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MHD Flow Past a Vertical Porous Plate in a Porous Medium in the Presence of Radiation, Dufour and Soret effects

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Abstract- A case of an MHD flow of a viscous fluid over a vertical plate moving with constant velocity in the presenceof radiation, Dufour and Soret effects is considered. The governing equations with the boundary conditions are converted to partial differential equations using an asymptotic expansion about the order of ε .The resulting systems of equations are then solved analytically. The effects of major parameters on the velocity, temperature and concentration profiles are examined and discussed.

Keywords: Asymtotic expansion, Dufor, Magnetohydrodynamics (MHD), Radiation, Soret, Viscous fluid.

Introduction

Magnetohydrodynamics (MHD) remains an area of attention in engineering science and applied Mathematics researches due to wide applications of such flows in aerodynamics, engineering, geophysics and aeronautics.Magnetohydrodynamics (MHD) can be explained as the physical-mathematical framework that concerns the dynamics of magnetic fields in electrically conducting fluids, e.g. in plasmas and liquid metals. The role of magnetohydrodynamics (MHD) in the evolution of the universe has been a challenging problem for many decades. Interests in MHD phenomena have existed ever since the end of the nineteenth century, especially in the astrophysics community where the work of Cowling [1] and Ferraro [2] can be seen as pioneering work establishing the formal theory of MHD on an astrophysical scale. Maturing interests in magnetohydrodynamics, however, occurred in the nineteen forties with the work of [3] whose contributions are associated with a unique MHD physical feature, namely: The Hartmann layer. In the light of the above applications, during the last few decades, many researchers, among which are [4-9 and host of others have studied extensively the effect of mass transfers on magnetohydrodynamics (MHD) free convection flow. Recently, [10] investigated a two-dimensional, steady, viscous, incompressible, electrically conducting and laminar free convection boundary layer flow with radiation from a flat plate in a chemically reactive medium in the presence of a transverse magnetic field.

The study of natural convection with mass and heat transfer along a vertical porous plate is of fundamental importance in nature and many industrial processes. Natural convection occurs due to the spatial variations in density, which is caused by the non-uniform distribution of temperature or/and concentration of a dissolved substance. Ample examples on the heat transfer by natural convection can be found in geophysics, astrophysics, engineering, soil sciences and so on. Permeable porous plates are used in the filtration processes and also for a heated body to keep its temperature constant and to make the heat insulation of the surface more effective. In addition, the phenomenon of heat and mass transfer is also encountered in chemical processes such as polymer production and food processing.

In many past research works, the diffusion-thermo and thermal-diffusion term were neglected from the energy and concentration equations respectively. However,the relation between the fluxes and the driving potentials when heat and mass transfer occurs simultaneously in a moving fluid, are of intricate nature. Investigation shows an energy flux can be generated not only by temperature gradient but also by composition gradients. The energy flux caused by composition gradient is called the Dufour or diffusion-thermal effect. The diffusion-thermo (Dufour) effect was found to be of considerable magnitude such that it cannot be ignored [11]. Considering the significance of this diffusion-thermo effect, [12] investigated free convection and mass transfer flow about an infinite vertical flat plate moving impulsively in its own plane. [13] presented thermal-diffusion and diffusion-thermo effects on mixed free forced convective and mass transfer boundary layer flow with temperature dependent. Much later, [14] studied numerically the influence of a magnetic field on heat and mass transfer by natural convection from vertical surfaces in porous media considering Soret and Dufour effects.Thermal-diffusion and diffusion thermo-effects on mixed free-forced convective flow and mass transfer over accelerating surface with a heat source in the presence of suction and blowing in the case of variable viscosity was investigated by [15]. [16] studied the Dufour and Soret effects on steady MHD free convective heat and mass transfer flow past a semi-infinite vertical porous plate embedded in a porous medium. [17] studied the effects of chemical reaction and thermal stratification on magnetohydrodynamic free convective heat and mass transfer over a vertical stretching surface embedded in a porous media. [18] studied the steady and unsteady magnetohydrodynamic (MHD) free forced convective flow of electrically, conducting, Newtonian fluid in the presence of appreciable thermal radiation heat transfer and surface temperature oscillation.

Inspired by the above investigators, we propose the problem of MHD flow past a vertical porous plate with viscous dissipation in a porous medium in the presence of radiation, Dufour and Soret effects.

2.0 Mathematical Formulation

Considering MHD fluid flow of a viscous, incompressible, electrically-conducting fluid over a vertical plate moving with constant velocity Uin the presence of Dufour and Soret effects is considered. The surface temperature of the plate oscillates with small amplitude about a non-uniform mean temperature. The system representation is such that the x-axis is taken along the plate and y-axis is normal to the plate. A uniform magnetic field is applied normal to the direction of the flow. The physical model of the problem is shown in figure 1. It is assumed that the magnetic Reynolds number is less than unity so that the induced magnetic field is neglected in comparison to the applied magnetic field. We further assumed that the fluid is assumed to have constant properties except for the influence of density variations with temperature and concentration, which are considered only in the body force term. Following the above assumptions, the physical variables are functions of$y'$and t'.

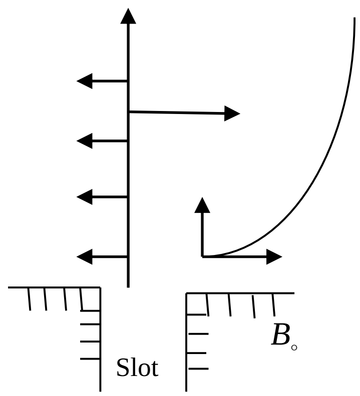

Figure 1: Physical model of the problem

Under the above assumptions and taking the usual Boussinesq's approximation into account, the governing equations for continuity, concentration, energy and momentum are presented below:

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

$$\frac{\partial u'}{\partial t'} = \vartheta \frac{\partial^2 u'}{\partial y'^2} + g\beta\left(T' - T'_\infty\right) + g\beta^*\left(c' - c'_\infty\right) - \frac{\sigma B_o^2 u'}{\rho} - \frac{u'}{k_0} \quad (2)$$

$$\frac{\partial T'}{\partial t'} + v'\frac{\partial T'}{\partial y'} = \frac{k_t}{\rho c_p}\frac{\partial^2 T'}{\partial y'^2} - \frac{1}{\rho c_p}\frac{\partial q_r}{\partial y} + \phi\left(T' - T'_\infty\right) + \frac{D_m K_T}{c_s c_p}\frac{\partial^2 c'}{\partial y'^2} \quad (3)$$

$$\frac{\partial c'}{\partial t'} + v'\frac{\partial c'}{\partial y'} = D\frac{\partial^2 c'}{\partial y'^2} + \frac{D_m K_T}{T_m}\frac{\partial^2 T'}{\partial y'^2} \quad (4)$$

The corresponding boundary conditions are:

$$u' = U,\ T' = T'_\infty + \varepsilon\left(T'_w - T'_\infty\right)e^{i\omega t}, \qquad c' = c'_\infty + \varepsilon\left(c'_w - c'_\infty\right)e^{i\omega t} \ \text{at} \quad y = 0 \quad (5)$$

$$u' \to 0, \qquad T' \to 0, \qquad c' \to 0, \qquad \text{as} \quad y \to \infty \quad (6)$$

where x', y' and t' are the dimensional distances along and perpendicular to the plate and dimensional time respectively; u' and v' are the components of dimensional velocities along x' and y' directions respectively; g is the gravitational acceleration, ϑ represents the kinematic viscosity, ρ stands for the fluid density, ϕ is heat generation parameter, k_0 is the permeability, $\frac{D_m K_T}{c_s c_p}$ is the dufour type diffusivity, k_t is the fluid thermal conductivity, c_p specific heat capacity at constant pressure, T' is the dimensional temperature, T'_w is the dimensional temperature at the wall, T'_∞ is the ambient temperature , c' is the dimensional concentration, c'_∞ is the ambient concentration, D is the solutal diffusivity.

Following the idea of [19], the Rosseland approximation q_r takes the form $q_r = -\frac{4\sigma^*}{3k^*}\frac{dT'^4}{dy'}$

The temperature difference within the fluid is assumed sufficiently small such that T^4 may be expressed as a linear function of the temperature. Expanding T^4 in a Taylor series about T_∞ and neglecting higher order terms, we have $T'^4 = 4T_\infty^3 T' - 3T_\infty^4$

Substituting this into the Rosselandapproximation q_r, we obtain thus

$$q_r = -\frac{16\sigma^* T_\infty^3 dT'}{3k^* dy'} \quad (7)$$

Introducing the dimensionless quantities in equation (8):

$$u = \frac{u'}{U} \qquad y = \frac{y'U}{\vartheta} \qquad t = \frac{t'U}{\vartheta} \qquad c = \frac{c' - c'_\infty}{c'_w - c'_\infty} \qquad \theta = \frac{T' - T'_\infty}{T_w - T'_\infty} \quad (8)$$

We obtained the dimensionless governing equation for momentum, energy and concentration and the boundary conditions:

$$\frac{\partial u}{\partial t} = \frac{\partial^2 u}{\partial y^2} + G_{rt}\theta + G_{rc}c - \frac{u}{K} - M^2 u \quad (9)$$

$$\frac{\partial \theta}{\partial t} = \frac{1+R}{P_r}\frac{\partial^2 \theta}{\partial y^2} + D_u\frac{\partial^2 c}{\partial y^2} + \phi\theta \quad (10)$$

$$\frac{\partial c}{\partial t} = \frac{1}{S_c}\frac{\partial^2 c}{\partial y^2} + S_r\frac{\partial^2 \theta}{\partial y^2} \quad (11)$$

$u = 1, \quad \theta = 1 + \varepsilon e^{i\omega t}, \quad c = 1 + \varepsilon e^{i\omega t}$ at $y = 0$ (12)

$u \to 0, \quad \theta \to 0, \quad c \to 0$ as $y \to \infty$ (13)

Where thermal Grashof number $G_{rt} = \frac{g\beta\vartheta(T_w' - T_\infty')}{U^3}$, solutal Grashof number $G_{rc} = \frac{g\beta^*\vartheta(c_w' - c_\infty')}{U^3}$, Porosity parameter $k = \frac{U^2 k'}{\vartheta}$,magnetic parameter $M = \frac{B_o}{U}\sqrt{\frac{\sigma\vartheta}{\rho}}$, heat generation parameter $\phi = \frac{\vartheta\phi'}{U^2}$, radiation parameter $R = \frac{16\sigma^* T_\infty'^3}{3kk_t}$, Prandtl number $P_r = \frac{\rho c_p \vartheta}{k_t}$, Dufour number $D_u = \frac{D_m K_T (c_w' - c_\infty')}{c_\infty c_p \vartheta (T_w' - T_\infty')}$, Schmidt number $S_c = \frac{\vartheta}{D}$, Soret parameter $S_r = \frac{D_m K_T (T_w' - T_\infty')}{T_m \vartheta (c_w' - c_\infty')}$

3.0 Analytical Solution of the problem

To solve equations (9) – (13), we assume that ε is small, therefore, we seek solutions having the forms

$$u(y,t) = u_0(y) + \varepsilon u_1(y) e^{i\omega t} \quad (14)$$

$$\theta(y,t) = \theta_0(y) + \varepsilon \theta_1(y) e^{i\omega t} \quad (15)$$

$$c(y,t) = c_0(y) + \varepsilon c_1(y) e^{i\omega t} \quad (16)$$

By substituting equations (14) – (16) into equations (9) – (11), and then

(i) Order of ε^0 respectively give

$$u_0' - b_1 u_0 = -G_{rt}\theta_0 - G_{rc}c_0 \quad (17)$$

$$\theta'' - b_3\theta_0 = -b_4 c_0' \quad (18)$$

$$c'' = -b_6\theta_0'' \quad (19)$$

The boundary conditions are

$$u_0 = 1, u_0 \to 0$$
$$\theta_0 = 0, \theta_0 \to 0$$
$$c_0 = 1, c_0 \to 0 \quad (20)$$

where $b_1 = \left(M^2 + \frac{1}{K}\right), h = \frac{P_r}{1+R}, b_3 = -h\phi, b_4 = hD_u, b_6 = S_c S_r$

(ii) Order of ε^1 respectively give

$$u_1' - b_2 u_1 = -G_{rt}\theta_1 - G_{rc}c_1 \quad (21)$$

$$\theta_1'' - b_5\theta_1 = -b_4 c_1'' \quad (22)$$

$$c_1'' - b_7 c_1 = -b_6\theta_1'' \quad (23)$$

The boundary conditions are

$$u_1 = 1, u_1 \to 0$$

$$\theta_1 = 1, \theta_1 \to 0$$

$$c_1 = 1, c_1 \to 0 \quad (24)$$

where $b_2 = \left(i\omega + M^2 + \frac{1}{K}\right), b_5 = b_3 + ih\omega, b_7 = i\omega S_c$

The system of equations (17) – (24) are coupled equations which are solved simultaneously. By putting $\frac{d}{dy} = D$ and employing basic methods of solving homogeneous differential equations, we thus obtain the analytic solution for equations (9) – (13) to be

$$u(y) = a_6 e^{xy} - a_7 e^{my} - a_8 e^{my} + \varepsilon(a_{18} e^{qy} - a_{19} e^{r_2 y} - a_{20} e^{r_3 y}) e^{iwt} \quad (25)$$

$$\theta(y) = e^{my} + \varepsilon(a_{10} e^{r_2 y} - a_{11} e^{r_3 y}) e^{iwt} \quad (26)$$

$$c(y) = e^{my} + \varepsilon(a_{10} e^{r_2 y} - a_{11} e^{r_3 y}) e^{iwt} \quad (27)$$

where $m = -\sqrt{\frac{b_3}{(1-b_6 b_4)}}, x = -\sqrt{b_1}, \; a_7 = \frac{G_{rt}}{(m^2 - b_1)}, a_8 = \frac{G_{rc}}{(m^2 - b_1)}, a_6 = 1 + a_7 + a_8,$

$$r_2 = \left(-\frac{b_8}{2b_{10}} - \frac{b_9}{2b_{10}}\right)^{\frac{1}{2}}, r_3 = -\left(\frac{-b_8}{2b_{10}} + \frac{b_9}{2b_{10}}\right)^{\frac{1}{2}}, \alpha_1 = \left(\frac{b_5 - r_2^2}{b_4 r_2^2}\right), \alpha_2 = \left(\frac{b_5 - r_3^2}{b_4 r_3^2}\right),$$

$$a_{10} = \frac{\alpha_2 - 1}{\alpha_2 - \alpha_1}, \; a_{11} = \frac{1 - \alpha_1}{\alpha_2 - \alpha_1}, \; q = -\sqrt{b_2}, \quad a_{19} = \frac{a_{10}(G_{rt} + G_{rc})}{(r_2{}^2 - b_2)}, \quad a_{20} = \frac{a_{11}(G_{rt} + G_{rc})}{(r_3{}^2 - b_2)}$$

$$a_{18} = a_{19} + a_{20}, h = \frac{P_r}{1+R}, b_3 = h\phi, \quad b_4 = hD_u, \quad b_5 = ih\omega + b_3, \; b_2 = \left(i\omega + M^2 + \frac{1}{K}\right)$$

$$, b_1 = \left(M^2 + \frac{1}{K}\right), \; b_6 = S_c S_r, \; b_5 = ih\omega + b_3, \quad b_7 = i\omega S_c, \; b_8 = b_5 + b_7,$$

$$b_9 = \sqrt{(b_5 + b_7)^2 + 4(b_6 b_4 - 1) b_5 b_7}, \quad b_{10} = (b_6 b_4 - 1)$$

4.0 Discussion of results

MHD fluid flow over a vertical plate with Dufour and Soret effects has been formulated and solved analytically. For the purpose of discussing the effects of various parameters on the flow profiles,some numerical calculations were carried out for the non-dimensional velocity U, temperature θ and concentration C based on various values of the varying parameters: $M, D_u, S_r, G_{rt}, G_{rc}, R, \varepsilon, t, P_r$ and S_c.These parameters were assigned the following values $M = 1.0, D_u = 0.15, S_r = 0.4, G_{rt} = 5.0, G_{rc} = 5.0, R = 0.2, \varepsilon = 0.01, t = 1.0, P_r = 0.71, S_c = 0.3, \phi = -0.5$ and $\omega = \frac{pi}{4}$.

The influence of the solutalGrashof number (G_{rc}) on the fluid velocity distribution is graphically represented in Figure 2. The figure revealed thatthe solutalGrashof number enhances the fluid velocity. Thermal Grashof number (G_{rt}) refersto thecomparative effect of the thermal buoyancy force to the viscoushydrodynamic force in the boundary layer. It is observed in Figure 3 that an increase in G_r leads to a rise in the velocity distribution which is due to enhancement of thermal buoyancy force. This is in good agreement with Figure1 and 2 reported in [20].

Figure 4 portrays the influence of Prandtl number (P_r) on the velocity profile. It is detected that the Prandtl number retards the fluid velocity. Similar effect is observed on the temperature profile in Figure 5 as Prandtl number increases. This is in harmony with Figure 5b reported in [20]. The Physics behind this, is that smaller values of Prandtl number is equivalent to an increase in the fluid thermal conductivity as such, heat is able to diffuse away from heated surface more rapidly for higher values of Prandtl number. Consequently, the thermal boundary layer is thicker in a case of smaller Prandtl number and the rate of heat transfer is therefore reduced. Figure 6 demonstrated that Prandtl number deflates the concentration distribution.

Influence of Soret parameter (S_r) on velocity profile is exhibited in Figure 7. The Figure revealed that the Soret parameter retards fluid velocity. In Figure 8, it is presented that the temperature profile reduces slightly as Soret parameter increases in value. The concentration profile also decreases slightly for increase in S_r, as illustrated in Figure 9. The influence of Dufour parameter (Du) on the concentration profile is presented in Figure 10. The figure illustrated that Dufour parameter slightly enhances the concentration distribution.

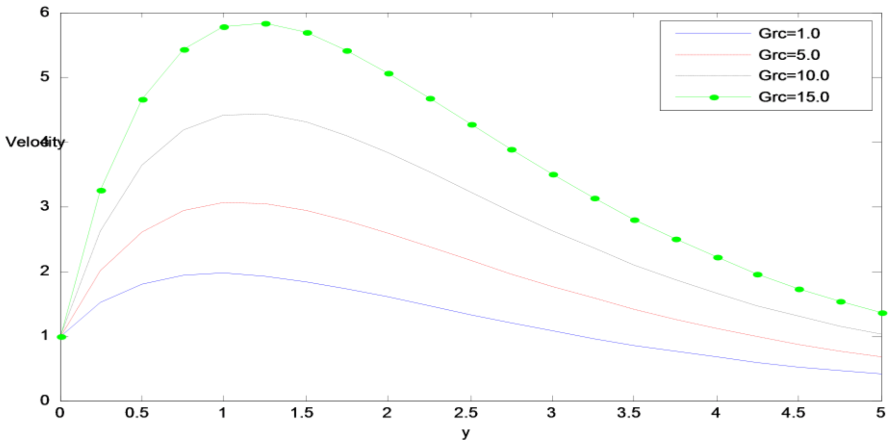

Figure 2: *Effect of solutalgrashof number* (G_{rc})*on velocity*

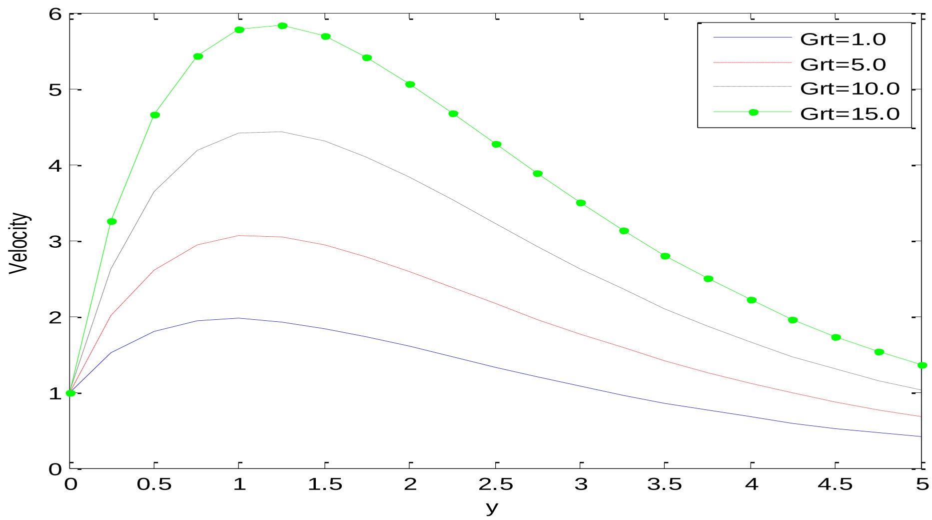

Figure 3: Effect of thermal grashof number (G_{rt}) on velocity

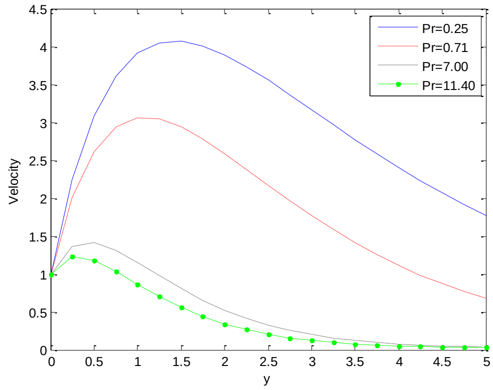

Figure 4: Effect of Prandtl number (P_r)on velocity profile

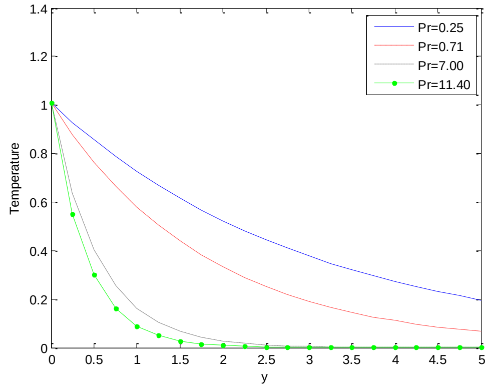

Figure 5: Variation of P_r with Temperature

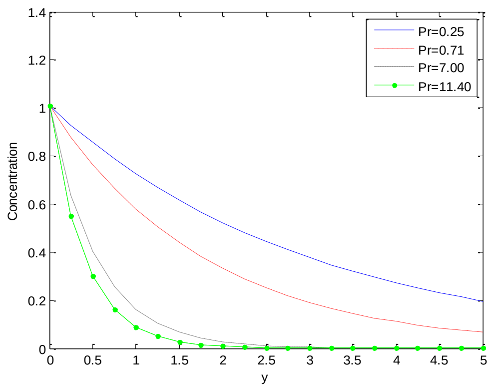

Figure 6: Influence of P_r on Concentration profile

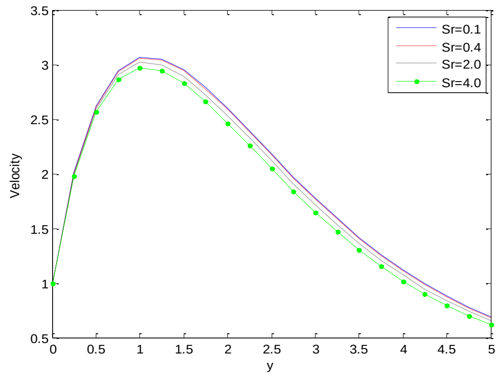

Figure 7: Effect of Soret parameter (S_r) on Velocity profile

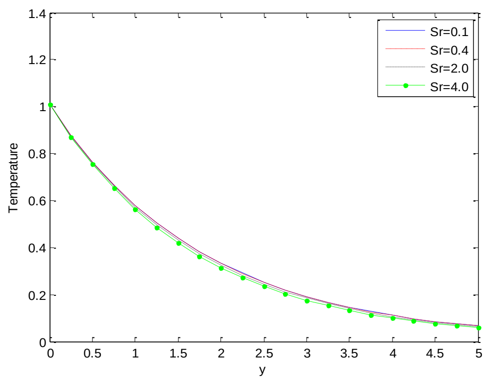

Figure 8: Variation of Soret parameter(S_r) with Temperature distribution

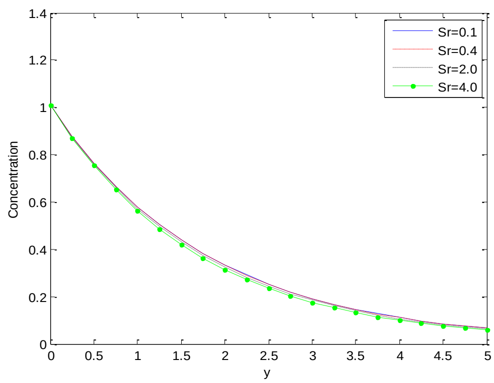

Figure 9: Influence of S_r on Concentration profile

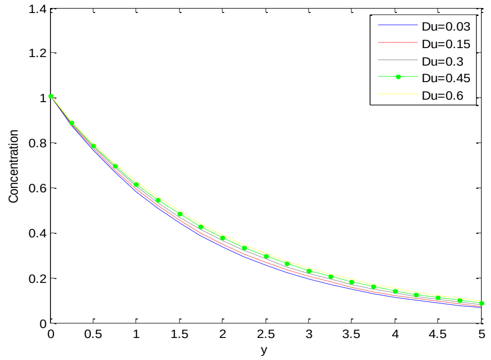

Figure 10: Variation in Concentration with Dufour parameter (Du)

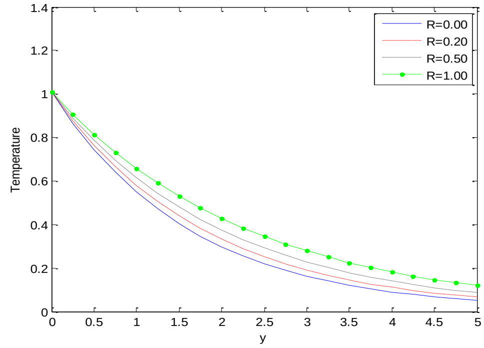

Figure 11: Effect of Radiation parameter (R) on Temperature profile

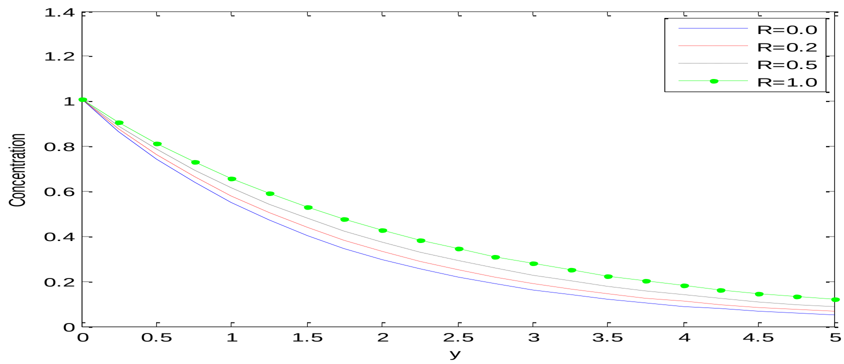

Figure 12: Effect of Radiation parameter on Concentration profile

The effect of radiation on temperature profile is demonstrated in Figure 11. The figure established that radiation enhances temperature distribution. In Figure 12, radiation is portrayed to inflate the concentration distribution.Table 1 presents the effects of $R, P_r, t, G_{rt}, G_{rc}$ on skin friction coefficient C_f and Nusselt number Nu_x. From the table, it is revealed that the radiation parameter decreases the skin friction coefficient but inflates the Nusselt number. Time parameter inflates both skin friction and heat transfer rate. The Prandtl number is found to reduce the skin friction coefficient but enhances the heat transfer rate. It is also observed that the thermal and solutalGrashof numbers inflates the friction factor.

5.0 Conclusion

An MHD flow of a viscous fluid over a vertical plate moving with constant velocity in the presence of Dufour and Soret effects is considered. The governing equations were solved analytically and the effects of major parameters were investigated. It was found that the dimensionless time parameter improves the friction factor, heat and mass transfer rate. An increase in the value of Soret parameter causes the velocity, temperature and concentration profiles to decrease. Concentration profile can be enhanced by increasing the value of Dufour or radiation parameter. Prandtl number deflates both velocity and temperature profiles. It is also revealed that radiation causes friction factor to decrease but inflates heat transfer rate. On the other hand, thermal and solutalGrashof numbers inflates the friction factor. It is also revealed that Prandtl number is found to reduce the skin friction coefficient but causes the heat transfer rate to increase.

Table 1: Numerical values of skin friction coefficient(C_f) and Nusselt number(Nu_x) for different values of physical parameters when $\omega = {}^{pi}/_{4}$,

$$M = 1.0, D_u = 0.15, S_r = 0.4, G_{r\tau} = 5.0, G_{rc} = 5.0, R = 0.2, \varepsilon = 0.01, t = 1.0, P_r = 0.71, S_c = 0.30, \phi = -0.5$$

R	P_r	t	G_{rt}	G_{rc}	C_f	Nu_x
3.0					5.7752	0.35770
5.0					5.2735	0.43690
7.0					5.0693	0.47630
	0.71				5.2754	0.4369
	0.8				4.8825	0.5147
	1.0				4.7514	0.6812
	1.25				3.2124	0.8765
		0.1			–1.7296	0.4547
		0.2			–1.7067	0.5331
		0.3			–1.6828	0.5807
			1.0		3.5947	
			2.0		5.2795	
			3.0		6.7521	
				1.0	4.1498	
				2.0	5.2766	
				3.0	6.3872	

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