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DOUBLE DISPERSION, CHEMICAL REACTION, RADIATION EFFECTS ON HEAT AND MASS TRANSFER IN NON-DARCY FREE CONVECTIVE FLOW OVER A VERTICAL SURFACE

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ABSTRACT: In the present paper we examine the study of double-diffusive free convective heat and mass transfer of a chemically-reacting radiative fluid flowing through a non- Darcian porous regime adjacent to a vertical surface. The Forchheimer extension is considered in the flow equation, while the radiation, chemical reaction power-law term are considered in energy and concentration equations. The governing equations are solved numerically by means of Fourth-order, Runge-Kutta method, coupled with double-shooting technique. The influence of radiation on thermal dispersion, solute dispersion, velocity, temperature and concentration profiles as well as heat and mass transfer rates are discussed.

***Keywords**:* Radiation, chemical reaction, double dispersion, free convection, heat and mass transfer.

1. INTRODUCTION

Convective heat transfer has been found a lot of applications in thermal engineering, including reservoir engineering. Heat transfer in case of homogeneous fluid saturated porous media has been studied with relation to different applications like dynamics of hot underground springs, terrestrial heat flow through aquifer. Chemical reaction effects should be considered in many applications of heat and mass transfer especially those are encountered in chemical reactors of porous structure, geothermal reservoirs. Radiation heat transfer accounts in high temperature applications, plasma physics, nuclear reactors, magneto hydrodynamic accelerators and in power generation systems.

Radiation effects on convection can be quite important in the context of many industrial applications involving high-temperature such as nuclear power plant, gas turbines and various propulsion engines for aircraft, missiles, satellites and space technology. The inertial and viscous effects have been analyzed and a review of both natural and mixed-convection boundary layer flows in fluid saturated porous media as given in Neild and Bejan [1], Ali *et al*., [2] studied the natural convection-radiation interaction in boundary layer flow over a horizontal surfaces. Hossian and Pop [3] considered the effect of radiation on free convection of an optically dense viscous incompressible fluid along a heated inclined flat surface maintained at uniform temperature placed in a saturated porous medium. Hossain and Takhar [4] investigated the radiation effect on the mixed convection flow of an optically dense viscous incompressible fluid over a vertical plate. Yih [5] investigated the radiation effect on the mixed convection flow of an optically dense viscous fluid adjacent to an isothermal cone embedded in a saturated porous medium. The influence of thermal radiation and lateral mass flux on non-Darcy free convection was investigated by El Hakiem and El-Amin [6] over a vertical flat plate. Bakier [7] analyzed the effect of radiation on mixed-convection from a vertical plate in a saturated medium. Viskanta and Grosh [8] considered the effect of thermal radiation on free convection heat and mass transfer in an absorbing and emitting media over a wedge by using the Rosseland approximation. Anjalidevi and Kandasamy [9] studied the effects caused by the chemical diffusion mechanisms and the inclusion of a general chemical reaction of order n on the combined forced and natural convection flows over a semi-infinite vertical plate immersed in an ambient fluid. They stated that the presence of pure air or water is not possible in nature and some foreign mass may be present either naturally or mixed with air or water. Mulolani and Rahmann [10] studied the laminar natural convection flow over a semi-infinite vertical plate under the assumption that the concentrations of species along the plate follow some algebraic law with respect to the chemical reaction. They obtained similarity solutions for different order of reaction rates and Schmidt number *Sc*. Prasad *et al*., [11] Studied the influence of reaction rates on the transfer of chemically reactive species in the laminar non-Newtonian fluid immersed in porous medium over a stretched sheet. Kandasamy and Palanimani [12], carried out an analysis on the effects of chemical reactions, heat and mass transfer on non-linear magneto hydrodynamic boundary layer flow over a viscous dissipation.

The present paper is aimed at analyzing the effects of radiation with chemical reaction on non-Darcy free convective flow from a vertical surface embedded in a porous medium. The present work is applied to improve that fire resistance of MDF (Medium density fiberboard) panels for vertical applications (doors, Partitions wall) and frame retardant radiation, curable coatings for wood applications, industrial air conditioning and industrial refrigeration.

2. MATHEMATICAL FORMULATION

The chemical reaction of order *n,* on natural convective heat and mass transfer in a non Darcian porous medium saturated with a homogeneous Newtonian fluid adjacent to a vertical surface is considered. It is assumed that the medium is isotropic with neither radiative nor viscous dissipation effects. More over thermal local equilibrium is also assumed.

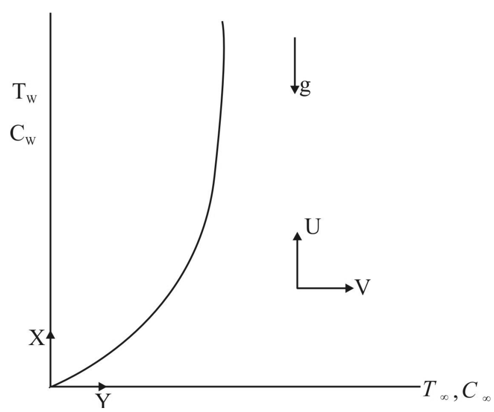

Figure 1: Schematic Diagram of the Problem

The coordinate system $x \rightarrow y$ is attached to the vertical surface as shown in Fig. 1. The x axis is taken along the plate and y axis is normal to it. The wall is maintained at constant temperature T_w and concentration C_w respectively. Taking into account the effects of thermal dispersion, the governing equations for steady non-Darcy flow in a saturated porous medium can be written as follows.

Continuity Equation:

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

Momentum Equation:

$$u + \frac{c\sqrt{K}}{\upsilon} u|\mathrm{v}| = -\frac{K}{\mu}\left(\frac{\partial \rho}{\partial x} + \rho g\right) \tag{2}$$

$$v + \frac{c\sqrt{K}}{\upsilon} v|\mathrm{v}| = -\frac{K}{\mu}\left(\frac{\partial \rho}{\partial y}\right) \tag{3}$$

Energy Equation:

$$u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}=\frac{\partial}{\partial x}\left(\alpha_x\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(\alpha_y\frac{\partial T}{\partial y}\right)-\frac{1}{\rho C_p}\frac{\partial q}{\partial y} \tag{4}$$

where

$$\frac{\partial q}{\partial y}=-16\,a\sigma RT_\infty^3(T_\infty-T)\,.$$

Concentration equation:

$$u\frac{\partial C}{\partial x}+v\frac{\partial C}{\partial y}=\frac{\partial}{\partial x}\left(D_x\frac{\partial C}{\partial x}\right)+\frac{\partial}{\partial y}\left(D_y\frac{\partial C}{\partial y}\right)-K_0(C-C_\infty)^n\,. \tag{5}$$

Density:

$$\rho=\rho_\infty[1-\beta(T-T_\infty)-\beta^*(C-C_\infty)]\,. \tag{6}$$

where u and v are velocities in the $x-y$ directions respectively, T is the temperature in the thermal boundary layer, K is the permeability. The energy equation includes radiation heat transfer effect with Joul heating. σ, μ_e and H_0 are called electrical conductivity. q is the radiative heat flux simplified by using Rosseland approximation. The chemical reaction effect is added as the last-term in the right hand side of equation (5) where the power n is the order of reaction. It is assumed that the normal component of the velocity near the boundary is small compared with the other components of the velocity and the derivatives of any quantity in the normal direction are large compared with derivatives of the quantity in the direction of the wall. $q=-\frac{4\sigma_0}{3k^*}\frac{\partial T^4}{\partial y}$ where σ_0, k^* are Stefan-Boltzmann constant and mean absorption coefficients, respectively. The necessary boundary conditions for this problem are

$$\left.\begin{array}{llll} y=0, & v=0, & T_w=\text{constant}, & C_w=\text{constant} \\ y\to\infty\,, & u\to 0, & T=T_\infty,\ C=C_\infty & \end{array}\right\} \tag{7}$$

Under the above assumptions equation (1) remains same and the equations (2)-(6) become.

$$u+\frac{c\sqrt{K}}{\upsilon}u^2=-\frac{K}{\mu}\left(\frac{\partial\rho}{\partial x}+\rho g\right) \tag{8}$$

$$\frac{\partial\rho}{\partial y}=0 \tag{9}$$

$$u\frac{\partial T}{\partial x}+v\,.\frac{\partial T}{\partial y}=\frac{\partial}{\partial y}\left(\alpha_y\frac{\partial T}{\partial y}\right)-\frac{1}{\rho C_p}\frac{\partial q}{\partial y} \tag{10}$$

$$u\frac{\partial T}{\partial x}+v\,.\frac{\partial T}{\partial y}=\frac{\partial}{\partial y}\left(D_y\frac{\partial C}{\partial y}\right)-K_0(C-C_\infty)^n \tag{11}$$

Following Telles and Trevisan [13], the quantities α_y and D_y are variables defined as $\alpha_y=\alpha+\gamma d\left|\mathrm{v}\right|$ and $D_y=D+\zeta d\left|\mathrm{v}\right|$ represent thermal dispersion and solute diffusivity respectively. This model for thermal dispersion has been used extensively by Cheng [14], Plumb [15], Hong and Tien [16], Lai and Kulacki [17], Murthy and Singh [18] in studies of non-Darcy convective heat transfer in porous media. Introducing the stream function ψ such that $u = \frac{\partial \psi}{\partial y}$ and $v = -\frac{\partial \psi}{\partial x}$ the above equations (8), (10), (11) are transformed to

$$\frac{\partial^2 \psi}{\partial y^2} + \frac{2c\sqrt{K}}{\upsilon}\left(\frac{\partial \psi}{\partial y}\right)\frac{\partial^2 \psi}{\partial y^2} = \rho_\infty \left(\frac{Kg\beta}{\mu}\frac{\partial T}{\partial y} + \frac{Kg\beta^*}{\mu}\frac{\partial C}{\partial y}\right) \tag{12}$$

$$\frac{\partial \psi}{\partial y}\frac{\partial T}{\partial x} - \frac{\partial \psi}{\partial x}\frac{\partial T}{\partial y} = \gamma d \frac{\partial^2 \psi}{\partial y^2}\frac{\partial T}{\partial y} + \alpha_m \frac{\partial^2 T}{\partial y^2} + \gamma d \frac{\partial \psi}{\partial y}\frac{\partial^2 T}{\partial y^2} + \frac{16\sigma}{3a\rho C_p}\left[3T^2\left(\frac{\partial T}{\partial y}\right)^2 + T^3 \frac{\partial^2 T}{\partial y^2}\right] \tag{13}$$

$$\frac{\partial \psi}{\partial y}\frac{\partial C}{\partial x} - \frac{\partial \psi}{\partial x}\frac{\partial C}{\partial y} = \zeta d \frac{\partial^2 \psi}{\partial y^2}\frac{\partial C}{\partial y} + \left(D + \zeta d \frac{\partial \psi}{\partial y}\right)\frac{\partial^2 C}{\partial y^2} - K_0 (C - C_\infty)^n . \tag{14}$$

Introducing similarity variables

$$\psi = f(\eta)\,\alpha\sqrt{Ra_x}, \quad \eta = Ra_x^{\frac{1}{2}}\frac{y}{x}, \quad \theta(\eta) = \frac{T - T_w}{T_w - T_\infty}, \quad \phi(\eta) = \frac{C - C_w}{C_w - C_\infty} \tag{15}$$

the Momentum Equation (12), Energy equation (13) and Concentration equation (14) reduces to

$$f'' + 2F_0 Ra_d f' f'' = \theta' + N\phi' \tag{16}$$

$$\theta'' + \frac{1}{2} f\theta' + \gamma Ra_d (f'\theta'' + f''\theta) + \frac{4R}{3}[3\theta'^2(\theta + c_r)^2 + \theta''(\theta + c_r)^3] = 0 \tag{17}$$

$$\phi'' + \frac{1}{2} Lef\phi' + \zeta Ra_d Le (f'\phi'' + f''\phi') - Sc\lambda \frac{Gc}{\mathrm{Re}_x^2} = 0 \tag{18}$$

where the primes denote the differentiation with respect to the similarity variable η. As mentioned in El-Amin (2004), the parameter $F_0 = \frac{c\sqrt{K}\alpha}{\upsilon d}$ collects a set of parameters that depend on the structure of the porous medium and the thermo-physical properties of the fluid saturating it. $R = \frac{4\sigma\theta_w^3}{kk^*}$ is the conduction radiation parameter. $Ra_d = \frac{Kg\beta(T_w - T_\infty)d}{\alpha\upsilon}$ is the modified, pore-diameter-dependent Rayleigh number and $N = \frac{\beta^*(C_w - C_\infty)}{\beta(T_w - T_\infty)}$ is the buoyancy ratio. Analogous to Mulolani and Rahman [10], Aissa and Mohammadien [19], we define Gc the modified Grashof number, Re_x the local Reynolds number, Sc the Schmidt number and λ the non-dimensional chemical reaction parameter as $Gc = \frac{\beta^* g (C_w - C_\infty)^2 x^3}{\upsilon^2}$, $\mathrm{Re}_x = \frac{u_r x}{\upsilon}$, $Sc = \frac{\upsilon}{D}$, $\lambda = \frac{K_0 \alpha d (C_w - C_\infty)^{n-3}}{kg\beta^*}$ where Le is the ratio of Schmidt number and Prandtl number and $u_r = \sqrt{g\beta d(T_w - T_\infty)}$ is the reference velocity as defined by Elbashbeshy [20]. Now the equation (18) can be written as

$$\phi'' + \frac{1}{2} Lef\phi' + \zeta Ra_d\, Le\,(f'\phi'' + f''\phi') - \chi\phi^n = 0 . \tag{19}$$

And analogous to Prasad *et al.*, [11], Aissa and Mohammadein [19], the non-dimensional chemical reaction parameter χ is defined as $\chi = \frac{Sc\lambda Gc}{\mathrm{Re}_x^2}$. Now the boundary conditions become

$$f(0) = 0,\ \theta(0) = \phi(0) = 1, \quad f'(\infty) = 1,\ \theta(\infty) = \phi(\infty) = 0. \tag{20}$$

It is noted for the Darcian free convection $F_0 = 0$, both the thermal dispersion and solute-dispersion effects are neglected. In equation (4.16) $N > 0$ indicates the aiding buoyancy and $N < 0$ indicates the opposing buoyancy. On the other hand from the definition of stream function, the velocity components become $u = \frac{\alpha Ra_x}{D} f'$ and $\nu = -\frac{\alpha Ra_x^2}{2x}[f - \eta f']$.

The local heat transfer rate from the surface of the plate is given by

$$q_w = -k_e \left[\frac{\partial T}{\partial y}\right]_{y=0}. \tag{21}$$

The local Nusselt number is

$$Nu_x = \frac{q_w x}{(T_w - T_\infty) k_e} \tag{22}$$

where k_e is the effective thermal conductivity of the porous medium which is the sum of the molecular and thermal conductivity k and the thermal dispersion conductivity k_d. Substituting $\theta(\eta)$ and equation (21) in equation (22) the modified Nusselt number is obtained as $\frac{Nu_x}{(Ra_x)^{\frac{1}{2}}} = -[1 + \gamma Ra_d f'(0)]\,\theta'(0)$. Also the local mass flux at the vertical wall is given by $j_w = -D_y \left(\frac{\partial C}{\partial y}\right)_{y=0}$ and the local Sherwood number is $\frac{Sh_x}{(Ra_x)^{\frac{1}{2}}} = -[1 + \zeta Ra_d f'(0)]\,\theta'(0)$.

3. SOLUTION

The dimensionless equations (16), (17) and (18) together with the boundary conditions (20) are solved numerically by means of the fourth order Runge-Kutta method coupled with the double shooting technique. By giving appropriate hypothetical values for $f'(0)$, $\theta'(0)$, $\phi'(0)$ we get corresponding boundary conditions at $f'(\infty)$, $\theta(\infty)$, $\phi(\infty)$ respectively. 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. This choice of η_{max} helps in comparison of the present results with those of earlier works.

4. RESULTS AND DISCUSSION

Figure 2, Shows that the effect of inertia on velocity profile under different radiation conditions. It is found from the figure that with increase in inertia parameter the velocity at a given location decreases i.e., the velocity steeply changes within the boundary. The velocity profile increases more in presence of radiation than absence of radiation.

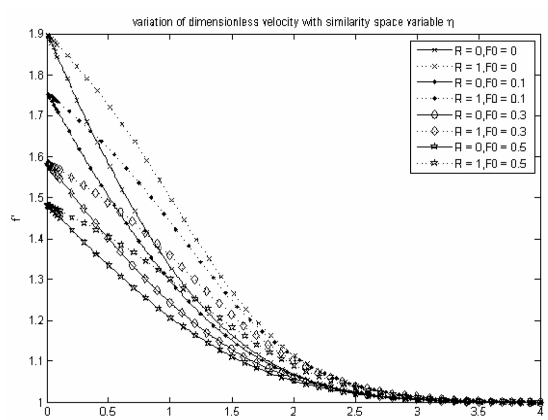

Figure 2: Variation of $f'(\eta)$ with η for Different Values of F_0 and Radiation R ($Le = 0.5$, $Ra_d = 0.7$, $N = -0.1$, $\gamma = \zeta = 0$, $\chi = 0.02$)

Figure 3, Shows that the effect of inertia on temperature profile under different radiation conditions. With increase in radiation parameter the temperature profile at a location in the boundary layer decreases. For fixed radiation conditions with increase in inertia parameter the temperature also increases.

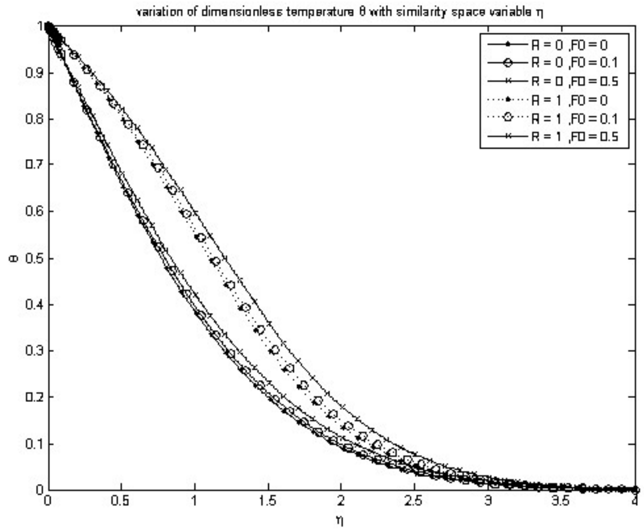

Figure 3: The Effect of Radiation and Non-Darcy Parameter on Temperature Distribution (Le = 0.5, Ra_d = 0.7, N = – 0.1, $\gamma = \zeta = 0$, χ = 0.02)

Figure 4. Shows that the effect of radiation under the influence of Lewis number on velocity boundary layer. As Lewis number increases the velocity increases. The thickening of the boundary due to radiation can also be seen in this figure. A similar phenomenon is observed with an increase in radiation.

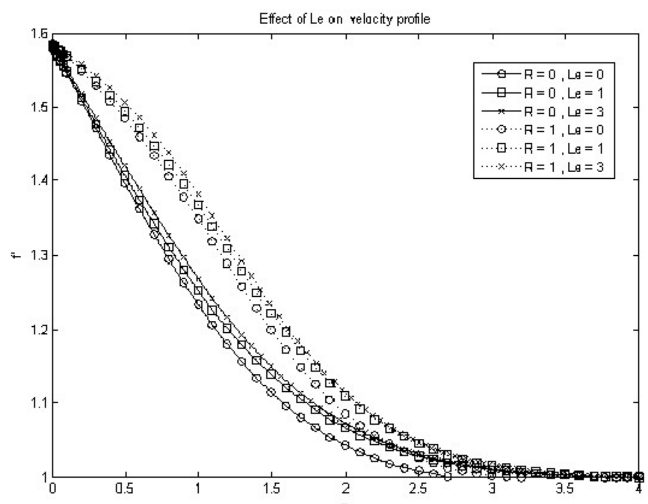

Figure 4: Variation of $f'(\eta)$ with η for Different Values of Le and radiation R (F_0 = 0.3, Ra_d = 0.7, N = – 0.1, $\gamma = \zeta = 0$, χ = 0.02)

Figure 5, Shows that the combined effect of radiation and Lewis number on concentration profile. It is clear from the figure that with increase in Lewis number the concentration decreases. Within the boundary layer the rate of change of concentration decreases the boundary decreases. Same trend is observed with radiation also. However the effect of radiation in presence of Lewis number is less. Further at any given location within the boundary layer the concentration decreases with increase in radiation

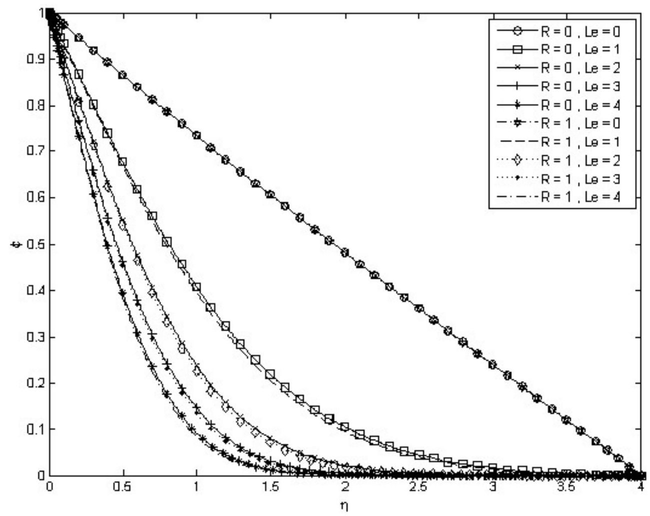

Figure 5: The Effect of Radiation and Lewis number on Concentration Profile
(F_0 = 0.3, Ra_d = 0.7, N = – 0.1, $\gamma = \zeta = 0$, χ = 0.02)

Figure 6, Shows that the effect of radiation and buoyancy ratio on the velocity distribution . It is clear from the figure that with increase in buoyancy ratio the velocity increases within the boundary layer. For a fixed value of buoyancy ratio velocity increases with increase in Radiation parameter.

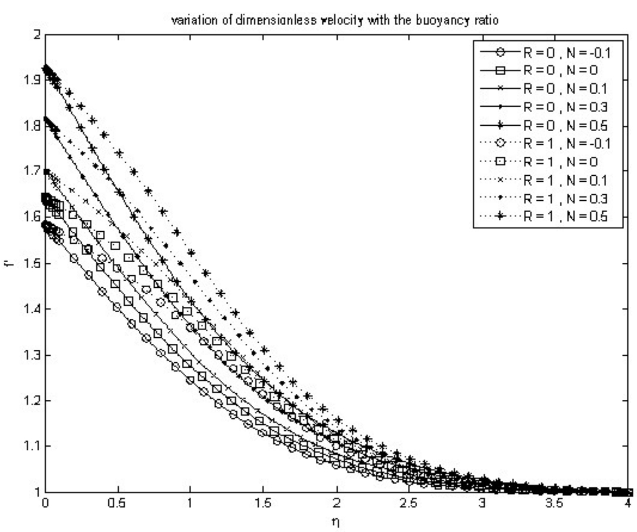

Figure 6: The Effect of Radiation and Buoyancy Ratio on Velocity Profile
(F_0 = 0.3, Ra_d = 0.7, N = – 0.1, $\gamma = \zeta = 0$, χ = 0.02)

Figure 7, Shows that the effect of radiation and buoyancy ratio on concentration profile. With increase in buoyancy ratio concentration profile decreases under the boundary layer. As well as the radiation parameter increases for a fixed value of buoyancy ratio concentration decreases.

Figure 8, Shows that the radiation and parameter on velocity profile. It is found that with increase in parameter the velocity at a given location decreases i.e., the velocity steeply changes within the boundary layer.

Figure 9, Shows that the effect of Radiation and chemical reaction on concentration profile. Concentration decreases with increase in chemical reaction parameter. For a fixed value of chemical reaction parameter concentration decreases with decrease in radiation.

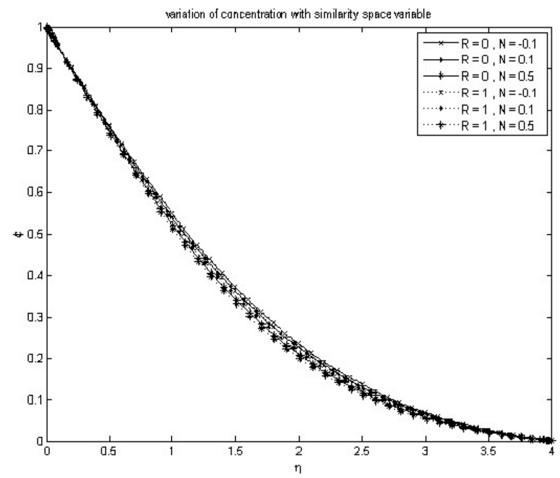

Figure 7: The Effect of Radiation and buoyancy Ratio on Concentration Distribution ($Le = 0.5, F_0 = 0.3, Ra_d = 0.7, \gamma = \zeta = 0, \chi = 0.02$)

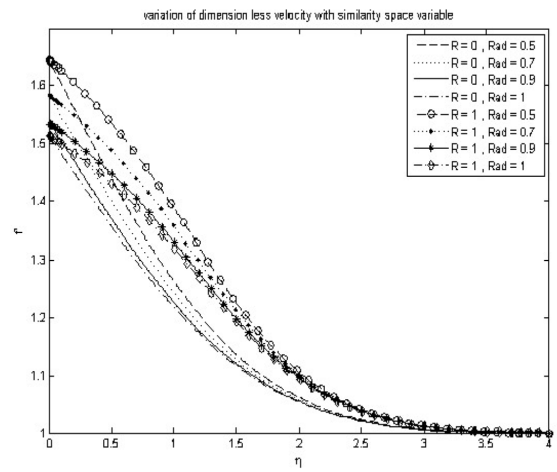

Figure 8: The Effect of Radiation and Ra_d Parameter on Velocity Profile ($Le = 0.5, F_0 = 0.3, Ra_d = 0.7, \gamma = \zeta = 0, N = -0.1$)

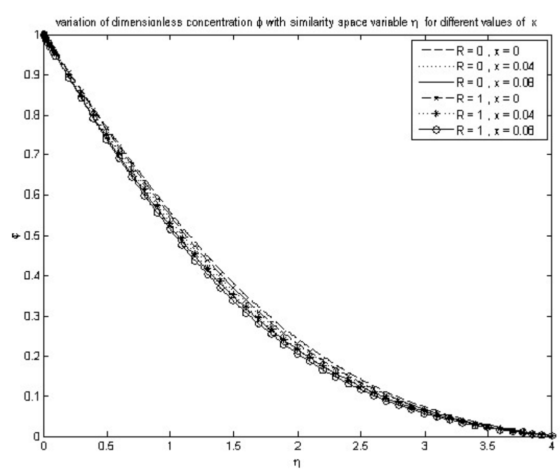

Figure 9: The Effect of Radiation and Chemical Reaction on Concentration Profile ($Le = 0.5, F_0 = 0.3, Ra_d = 0.7, \gamma = \zeta = 0, N = -0.1$)

Figure 10, It is clear that from the figure Nusselt number is decreasing with increase in inertia parameter. But this increment is less in the absence of Radiation than in the presence of radiation.

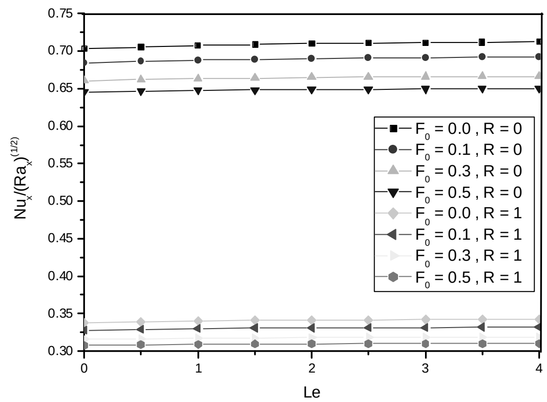

Fig ure 10: Effect of Lewis Number on Nusselt Number for Different Values of F_0 and R (Ra_d = 0.7, N = –0.01, $\gamma = \zeta = 0$, χ = 0.02)

Figure 11, It is clear that from the figure with increase in inertia parameter mass transfer rate decreases. For fixed value of inertia parameter mass transfer rate decreases with increase in Radiation parameter.

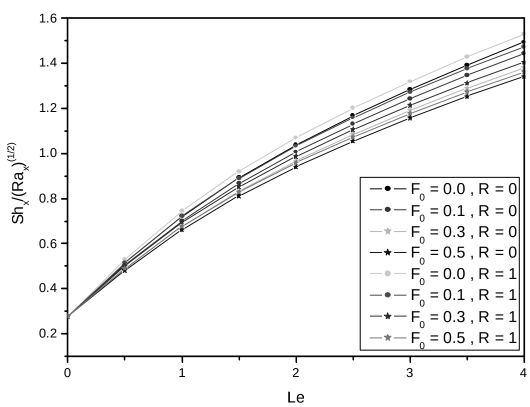

Figure 11: Effect of Lewis Number on Sherwood Number for Different Values of F_0 and R (Ra_d = 0.7, N = –0.01, $\gamma = \zeta = 0$, χ = 0.02)

Figure12, With the help of Nusselt number defined in Eq. (22), this shows that Nusselt number decreases significantly with increase in buoyancy ratio.

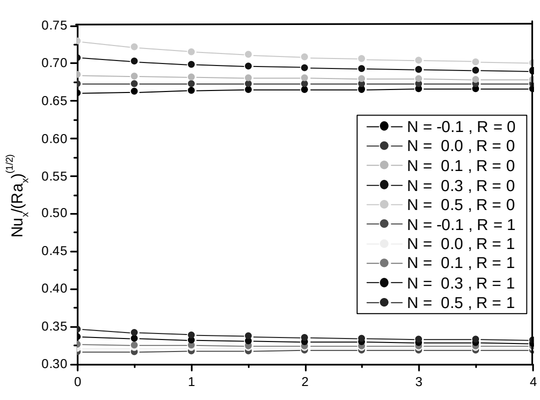

Figure 12: Effect of Lewis Number on Nusselt Number for Different Values of Buoyancy Ratio and Radiation (F_0 = 0.3, Le = 0.5, Ra_d = 0.7, $\gamma = \zeta = 0$, χ = 0.02)

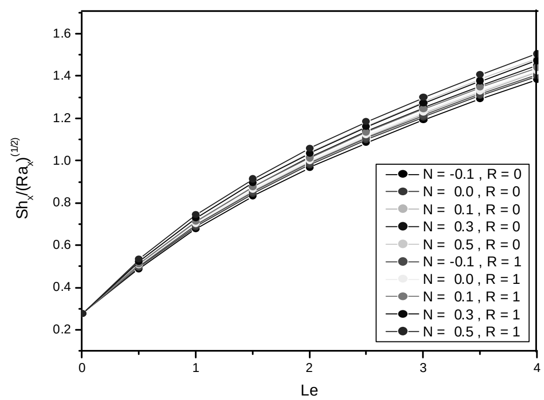

Figure 13: Effect of Lewis Number on Sherwood Number for Different Values of Buoyancy Ratio and Radiation (F_0 = 0.3, Le = 0.5, Ra_d = 0.7, $\gamma = \zeta = 0$, χ = 0.02)

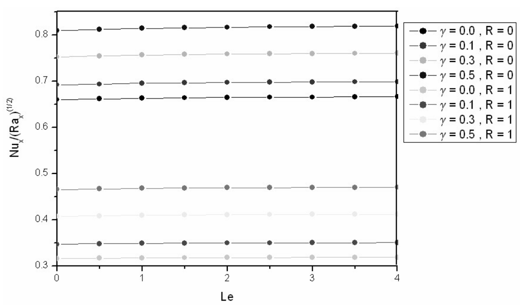

Figure 14: Effect of Lewis Number on Nusselt Number for Different Values of Radiation and Thermal Dispersion (F_0 = 0.3, N = –0.1, Ra_d = 0.7, $\gamma = \zeta = 0$, χ = 0.02)

Figure 14, Represents the variation of local Nusselt number on radiation parameter for different thermal dispersion values. Nusselt number increases with increase in thermal dispersion coefficient. For a fixed value of radiation parameter Nusselt number decreases with increase in radiation parameter. Hence low heat transfer rates occur with the effect of radiation.

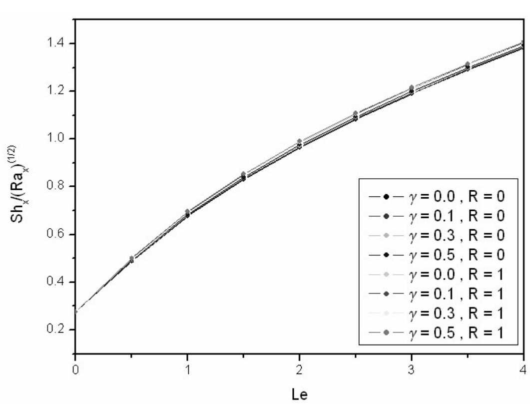

Figure 15: Effect of Lewis Number on Sherwood Number for Different Values of Thermal Dispersion and Radiation (F_0 = 0.3, N = –0.1, Ra_d = 0.7, $\gamma = \zeta = 0$, χ = 0.02)

Figure 15, It is clear that from the figure Sherwood number increases with increase in thermal dispersion coefficient in presence and absence of radiation parameter. But this increment is very less in presence of radiation parameter.

5. CONCLUSIONS

The chemical reaction phenomenon has been analyzed with natural convective flow and heat transfer in a fluid saturated porous medium. It is observed that with an increase in inertia parameter velocity decreases. And with an increase in radiation velocity increases. It is also seen that with increase in radiation the temperature at a location in the boundary layer decreases. when inertia parameter increases the temperature also increases. It is also noted that with increase in Lewis number velocity increases. With increase in buoyancy ratio, concentration profile decreases in the boundary layer. For a fixed value of the chemical reaction parameter concentration decrease with decrease in radiation. Nusselt number increases with an increase in thermal dispersion coefficient. For a fixed value of radiation parameter Nusselt number decreases with increase in radiation parameter. Hence low heat transfer rates occur with the effect of radiation. Share wood number increases with increase in thermal dispersion coefficient in the presence and absence of radiation parameter. But this increase is very less in presence of radiation parameter.

6. NOMENCLATURES

c	Empirical constant
C	Concentration
c_p	Specific heat at constant pressure
d	Pore diameter
D	Mass diffusivity
f	Dimensionless stream function
F_0	Structural and thermo-physical parameter
g	Gravitational acceleration
Gc	Modified Grashof number
J_w	Local mass flux
k	Molecular thermal conductivity
K	Permeability of the porous medium
K_0	Chemical reaction parameter
k_d	Dispersion thermal conductivity
k_e	Effective thermal conductivity
Le	Lewis number
n	Order of reaction
N	Buoyancy ratio
Nu_x	Local Nusselt number
P	Pressure
Pr	Prandtl number
q	Heat transfer rate
Ra	Rayleigh number
Re_x	Local Reynolds number
Sc	Schmidt number
Sh_x	Local Sherwood number
T	Temperature
u, v	Velocity components in the x and y directions
u_r	Reference velocity
v	Velocity vector
x, y	Axes along and normal to the plate
α	Molecular thermal diffusivity
α_d	Dispersion diffusivity
α_x, α_y	Components of the thermal diffusivity in and directions
β	Thermal expansion coefficient
β^*	Solutal expansion coefficient
R	Radiation parameter
χ	Non-dimensional chemical reaction-porous media parameter
ϕ	Dimensionless concentration
γ	Mechanical thermal-dispersion coefficient
η	Similarity space variable
λ	Non-dimensional chemical reaction parameter
μ	Fluid dynamic viscosity
υ	Fluid kinematic viscosity
θ	Dimension less temperature
ρ	Fluid density
ψ	Stream function
ζ	Mechanical solutal-dispersion coefficient
σ	Electrical conductivity, mho
a	Mean absorption coefficient

SUBSCRIPTS

d	Pore diameter
x, y	In the directions of x and y axes
w	Surface conditions
∞	Conditions away from the surface

SUPERSCRIPTS

$'$	Derivative with respect to η

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