far away from the plate	T_w Temperature of the fluid near the plate
B_0 External magnetic field	R radiation parameter
Greek alphabets	
β Volumetric coefficient of thermal expansion	ν Kinematic viscosity

ρ Density of the fluid	σ Stefan Boltzmann constant (electrical Conductivity)
Gm mass Grashof number	

1.0 INTRODUCTION

The study of convection processes in porous media has attracted significant attention in recent years because of the wide spread application of such flows in science, industry and many engineering processes. These include cooling of electronic equipment, heating of the Trombe wall system, gas-cooled nuclear reactors. Detailed review of the flow through and past porous media can be found in the book of Neild and Bejan, (2006). Unsteady flow investigations with porous boundaries include the works of Wang *et al.*, (2001). Jha *et al.,* (2012) investigated the theoretical analysis of natural convection flow between infinite vertical parallel plates with ramped temperature on one of the plates using Laplace transform technique and reported that convection current due to isothermal heating of the boundary is higher than the ramped heating of the boundary. The velocity due to ramped temperature on the plate is always less than the velocity induced by isothermal temperature on plate. Elbashbeshy *et al*., (2010) studied the unsteady boundary layer flow over a porous stretching surface embedded in a porous medium in presence of heat source. Sharma and Gupta, (2006) analyzed the unsteady flow and heat transfer along a hot vertical porous plate in the presence of periodic suction and heat source. Kim, (2000) examined the unsteady MHD free convection flow past a moving semi-infinite vertical porous plate embedded in a porous medium with variable suction. Theoretical/experimental investigations of convective boundary layer flow with heat and mass transfer induced due to a moving surface with a uniform or non-uniform velocity play an important role in several manufacturing processes in industry which include the boundary layer flow along material handling conveyers, extrusion of plastic sheets, cooling of an infinite metallic plate in cooling bath, glass blowing, continuous casting and levitation, design of chemical processing equipment, formation and dispersion of fog, distribution of temperature and moisture over agricultural fields and groves of trees, damage of crops due to freezing common industrial sight especially in power plants and soon. Kamel, (2001) investigated the unsteady hydro magnetic convection flow due to heat and mass transfer through a porous medium bounded by an infinite vertical porous plate with temperature depended heat sources and sinks. Chamkha, (2004) studied the unsteady hydro magnetic two dimensional convective laminar boundary layer flow with heat and mass transfer of a viscous, incompressible, electrically conducting and temperature dependent heat absorbing fluid along a semi infinite vertical permeable moving plate in the presence of a uniform transverse magnetic field. Aruna *et al.,* (2012) studied the effects of magnetic field on free convective flow of Jeffery fluid past an infinite vertical porous plate with constant heat flux. Adeniyan *et al.,* (2015) investigated the effects of thermal dissipation heat generation/absorption on MHD mixed convection boundary layer flow over a permeable vertical flat plate embedded in an anisotropic porous medium. Ajibade and Jha, (2009) analyzed the transient natural convection flow between vertical parallel plate with temperature dependent heat source/sinks. Chamkha, (2003) reported the effect of heat generation on g-jitter induced natural convective flow in a channel with isothermal or isoflux walls. Chamkha *et al.,* (2001) analyzed the radiation effects on a free convection flow past a semi infinite vertical plate with mass transfer. Singh, (2010) also Mishra *et al*., (2013) considered free convection flow due to heat and mass transfer through a porous medium bounded by two vertical wall, in an unsteady state. Chand *et al.,* (2012) studied the hydromagnetic oscillatory flow through a porous medium bounded by two vertical porous plates with heat source and soret effect. Mahanti and Gau, (2009) analyzed the effect of varying viscosity and thermal conductivity on steady free convective flow and heat transfer along an isothermal vertical plate in the presence of heat sink. Muthukumaraswamy and Kumar, (2004) reported on heat and mass transfer effect on moving vertical plate in the presence of thermal radiation. Patil and Kulkarni, (2008) investigated the effects of chemical reaction on free convective flow of a polar fluid through a porous medium in the presence of internal heat generation. Raptis and Perdikis, (2004) analyzed the unsteady flow through a porous medium in the presence of radiation. Seddeek, (2007) reported on heat and mass transfer on a stretching sheet with a magnetic field in a viscoelastic fluid flow in a porous medium with heat source.

2.0 MATHEMATICAL FORMULATION

The effects of unsteady convective flow in a porous medium with heat generation in an infinite vertical plate are considered. The Fluid is viscous, incompressible electrically conductive and a uniform magnetic field B_0 is applied to porous plate. The axial $(x' - direction)$ velocity depends only on transverse coordinate, y'. The system under consideration is sketched in figure 1.The x' - axis is taken along the direction of the flow and parallel to the infinite vertical porous plate and y' - direction perpendicular to the flow. T_∞ is the initial fluid and wall temperature, T' dimensional temperature, T_∞ is the temperature of the fluid near the plate.

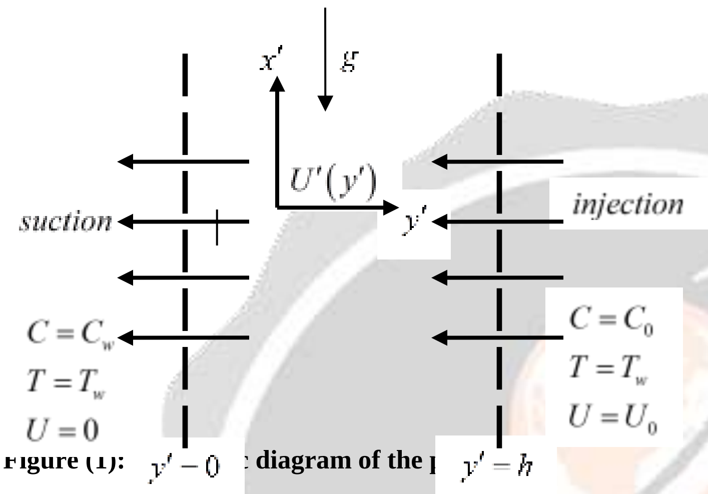

Figure (1): **diagram of the**

Under, bonssineques approximation the required governing equations are

$$\frac{\partial V'}{\partial y'} = 0 \tag{1}$$

$$\frac{\partial U'}{\partial t'} + \frac{\partial U'}{\partial y'} = \nu \frac{\partial^2 U'}{\partial y'^2} - \frac{U'}{K} + g\beta(T' - T_\infty{}') + g\beta_m\left(C' - C'_\infty\right) \tag{2}$$

$$\frac{\partial T'}{\partial t'} + \frac{\partial T'}{\partial y'} = K\frac{\partial^2 T'}{\partial y'^2} - \frac{\partial q_r}{\partial y'} \tag{3}$$

$$\frac{\partial C'}{\partial t'} + \frac{\partial C'}{\partial y'} = D\frac{\partial^2 C'}{\partial y'^2} \tag{4}$$

The boundary conditions are

$$\left.\begin{aligned} y' = 0 : U' = 0, T' = T'_w, C' = C'_w \\ y' = 1 : U' = 0, T' = T'_\infty, C' = C'_\infty \end{aligned}\right\} \tag{5}$$

The non dimensional quantities are introduced, to obtain the governing equations and the boundary conditions in dimensionless form.

$$\left.\begin{array}{l} U=\frac{U'}{U_0}, y=\frac{y'U_0}{\nu}, t=\frac{t'U_0}{\nu}, T=\frac{T'-T'_\infty}{T'_w-T'_\infty}, C=\frac{C'-C'_\infty}{C'_w-C'_\infty} \\ P_r=\frac{\mu Cp}{K}, Gr=\frac{g\beta\nu\left(T'_w-T'_\infty\right)}{U_0^2}, Gm=\frac{g\beta\nu\left(C'_w-C'_\infty\right)}{U_0^2} \\ Sc=\frac{\nu}{D}, R=\frac{16aR\sigma T_0'^3\nu}{\alpha V_0^2}, Da=\frac{K\nu}{U_0^2}, \mu=\rho\nu \end{array}\right\} \tag{6}$$

Substituting equation (6) in equations (1-5) to obtain the dimensional form

$$\frac{\partial U}{\partial t}-\frac{\partial U}{\partial y}=\nu\frac{\partial^2 U}{\partial y^2}-\frac{U}{Da}+GrT+GmC \tag{7}$$

$$\Pr\left(\frac{\partial T}{\partial t}-\frac{\partial T}{\partial y}\right)=\frac{\partial T}{\partial y}-RT-\Pr E\left(\frac{\partial U}{\partial y}\right)^2 \tag{8}$$

$$Sc\left(\frac{\partial C}{\partial t}-\frac{\partial C}{\partial y}\right)=\frac{\partial^2 C}{\partial y^2} \tag{9}$$

With boundary conditions

$$\left.\begin{array}{l} U=0, T=1, C=1\, at\ y=0 \\ U=0, T=0, C=0\, at\ y=1 \end{array}\right\} \tag{10}$$

The solution to the dimensionless partial differential equations set in equations (7) to (10) can be obtained by representing concentration, temperature and velocity as follows:

$$C\left(y\right)=C_0+C_1\varepsilon e^{i\omega t}+C_2\varepsilon^2 e^{2i\omega t}+C_3\varepsilon^3 e^{3i\omega t}+\cdots=\sum_{j=0}^{\infty}\varepsilon^j C_j e^{j(i\omega t)} \tag{11}$$

$$T\left(y\right)=T_0+T_1\varepsilon e^{i\omega t}+T_2\varepsilon^2 e^{2i\omega t}+T_3\varepsilon^3 e^{3i\omega t}+\cdots=\sum_{j=0}^{\infty}\varepsilon^j T_j e^{j(i\omega t)} \tag{12}$$

$$U\left(y\right)=U_0+U_1\varepsilon e^{i\omega t}+U_2\varepsilon^2 e^{2i\omega t}+U_3\varepsilon^3 e^{3i\omega t}+\cdots=\sum_{j=0}^{\infty}\varepsilon^j U_j e^{j(i\omega t)} \tag{13}$$

The corresponding boundary conditions are:

When $y=0$,

$$\left.\begin{aligned} &C_0 = 1, C_1 = 1, C_2 = 1, C_3 = 1 \\ &T_0 = 1, T_1 = 1, T_2 = 1, T_3 = 1 \\ &U_0 = 0, U_1 = 0, U_2 = 0, U_3 = 0 \end{aligned}\right\} \tag{14}$$

When $y = 1$,

$$\left.\begin{aligned} &C_0 = 0, C_1 = 0, C_2 = 0, C_3 = 0 \\ &T_0 = 0, T_1 = 0, T_2 = 0, T_3 = 0 \\ &U_0 = 0, U_1 = 0, U_2 = 0, U_3 = 0 \end{aligned}\right\} \tag{15}$$

The complete solution of concentration, temperature and velocity equations are obtained as:

$$\begin{aligned} C(y) = {} & A_1 + A_2 e^{-m_2 y} + \left(A_3 e^{m_3 y} + A_4 e^{-m_4 y}\right)\varepsilon e^{i\omega t} + \left(A_5 e^{m_5 y} + A_6 e^{-m_6 y}\right)\varepsilon^2 e^{2i\omega t} \\ & + \left(A_7 e^{m_7 y} + A_8 e^{-m_8 y}\right)\varepsilon^3 e^{3i\omega t} \end{aligned} \tag{16}$$

$$\begin{aligned} T(y) = {} & A_9 e^{m_9 y} + A_{10} e^{-m_{10} y} + \left(A_{11} e^{m_{11} y} + A_{12} e^{-m_{12} y}\right)\varepsilon e^{i\omega t} + \left(A_{13} e^{m_{13} y} + A_{14} e^{-m_{14} y}\right)\varepsilon^2 e^{2i\omega t} \\ & + \left(A_{15} e^{m_{15} y} + A_{16} e^{-m_{16} y}\right)\varepsilon^3 e^{3i\omega t} \end{aligned} \tag{17}$$

$$\begin{aligned} U(y) = {} & A_{17} e^{m_{17} y} + A_{18} e^{-m_{18} y} + A_{19} e^{m_9 y} + A_{20} e^{-m_{10} y} + A_{21} + A_{22} e^{-m_2 y} + \left(A_{25} e^{m_{19} y} + A_{26} e^{-m_{20} y}\right. \\ & \left. + A_{27} e^{m_{11} y} + A_{28} e^{-m_{12} y} + A_{29} e^{m_3 y} + A_{30} e^{-m_4 y}\right)\varepsilon e^{i\omega t} + \left(A_{33} e^{m_{21} y} + A_{34} e^{-m_{22} y} + A_{35} e^{m_{13} y}\right. \\ & \left. + A_{36} e^{-m_{14} y} + A_{37} e^{m_5 y} + A_{38} e^{-m_6 y}\right)\varepsilon^2 e^{2i\omega t} + \left(A_{41} e^{m_{23} y} + A_{42} e^{-m_{24} y} + A_{43} e^{m_{13} y} + A_{44} e^{-m_{14} y}\right. \\ & \left. + A_{45} e^{m_5 y} + A_{46} e^{-m_6 y}\right)\varepsilon^3 e^{3i\omega t} \end{aligned} \tag{18}$$

Finally, the Sherwood number, Nusselt number and Skin friction are obtained when the expressions for concentration, temperature and velocity field are differentiated partially with respect to y and evaluated at y = 0 and y = 1, respectively, to have:

$$\begin{aligned} Sh_0 = \frac{dC}{dy}\Big|_{y=0} = {} & -m_2 A_2 + \left(m_3 A_3 - m_4 A_4\right)\varepsilon e^{i\omega t} + \left(m_5 A_5 - m_6 A_6\right)\varepsilon^2 e^{2i\omega t} \\ & + \left(m_7 A_7 - m_8 A_8\right)\varepsilon^3 e^{3i\omega t} \end{aligned} \tag{19}$$

$$\begin{aligned} Sh_1 = \frac{dC}{dy}\Big|_{y=1} = {} & -m_2 A_2 e^{-m_2} + \left(m_3 A_3 e^{m_3} - m_4 A_4 e^{-m_4}\right)\varepsilon e^{i\omega t} \\ & \left(m_5 A_5 e^{m_5} - m_6 A_6 e^{-m_6}\right)\varepsilon^2 e^{2i\omega t} + \left(m_7 A_7 e^{m_7} - m_8 A_8 e^{-m_8}\right)\varepsilon^3 e^{3i\omega t} \end{aligned} \tag{20}$$

$$Nu_0 = \frac{dT}{dy}\Big|_{y=0} = m_9 A_9 - m_{10} A_{10} + \left(m_{11} A_{11} - m_{12} A_{12}\right)\varepsilon e^{i\omega t} + \left(m_{13} A_{13} - m_{14} A_{14}\right)\varepsilon^2 e^{2i\omega t} + \left(m_{15} A_{15} - m_{16} A_{16}\right)\varepsilon^3 e^{3i\omega t} \quad (21)$$

$$Nu_1 = \frac{dT}{dy}\Big|_{y=1} = m_9 A_9 e^{m_9} - m_{10} A_{10} e^{-m_{10}} - \left(m_{11} A_{11} e^{m_{11}} - m_{12} A_{12} e^{-m_{12}}\right)\varepsilon e^{i\omega t} + \left(m_{13} A_{13} e^{m_{13}} - m_{14} A_{14} e^{-m_{14}}\right)\varepsilon^2 e^{2i\omega t} + \left(m_{15} A_{15} e^{m_{15}} - m_{16} A_{16} e^{-m_{16}}\right)\varepsilon^3 e^{3i\omega t} \quad (22)$$

$$\begin{aligned}\tau_0 = \frac{dU}{dy}\Big|_{y=0} &= m_{17} A_{17} - m_{18} A_{18} + m_9 A_{19} - m_{10} A_{20} - m_2 A_{22} \\ &+ \left(m_{19} A_{25} - m_{20} A_{26} + m_{11} A_{27} - m_{12} A_{28} + m_3 A_{29} - m_4 A_{30}\right)\varepsilon e^{i\omega t} \\ &+ \left(m_{21} A_{33} - m_{22} A_{34} + m_{13} A_{35} - m_{14} A_{36} + m_5 A_{37} - m_6 A_{38}\right)\varepsilon^2 e^{2i\omega t} \\ &+ \left(m_{23} A_{41} - m_{24} A_{42} + m_{13} A_{43} - m_{14} A_{44} + m_5 A_{45} - m_6 A_{46}\right)\varepsilon^3 e^{3i\omega t} \quad (23)\end{aligned}$$

$$\begin{aligned}\tau_1 = \frac{dU}{dy}\Big|_{y=1} &= m_{17} A_{17} e^{m_{17}} - m_{18} A_{18} e^{-m_{18}} + m_9 A_{19} e^{m_9} - m_{10} A_{20} e^{-m_{10}} - m_2 A_{22} e^{-m_2} \\ &+ \Big(m_{19} A_{25} e^{m_{19}} - m_{20} A_{26} e^{-m_{20}} + m_{11} A_{27} e^{m_{11}} - m_{12} A_{28} e^{-m_{12}} \\ &+ m_3 A_{29} e^{m_3} - m_4 A_{30} e^{-m_4}\Big)\varepsilon e^{i\omega t} + \Big(m_{21} A_{33} e^{m_{21}} - m_{22} A_{34} e^{-m_{22}} + m_{13} A_{35} e^{m_{13}} \\ &- m_{14} A_{36} e^{-m_{14}} + m_5 A_{37} e^{m_5} - m_6 A_{38} e^{-m_6}\Big)\varepsilon^2 e^{2i\omega t} + \Big(m_{23} A_{41} e^{m_{23}} - m_{24} A_{42} e^{-m_{24}} \\ &+ m_{13} A_{43} e^{m_{13}} - m_{14} A_{44} e^{-m_{14}} + m_5 A_{45} e^{m_5} - m_6 A_{46} e^{-m_6}\Big)\varepsilon^3 e^{3i\omega t} \quad (24)\end{aligned}$$

3.0 RESULT AND DISCUSSION

The profiles of velocity, temperature and concentration in this case are shown in Figures (2 – 3), (4 – 5) and (6) respectively. The Figures exhibit the effect of radiation parameter (R), mass Grashof number (Gm), thermal Grashof number (Gr), Prandlt number (Pr) and Schmidt number (Sc) respectively. While Tables (1), (2) and (3) show the numerical values for Skin friction (τ), rate of heat transfer (Nu) and Sherwood number of (R), (Gm), (Gr), (Pr) and (Sc).

The effects of those parameters on the velocity field is found to change more or less with the variation of the flow parameters. The major characteristics affecting the velocity of the flow field are the thermal Grashof number (Gr) and mass Grashof number (Gm). The effects of these parameters on velocity profiles have been analyzed with the aid of Figures (2) to (3) respectively.

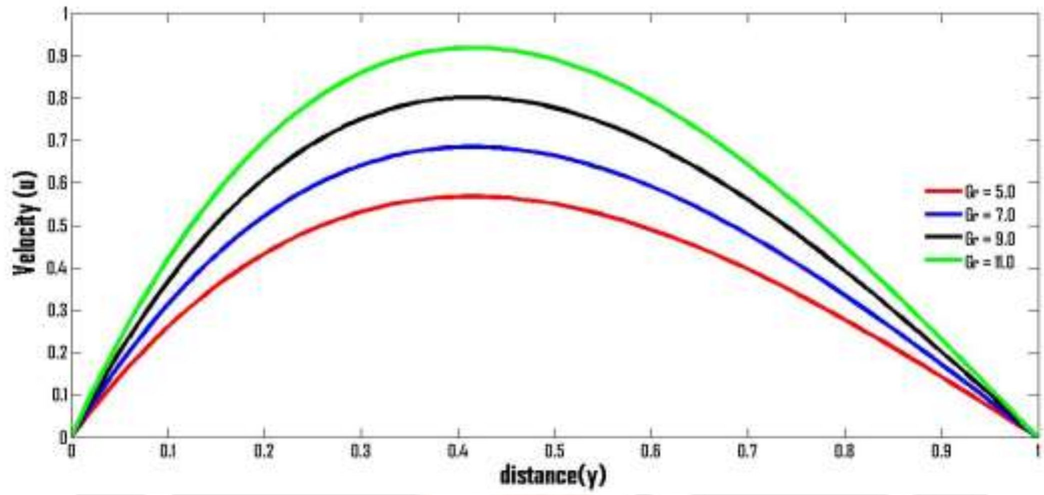

Figure 2: Effect of thermal Grashof number (Gr) on velocity.

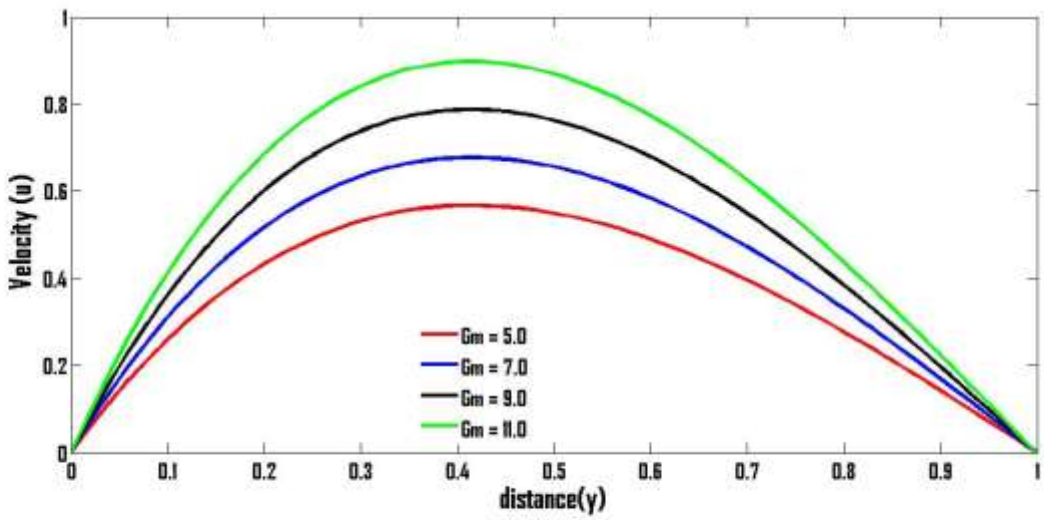

Figure 3 : Effect of mass Grashof number (Gm) on velocity.

Figures (2) and (3) show the velocity behavior for different values of the thermal Grashof number (Gr) and mass Grashof number (Gm). It is observed that there is a rise in the velocity due to the enhancement of thermal buoyancy force and increases in the species buoyancy force respectively. Here, the positive values of (Gr) and (Gm) correspond to the cooling of the plate where other parameters are kept constant.

The temperature of the flow suffers a substantial change with the variation of the flow parameters such as radiation (R) and Prandtl number (Pr). These variations are presented in Figures (4) to (5) respectively.

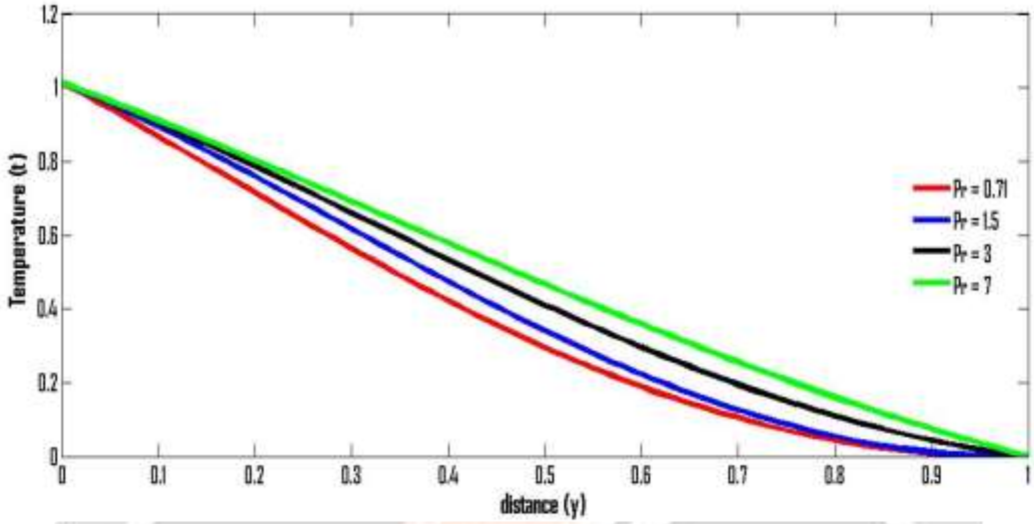

Figure 4: Effect of Prandtl number (Pr) on temperature.

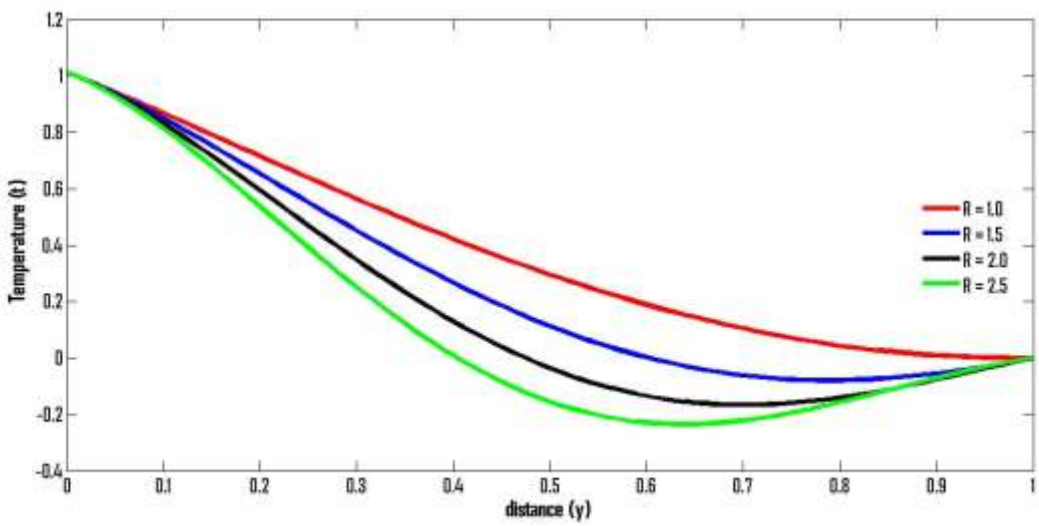

Figure 5: Effect of radiation parameter (*R*) on temperature.

From Figure (4) keeping other parameters of the flow field constant shows the effect of Prandtl number (Pr) against the temperature field. It is interesting to observe that an increase in the Prandtl number (Pr) increases the temperature of the flow field. The effect of radiation (R) parameter on the temperature of the flow field is shown in Figure (5) keeping other parameters of the flow field constant. The temperature of the flow field is found to decrease in the presence of growing radiation. The variation in the concentration profile suffers a substantial change with the variation of the flow parameter such as Schmidt number (Sc).

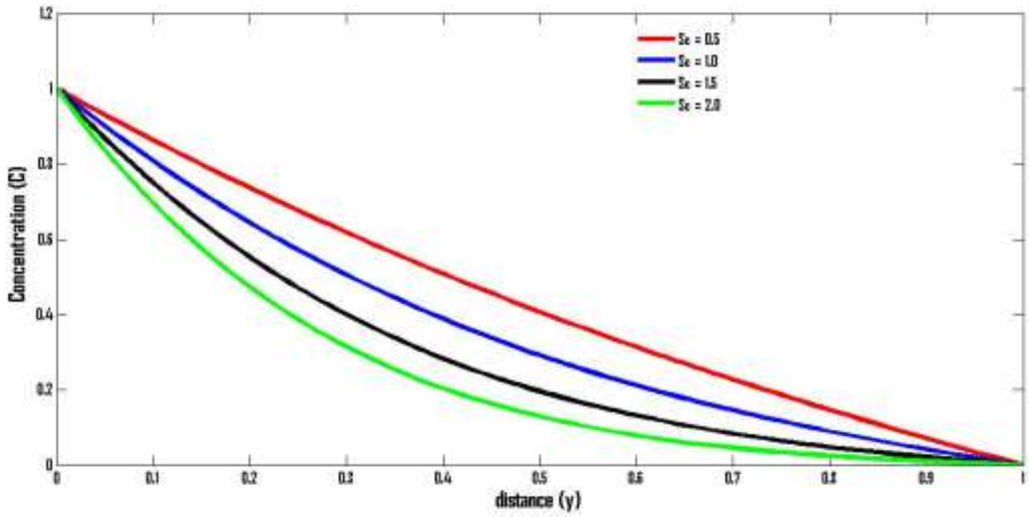

Figure 6: Effect of Schmidt number (Sc) on concentration.

It is shown in Figure (6) that when Schmidt number (Sc) increases the concentration decreases due to diffusing foreign species.

Numerical computations are carried out for skin friction coefficient (τ),Nusselt number (Nu) and Sherwood number (Sh) at y = 0 and y = 1,for various values of thermal Grashof number (Gr), mass Grashof number (Gm), Prandtl number (Pr), Schmidt number (Sc) and radiation (R).

Table 1: Values of skin friction coefficient (τ) at y = 0 and y = 1

Gr	Gm	τ_0	τ_1
5	5	3.5015×10^4	1.9934×10^6
10	5	3.5680×10^4	2.0315×10^6
5	10	1.0466×10^5	5.9585×10^6

From Table (1), it is observed that, an increase in thermal Groshof number (Gr) and mass Grashof number (Gc) at y = 0 and y = 1 enhances the values of skin friction (τ).

Table 2: Values of Nusselt number (Nu) at y = 0 and y = 1

Pr	R	Nu_0	Nu_1
0.71	1.00	1.4072	0.0357
1.00	1.00	1.2054	0.1420
0.71	2.00	1.4066	0.7556

In Table (2), an increase in Prandtl number (Pr) and radiation (R) at y = 0 decreases the rate of heat transfer (Nu) while at y = 1 enhances the rate of heat transfer (Nu).

Table 3: Values of Sherwood number (Sh) at y = 0 and y = 1 for problem 3.2.3

Sc	Sh_0	Sh_1
0.5	0.8138	1.3376
1.0	1.3807	3.7279

It is observed in Table (3) that, an increase in Schmidt number (Sc) at y = 0 and y = 1 enhances the value of Sherwood number (Sh).

4.0 CONCLUSION

Effects of Radiation and Heat Dissipation on Free Convective Heat and Mass Transfer Flow through a Porous Medium. The governing equations are transformed into dimensionless form and solved numerically using finite difference scheme. The results are obtained and presented graphically and on tables to illustrate the details of the characteristics parameters. From the present investigation it is concluded that:

i. Concentration decreases with increase in parameter Sc.
ii. The increase of variable parameter Pr, results in the increase in temperature and decrease with R.
iii. The results show that the velocity increases with increase in material parameters Gr and Gm.
iv. Table 1shows that Skin friction coefficient (τ) increases with increase in material parameters Gr and Gm.
v. Also Table 2 shows that the Nusselt number (Nu) increases in the material parameters Pr and R at y = 1 and decreases at y = 0.
vi. Table 3 shows that the sherwood number (Sh) increases with increase of material parameter (Sc) at y = 1 and y = 0.

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APPENDIX

$$m_1 = 0, m_2 = -Sc, A_1 = \frac{-e^{-m_2}}{1-e^{-m_2}}, A_2 = \frac{1}{1-e^{-m_2}}, H_1\sqrt{Sc^2 + (Sci\omega)}, m_3 = \frac{-Sc+H_1}{2}, m_4 = \frac{Sc+H_1}{2}$$

$$A_3 = \frac{-e^{-m_4}}{e^{m_3}-e^{-m_4}}, A_4 = \frac{e^{m_3}}{e^{m_3}-e^{-m_4}}, H_2 = \sqrt{Sc^2 + 8(Sci\omega)}, m_5 = \frac{-Sc+H_2}{2}, m_6 = \frac{Sc+H_2}{2}$$

$$A_5 = \frac{-e^{-m_6}}{e^{m_5}-e^{-m_6}}, A_6 = \frac{e^{m_5}}{e^{m_5}-e^{-m_6}}, H_3 = \sqrt{Sc^2 + 12(Sci\omega)}, m_7 = \frac{-Sc+H_3}{2}, m_8 = \frac{Sc+H_3}{2}$$

$$A_7 = \frac{-e^{-m_8}}{e^{m_7}-e^{-m_8}}, A_8 = \frac{e^{m_7}}{e^{m_7}-e^{-m_8}}, H_4 = \sqrt{P^2 - \frac{4R}{\Pr E}}, m_9 = \frac{P+H_4}{2}, m_{10} = \frac{P-H_4}{2}$$

$$A_9 = \frac{e^{-m_{10}}}{e^{-m_{10}}-e^{m_9}}, A_{10} = \frac{-e^{m_9}}{e^{-m_{10}}-e^{m_9}}, H_5 = \sqrt{P^2 - \frac{4}{E}\left(i\omega + \frac{R}{\Pr}\right)}, m_{11} = \frac{P+H_5}{2}, m_{12} = \frac{P-H_5}{2}$$

$$A_{11} = \frac{e^{-M_{12}}}{e^{-M_{12}}-e^{M_{11}}}, A_{12} = \frac{-e^{M_{11}}}{e^{-M_{12}}-e^{M_{11}}}, H_6 = \sqrt{P^2 - \frac{4}{E}\left(2i\omega + \frac{R}{\Pr}\right)}, m_{13} = \frac{P+H_6}{2}, m_{14} = \frac{P-H_6}{2}$$

$$A_{13} = \frac{e^{-m_{14}}}{e^{-m_{14}}-e^{m_{13}}}, A_{14} = \frac{-e^{m_{13}}}{e^{-m_{14}}-e^{m_{13}}}, H_7 = \sqrt{P^2 - \frac{4}{E}\left(3i\omega + \frac{R}{\Pr}\right)}, m_{15} = \frac{P+H_7}{2}, m_{16} = \frac{P-H_7}{2}$$

$$A_{15} = \frac{e^{-m_{16}}}{e^{-m_{16}}-e^{m_{15}}}, A_{16} = \frac{-e^{m_{15}}}{e^{-m_{16}}-e^{m_{15}}}, H_8 = \sqrt{\left(\frac{1}{V}\right)^2 + \frac{4}{VDa}}, m_{17} = \frac{-\frac{1}{V}+H_8}{2}, m_{18} = \frac{\frac{1}{V}+H_8}{2}$$

$$A_{19} = \frac{-GrA_9}{m_9{}^2 + \frac{m_9}{V} - \frac{1}{VDa}}, A_{20} = \frac{-GrA_{10}}{m_{10}{}^2 - \frac{m_{10}}{V} - \frac{1}{VDa}}, A_{21} = GmA_{10}VDa, A_{22} = \frac{-GmA_2}{m_2{}^2 - \frac{m_2}{V} - \frac{1}{VDa}}$$

$$A_{23} = A_{19} + A_{20} + A_{21} + A_{22}, A_{17} = -A_{18} - A_{23}, A_{24} = A_{19}e^{m_9} + A_{20}e^{-m_{10}} + A_{21} + A_{22}e^{-m_2},$$

$$A_{18} = \frac{A_{23}e^{m_{17}} - A_{24}}{e^{-m_{18}} - e^{m_{17}}}, H_9 = \sqrt{\left(\frac{1}{V}\right)^2 + \frac{4}{V}\left(i\omega + \frac{1}{Da}\right)}, m_{19} = \frac{-\frac{1}{V} + H_9}{2}, m_{20} = \frac{\frac{1}{V} + H_9}{2}$$

$$A_{27} = \frac{-GrA_{11}}{m_{11}{}^2 + \frac{m_{11}}{V} - \frac{1}{V}\left(i\omega + \frac{1}{Da}\right)}, A_{28} = \frac{-GrA_{12}}{m_{12}{}^2 - \frac{m_{12}}{V} - \frac{1}{V}\left(i\omega + \frac{1}{Da}\right)}, A_{29} = \frac{-GmA_3}{m_3{}^2 + \frac{m_3}{V} - \frac{1}{V}\left(i\omega + \frac{1}{Da}\right)}$$

$$A_{30} = \frac{-GmA_4}{m_4{}^2 + \frac{m_4}{V} - \frac{1}{V}\left(i\omega + \frac{1}{Da}\right)}, A_{31} = A_{27} + A_{28} + A_{29} + A_{30}, A_{25} = -A_{26} - A_{31}$$

$$A_{32} = A_{27}e^{m_{11}} + A_{28}e^{-m_{12}} + A_{29}e^{m_3} + A_{30}e^{-m_4}, A_{26} = \frac{-A_{31}e^{m_{19}} - A_{32}}{e^{m_{19}} + e^{-m_{20}}}, H_{10} = \sqrt{\left(\frac{1}{V}\right)^2 + \frac{4}{V}\left(2i\omega + \frac{1}{Da}\right)}$$

$$m_{21} = \frac{-\frac{1}{V} + H_{10}}{2}, m_{22} = \frac{\frac{1}{V} + H_{10}}{2}, A_{35} = \frac{-GrA_{13}}{m_{13}{}^2 + \frac{m_{13}}{V} - \frac{1}{V}\left(2i\omega + \frac{1}{Da}\right)}$$

$$A_{37} = \frac{-GmA_5}{m_5{}^2 + \frac{m_5}{V} - \frac{1}{V}\left(2i\omega + \frac{1}{Da}\right)}, A_{38} = \frac{-GmA_6}{m_6{}^2 - \frac{m_6}{V} - \frac{1}{V}\left(2i\omega + \frac{1}{Da}\right)}, A_{39} = A_{35} + A_{36} + A_{37} + A_{38}$$

$$A_{33} = -A_{34} - A_{39}, A_{40} = A_{35}e^{m_{13}} + A_{36}e^{-m_{14}} + A_{37}e^{m_5} + A_{30}e^{-m_6}, A_{34} = \frac{-A_{40}e^{m_{19}} - A_{39}e^{m_{21}}}{e^{m_{21}} + e^{-m_{22}}}$$

$$A_{36} = \frac{-GrA_{14}}{m_{14}{}^2 - \frac{m_{14}}{V} - \frac{1}{V}\left(2i\omega + \frac{1}{Da}\right)}$$