Visco-Elastic MHD Fluid Flow Over a Vertical Plate with Dufour and Soret Effects

Rita Choudhury and Sajal Kumar Das

Abstract—An analysis of free convective MHD visco-elastic fluid flow with heat and mass transfer over a vertical plate moving with a constant velocity in presence of Dufour and Soret effects has been presented. The fluid is considered to be non-Newtonian characterized by Walters liquid (Model B′). The surface temperature is assumed to oscillate with small amplitude about a non-uniform mean temperature. The system representation is such that the $\bar{x}$-axis is taken along the plate and $\bar{y}$-axis is normal to the plate. The equations governing the fluid flow, heat and mass transfer are solved by perturbation technique. Analytical expressions for velocity, temperature and concentration fields, non-dimensional skin friction coefficient are obtained. The first-order velocity profile and skin friction coefficient are obtained numerically and illustrated graphically to observe the visco-elastic effects in combination of other flow parameters involved in the solution. It is observed that the flow field is significantly affected by the visco-elastic parameter in comparison with Newtonian fluid flow phenomena. Possible applications of the present study include engineering science and applied mathematics in the context of aerodynamics, geophysics and aeronautics.

Keywords: Dufour and Soret effects, Grashof number, MHD, perturbation technique, Prandtl number, Schmidt number, skin friction, visco-elastic.
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1 Introduction

THE investigation of visco-elastic fluid flows over a vertical plate in presence of magnetic field has attracted the researchers for its application in various fields like geophysics, engineering sciences, astrophysics, biological system, soil physics, aerodynamics and aeronautics. The study of heat and mass transfer is important because of its wide applications in geothermal and oil reservoir engineering studies. Stokes [1] has studied the effects of internal friction of fluids in the motion of pendulum. Raptis and Kafousis [2] have studied the free convective MHD flow with mass transfer in porous medium with constant heat flux. Jha and Singh [3] have analyzed the Soret effect on free convection with mass transfer in the Stokes problem for an infinite vertical plate. Dursunkaya and Worek [4] have studied the diffusion thermo and thermal-diffusion effects in transient and natural convection and Kafousis and Williams [5] have continued the same for temperature dependant forced convection with mass transfer. Anghel *et al*. [6] has investigated the Dufour and Soret effects on free convection boundary layer over a vertical surface in porous medium. Aboeldahab and Elbarbary [7] have studied the Hall current effect on MHD free convection past a semi-infinite vertical plate with mass transfer. Megahead *et al.* [8] have studied the similarity analysis MHD effect on free convection with mass transfer past a semi-infinite vertical plate. Postelincus [9] has analyzed the effect of magnetic field on heat and mass transfer for free convection from vertical surface in porous media with Dufour and Soret effects. Sedeek [10] has investigated the diffusion thermo and thermal diffusion effects on mixed convection with mass transfer in presence of suction and blowing. Chen [11] has analyzed heat and mass transfer in MHD free convection from a permeable inclined surface with variable temperature. Alam and Rahman [12] have studied the Dufour and Soret effects in MHD free convection with heat and mass transfer past vertical plate in porous medium. Nazmul and Mahmud [13] have studied the Dufour and Soret effects on steady MHD free convection with mass transfer through a porous medium in a rotating system.

Ibrahim *et al*. [14] have studied the effects of chemical reaction and radiation absorption on the unsteady MHD free convection past a semi-infinite permeable moving plate in presence of heat source. Ananda *et al*. [15] have investigated the thermal diffusion and chemical effects with simultaneous heat and mass transfer in MHD mixed convection with Ohming heating. Beg and Ghosh [16] have presented an analytical study of MHD radiation convection with surface oscillation and secondary flow effects. Uwanta *et al*. [17] have studied the radiative convection flow with chemical reaction. Uwanta *et al*. [18] have also analyzed the MHD free convection over a vertical plate with Dufour and soret effect. Mansour *et al*. [19] have investigated the effect of chemical reaction and thermal stratification on MHD free convection with heat and mass transfer over a vertical stretching surface in a porous medium in presence of Dufour and Soret effects. Oladapo [20] has studied the Dufour and Soret effects of transient free convection with radiation past a flat moving plate.

In this paper, we have studied the free convective MHD flow with heat and mass transfer over a vertical plate in presence of Dufour and Soret effect and observe the visco-elastic effects on the fluid flow field along with other flow parameters. The visco-elastic fluid flow is characterized by Walters liquid (Model B′).
The constitutive equation for Walters liquid (Model B′) is

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$$\sigma_{ik} = -pg_{ik} + \sigma_{ik}', \quad \sigma_{ik}' = 2\eta_0 e^{ik} - 2K_0 e'^{ik} \tag{1}$$

where σ_{ik} is the stress tensor, p is isotropic pressure, g_{ik} is the metric tensor of a fixed co-ordinate system x^i, v^i is the velocity vector, the contravariant form of e'^{ik} is given by

$$e'^{ik} = \frac{\partial e^{ik}}{\partial t} + v^m e^{ik}{}_{,m} - v^i{}_{,m} e^{im} - v^i{}_{,m} e^{mk} \tag{2}$$

It is the convected derivative of the deformation rate tensor e^{ik} defined by

$$2e^{ik} = v^i{}_{,k} + v^k{}_{,i} \tag{3}$$

Here η_0 is the limiting viscosity at the small rate of shear which is given by

$$\eta_0 = \int_0^\infty N(\tau)d\tau \ \ and \ \ k_0 = \int_0^\infty \tau N(\tau)d\tau \tag{4}$$

$N(\tau)$ being the relaxation spectrum as introduced by Walters [21, 22]. This idealized model is a valid approximation of Walters liquid (Model B′) taking very short memories into account so that terms involving

$$\int_0^\infty \tau^n N(\tau)d\tau, \quad n \geq 2 \tag{5}$$

have been neglected.

2 Mathematical formulation

The region of unsteady free convective MHD flow of a visco-elastic electrically conducting fluid characterized by Walters liquid (Model B′) with heat and mass transfer over a semi-infinite region perpendicular to a vertical plate, moving with a constant velocity U, in the presence of Dufour and Soret effects is considered. The $\bar{x}$-axis is taken along the length of the porous plate and $\bar{y}$-axis is perpendicular to it. Let $\bar{u}$ be the velocity of the fluid along $\bar{x}$ direction. The surface temperature is assumed to oscillate with small amplitude about a non-uniform mean temperature. The variation of density with temperature and concentration is considered only in the body force term so that under the above assumption, all the physical quantities are functions of $\bar{y}$ and $\bar{t}$. The governing equations for the fluid flow are as follows:

momemtum equation:

$$\frac{\partial \bar{u}}{\partial \bar{t}} = \nu \frac{\partial^2 \bar{u}}{\partial \bar{y}^2} - \frac{K_0}{\rho}\frac{\partial^3 \bar{u}}{\partial \bar{t}\partial \bar{y}^2} + g\beta(\bar{T} - \bar{T}_\infty) - \frac{\sigma {B_0}^2 \bar{u}}{\rho} + \bar{\beta}(\bar{C} - \bar{C}_\infty) \tag{6}$$

energy equation:

$$\frac{\partial \bar{T}}{\partial \bar{t}} = \frac{\kappa}{\rho C_p}\frac{\partial^2 \bar{T}}{\partial \bar{y}^2} - \frac{1}{\rho C_p}\frac{\partial q_r}{\partial \bar{y}} + \frac{D_m K_r}{C_s C_p}\frac{\partial^2 \bar{C}}{\partial \bar{y}^2} \tag{7}$$

concentration equation:

$$\frac{\partial \bar{C}}{\partial \bar{t}} = D\frac{\partial^2 \bar{C}}{\partial \bar{y}^2} + \frac{D_m K_r}{T_m}\frac{\partial^2 \bar{T}}{\partial \bar{y}^2} \tag{8}$$

where, β is the volumetric co-efficient of expansion for heat transfer, $\bar{\beta}$ is the volumetric co-efficient of expansion for the fluid, B_0 is the magnetic field, $\bar{t}$ is the time, $\bar{T}$ is the temperature of the fluid, T_m is the mean temperature of the fluid, $\bar{T}_\infty$ is the temperature of fluid at infinity, $\bar{T}_w$ is the temperature of the plate, K_r is the thermal diffusion, C_p is the specific heat at constant pressure, C_s is the concentration susceptibility, $\bar{C}$ is the mass concentration, $\bar{C}_w$ is the concentration at the plate surface, $\bar{C}_\infty$ is the concentration in fluid far away from plate, D is the molecular diffusivity, D_m is the coefficient of mass diffusivity and κ is the thermal conductivity.

The initial boundary conditions are

$$\bar{y} = 0: \ \bar{u} = U, \bar{T} = \bar{T}_w + \varepsilon e^{i\bar{\omega}\bar{t}}(\bar{T}_w - \bar{T}_\infty), \ \bar{C} = \bar{C}_w + \varepsilon e^{i\bar{\omega}\bar{t}}(\bar{C}_w - \bar{C}_\infty)$$
$$\bar{y} \to \infty: \ \bar{u} \to 0, \bar{T} \to 0, \bar{C} \to 0 \tag{9}$$

We introduce the dimensionless quantities

$$u = \frac{\bar{u}}{U}, y = \frac{\bar{y}U}{\nu}, t = \frac{\bar{t}U^2}{\nu}, G_r = \frac{g\beta\nu(\bar{T}_w - \bar{T}_\infty)}{U^3},$$
$$G_m = \frac{g\beta'\nu(\bar{C}_w - \bar{C}_\infty)}{U^3}, M = \frac{\sigma {B_0}^2 \nu}{\rho U^2}, P_r = \frac{\mu C_p}{\kappa},$$
$$K_2 = \frac{16a\sigma^* \nu^2 {\bar{T}_\infty}^3}{\kappa U^2}, D_u = \frac{D_m K_r(\bar{C}_w - \bar{C}_\infty)}{C_s C_p \nu(\bar{T}_w - \bar{T}_\infty)}, S_r = \frac{D_m K_r(\bar{T}_w - \bar{T}_\infty)}{T_m \nu(\bar{C}_w - \bar{C}_\infty)},$$
$$S_c = \frac{\nu}{D}, \omega = \frac{\bar{\omega}\nu}{U^2}, \theta = \frac{\bar{T} - \bar{T}_\infty}{\bar{T}_w - \bar{T}_\infty}, C = \frac{\bar{C} - \bar{C}_\infty}{\bar{C}_w - \bar{C}_\infty}. \tag{10}$$

where G_r is the thermal Grashof number, G_m is the mass Grashof number, M is the Hartmann number, $K_1 = \frac{K_0 U^2}{\rho \nu^2}$ is the visco-elastic parameter, K_2 is the thermal radiation conduction number, S_c is the Schmidt number, P_r is the Prandtl number, S_r is the Soret number, D_u is the Dufour number, ν is the kinematic viscosity, θ is the dimensionless temperature, C is the dimensionless concentration.

The thermal radiation flux gradient may be expressed as

$$-\frac{\partial q_r}{\partial y} = 4a\sigma^*\left({\bar{T}_\infty}^4 - \bar{T}^4\right) \tag{11}$$

where, q_r is the radiative heat flux, a is the absorption coefficient of the fluid and σ^* is the Stefan-Boltzmann constant.

By Taylor's expansion, we get

$$\bar{T}^4 = 4{\bar{T}_\infty}^3\bar{T} - 3{\bar{T}_\infty}^4 \tag{12}$$

Using (10) to (12) in (6) to (8), we get

$$\frac{\partial u}{\partial t} = \frac{\partial^2 u}{\partial y^2} - K_1\frac{\partial^3 u}{\partial t \partial y^2} + G_r\theta - Mu + G_m C \tag{13}$$

$$\frac{\partial \theta}{\partial t} = \frac{1}{P_r}\frac{\partial^2 \theta}{\partial y^2} - K_2\theta + D_u\frac{\partial^2 C}{\partial y^2} \tag{14}$$

$$\frac{\partial C}{\partial t} = \frac{1}{S_c}\frac{\partial^2 C}{\partial y^2} + S_r\frac{\partial^2 \theta}{\partial y^2} \tag{15}$$

The relevant boundary conditions are

$$y = 0: \ u = 1, C = 1 + \varepsilon e^{i\omega t}, \theta = 1 + \varepsilon e^{i\omega t}$$
$$y \to \infty: u \to 0, \theta \to 0, C \to 0. \tag{16}$$

3 Method of solution

For $\varepsilon \ll 1$, we apply the perturbation scheme

$$f(y,t) = f_0(y) + \varepsilon e^{i\omega t} f_1(y) + o(\varepsilon^2) \tag{17}$$

to equations (13) to (15) where f represents u, θ and C. Comparing the coefficients of various powers of ε and neglecting those of second and higher powers of ε, we get the following equations.

3.1 Zeroth order equations

$$\frac{d^2u_0}{dy^2} - Mu_0 = -G_r\theta_0 - G_mC_0 \tag{18}$$

$$\frac{d^2\theta_0}{dy^2} - K_2P_r\theta_0 = -P_rD_u\frac{d^2C_0}{dy^2} \tag{19}$$

$$\frac{1}{S_c}\frac{d^2C_0}{dy^2} + S_r\frac{d^2\theta_0}{dy^2} = 0 \tag{20}$$

3.2 First order equations

$$(1 - i\omega K_1)\frac{d^2u_1}{dy^2} - (M + i\omega)u_1 = -G_r\theta_1 - G_mC_1 \tag{21}$$

$$\frac{d^2\theta_1}{dy^2} - P_r(K_2 + i\omega)\theta_1 = -P_rD_u\frac{d^2C_1}{dy^2} \tag{22}$$

$$\frac{d^2C_1}{dy^2} - i\omega S_cC_1 = -S_rS_c\frac{d^2\theta_1}{dy^2} \tag{23}$$

The modified boundary conditions are

$y = 0: \; u_0 = 1, \theta_0 = 1, C_0 = 1, u_1 = 0, \theta_1 = 1,$
$C_1 = 1.$
$y \to \infty: u_0 \to 0,\ \theta_0 \to 0, C_0 \to 0,\ u_1 \to 0,$
$\theta_1 \to 0,\ C_1 \to 0.$ (24)

Solutions of the equations (18) to (23) are obtained as follows:

$$u_0 = b_1e^{-\sqrt{M}y} + b_2e^{-D_2y} \tag{25}$$

$$\theta_0 = e^{-D_2y} \tag{26}$$

$$C_0 = e^{-D_2y} \tag{27}$$

$$u_1 = b_7e^{-Ly} + b_8e^{-H_1y} + b_9e^{-H_2y} + b_{10}e^{-G_1y} + b_{11}e^{-G_2y} \tag{28}$$

$$\theta_1 = b_5e^{-H_1y} + b_6e^{-H_2y} \tag{29}$$

$$C_1 = b_3e^{-G_1y} + b_4e^{-G_2y} \tag{30}$$

The velocity profile u is given by

$$u = u_0 + \varepsilon e^{i\omega t}u_1 \tag{31}$$

The non-dimensional skin friction coefficient σ_0 on the plate y=0 is given by

$$\sigma_0 = \left(\frac{\partial u}{\partial y} - K_1\frac{\partial^2 u}{\partial t\partial y}\right)_{y=0} = \{u_0{}' + \varepsilon e^{i\omega t}(u_1{}' - i\,\omega K_1u_1{}')\}_{y=0} \tag{32}$$

The non-dimensional rate of heat transfer in terms of Nusselt number N_u is given by,

$$N_u = \left(\frac{\partial T}{\partial y}\right)_{y=0} = (T_0{}' + \varepsilon e^{i\omega t}T_1{}')_{y=0} \tag{33}$$

The non-dimensional rate of mass transfer in terms of Sherwood number S_h is given by

$$S_h = \left(\frac{\partial C}{\partial y}\right)_{y=0} = (C_0{}' + \varepsilon e^{i\omega t}C_1{}')_{y=0} \tag{34}$$

where dash denotes differentiation w.r.t. y.

The constants are obtained but not given here due to brevity.

4 Results and discussion

The object of the present paper is to study the effects of visco-elasticity on the free convective MHD flow with heat and mass transfer over a vertical plate in presence of Dufour and Soret effects along with other flow parameters.

The visco-elastic effect is exhibited through the non zero values of the non-dimensional parameter K_1. The Newtonian fluid flow mechanism can be illustrated throughout the study by considering K_1=0 and it is worth mentioning that these results show conformity with that of Uwanta *et al*. [18].

To understand the physics of the problem the first order velocity u_1 is depicted against y in the figures 1 and 2. The behavior of skin-friction coefficient σ_0 against M, S_c, S_r, D_u and P_r on the plate y=0 is illustrated in the figures 3 to 12. The numerical calculations are to be carried out for K=.1, K_2=.2, $\omega t = \frac{\pi}{2}$, $\omega = 1$, ε=.001 throughout the discussion.

For externally cooled plate ($G_r > 0$), the first order velocity profile u_1 (figure 1) exhibits an accelerating trend with the growing effect of visco-elasticity. It is also observed that the velocity field enhances near the plate y=0 and then diminishes with the increasing values of y.

For externally heated plate ($G_r < 0$), the first order velocity profile u_1 (figure 2) reveals a decelerating trend with the growing effect of visco-elasticity. Also the velocity field decreases near the plate y=0 and then rises with the increasing values of y.

Figure 3 depicts that the skin friction coefficient σ_0 against the magnetic parameter M decreases with the growing effect of the visco-elastic parameter K_1 and the magnetic parameter M as well for externally cooled plate ($G_r > 0$).

From figure 4, it is observed that the skin friction coefficient decreases with the enhancement of the magnetic parameter M but increases with the growth of the visco-elastic parameter K_1 for externally heated plate ($G_r < 0$).

The behavior of the skin friction coefficient against Schmidt number is illustrated in figures 5 and 6. It is observed from figure 5 that for externally cooled plate ($G_r > 0$), the skin friction coefficient increases up to S_c=.85 and then decreases with the growing effect of the visco-elastic parameter K_1. It is also found that the skin friction coefficient decreases with the increasing values of Schmidt number S_c.

An opposite nature in the behavior of the skin friction coefficient against S_c is observed from figure 6 for externally heated plate ($G_r < 0$).

Figure 7 illustrates that the skin friction coefficient against Soret number S_r diminishes with the growing effect of the visco-elastic parameter K_1 and the Soret number S_r as well for externally cooled plate ($G_r > 0$).

Figure 8 depicts that the skin friction coefficient against Soret number S_r enhances with the growing effect of the visco-elastic parameter K_1 for externally heated plate ($G_r < 0$) but it decelerates with the rise of Soret number S_r.

Figure 9 shows that the skin friction coefficient against Dufour number D_u diminishes with the growing effect of the visco-elastic parameter K_1 and the Dufour number D_u as well for externally cooled plate ($G_r > 0$).

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Figure 10 exhibits that the skin friction coefficient against Dufour number D_u accelerates with the growing effect of the visco-elastic parameter K_1 for externally heated plate $(G_r < 0)$ but it decelerates with the rise of Dufour number D_u.

It is observed from figure 11 that the skin friction coefficient against Prandtl number P_r decelerates with the rising effect of the visco-elastic parameter K_1 and the Prandtl number P_r as well for externally cooled plate $(G_r > 0)$.

Figure 12 reveals an accelerating trend of the skin friction coefficient against Prandtl number P_r with the growth of the visco-elastic parameter K_1 and Prandtl number P_r as well for externally heated plate $(G_r < 0)$.

The temperature and concentration fields are not affected by the growth of visco-elastic parameter.

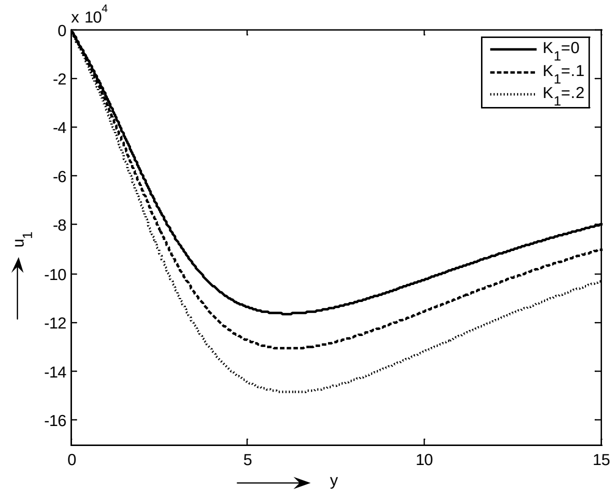

Fig 2: First order velocity profile u_1 against y for M=1, D_u=.1, P_r=.2, G_r=-3, G_m=3, S_c=1, S_r=.1

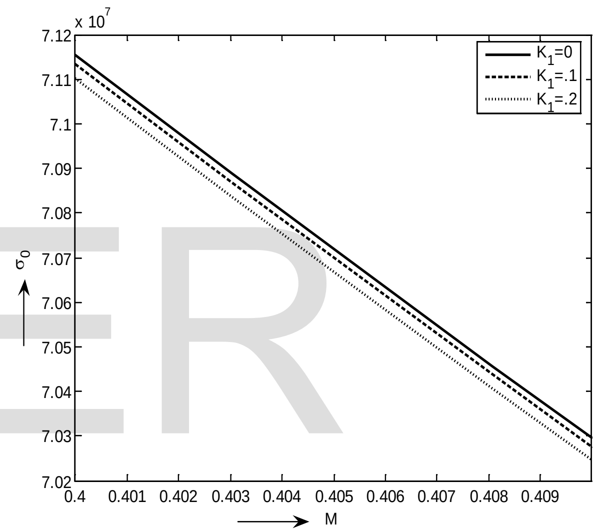

Figure 3: Skin friction coefficient σ_0 against M for D_u=.1, P_r=.2, G_r=3, G_m=3, S_c=1, S_r=.1

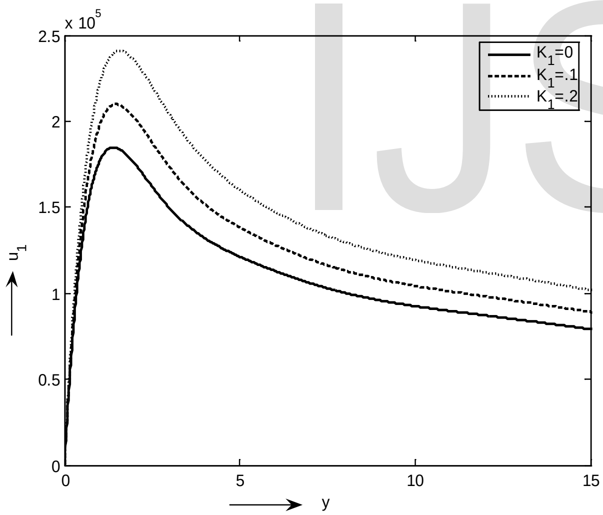

Fig 1: First order velocity profile u_1 against y for M=1, D_u=.1, P_r=.2, G_r= 3, G_m= 3, S_c=1, S_r=.1

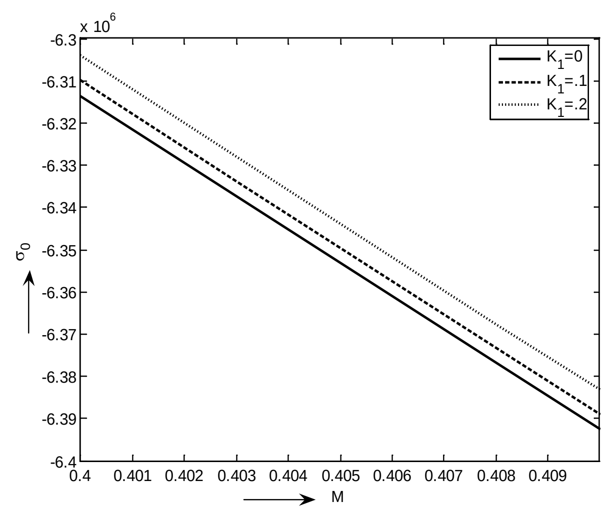

Figure 4: Skin friction coefficient σ_0 against M for D_u=.1, P_r=.2, G_r=-3, G_m=3, S_c=1, S_r=.1

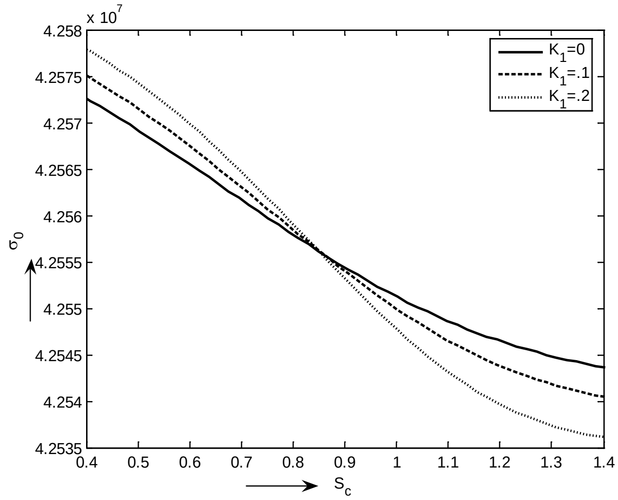

Figure 5: Skin friction coefficient σ_0 against S_c for D_u=.1, M=1, P_r=.2, G_r=3, G_m=3, S_r=.1

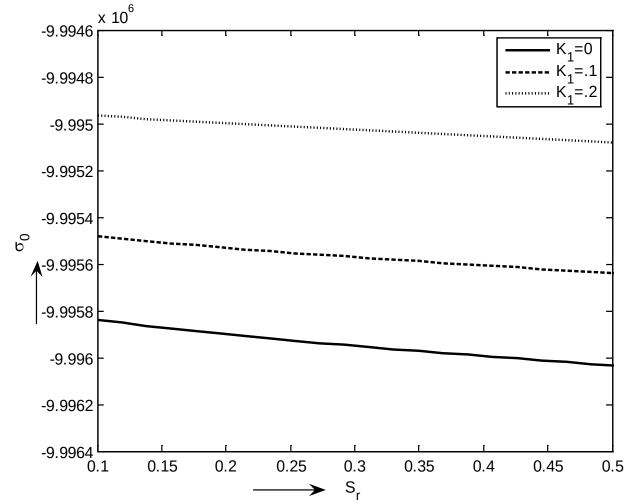

Figure 8: Skin friction coefficient σ_0 against S_r for D_u=.1, M=1, P_r=.2, G_r=-3, G_m=3, S_c=1

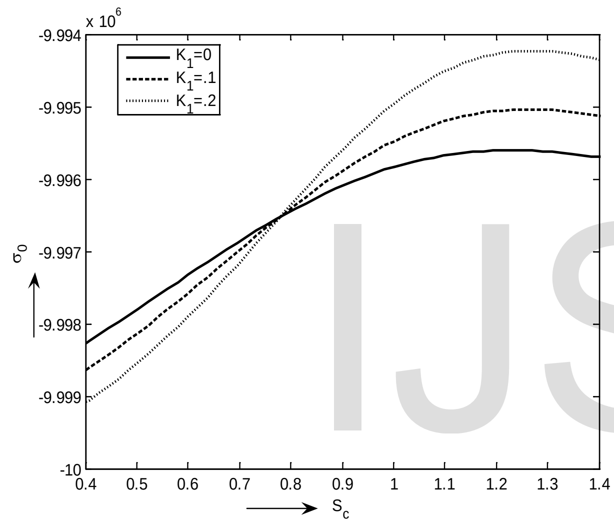

Figure 6: Skin friction coefficient σ_0 against S_c for D_u=.1, M=1, P_r=.2, G_r=-3, G_m=3, S_r=.1

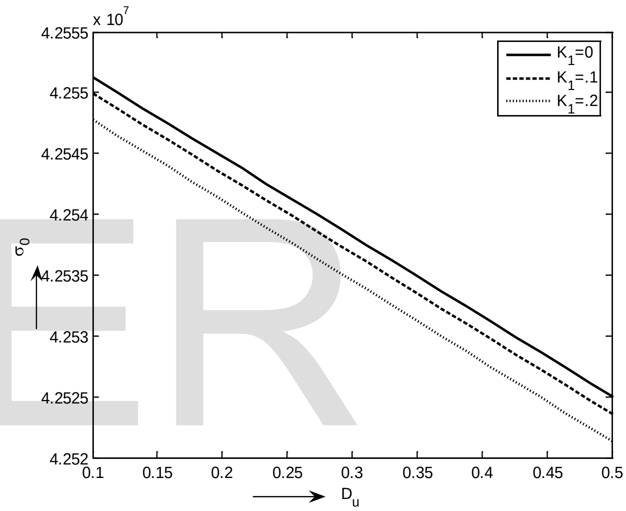

Figure 9: Skin friction coefficient σ_0 against D_u for S_r=.1, M=1, P_r=.2, G_r=3, G_m=3, S_c=1

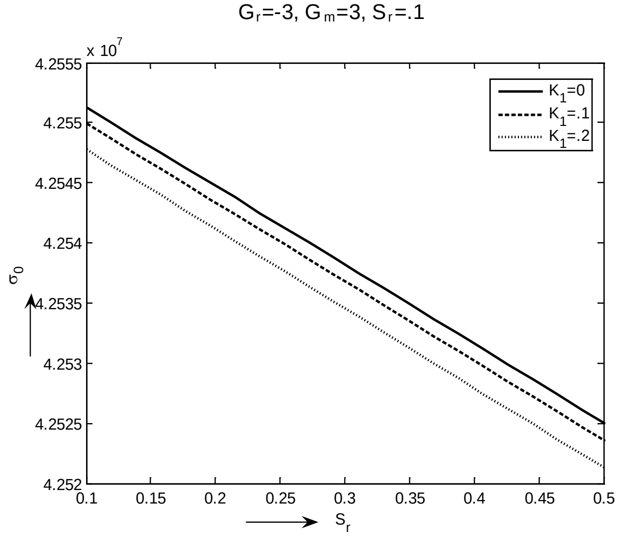

Figure 7: Skin friction coefficient σ_0 against S_r for D_u=.1, M=1, P_r=.2, G_r=3, G_m=3, S_c=1

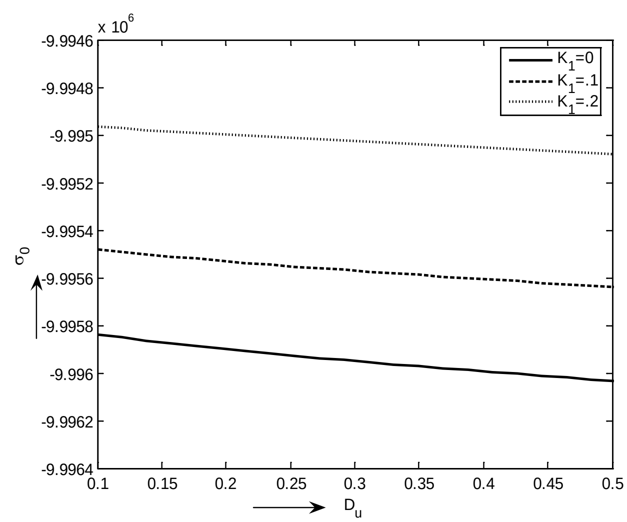

Figure 10: Skin friction coefficient σ_0 against D_u for S_r=.1, M=1, P_r=.2,

=1

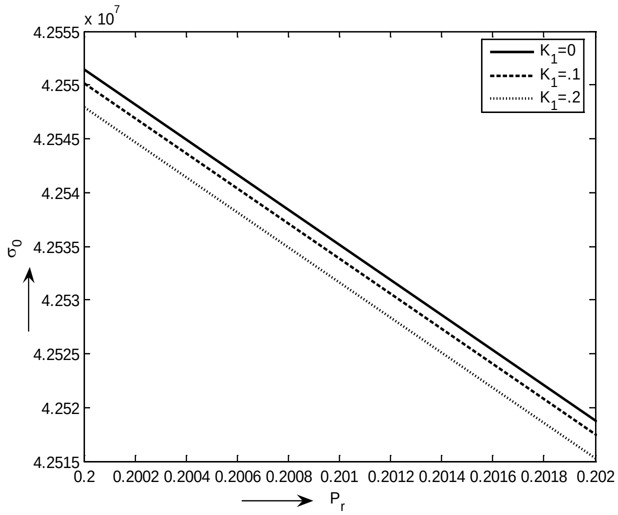

Figure 11: Skin friction coefficient σ_0 against P_r for D_u=.1, M=1, G_r=3, G_m=3, S_r=.1, S_c=1.

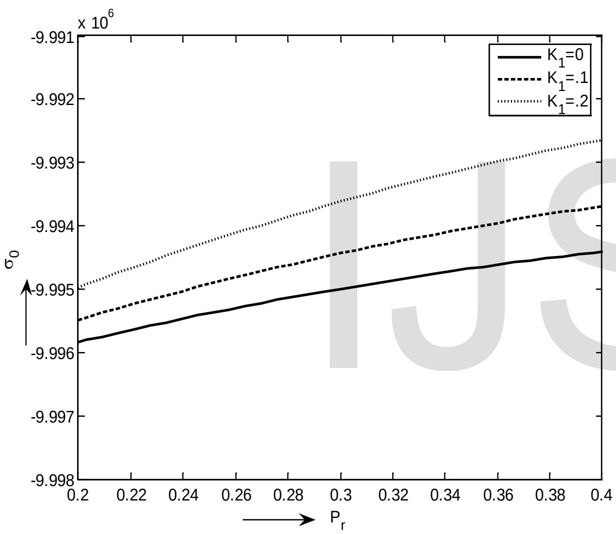

Figure 12: Skin friction coefficient σ_0 against P_r for D_u=.1, M=1, G_r=-3, G_m=3, S_r=.1, S_c=1.

5 Conclusion

An analysis of free convective MHD flow of a visco-elastic fluid with heat and mass transfer over a vertical plate in presence of Dufour and Soret effects is presented.
From this study, we make the following conclusions:

- The velocity field is considerably affected by the visco-elastic parameter along with other flow parameters at all points of the fluid flow region.
- The first order velocity profile exhibits an accelerating trend with the growing effect of visco-elasticity for externally cooled plate but an opposite trend is observed for externally heated plate.
- The skin friction coefficient on the plate is significantly affected by the visco-elastic parameter along with other flow parameters.
- The temperature and concentration fields are not affected by the growth of visco-elasticity.

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