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Unsteady Heat and Mass Transfer to Magnetohydrodynamics Oscillatory Flow of Jeffery Fluid in a Channel Filled with Porous Material

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Abstract

The study on unsteady Heat and Mass transfer to MHD Oscillatory flow of Jeffery fluid through a porous medium under slip condition was investigated. The dimensionless governing equations are solved using perturbation technique. The analytical expressions for the velocity, temperature, concentration, skin friction and Sherwood number of the fluid have been obtained. The effects of flow parameters of thermal Grashof number, Mass Grashof number, Schmidt number, Hartmann number, radiation parameter, Jeffery fluid parameter and frequency of the oscillation are carried out. The result obtained shows that velocity and skin friction decreases with increasing Hartmann number. It was also observed that the velocity and skin friction increases with increase in Darcy number. It is pointed that increase in Schmidt number decreases concentration. The results obtained for Jeffery fluid parameter was computed for velocity and skin friction and shows that the velocity and skin friction increases with increasing Jeffery fluid parameter.

1. Introduction

The study of non-Newtonian fluids with heat and mass transfer has continue to attract the attention of many researchers in recent years due to its possible applications in many industrial and engineering processes especially in recovery and extraction of crude oil, cooling of nuclear reactor, geothermal system, underground energy transport, polymer production, manufacturing of ceramics or glass ware, drying and dehydration operations in chemical food processing plants and food perseveration process. Jeffery fluid is a type of non-Newtonian fluid that uses a relatively simpler linear model using time derivative instead of convected derivatives, which are used by most fluid models. It is one of the rate type materials that show the linear viscoelastic effect of fluid which has many applications in polymer industries.

Many researchers have extensively worked on this area some of which includes, Makinde and Mhone [1] examined heat transfer to MHD oscillatory flow in a channel filled with porous medium. Mehmood and Ali [2] extended the work of Makinde and Mhone by considering the fluid slip at the lower wall. Kumar *et al.* [3] was also extended the work of Mehmood and Ali by employing perturbation technique to the problem. Umavathi *et al.* [4] have reported the study on unsteady oscillatory flow and heat transfer in a horizontal composite channel. In addition, Abdul-Hakeem and Sathiyanathan [5] presented analytical solution for two-dimensional oscillatory flow of an incompressible viscous fluid, through a highly porous medium bounded by an infinite vertical plate.

Hamza *et al.* [6] investigated the transient heat transfer to MHD oscillatory flow through porous medium under slip condition and oscillating temperature. Uwanta and Hamza [7] checked unsteady heat transfer flow of a viscous, incompressible, electrically conductive fluid through porous medium with periodic suction and temperature oscillation. Kavita *et al.* [8] considers the influence of heat transfer on MHD oscillatory flow of Jeffery fluid in a channel. In their work, they observe that, the axial velocity increases with increase in Jeffery fluid. Also, the maximum velocity occurs at the centerline of the channel while the minimum at the channel walls. However, they found out that, the velocity is more of Jeffrey fluid than that of Newtonian fluid. Aruna Kumari *et al.* [9] made attempt to study the effect of heat transfer on MHD oscillatory flow of Jeffrey fluid in a channel with slip effect at a lower wall where the expressions for the velocity and temperature were obtained analytically. Uwanta and Sani [10] studied heat and mass transfer flow past an infinite vertical plate with variable thermal conductivity where they found out that, the temperature increases with increase in thermal conductivity parameter and time. But the temperature decreases with increasing Prandtl number and suction parameter. Asadullah *et al.* [11] consider the MHD flow of a Jeffery fluid in converging and diverging channels. Idowu *et al.* [12] studied the effect of heat and mass transfer on unsteady MHD oscillatory flow of Jeffery fluid in a horizontal channel with chemical reaction.

MHD Oscillatory slip flow and heat transfer in a channel filled with porous medium was investigated by Adesanya and Makinde [13]. Chamkha and Kumar [14] established a numerical analysis carried out to study heat and mass transfer effects on MHD natural convection flow past an impulsively moving vertical plate with ramped temperature. The effect of heat transfer on MHD Oscillatory flow of Jeffery fluid with variable viscosity through porous medium was analyzed by Al-Khafajy [15]. Seth *et al.* [16] presented an investigation of heat and mass transfer effects on unsteady MHD Natural Convection flow of a chemically Reactive and Radiating fluid through a porous medium past a moving vertical plate with Arbitrary Ramped temperature. Ahmad and Ishak [17] studied steady two dimensional mixed convection boundary layer flow and heat transfer of a Jeffery fluid over a stretched sheet immersed in a porous medium in the presence of a transverse magnetic field. The effect of suction/injection on MHD oscillatory flow of Jeffery fluid with heat source through a porous medium was investigated by Mustapha *et al.* [18]. Hydro magnetic mixed convection flow of an exothermic fluid in a vertical channel was studied by sheriff, A. and Murtala Sani [19].

Yale *et al.* [20] studied transient heat transfer to MHD oscillatory flow of Jeffery fluid through a porous medium under slip condition and oscillating temperature, but the authors in their work have not considered the problem under the influence of mass transfer on unsteady MHD oscillatory flow of Jeffery fluid. Therefore, in the present study, heat and mass transfer on unsteady oscillatory flow of Jeffery fluid through a porous medium have been investigated.

2. Methodology

2.1 Formulation of the Problem

Consider the flow of incompressible Jeffery fluid in a channel filled with saturated porous medium chosen along the plate under the influence of an externally applied homogeneous magnetic field. A magnetic field of uniform strength B_o is applied transversely to the plate. The flow is assumed to be

in the x' −axis direction which is taken to be vertically upward along the channel walls and y' − axis is taken to be normal to the plates that are h distance apart.
Initially, the plate and the fluid are at same temperature T_o' with concentration level C_o' at time $t' > 0$, the plate temperature and the mass concentration is raised to T_w' and C_w' causing the presence of temperature and concentration difference to be $T' - T_o'$ and $C' - C_o'$ respectively. Under the usual Boussinesq's approximation, the governing equations in dimensional form for momentum, energy and concentration for the unsteady flow can be written as:

$$\frac{\partial u'}{\partial t'} = -\frac{1}{\rho}\frac{\partial p'}{\partial x'} + \frac{v}{(1+\beta_1)}\frac{\partial^2 u'}{\partial y'^2} - \frac{v}{k'}u' - \frac{\delta_e B_o^2 u'}{\rho} + g\beta(T' - T'_o) + g\beta^*(C' - C'_o) \tag{1}$$

$$\frac{\partial T'}{\partial t'} = \frac{k}{\rho c_p}\frac{\partial^2 T'}{\partial y'^2} - \frac{1}{\rho c_p}\frac{\partial q'}{\partial y'} \tag{2}$$

$$\frac{\partial C'}{\partial t'} = D\frac{\partial^2 C'}{\partial y'^2} \tag{3}$$

The boundary conditions are:

$$\left.\begin{array}{l} u' - \gamma^*\dfrac{\partial u'}{\partial y'} = 0, \quad T' = T'_o, \quad C' = C'_o \quad on\, y' = 0 \\ u' = o, \quad T' = T'_o + (T'_w - T'_o)\cos w't', \quad C' = C'_o + (C'_w - C'_o)\cos w't' \quad on\, y' = a \end{array}\right\} \tag{4}$$

Where u' is the axial velocity, $t^{'}$ is time, $\omega^{'}$ is frequency of the oscillation, $T^{'}$ is the fluid temperature, g is the pressure gravitational force, c_p is the specific heat at constant pressure, k is the thermal conductivity, q is the radiative heat flux, β is the thermal expansion coefficient, β^* is the concentration expansion coefficient, $C^{'}$ is the mass concentration, B_o is the electromagnetic induction, σ_e is the conductivity of the fluid, ρ is the density of the fluid, v is the kinematics viscosity coefficient, D is the chemical molecular diffusivity, γ^* is the dimensionless slip parameter, $T_o^{'}$ and $T_w^{'}$ are walls temperature, $C_w^{'}$ is the species concentration at the plate surface, $C_o^{'}$ is the free stream concentration, β_1 is the Jeffery fluid, k' is the porous medium permeability coefficient. Following Makindi and Mhone (2005), it is assumed that the fluid is optically thin with a relatively low density and the radiative heat flux is given by:

$$\frac{\partial q'}{\partial y'} = -4\alpha^2(T' - T'_o) \tag{5}$$

Where α is the mean radiation absorption Coefficient.

The following dimensionless variables and parameters are introduced:

$$x=\frac{x'}{a},\quad y=\frac{y'}{a},\quad u=\frac{u'}{U},\quad w=\frac{w'a}{U},\quad t=\frac{t'U}{a},\quad \theta=\frac{T'-T'_o}{T'_w-T'_o},$$
$$p=\frac{ap'}{\rho vU},\quad \gamma=\frac{\gamma^*}{a},\quad S^2=\frac{1}{Da},\quad Da=\frac{k'}{a^2},\quad H^2=\frac{a^2\sigma_e B^2_o}{\rho v},$$
$$N^2=\frac{4\alpha^2a^2}{k},\quad \frac{1}{Sc}=\frac{D}{Ua},\quad C=\frac{C'-C'_o}{C'_w-C'_o},\quad Gc=\frac{a^2g\beta^*(C'_w-C'_o)c}{UV} \tag{6}$$
$$Gr=\frac{a^2g\beta(T'_w-T'_o)}{UV},\qquad Pe=\frac{Ua\rho c_p}{k},\qquad \mathrm{Re}=\frac{Ua}{v},$$

Substituting (6) into (1), (2), (3), and (4) yield:

$$\mathrm{Re}\frac{\partial u}{\partial t}=-\frac{\partial p}{\partial x}+\frac{1}{(1+\beta_1)}\frac{\partial^2 u}{\partial y^2}-(S^2+H^2)U+Gr\theta+GcC \tag{7}$$

$$Pe\frac{\partial \theta}{\partial t}=\frac{\partial^2\theta}{\partial y^2}+N^2\theta \tag{8}$$

$$\frac{\partial C}{\partial t}=\frac{1}{Sc}\frac{\partial^2 C}{\partial y^2} \tag{9}$$

The boundary conditions becomes:

$$u-\gamma\frac{\partial u}{\partial y}=0,\quad \theta=0,\quad c=0 \qquad at\ \ y=0$$
$$u=0,\ \theta=\cos\omega t,\ c=\cos\omega t \qquad at\ \ y=1 \tag{10}$$

Where Pr is the Prandtl number, Sc is the Schmidt number, Gr is the thermal Grashof number, Gc is the mass Grashof number, Re is the Reynolds number, Da is the Darcy number, H is the Hartmann number, Pe is the Peclet number, N is the radiation parameter and β_1 is the Jeffery fluid parameter and s is the porous medium shape factor.

2.2. Analytical Solutions

In order to solve equations (7), (8) and (9) for purely oscillatory flow, let the pressure gradient, fluid velocity, temperature and concentration be:

$$u(y,t)=u_o(y)e^{iwt}+u_1(y)e^{-iwt} \tag{11}$$

$$\theta(y,t)=\theta_o(y)e^{iwt}+\theta_1(y)e^{-iwt} \tag{12}$$

$$c(y,t)=c_o(y)e^{iwt}+c_1(y)e^{-iwt} \tag{13}$$

Assume that $-\frac{\partial P}{\partial x}=\lambda\left[e^{iwt}+e^{-iwt}\right]$

Where $\lambda < 0$ for favorable pressure, ω is the frequency of the oscillation. Substituting the above expressions: (11), (12) and (13) into (7), (8) and (9) subject to (10) enable:

$$u_o'' - \alpha_1^2 u_o = \left[-\lambda - \frac{Gr \operatorname{Sin} N_1 y}{2 \operatorname{Sin} N_1} - \frac{Gc \operatorname{Sinh} S_1 y}{2 \operatorname{Sinh} S_1} \right] (1+\beta_1) \tag{14}$$

$$u_1'' - \alpha_2^2 u_1 = \left[-\lambda - \frac{Gr \operatorname{Sin} N_2 y}{2 \operatorname{Sin} N_2} - \frac{Gc \operatorname{Sinh} S_2 y}{2 \operatorname{Sinh} S_2} \right] (1+\beta_1) \tag{15}$$

$$\theta_o'' + N_1^2 \theta_o = 0 \tag{16}$$

$$\theta_1'' + N_2^2 \theta_1 = 0 \tag{17}$$

$$C_o'' - S_1^2 C_o = 0 \tag{18}$$

$$C_1'' + S_2^2 C_1 = 0 \tag{19}$$

The boundary conditions becomes:

$$\begin{aligned} &u_o - \gamma u_o' = 0,\ u_1 - \gamma u_1' = 0,\ \theta_o = 0,\ \theta_1 = 0 && at\ \ y = 0 \\ &u_o = 0, \quad u_1 = 0, \quad \theta_o = \frac{1}{2}, \quad \theta_1 = \frac{1}{2} && at\ \ y = 0 \end{aligned} \tag{20}$$

Equations (14) to (19) subject to (20) are solved and the solution for fluid temperature, concentration and velocity are given as follows:

$$\begin{aligned} u(y,t) = &\left[I_1 \operatorname{Cosh} \alpha_1 y + I_2 \operatorname{Sinh} \alpha_1 y + I_3 + I_4 \operatorname{Sin} N_1 y + I_5 \operatorname{Sinh} S_1 y \right] e^{iwt} + \\ &\left[D_1 \operatorname{Cosh} \alpha_2 y + D_2 \operatorname{Sinh} \alpha_2 y + D_3 + D_4 \operatorname{Sin} N_2 y + D_5 \operatorname{Sinh} S_2 y \right] e^{-iwt} \end{aligned} \tag{21}$$

$$\theta(y,t) = \frac{1}{2} \left[\frac{\operatorname{Sin} N_1 y}{\operatorname{Sin} N_1} e^{iwt} + \frac{\operatorname{Sin} N_2 y}{\operatorname{Sin} N_2} e^{-iwt} \right] \tag{22}$$

$$c(y,t) = \frac{1}{2} \left[\frac{\operatorname{Sinh} S_1 y}{\operatorname{Sinh} S_1} e^{iwt} + \frac{\operatorname{Sin} S_2 y}{\operatorname{Sin} S_2} e^{-iwt} \right] \tag{23}$$

Skin friction or shear stress is given by:

$$\left. \frac{dU}{dy} \right|_{y=0} = \left[\alpha_1 I_2 + N_1 I_4 + S_1 I_5 \right] e^{iwt} + \left[\alpha_2 D_2 + N_2 D_4 + S_2 D_5 \right] e^{-iwt} \tag{24}$$

$$\begin{aligned} \left. \frac{dU}{dy} \right|_{y=1} = &\left[\alpha_1 I_1 \operatorname{Sinh} \alpha_1 + \alpha_1 I_2 \operatorname{Cosh} \alpha_1 + N_1 I_4 \operatorname{Cos} N_1 + S_1 I_5 \operatorname{Cosh} S_1 \right] e^{iwt} + \\ &\left[\alpha_2 D_1 \operatorname{Sinh} \alpha_2 + \alpha_2 D_2 \operatorname{Cosh} \alpha_2 + N_2 D_4 \operatorname{Cos} N_2 + S_2 D_5 \operatorname{Cosh} S_2 \right] e^{-iwt} \end{aligned} \tag{25}$$

Nusselt number or rate of heat transfer is given by:

$$\left. \frac{d\theta}{dy} \right|_{y=0} = \frac{1}{2} \left[\frac{N_1}{\operatorname{Sin} N_1} e^{iwt} + \frac{N_2}{\operatorname{Sin} N_2} e^{-iwt} \right] \tag{26}$$

$$\left.\frac{d\theta}{dy}\right|_{y=1} = \frac{1}{2}\left[N_1 Cot N_1 e^{iwt} + N_2 Cot N_2 e^{-iwt}\right] \tag{27}$$

Sherwood number or rate of mass transfer is given by:

$$\left.\frac{dC}{dy}\right|_{y=0} = \frac{1}{2}\left[\frac{S_1}{\text{Sinh}\, S_1} e^{iwt} + \frac{S_2}{\text{Sin}\, S_2} e^{-iwt}\right] \tag{28}$$

$$\left.\frac{dC}{dy}\right|_{y=1} = \frac{1}{2}\left[S_1 Cot S_1 e^{iwt} + S_2 Cot S_2 e^{-iwt}\right] \tag{29}$$

Where,

$N_1^2 = (N^2 - Peiw)$, $N_2^2 = (N^2 + Peiw)$, $S_1^2 = Sciw$, $S_2^2 = Sciw$

$\alpha_1^2 = (1+\beta_1)(S^2 + H^2 + \text{Re}\, iw)$, $\alpha_2^2 = (1+\beta_1)(S^2 + H^2 - \text{Re}\, iw)$,

3. Result and Discussion

To investigates the MHD Oscillatory flow of Jeffery fluid in a channel filled with porous medium, the velocity u, temperature θ, concentration c and skin friction profiles are presented graphically against y for different values of different parameters; Jeffery fluid β_1, thermal Grashof number Gr, Mass Grashof number Gc, Schmidt number Sc, Hartmann number H, Radiation parameter N, Peclet number Pe, Reynolds number Re, Darcy number Da, Prandtl number Pr, and porous medium shape factor s.

The following parameter values are fixed throughout the computation except where otherwise stated, Pr = 0.71, β_1 = 0.1, Ha = 1, Re = 1, Pe = 1, N = 3, Sc = 2, Gc =1, t = 1.57, Gr = 1, Da = 0.01, and $\omega = 0.6$.

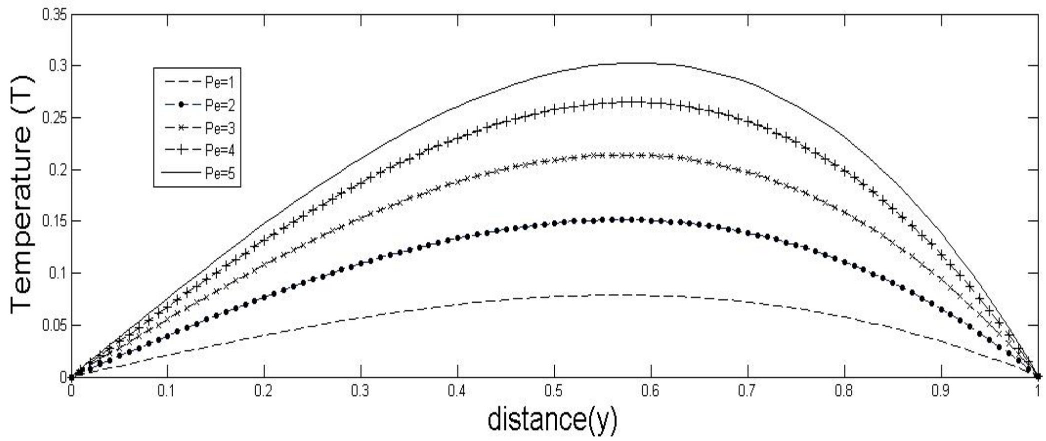

Figure 1: Temperature profile for different values of Peclet number

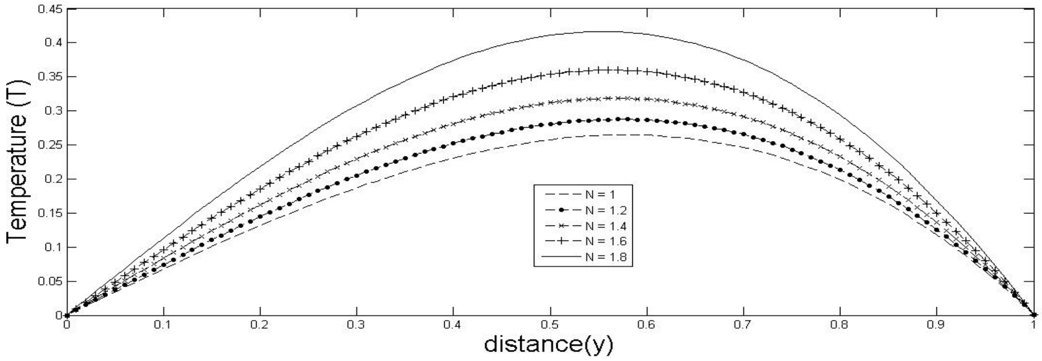

Figure 2: Temperature profile for different values of Radiation parameter

The temperature profiles for different values of the Peclet number (Pe = 1, 2, 3, 4, 5) and radiation parameter (N = 1, 1.2, 1.4, 1.6, 1.8) are shown in figures 1 and 2. It is observed that the temperature increases with increasing Peclet number and radiation parameter.

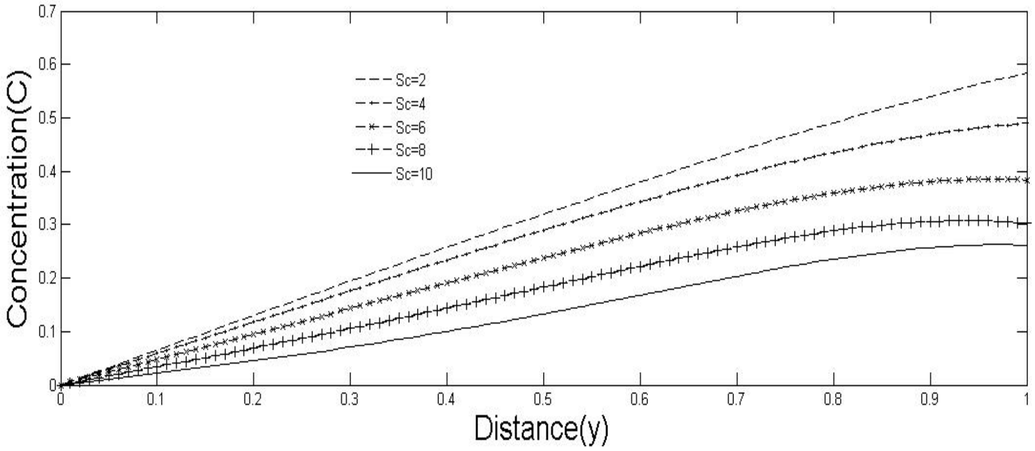

Figure 3: Concentration profile for different values of Schmidt number

The concentration profile for different values of Schmidt number (Sc = 2, 4, 6, 8, 10) is illustrated in figure 3 above. It is clear that the concentration decreases with increase in Schmidt number.

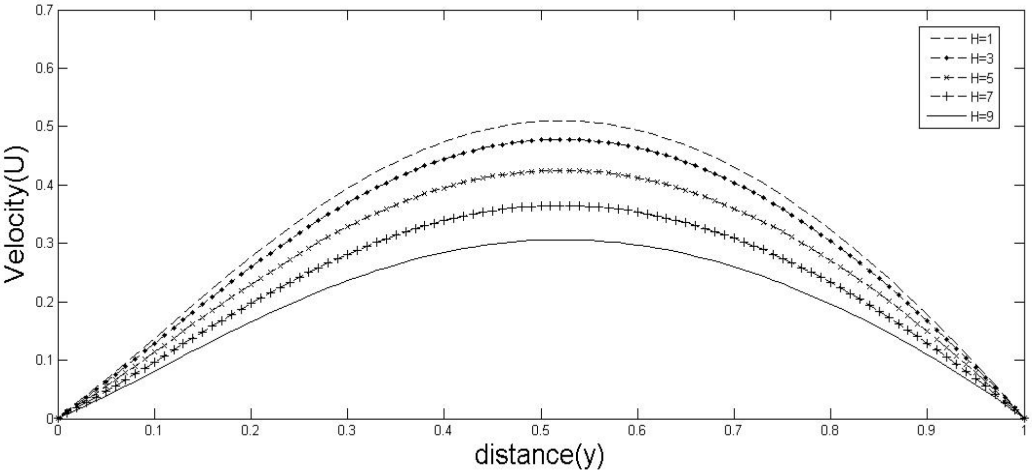

Figure 4: Velocity profile for different values of Hartmann number

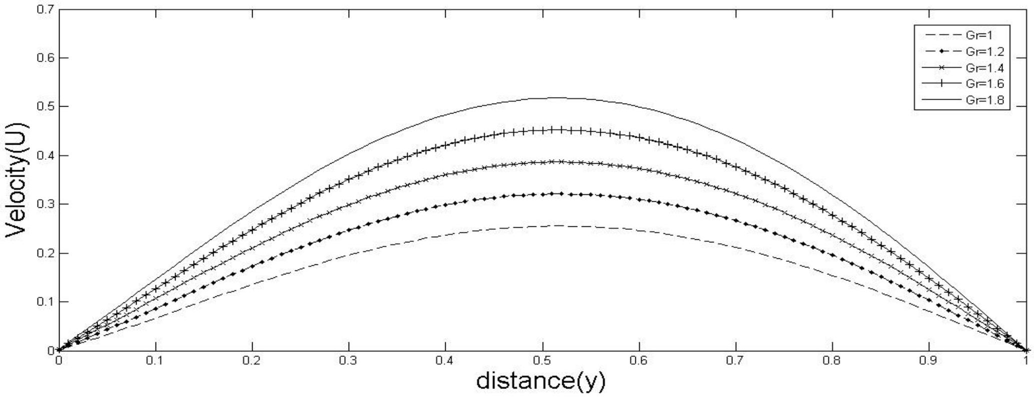

Figure 5: Velocity profile for different values of thermal Grashof number

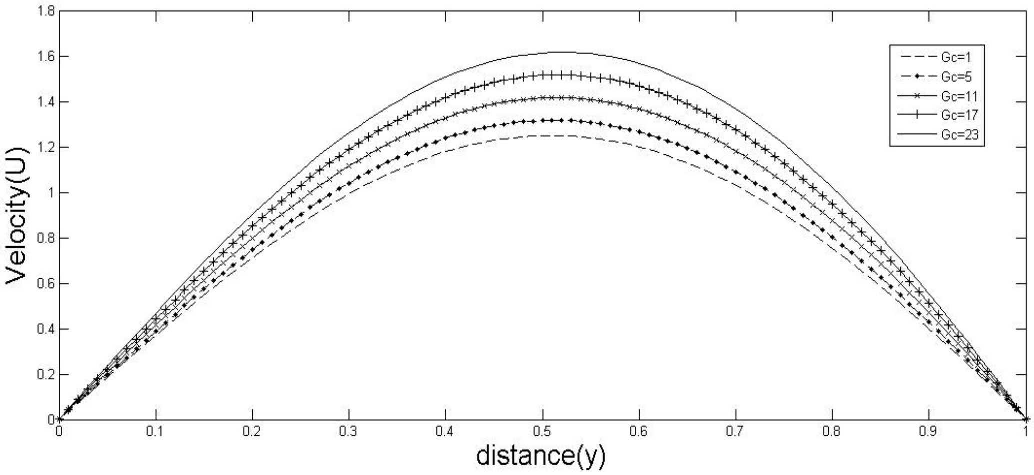

Figure 6: Velocity profile for different values of Mass Grashof number

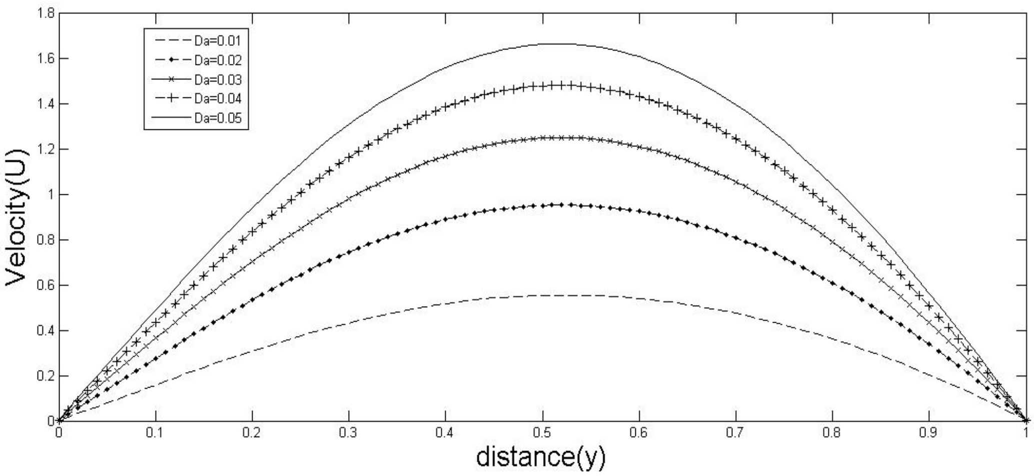

Figure 7: Velocity profile for different values of Darcy number

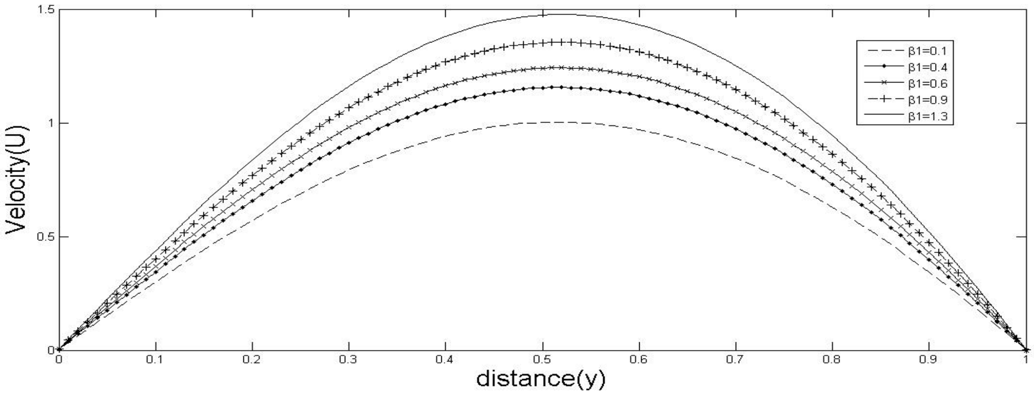

Figure 8: Velocity profile for different values of Jeffery fluid parameter

The velocity profiles have been studied and presented in figures 4 to 8. The velocity profiles for different values of the Hartmann number (Ha = 1, 3, 5, 7, 9) is shown in figure 4. It is cleared that the velocity decreases whenever Hartmann number increase. The velocity profiles for different values of thermal Grashof number (Gr = 1, 1.2, 1.4, 1.6, 1.8), Mass Grashof number (Gc = 1, 5, 11, 17, 23), Darcy number (Da = 0.01, 0.02, 0.03, 0.04, 0.05) and Jeffery fluid parameter (β_1 = 0.1, 0.4, 0.6, 0.9, 1.3) are shown in Figure 5, 6, 7 and 8 respectively. It is indicated that the velocity increases with respect to increase in thermal Grashof number, Mass Grashof number, Darcy number and Jeffery fluid parameter.

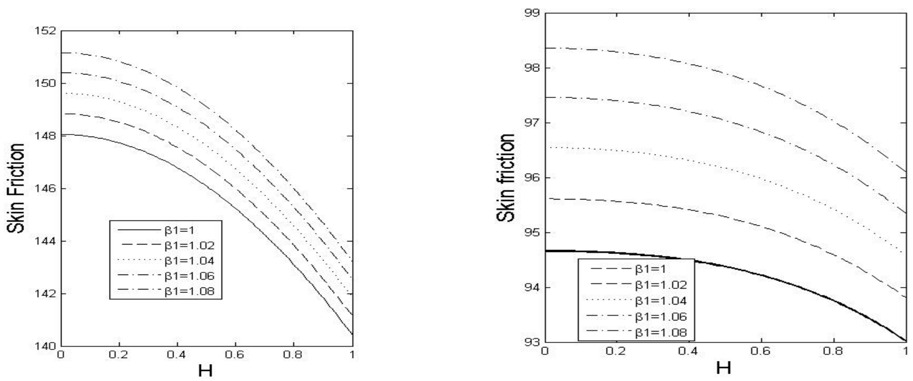

Figure 9: Skin friction profile for different values of β_1 and H

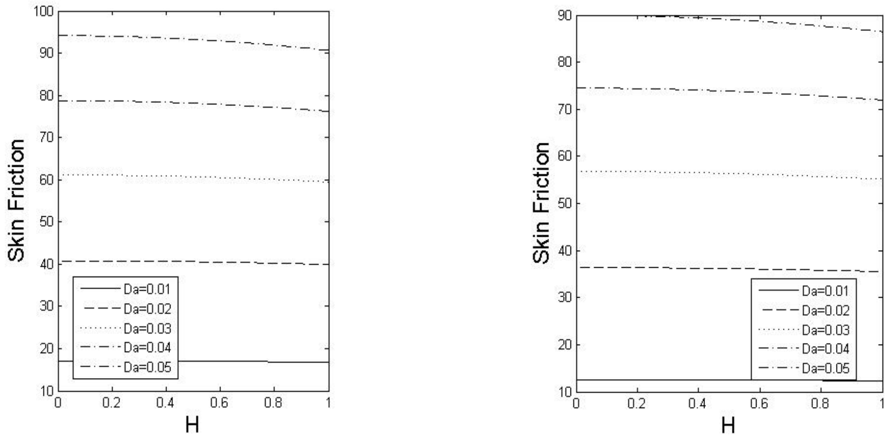

Figure 10: Skin friction profile for different values of Da and H

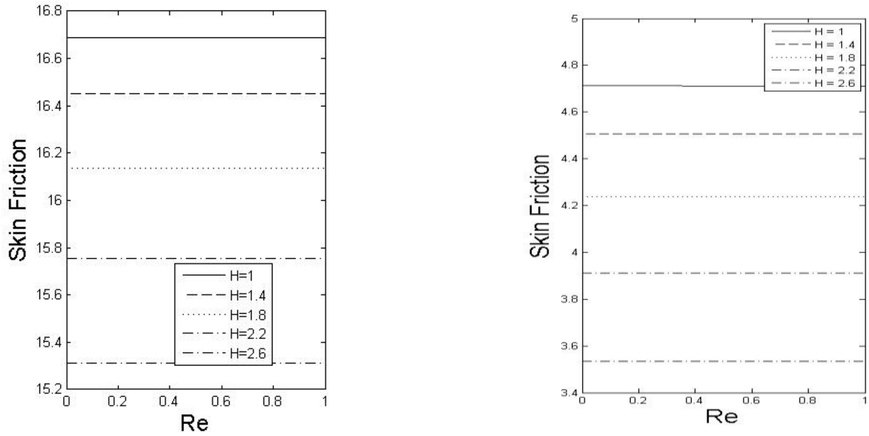

Figure 11: Skin friction profile for different values of H and Re

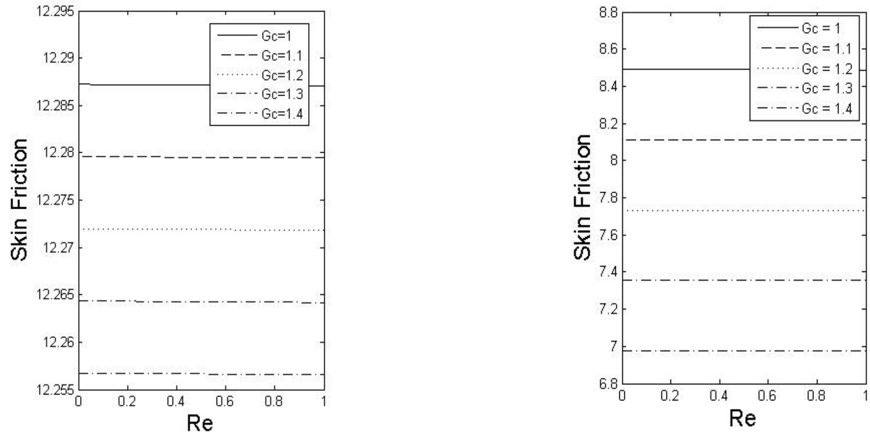

Figure 12: Skin friction profile for different values of Gc and Re

The variation of the skin friction on the porous plate with material parameters are shown in figures 9 to 12. The skin friction profiles for different values of Jeffery fluid parameter (β_1 = 1, 1.02, 1.04, 1.06, 1.08), Darcy number (Da = 0.01, 0.02, 0.03, 0.04, 0.05) are shown in figure 9 and 10. It is seen that at a wall y = 0 and y = 1, the skin friction increases with increase in Jeffery fluid parameter and Darcy number. While figures 11 and 12 illustrate the skin friction profile for different values of Hartmann number (Ha = 1, 1.4, 1.8, 2.2, 2.6) and Mass Grashof number (Gc = 1, 1.1, 1.2, 1.3, 1.4). It is noticed that the skin friction decreases at both lower and upper plate i.e. when y = 0 and when y = 1 with increase in Hartmann number and mass Grashof number.

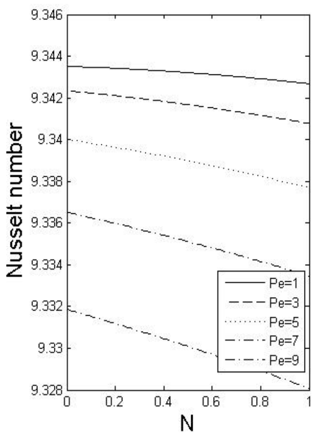

Figure 13: Nusselt number for different values of Pe and N

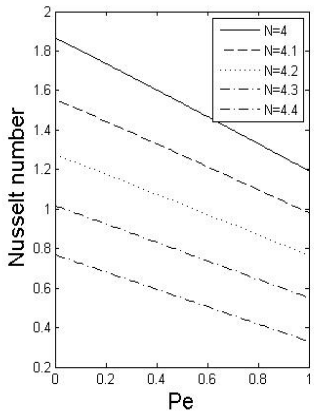

Figure 14: Nusselt number for different values of N and Pe

Figure 13 and 14 illustrates the rate of heat transfer (Nusselt number) for different values of Peclet number (Pe = 1, 3, 5, 7, 9) and radiation parameter (N = 4, 4.1, 4.2, 4.3, 4.4). It is interesting to note from the figures (13 and 14) that the Nusselt number decreases with increasing Peclet number and radiation parameter.

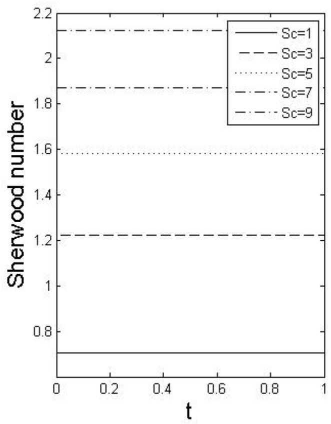

Figure 15: Sherwood number for different values of Sc and t

The effect of Schmidt number (Sc = 1, 3, 5, 7, 9) on rate of mass transfer (Sherwood number) is provided on figure 15. It is observed that the Sherwood number decreases with increase in Schmidt number.

4. Conclusion

This paper investigates the heat and mass transfer to MHD Oscillatory flow of Jeffery fluid in a channel filled with porous medium. The velocity, temperature, concentration, skin friction as well as rate of heat and mass transfer are obtained analytically. The effect of different parameters namely, Thermal Grashof number, Mass Grashof number, Schmidt number, Hartmann number, Peclet number, Radiation parameter and Jeffery fluid parameter are studied. The conclusions from the study show that:

(i) The temperature increases with increasing Peclet number and radiation parameter.
(ii) The concentration decreases with increase in Schmidt number.

(iii) The velocity increases with respect to increase in thermal Grashof number, Mass Grashof number, Darcy number and Jeffery fluid parameter.
(iv) The velocity decreases with increasing Hartmann number.
(v) The skin friction decreases with increasing Mass Grashof number and Hartmann number.
(vi) The nusselt number decreases with increasing peclet number and radiation parameter.
(vii) The Sherwood number decreases with increase in Schmidt number.

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