Magnetic field and radiation effects on a double diffusive free convective flow bounded by two infinite impermeable plates in the presence of chemical reaction

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Abstract
This article deals with a two dimensional double diffusive steady free convective Poiseuille flow of an electrically conducting, viscous fluid through a porous medium bounded by two stationary infinite vertical porous plates in presence of thermal radiation and chemical reaction of first order. A uniform magnetic field is assumed to be applied transversely in the direction of the flow. The plates are subjected to a constant normal suction/injection velocity. Analytical solutions of the governing equations are found by using a regular perturbation technique. The expressions for the velocity, temperature, and concentration are obtained and their numerical values are demonstrated with the help of the graphs. With the aid of the above expressions of the flow quantities, the expressions for skin friction and the coefficient of heat transfer in terms of Nusselt number, and the coefficient of mass transfer in the form of Sherwood number at the walls are also calculated and the effect of various physical parameters on these quantities are discussed.

Keywords: MHD, Radiation, Soret effect, homogeneous chemical reaction, porous medium, double diffusion and impermeable plate.

1. INTRODUCTION

Problems involving Magneto Hydrodynamics (MHD) are very important in many fields such as geophysical and astrophysical problems, plasma studies, nuclear reactors, geothermal energy extractions and the boundary layer control in the field of aerodynamics. The possible usage of MHD is effect a flow stream of an electrically conducting fluid for the purpose of thermal production, braking, propulsion and control. The effects of Magnetic field on free convection flow problems have been attracted by many investigators [1-3]. Chemical reactions can be codified as either heterogeneous or homogeneous processes. This depends on whether they occur at an interface or as a single phase volume reaction. In well-mixed systems, the reaction is heterogeneous, if it takes place at an interface and homogeneous, if it takes place in solution. In most cases of chemical reactions, the reaction rate depends on the concentration of the species itself.

A reaction is said to be of first order, if the rate of reaction is directly proportional to the concentration itself. Anjalidevi and Kandaswamy [4] have considered a chemical reaction flow past a semi infinite plate. Kandaswamy et al. [5, 6] and Ibrahim et al. [7], have studied boundary layer flow problems which are involved with chemical reaction. Effects of chemical reaction and viscous dissipation on MHD free convection flows in porous medium have been investigated by Mansour et al. [8]. The flow is also affected by the difference in concentrations on material constitution. In most of the practical situations, the level of concentration of foreign mass cannot be ignored. Therefore the soret effect for instance will be utilized for isotope separation and in mixture between gases with very light molecular weight [6]. Groot and Mazur [10] showed that if separation due to thermal diffusion occurred, if might even render an unstable system for a stable one. This effect sometimes is also quite small, but devices can be arranged to produce very steep temperature gradients, so that separations of mixtures are affected. Perhaps Raju et al. [11] studied the problem of soret effects due to natural convection between heeded inclined plates with magnetic field. Many researchers studied the combined effects of chemical reaction and thermal diffusion in different boundaries [4-11]. For example Reddy et al. [12] discussed thermo diffusion and chemical effects in MHD mixed convection flow with ohmic heating. Again Reddy et al. [13] studied soret effects on MHD three dimensional free convection Couette flow with heat and Mass transfer. Thermal diffusion effects on Magneto hydrodynamic free convection flow between heated inclined plates in porous medium was studied by Raju et al. [14]. Balamurugan et al. [15] have investigated thermo diffusion and chemical reaction effects on a three dimensional mixed convective flow along an infinite vertical porous plate with magnetic field. Radiative convective flows are encountered in many environmental and industrial processes, for example, heating and cooling

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chambers, evaporation from large open reservoirs, astrophysical flows, solar power technology and space vehicle reentry. Radiative heat and mass transfer play an important role in manufacturing industry for the design of reliable equipment. Besides that nuclear power plants, gas turbines, and various propulsion devises for air craft, missiles, satellites and space vehicles are the other examples of such engineering applications [18]. Muthucumaraswamy and Ravi Sankar [16], concentrated on first order chemical reaction and thermal radiation effects on unsteady flow past an accelerated isothermal infinite vertical plates. Mazumdar and Deka [17], investigated MHD flow past an impulsively started infinite vertical plates in presence of thermal radiation. Radiation and Mass Transfer effects on MHD free convection flow past an exponentially accelerated vertical plates with variable temperature, was studied by Rajesh and Varma [19]. Radiation effects on flow past an impulsively started vertical infinite plate was considered by Das et al. [20]. Few other works that are reported on radiation in various geometries by Muthucumaraswamy and Janakiraman [21], Afify [22], Sharma et al. [23], Hossain and Takhar [24], and Raju et al. [25]. For the case of thin gray gas the local radiant is expressed by Rajesh and Varma [19], Singh and Kumar [18] as

$$\frac{\partial q_r}{\partial y^*} = -4a^*\sigma^*(T_\infty^{*4} - T^{*4}) \tag{1}$$

Where a^* is the mean absorption coefficient and σ^* is Stefan – Boltzmann constant. It is assumed that the temperature differences within the flow are sufficiently small, so that T^{*4} may be expressed as a linear function of the temperature. This is accomplished by expanding T^{*4} as a Taylor's series about T_∞^* and neglecting the higher order terms, it gives the following

$$T^{*4} \cong 4T_\infty^{*3}T^* - 3T_\infty^{*4} \tag{2}$$

In this paper we have made an attempt to study magnetic field and radiation effects on a double diffusive free convective flow bounded by two infinite impermeable plates in the presence of chemical reaction. The equations governing the flow are solved by a simple perturbation technique and the expressions for velocity, temperature and concentration distributions are obtained.

2. MATHEMATICAL FORMULATION

We have considered a two dimensional steady flow of a laminar free convective, viscous incompressible electrically conducting fluid past an infinite vertical porous plate, embedded in a porous medium in the presence of thermal diffusion, thermal radiation and a homogeneous chemical reaction. A uniform magnetic field of strength B_0 is applied perpendicular to the plate. Let h be the distance between the plates. It is assumed that there is applied voltage which results the absence of electric field. The transversely applied magnetic field and magnetic Reynolds number are assumed to be very small so that the induced magnetic field and Hall currents are negligible [1]. The suction velocity is assumed in the form $v^* = -v_0$, where v_0 is the constant suction /injection. We have introduced a Cartesian coordinate system (x^*, y^*, z^*), with x^* is taken vertically upward direction along the plate and y^* is perpendicular to it, directed into the fluid region. Let $q^* = u^*i + v^*j$ be the fluid velocity at the point(x^*, y^*, z^*). Since the plates are infinite in length therefore all the physical quantities are independent of x^*. The governing equations are based on the balances of mass, linear momentum, energy and concentration species. Taking into consideration the assumptions made above, these equations can be written as follows.

$$\frac{\partial v^*}{\partial y^*} = 0 \tag{3}$$

$$-v_0\frac{du^*}{dy^*} = \nu\frac{d^2u^*}{dy^{*2}} + g\beta(T^* - T_\infty^*) + g\beta(C^* - C_\infty^*) - \frac{\upsilon u^*}{k} - \frac{\sigma B_0^2 u^*}{\rho} \tag{4}$$

$$-v_0\frac{dT^*}{dy^*} = \frac{\lambda}{\rho c_p}\frac{d^2T^*}{dy^{*2}} + \frac{\upsilon}{c_p}\left(\frac{du^*}{dy^*}\right)^2 - \frac{1}{\rho c_p}\frac{\partial q_r}{\partial y^*} \tag{5}$$

$$-v_0\frac{dc^*}{dy^*} = D\frac{d^2c^*}{dy^{*2}} - K_1(C^* - C_s^*) + D_1\frac{d^2T^*}{dy^{*2}} \tag{6}$$

where ϱ is the density, υ is the kinematic viscosity, g is the acceleration due to gravity, v_o is the constant suction/injection velocity, β is the coefficient of volume expansion for heat transfer, β^* is the coefficient of volume expansion for mass transfer, D is the chemical molecular diffusivity, K is the permeability of porous medium, σ is the electrical conductivity, c_p is the specific heat at constant pressure, β_0 is the strength of applied magnetic field, $T^*$is the temperature, T_s^* is the temperature at static condition, C^* is the species concentration, C_∞^* is the concentration at static condition and the other symbols have their usual meanings, a^* is the mean absorption coefficient and σ^* is Stefan – Boltzmann constant.

The relevant boundary conditions are

$$u^* = 0, T^* = T_0^*, C^* = C_0^* \ at \ y^* = 0$$
$$u^* = 0, T^* = T_1^*, C^* = C_1^* \ at \ y^* = h \quad (7)$$

We introduce the following non-dimensional quantities

$$y = \frac{y^*}{h}, \ u = \frac{u^*}{v_0}, \theta = \frac{T^* - T^*_s}{T^*_0 - T^*_s}, \phi = \frac{C^* - C^*_s}{C^*_0 - C^*_s},$$
$$p_r = \frac{\mu c_p}{\lambda}, Sc = \frac{v}{D}, \text{Re} = \frac{v_0 h}{\upsilon}, \alpha = \frac{k}{h^2}, F = \frac{4I_1 h^2}{v\rho c_p},$$
$$G_r = \frac{hg\beta(T^*_0 - T^*_s)}{v_0^2}, G_m = \frac{hg\beta^*(C^*_0 - C^*_s)}{v_0^2}, \quad (8)$$
$$E = \frac{v_0^2}{c_p(T^*_0 - T^*_s)}, k = \frac{Kc}{h^2}, M = \frac{\sigma B_0^2 h^2}{\rho v}, Kc = \frac{K_1 \upsilon}{v_0^2},$$
$$m = \frac{T^*_1 - T^*_s}{T^*_0 - T^*_s}, n = \frac{C^*_1 - C^*_s}{C^*_0 - C^*_s}, S_0 = \frac{D_1(T^*_0 - T^*_s)}{\upsilon(C^*_0 - C^*_s)}.$$

where P_r, is the Prandtl number, Sc the Schmidt number, Re the Reynolds number, Gr the Grashoff number for heat transfer, Gm the Grashoff number for mass transfer, E the Eckert number, k the permeability parameter, F is the Radiation parameter, S_0 is the Soret number, α dimensionless permeability parameter, Sc Schmidt number, Kc chemical reaction parameter and M is the Hartmann number. The non-dimensional governing equations and boundary conditions are

$$-\frac{du}{dy} = \frac{1}{\text{Re}}\frac{d^2u}{dy^2} + G_r\theta + G_m\phi - \frac{u}{\text{Re}\,\alpha} - M\,\text{Re}\,u \quad (9)$$

$$-\frac{d\theta}{dy} = \frac{1}{\text{Re}\,p_r}\frac{d^2\theta}{dy^2} + \frac{E}{\text{Re}}\left(\frac{du}{dy}\right)^2 - \frac{F}{\text{Re}}\theta \quad (10)$$

$$-\frac{d\phi}{dy} = \frac{1}{\text{Re}\,Sc}\frac{d^2\phi}{dy^2} - K\,\text{Re}\,\phi + \frac{S_0}{\text{Re}}\frac{d^2\theta}{dy^2} \quad (11)$$

Subject to the boundary conditions

y = 0 u = 0 θ = 1 ϕ = 1 (12)
y = 1 u = 0 θ = m ϕ = n

3. SOLUTION OF THE PROBLEM

In order to solve the set partial differential equations (9) to (11) in non-dimensional form subject to boundary conditions (12), we assumed the velocity, temperature and concentration in a series expansion in powers of E where E<<1 as given below.

$$u = u_0(y) + Eu_1(y) + O(E^2) \quad (13)$$

$$\theta = \theta_0(y) + E\theta_1(y) + O(E^2) \quad (14)$$

$$\phi = \phi_0(y) + E\phi_1(y) + O(E^2) \quad (15)$$

Substituting equations (13) to (15) into equations (9) to (11) and equating the coefficient of similar powers of E and neglecting the higher powers of E, we obtain the following ordinary differential equations for (u_0, θ_0, ϕ_0) and (u_1, θ_1, ϕ_1).

$$u_0'' + \text{Re}\,u_0' - M_1 u_0 = -Gr\,\text{Re}\,\theta_0 - Gm\,\text{Re}\,\phi_0 \quad (16)$$

$$\theta_0'' + \text{Re}\,P_r\theta_0' = -FP_r\theta_0 \quad (17)$$

$$\phi_0'' + \text{Re}\,Sc\phi_0' - K\,\text{Re}^2\,S\phi_0 = -S_0 Sc\theta_0'' \quad (18)$$

$$u_1'' + \text{Re}\,u_1' - M_1 u_1 = -G_r\,\text{Re}\,\theta_1 - G_m\,\text{Re}\,\phi_1 \quad (19)$$

$$\theta_1'' + \text{Re}\,P_r\theta_1' - FP_r\theta_1 = -P_r u_0'^2 \quad (20)$$

$$\phi_1'' + \text{Re}\,Sc\phi_1' - K\,\text{Re}^2\,S\phi_1 = -S_0 Sc\theta_1'' \quad (21)$$

$$\phi_1'' + \text{Re}\,Sc\phi_1' - K\,\text{Re}^2\,S\phi_1 = -S_0 Sc\theta_1'' \quad (22)$$

Where $M_1 = \frac{1}{k} + MR^2$ and prime denotes the differentiation with respect to 'y'.

The boundary conditions (10) reduce to

at y = 0: $u_0 = 0, \theta_0 = 1, u_1 = 0, \theta_1 = 0, \phi_0 = 1, \phi_1 = 0$
at y = 1: $u_0 = 0, \theta_0 = m, u_1 = 0, \theta_1 = 0, \phi_0 = n, \phi_1 = 0$ (23)

Solving equations (16) to (22) w. r. t the boundary conditions (23), we obtain the following solutions

$$\theta_0 = c_1 e^{-m_1 y} + c_2 e^{-m_2 y} \quad (24)$$

$$\phi_0 = c_3 e^{-m_3 y} + c_4 e^{-m_4 y} + k_4 e^{-m_1 y} + k_5 e^{-m_2 y} \quad (25)$$

$$u_0 = c_5 e^{-m_5 y} + c_6 e^{-m_6 y} + k_{10} e^{-m_1 y} + k_{11} e^{-m_2 y} + k_{12} e^{-m_3 y} + k_{13} e^{-m_4 y} + k_{14} e^{-m_1 y} + k_{15} e^{-m_2 y} \quad (26)$$

$$\begin{aligned}
\theta_1 &= c_7 e^{-m_7 y} + c_8 e^{-m_8 y} + k_{18} e^{-2m_5 y} + k_{19} e^{-2m_6 y} \\
&+k_{20} e^{-2m_1 y} + k_{21} e^{-2m_2 y} + k_{22} e^{-2m_3 y} + k_{23} e^{-2m_4 y} \\
&+k_{24} e^{-2m_1 y} + k_{25} e^{-2m_2 y} + k_{26} e^{-(m_5+m_6) y} + k_{27} e^{-(m_1+m_5) y} \\
&+k_{28} e^{-(m_2+m_5) y} + k_{29} e^{-(m_3+m_5) y} + k_{30} e^{-(m_4+m_5) y} \\
&+k_{31} e^{-(m_1+m_5) y} + k_{32} e^{-(m_2+m_5) y} + k_{33} e^{-(m_1+m_6) y} \\
&+k_{34} e^{-(m_2+m_6) y} + k_{35} e^{-(m_3+m_6) y} + k_{36} e^{-(m_4+m_6) y} \\
&+k_{37} e^{-(m_1+m_6) y} + k_{38} e^{-(m_1+m_6) y} + k_{39} e^{-(m_1+m_2) y} \\
&+k_{40} e^{-(m_1+m_3) y} + k_{41} e^{-(m_1+m_4) y} + k_{42} e^{-2m_1 y} \\
&+k_{43} e^{-(m_1+m_2) y} + k_{44} e^{-(m_2+m_3) y} + k_{45} e^{-(m_2+m_4) y} \\
&+k_{46} e^{-(m_1+m_2) y} + k_{47} e^{-2m_2 y} + k_{48} e^{-(m_3+m_4) y} \\
&+k_{49} e^{-(m_1+m_3) y} + k_{50} e^{-(m_2+m_3) y} + k_{51} e^{-(m_1+m_4) y} \\
&+k_{52} e^{-(m_2+m_4) y} + k_{53} e^{-(m_1+m_2) y} \qquad (27)
\end{aligned}$$

$$\begin{aligned}
\phi_1 &= c_9 e^{-m_9 y} + c_{10} e^{-m_{10} y} + k_{56} e^{-m_7 y} + k_{57} e^{-m_8 y} \\
&+k_{58} e^{-2m_5 y} + k_{59} e^{-2m_6 y} + k_{60} e^{-2m_1 y} + k_{61} e^{-2m_2 y} \\
&+k_{62} e^{-2m_3 y} + k_{63} e^{-2m_4 y} + k_{64} e^{-2m_1 y} + k_{65} e^{-2m_2 y} \\
&+k_{66} e^{-(m_5+m_6) y} + k_{67} e^{-(m_1+m_5) y} + k_{68} e^{-(m_2+m_5) y} \\
&+k_{69} e^{-(m_3+m_5) y} + k_{70} e^{-(m_4+m_5) y} + k_{71} e^{-(m_1+m_5) y} \\
&+k_{72} e^{-(m_2+m_5) y} + k_{73} e^{-(m_1+m_6) y} + k_{74} e^{-(m_2+m_6) y} \\
&+k_{75} e^{-(m_3+m_6) y} + k_{76} e^{-(m_4+m_6) y} + k_{77} e^{-(m_1+m_6) y} \\
&+k_{78} e^{-(m_2+m_6) y} + k_{79} e^{-(m_1+m_2) y} + k_{80} e^{-(m_1+m_3) y} \\
&+k_{81} e^{-(m_1+m_4) y} + k_{82} e^{-2m_1 y} + k_{83} e^{-(m_1+m_2) y} \\
&+k_{84} e^{-(m_2+m_3) y} + k_{85} e^{-(m_2+m_4) y} + k_{86} e^{-(m_1+m_2) y} \\
&+k_{87} e^{-2m_2 y} + k_{88} e^{-(m_3+m_4) y} + k_{89} e^{-(m_1+m_3) y} \\
&+k_{90} e^{-(m_2+m_3) y} + k_{91} e^{-(m_1+m_4) y} + k_{92} e^{-(m_2+m_4) y} \\
&+k_{93} e^{-(m_1+m_2) y} \qquad (28)
\end{aligned}$$

$$\begin{aligned}
u_1 &= c_{11} e^{-m_{11} y} + c_{12} e^{-m_{12} y} + k_{139} e^{-m_7 y} + k_{140} e^{-m_8 y} \\
&+k_{141} e^{-2m_5 y} + k_{142} e^{-2m_6 y} + k_{143} e^{-2m_1 y} + k_{144} e^{-2m_2 y} \\
&+k_{145} e^{-2m_3 y} + k_{146} e^{-2m_4 y} + k_{147} e^{-(m_5+m_6) y} \\
&+k_{148} e^{-(m_1+m_5) y} + k_{149} e^{-(m_2+m_5) y} + k_{150} e^{-(m_3+m_5) y} \\
&+k_{151} e^{-(m_4+m_5) y} + k_{152} e^{-(m_1+m_6) y} + k_{153} e^{-(m_2+m_6) y} \\
&+k_{154} e^{-(m_3+m_6) y} + k_{155} e^{-(m_4+m_6) y} + k_{156} e^{-(m_1+m_2) y} \\
&+k_{157} e^{-(m_1+m_3) y} + k_{158} e^{-(m_1+m_4) y} + k_{159} e^{-(m_2+m_3) y} \\
&+k_{160} e^{-(m_2+m_4) y} + k_{161} e^{-(m_3+m_4) y} + k_{162} e^{-m_9 y} \\
&+k_{163} e^{-m_{10} y} + k_{164} e^{-m_7 y} + k_{165} e^{-m_8 y} \qquad (29)
\end{aligned}$$

The skin-friction coefficient, the Nusselt number and the Sherwood number near the plate, are important physical parameters for this type of boundary-layer flow. These parameters can be defined and determined as follows:

$$\tau_0 = \frac{1}{R}\left[\frac{du}{dy}\right]_{y=0} = \frac{1}{R}\left[u_0'(0) + E u_1'(0)\right] = \frac{1}{R}\left[k_{168} + E(k_{170})\right]$$

$$\tau_1 = \frac{1}{R}\left[\frac{du}{dy}\right]_{y=1} = \frac{1}{R}\left[u_0'(1) + E u_1'(1)\right] = \frac{1}{R}\left[k_{169} + E(k_{171})\right]$$

$$Nu_0 = \left[\frac{d\theta}{dy}\right]_{y=0} = \theta_0'(0) + E\theta_1'(0) = k_{172} + E(k_{174})$$

$$Nu_1 = \left[\frac{d\theta}{dy}\right]_{y=1} = \theta_0'(1) + E\theta_1'(1) = k_{173} + E(k_{175})$$

$$Sh_0 = \left[\frac{d\phi}{dy}\right]_{y=0} = \phi_0'(0) + E\phi_1'(0) = k_{176} + E(k_{178})$$

$$Sh_1 = \left[\frac{d\phi}{dy}\right]_{y=1} = \phi_0'(1) + E\phi_1'(1) = k_{177} + E(k_{179})$$

4. RESULTS AND DISCUSSIONS

The numerical values of the velocity, temperature, concentration, Skin friction, Nusselt number and Sherwood number are computed for different values of physical parameters like magnetic parameter (M), radiation parameter (R) ,chemical reaction (Kc), Soret number (S_0) etc., the effects of these parameters on flow quantities are studied through graphs 1-9. The effects of other parameters which are reported in [28] are not repeated here.

Velocity profiles are displayed against the special coordinate y for different values of M and F, in figures 1 and 2 respectively. From these figures it is noticed that, as expected, velocity decreases with an increase in M, since the magnetic field acts as a retorting force which drags the flow. A similar effect is noticed in the case of F also. The variations in temperature under the influence of F are shown in figure 3. From this figure it is observed that temperature decreases with an increase in F. The effects of kc, S_0 on concentration are displayed in figures 4 and 5. From these figures it is observed that concentration increases with a decrease in both kc and S_0.

Variations in skin friction with chemical reaction parameter are displayed in figure 6. From this figure it is noticed that skin friction increase with a decrease in F. Effects of F on Nusselt number are displayed in figure 7, form this figure it is noticed that a decrease in F effects an increase in Nu_0 and it is shown the reverse effect near the plate y=1, in the case of Nu_1. Figure 8 depits the effects of kc on Sherwood number. From figure it is observed that Sho increases with the decrease in kc and it shows the reverse in the case of Sh_1.

5. CONCLUSIONS:

The governing equations for MHD free convection flow through porous medium bounded by two vertical porous plates in presence of thermal diffusion, constant suction and chemical reaction is formulated. It is assumed that the fluid region is bounded by an infinite vertical plate which is at rest and the flow is subjected to a transverse magnetic field. The resulting partial differential equations were transformed into a set of ordinary differential equations using a two term series and solved in closed form. Numerical computations of the closed form results are performed and some graphical results were obtained to illustrate the details of the flow and heat and mass transfer characteristics and their dependence on some of the physical parameters. It is found that velocity decreases with the increase in M, Kc and So. Temperature increases with the increasing values of E. However concentration decreases with an increase in E, Kc and So. In addition, it is found that skin friction coefficient decreases with an increase in Kc. Nusselt number increases with an increase in E near one side of the plate and it shows reverse effect on the either side of the plate. Interestingly it is noticed that Sherwood number decreases with an increase in Kc and So near the plate y=0 and it shows opposite reaction near the plate y=1. However Sherwood number increases with an increase in M near both sides of the plate.

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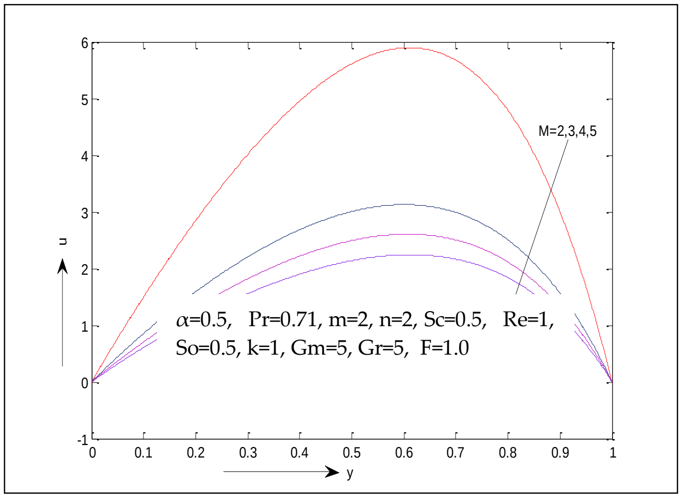

Fig. 1. Velocity profiles for various values of M.

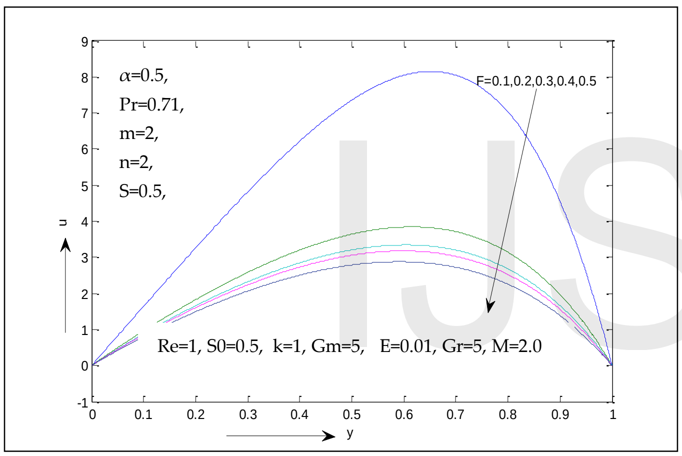

Fig. 2. Velocity profiles for various values of F.

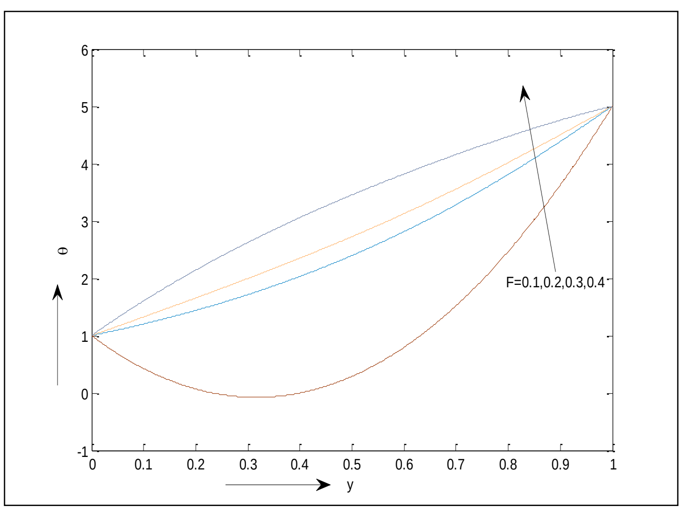

Fig.3. Temperature profiles for various values of F.

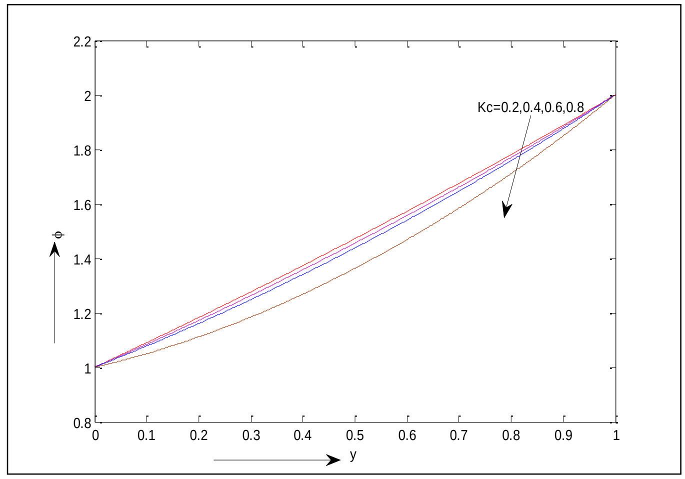

Fig. 4. Concentration profiles for various values of Kc.

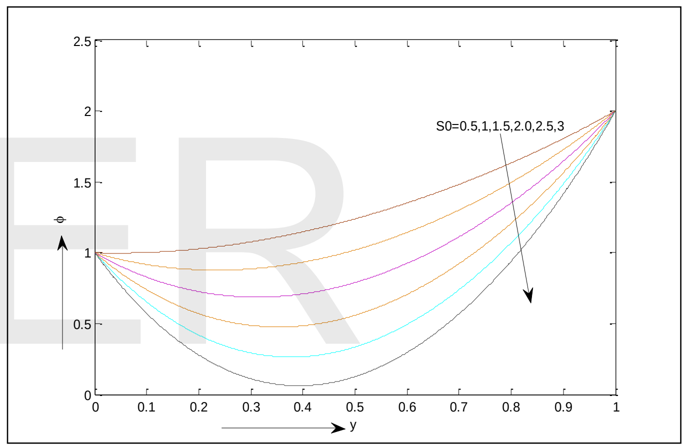

Fig. 5. Concentration profiles for various values of So.

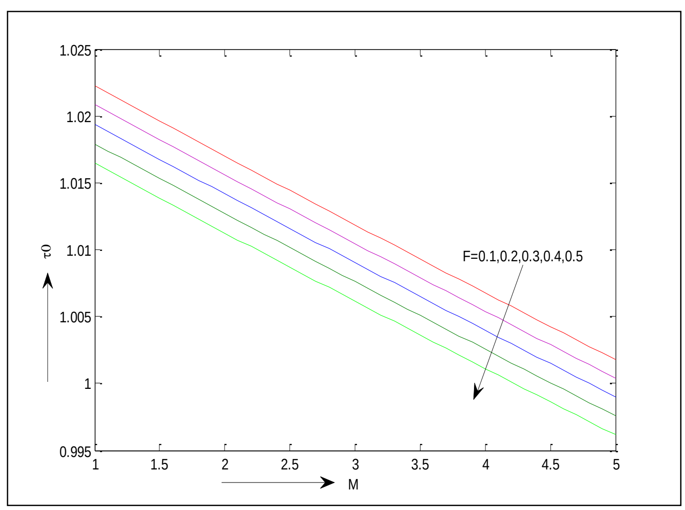

Fig. 6. Coefficient of skin-friction profiles for various values of F.

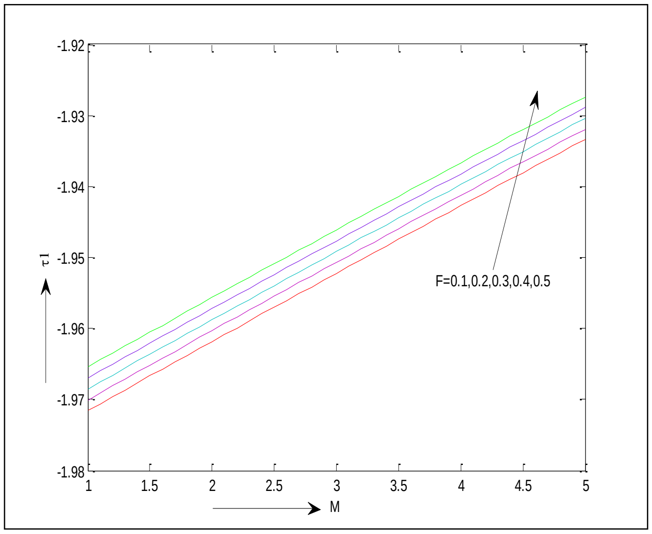

Fig. 7. Coefficient of skin-friction profiles for various values of F

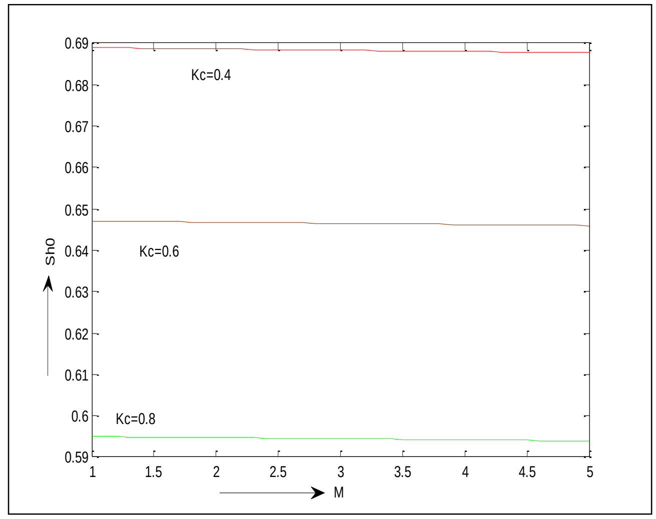

Fig. 10. Sherwood number profiles for various values of Kc

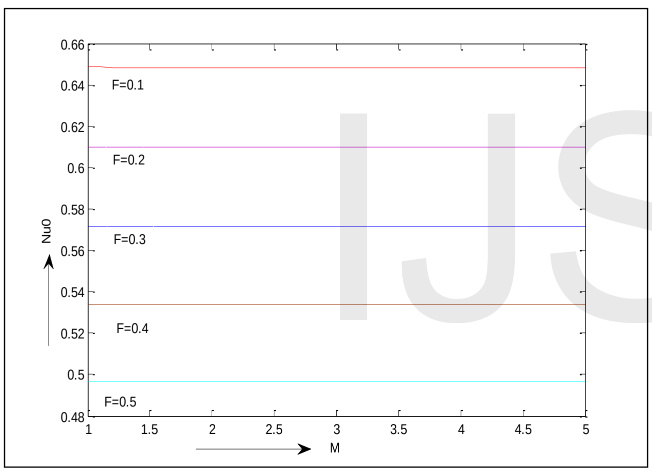

Fig. 8. Rate of Heat-Transfer profiles for various values of F

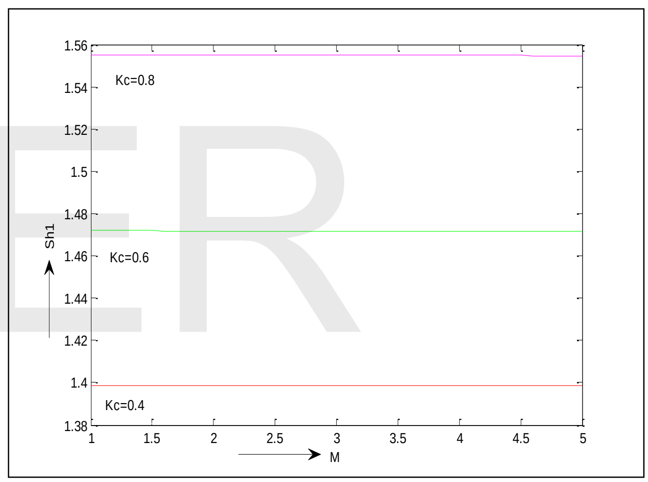

Fig.11. Sherwood number profiles for various values of Kc

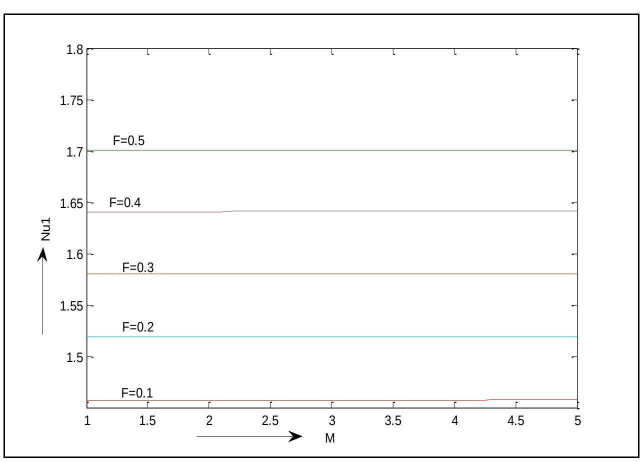

Fig. 9. Rate of Heat-Transfer profiles for various values of F

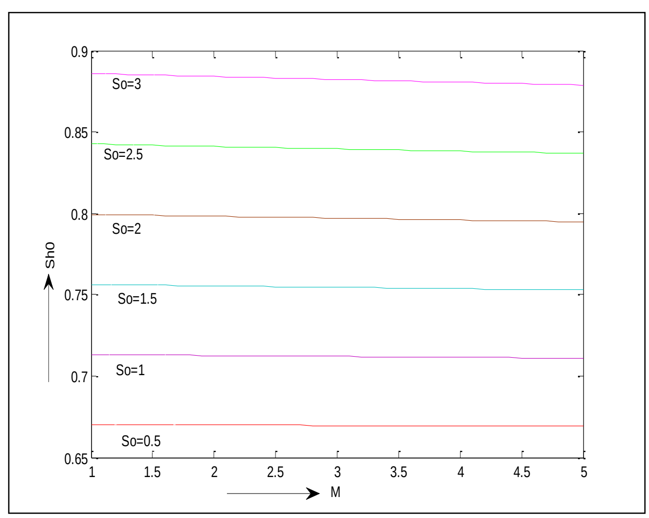

Fig. 12. Sherwood number profiles for various values of So

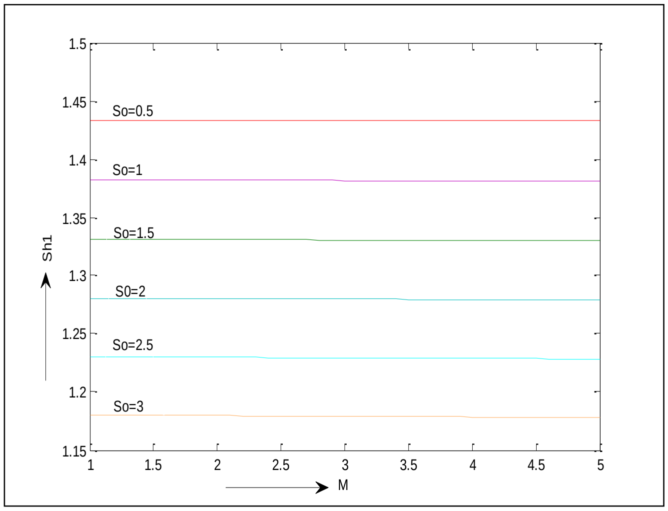

Fig. 13. Sherwood number profiles for various values of So

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