SORET AND DUFOUR EFFECTS IN A THREE-DIMENSIONAL MHD FLOW PAST A SEMI-INFINITE UNIFORMLY MOVING VERTICAL PLATE WITH CONSTANT HEAT FLUX

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Abstract*— The motivation of the present study behinds the three-dimensional MHD flow past a semi-infinite uniformly moving porous plate with Soret and Dufour effects. The plate is subjected to a sinusoidal suction velocity and constant heat flux in boundary conditions. It is assumed that a uniform strength of magnetic field (B_0) is applied normal to the plate and directed into the fluid region. But the induced magnetic field is neglected in the study on the assumption that the magnetic Reynolds number is very small. The analytical solutions for momentum, energy, and concentration equations are accomplished by implementing asymptotic series expansion method. The present work ascertains the influence of magnetic parameter (M), Soret number (Sr), Dufour number (Du), thermal Grashof number (Gr), modified Grashof number (Gm), Schmidt number (Sc), Prandtl number (Pr), Reynolds number (Re) on velocity profile (u), temperature profile (θ), concentration profile (ϕ), skin friction (τ), and Sherwood number (Sh). The results are established and discussed with the help of graphs which has been drawn by using the MATLAB software. It is found from the study that fluid velocity rises under the influence of Soret and Dufour effects and a reverse behavior is seen for increasing values of magnetic parameter. Moreover, it is seen that fluid temperature drops on hiking Dufour number.

***Keywords*—Sinusoidal suction, thermal diffusion, diffusion-thermo, heat flux**

I. INTRODUCTION

MHD is a branch of physics concerned with the study of behavior of electrically conducting fluids in presence of magnetic field. MHD generator is an example of application of MHD principle which converts thermal energy directly into electrical energy. It is used for driving submarines, aircraft etc. The applications of MHD principles are also widely seen in Biology and Medical sciences. The present form of MHD is due to the pioneer contributions of several notable authors, of whom the names of Alfven (1942), Cowling (1957), and Cramer and Pai (1973) are worth mentioning. Ahmed and Gonzalez (2017) have been carried out analytical solution of a MHD three-dimensional flow through two parallel porous plates by adopting small perturbation approximation. Influence of the dimensionless thermophysical and magneto physical parameters is studied in their investigation. Radiation effect on MHD flow past a porous vertical plate in the presence of heat sink has been carried out by Choudhury *et al*. (2022a). Variation of density leads the buoyancy force to exist. The flow induced merely due to of MHD free convection with mass transfer under different physical and geometrical conditions. Some of them are Samad and Rahman (2006), Prasad *et al*. (2006), Seth *et al*. (2011), Ahmed (2012, 2014), Ahmed *et al*. (2013), Ahmed and Dutta (2014, 2018) and Seth *et al.* (2016a, 2016b). Analytical and numerical solution of three-dimensional channel flow in presence of a sinusoidal fluid injection and a chemical reaction was investigated buoyancy force is called as natural or free convective flow. Many investigators have carried out model studies on the problem by Ahmed and Chamkha (2015). Three-dimensional flow with sinusoidal suction velocity has been studied by several researchers. Comprehensive literatures in this type of investigation can be seen in Ahmed *et al*. (2014), Ahmed and Sarma (1997), Ahmed *et al.* (2006, 2020), Ahmed and Sengupta (2011), and Ahmed and Choudhury (2019).

The effect of energy flux generated due to composition gradient on the flow characteristics is termed as Dufour effect or diffusion-thermo effect. Eckert and Drake (1972) have emphasized that the Soret effect is significant in cases concerning isotope separation and in mixtures between gases with very light molecular weight (H_2,He), and for medium molecular weight (N_2,air) the Dufour effect is found to be of considerable magnitude as mentioned earlier. Diffusion-thermo effect on MHD dissipative flow past a porous vertical plate through porous media is studied by Choudhury *et al*. (2022a). They have considered constant heat flux in the boundary condition and the solutions carried out by using perturbation technique. Singh and Seth (2021a) studied thermo-diffusion impacts on the flow of fluid over an inclined heated plane with magnetized wall. Singh and Seth (2021b) investigated heat and mass transport of MHD fluid over a vertically oriented magnetized surface with thermo diffusions. In this regard, Soret and Dufour effects on MHD flow problems have been studied by of Alam *et al.* (2006), Ahmed (2010) and Ahmed and Sengupta (2011) etc.

The novelty of the present work is to analyze the Soret and Dufour effects on the flow phenomena in the presence of constant heat flux with time independent flow.

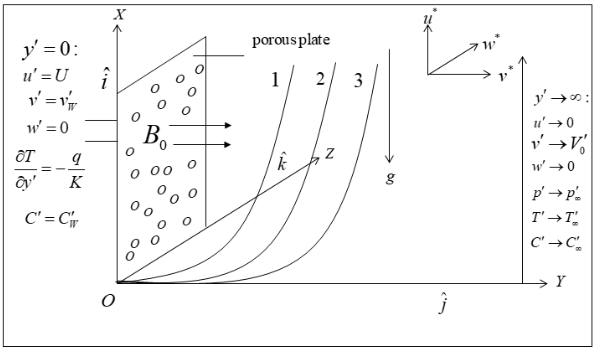

Figure 1: Flow model of the problem (Ahmed and Choudhury, 2019).

The flow problem undertaken is three-dimensional. The plate is also subjected to a sinusoidal suction velocity. A uniform magnetic field is applied normal to the plate directed into the fluid region.

The objective of the present work is to study the problem of a three-dimensional free convective MHD flow past a uniformly moving semi-infinite vertical porous plate considering both the thermal diffusion and diffusion-thermo effect. So far, no such reported work has come to the notice of the authors which considers both the thermal diffusion and diffusion-thermo effect in a three-dimensional MHD flow model with a constant heat flux. It is to be remembered that as most of the fluid flows occurring in nature are also three-dimensional, study of the three-dimensional flow problems is quite important.

II. MATHEMATICAL FORMULATION

The vector equations that describe the motion of electrically conducting, incompressible, having constant viscosity are

Continuity Equation

$$\vec{\nabla}.\vec{q} = 0 \tag{1}$$

Magnetic Field Continuity Equation

$$\vec{\nabla}.\vec{B} = 0 \tag{2}$$

Ohm's Law for moving conductor

$$\vec{J} = \sigma\left(\vec{E} + \vec{q} \times \vec{B}\right) \tag{3}$$

MHD Momentum Equation

$$\left(\vec{q}.\vec{\nabla}\right)\vec{q} = -\frac{1}{\rho}\vec{\nabla}p + \nu\nabla^2\vec{q} + \frac{\vec{J}\times\vec{B}}{\rho} + \vec{g} \tag{4}$$

Energy Equation

$$\rho C_p\left(\vec{q}.\vec{\nabla}\right)T = \kappa\nabla^2 T + \frac{\rho D_M K_T}{C_S}\nabla^2 C \tag{5}$$

Species Continuity Equation

$$\left(\vec{q}.\vec{\nabla}\right)C = D_M\nabla^2 C + \frac{D_M K_T}{T_m}\nabla^2 T \tag{6}$$

Equation of State

$$\rho_\infty = \rho\left[1 + \beta(T - T_\infty) + \bar{\beta}(C - C_\infty)\right] \tag{7}$$

All the physical quantities are defined in list of symbols.

We consider a steady three-dimensional free convective fully developed heat and mass transfer flow of an electrically conducting, viscous, incompressible fluid past a uniformly moving semi-infinite vertical porous plate in the presence of a transversely applied uniform magnetic field of strength B_0, with sinusoidal suction velocity, considering the thermal-diffusion and diffusion-thermo effects. For the sake of idealization of the mathematical model of the theoretical MHD flow problem, the following assumptions are made:

I. Except the density, the fluid properties are constant.
II. Viscous and Ohmic dissipations of energy are negligible.
III. There is no presence of any external electric field $\vec{E} = \vec{0}$.

Introduce a Cartesian coordinate system (x', y', z') with x' axis along the plate, y' axis normal to the plate and z' axis along the width of the plate. In the Fig. 1, 1, 2, 3 represent momentum, energy, and concentration boundary layer. Let $\vec{q} = (u', v', w')$ denote the fluid velocity at the point (x', y', z') in the fluid and $\vec{B} = B_0\hat{j}$ be the applied magnetic field where $\hat{j}$ is the unit vector along $\overrightarrow{OY}$. The plate is subjected to a space periodic suction velocity $\vec{v}_w$ defined by,

$$\vec{v}_w = -v_0\left(1 + \varepsilon\cos\frac{\pi z'}{L}\right)\hat{j} \tag{8}$$

which consists of a basic steady distribution v_0 with superimposed weak distribution confined in the boundary layer. The negative sign in the Eq. (8) indicates that the direction of suction is towards the plate. The velocity, temperature and concentration fields are independent of x', because an asymptotic flow is considered, whereas the flow itself is three-dimensional due to cross flow.

Based on the foregoing assumptions, the governing equations of motion are as follows by Ahmed *et al.* (2020), Choudhury *et al.* (2022a)

$$\frac{\partial v'}{\partial y'} + \frac{\partial w'}{\partial z'} = 0 \tag{9}$$

$$v'\frac{\partial u'}{\partial y'} + w'\frac{\partial u'}{\partial z'} = g\beta(T - T_\infty) + g\bar{\beta}(C - C_\infty) + \nu\left(\frac{\partial^2 u'}{\partial y'^2} + \frac{\partial^2 u'}{\partial z'^2}\right) - \frac{\sigma B_0^2 u'}{\rho} \tag{10}$$

$$v'\frac{\partial v'}{\partial y'} + w'\frac{\partial v'}{\partial z'} = -\frac{1}{\rho}\frac{\partial p'}{\partial y'} + \nu\left(\frac{\partial^2 v'}{\partial y'^2} + \frac{\partial^2 v'}{\partial z'^2}\right) \tag{11}$$

$$v'\frac{\partial w'}{\partial y'} + w'\frac{\partial w'}{\partial z'} = -\frac{1}{\rho}\frac{\partial p'}{\partial z'} + \nu\left(\frac{\partial^2 w'}{\partial y'^2} + \frac{\partial^2 w'}{\partial z'^2}\right) - \frac{\sigma B_0^2 w'}{\rho} \tag{12}$$

$$v'\frac{\partial T}{\partial y'} + w'\frac{\partial T}{\partial z'} = \frac{\kappa}{\rho C_p}\left(\frac{\partial^2 T}{\partial y'^2} + \frac{\partial^2 T}{\partial z'^2}\right) + \frac{D_M K_T}{C_S C_p}\left(\frac{\partial^2 C}{\partial y'^2} + \frac{\partial^2 C}{\partial z'^2}\right) \tag{13}$$

$$v'\frac{\partial C}{\partial y'} + w'\frac{\partial C}{\partial z'} = D_M\left(\frac{\partial^2 C}{\partial y'^2} + \frac{\partial^2 C}{\partial z'^2}\right) + \frac{D_M K_T}{T_m}\left(\frac{\partial^2 T}{\partial y'^2} + \frac{\partial^2 T}{\partial z'^2}\right) \tag{14}$$

with boundary conditions:

$$y' = 0: u' = U', v' = v_W', w' = 0, \frac{\partial T}{\partial y'} = -\frac{q}{\kappa}, C = C_W \tag{15}$$

$$y' \to \infty: u' \to 0, v' \to -V_0', w' \to 0, T \to T_\infty, C \to C_\infty, p' \to p_\infty' \tag{16}$$

The non-dimensional parameters which the model makes normalized are

$$u = \frac{u'}{U'}, v = \frac{v'}{V_0'}, w = \frac{w'}{V_0'}, y = \frac{y'}{L}, z = \frac{z'}{L}, \theta = \frac{\kappa(T - T_\infty)}{q^* L},$$

$$\phi = \frac{C - C_\infty}{C_W - C_\infty}, \mathrm{Gr} = \frac{Lg\beta q^* L}{\kappa U' V_0'}, \mathrm{Gm} = \frac{Lg\bar{\beta}(C_W - C_\infty)}{U' V_0'}, M = \frac{B_0^2\nu\sigma}{\rho V_0'^2},$$

$$\mathrm{Re} = \frac{V_0' L}{\nu}, \mathrm{Sr} = \frac{D_M K_T q^* L}{\kappa\nu T_m(C_W - C_\infty)}, \mathrm{Du} = \frac{\kappa D_M K_T(C_W - C_\infty)}{C_S C_p q^* L\nu},$$

$$\mathrm{Pr} = \frac{\mu C_p}{\kappa}, \mathrm{Sc} = \frac{\nu}{D_M}, p = \frac{p'}{\rho\left(\nu/L\right)^2}, p_\infty = \frac{p_\infty'}{\rho\left(\nu/L\right)^2}$$

The non-dimensional governing equations of motion with boundary conditions are:

$$\frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0 \tag{17}$$

$$v\frac{\partial u}{\partial y}+w\frac{\partial u}{\partial z}=\mathrm{Gr}\theta+\mathrm{Gm}\phi+\frac{1}{\mathrm{Re}}\left(\frac{\partial^2 u}{\partial y^2}+\frac{\partial^2 u}{\partial z^2}\right)-M\mathrm{Re}u \quad (18)$$

$$v\frac{\partial v}{\partial y}+w\frac{\partial v}{\partial z}=-\frac{1}{\mathrm{Re}^2}\frac{\partial p}{\partial y}+\frac{1}{\mathrm{Re}}\left(\frac{\partial^2 v}{\partial y^2}+\frac{\partial^2 v}{\partial z^2}\right) \quad (19)$$

$$v\frac{\partial w}{\partial y}+w\frac{\partial w}{\partial z}=-\frac{1}{\mathrm{Re}^2}\frac{\partial p}{\partial z}+\frac{1}{\mathrm{Re}}\left(\frac{\partial^2 w}{\partial y^2}+\frac{\partial^2 w}{\partial z^2}\right)-M\mathrm{Re}w \quad (20)$$

$$v\frac{\partial \theta}{\partial y}+w\frac{\partial \theta}{\partial z}=\frac{1}{\mathrm{RePr}}\left(\frac{\partial^2 \theta}{\partial y^2}+\frac{\partial^2 \theta}{\partial z^2}\right)+\frac{\mathrm{Du}}{\mathrm{Re}}\left(\frac{\partial^2 \phi}{\partial y^2}+\frac{\partial^2 \phi}{\partial z^2}\right) \quad (21)$$

$$v\frac{\partial \phi}{\partial y}+w\frac{\partial \phi}{\partial z}=\frac{1}{\mathrm{ReSc}}\left(\frac{\partial^2 \phi}{\partial y^2}+\frac{\partial^2 \phi}{\partial z^2}\right)+\frac{\mathrm{Sr}}{\mathrm{Re}}\left(\frac{\partial^2 \theta}{\partial y^2}+\frac{\partial^2 \theta}{\partial z^2}\right) \quad (22)$$

$$y=0: u=1, v=-1-\varepsilon\cos\pi z, w=0, \frac{\partial\theta}{\partial y}=-1, \phi=1 \quad (23)$$

$$y\to\infty: u\to 0, v\to -1, w\to 0, \theta\to 0, \phi\to 0, p\to p_\infty \quad (24)$$

III. METHOD OF SOLUTION

The solutions of the system of Eqs. (17)-(22) are assumed to be in the asymptotic form:

$$f=f_0(y)+\varepsilon f_1(y,z)+O(\varepsilon^2) \quad (25)$$

where f stands for u, v, w, θ, ϕ and p with $w_0=0, p_0=p_\infty$.

Substituting (25) into (17)-(22) and equating the coefficients of similar terms and neglecting $O(\varepsilon^2)$, we have

Zeroth Order Equations with conditions

$$\frac{dv_0}{dy}=0 \quad (26)$$

$$v_0\frac{du_0}{dy}=\mathrm{Gr}\theta_0+\mathrm{Gm}\phi_0+\frac{1}{\mathrm{Re}}\frac{d^2u_0}{dy^2}-M\mathrm{Re}u_0 \quad (27)$$

$$v_0\frac{d\theta_0}{dy}=\frac{1}{\mathrm{RePr}}\frac{d^2\theta_0}{dy^2}+\frac{\mathrm{Du}}{\mathrm{Re}}\frac{d^2\phi_0}{dy^2} \quad (28)$$

$$v_0\frac{d\phi_0}{dy}=\frac{1}{\mathrm{ReSc}}\frac{d^2\phi_0}{dy^2}+\frac{\mathrm{Sr}}{\mathrm{Re}}\frac{d^2\theta_0}{dy^2} \quad (29)$$

$$y=0: u_0=1, v_0=-1, \theta_0'=-1, \phi_0=1 \quad (30)$$

$$y\to\infty: u_0\to 0, v_0\to -1, \theta_0\to 0, \phi_0\to 0. \quad (31)$$

Solving (26) - (29) with the help of (30) and (31), we get

$$v_0=-1 \quad (32)$$

$$\theta_0=A_1e^{-\xi y}+B_1e^{-\bar{\xi}y} \quad (33)$$

$$\phi_0=A_2e^{-\xi y}+B_2e^{-\bar{\xi}y} \quad (34)$$

$$u_0=[1+\mathrm{Re}(A_4+B_4)]e^{-\lambda\mathrm{Re}\,y}-\mathrm{Re}\left(A_4e^{-\xi y}+B_4e^{-\bar{\xi}y}\right) \quad (35)$$

where:

$$K=\frac{1}{1-\mathrm{DuPrSrSc}},\ \mathrm{DuPrSrSc}<1,$$

$$\xi=\frac{\mathrm{Re}K}{2}\left[\mathrm{Pr}+\mathrm{Sc}+\sqrt{(\mathrm{Pr}-\mathrm{Sc})^2+4\mathrm{Pr}^2\mathrm{Sc}^2\mathrm{DuSr}}\right],$$

$$\bar{\xi}=\frac{\mathrm{Re}K}{2}\left[\mathrm{Pr}+\mathrm{Sc}-\sqrt{(\mathrm{Pr}-\mathrm{Sc})^2+4\mathrm{Pr}^2\mathrm{Sc}^2\mathrm{DuSr}}\right],$$

$$A_1=\frac{\mathrm{DuPr}\xi\bar{\xi}^2+\xi(\bar{\xi}-\mathrm{PrRe})}{\xi^2(\bar{\xi}-\mathrm{PrRe})-\bar{\xi}^2(\xi-\mathrm{PrRe})},\ B_1=\frac{\mathrm{DuPr}\xi^2\bar{\xi}+\bar{\xi}(\xi-\mathrm{PrRe})}{\xi^2(\bar{\xi}-\mathrm{PrRe})-\bar{\xi}^2(\xi-\mathrm{PrRe})}$$

$$A_2=-\frac{A_1(\xi-\mathrm{PrRe})}{\mathrm{DuPr}\xi},\ B_2=-\frac{B_1(\bar{\xi}-\mathrm{PrRe})}{\mathrm{DuPr}\bar{\xi}},$$

$$A_3=\mathrm{Gr}A_1+\mathrm{Gm}A_2,\ B_3=\mathrm{Gr}B_1+\mathrm{Gm}B_2,$$

$$A_4=\frac{A_3}{\xi^2-\mathrm{Re}\xi-M\mathrm{Re}^2},\ B_4=\frac{B_3}{\bar{\xi}^2-\mathrm{Re}\bar{\xi}-M\mathrm{Re}^2},\ \lambda=\frac{1+\sqrt{1+4M}}{2}.$$

First Order Equations with Boundary Conditions

$$\frac{\partial v_1}{\partial y}+\frac{\partial w_1}{\partial z}=0 \quad (36)$$

$$v_0\frac{\partial u_1}{\partial y}+v_1\frac{\partial u_0}{\partial y}=\mathrm{Gr}\theta_1+\mathrm{Gm}\phi_1+\frac{1}{\mathrm{Re}}\left(\frac{\partial^2 u_1}{\partial y^2}+\frac{\partial^2 u_1}{\partial z^2}\right)-M\mathrm{Re}u_1 \quad (37)$$

$$v_0\frac{\partial v_1}{\partial y}=-\frac{1}{\mathrm{Re}^2}\frac{\partial p_1}{\partial y}+\frac{1}{\mathrm{Re}}\left(\frac{\partial^2 v_1}{\partial y^2}+\frac{\partial^2 v_1}{\partial z^2}\right) \quad (38)$$

$$v_0\frac{\partial w_1}{\partial y}=-\frac{1}{\mathrm{Re}^2}\frac{\partial p_1}{\partial z}+\frac{1}{\mathrm{Re}}\left(\frac{\partial^2 w_1}{\partial y^2}+\frac{\partial^2 w_1}{\partial z^2}\right)-M\mathrm{Re}w_1 \quad (39)$$

$$v_0\frac{\partial \theta_1}{\partial y}+v_1\frac{\partial \theta_0}{\partial y}=\frac{1}{\mathrm{RePr}}\left(\frac{\partial^2 \theta_1}{\partial y^2}+\frac{\partial^2 \theta_1}{\partial z^2}\right)+\frac{\mathrm{Du}}{\mathrm{Re}}\left(\frac{\partial^2 \phi_1}{\partial y^2}+\frac{\partial^2 \phi_1}{\partial z^2}\right) \quad (40)$$

$$v_0\frac{\partial \phi_1}{\partial y}+v_1\frac{\partial \phi_0}{\partial y}=\frac{1}{\mathrm{ReSc}}\left(\frac{\partial^2 \phi_1}{\partial y^2}+\frac{\partial^2 \phi_1}{\partial z^2}\right)+\frac{\mathrm{Sr}}{\mathrm{Re}}\left(\frac{\partial^2 \theta_1}{\partial y^2}+\frac{\partial^2 \theta_1}{\partial z^2}\right) \quad (41)$$

$$y=0: u_1=0, v_1=-\cos\pi z, w_1=0, \frac{\partial\theta_1}{\partial y}=0, \phi_1=0 \quad (42)$$

$$y\to\infty: u_1\to 0, v_1\to 0,\ w_1\to 0, \theta_1\to 0, \phi_1\to 0, p_1\to 0 \quad (43)$$

Equations governing the transverse fluid motion are:

$$\frac{\partial v_1}{\partial y}+\frac{\partial w_1}{\partial z}=0 \quad (44)$$

$$-\frac{\partial v_1}{\partial y}=-\frac{1}{\mathrm{Re}^2}\frac{\partial p_1}{\partial y}+\frac{1}{\mathrm{Re}}\left(\frac{\partial^2 v_1}{\partial y^2}+\frac{\partial^2 v_1}{\partial z^2}\right) \quad (45)$$

$$-\frac{\partial w_1}{\partial y}=-\frac{1}{\mathrm{Re}^2}\frac{\partial p_1}{\partial z}+\frac{1}{\mathrm{Re}}\left(\frac{\partial^2 w_1}{\partial y^2}+\frac{\partial^2 w_1}{\partial z^2}\right)-M\mathrm{Re}w \quad (46)$$

Relevant boundary conditions:

$$y=0: v_1=-\cos\pi z, w_1=0, \quad (47)$$

$$y\to\infty: v_1\to 0,\ w_1\to 0,\ p_1\to 0 \quad (48)$$

The boundary condition $v_1=-\cos\pi z$ at $y=0$ suggests taking v_1, w_1 and p_1 in the following forms:

$$v_1=-\pi v_{11}(y)\cos\pi z, \quad (49)$$

$$w_1=v_{11}'(y)\sin\pi z, \quad (50)$$

$$p_1=\mathrm{Re}^2p_{11}(y)\cos\pi z, \quad (51)$$

Based on transformations (49) and (50), the Eq. (44) is trivially satisfied.

Under the transformations (49) - (51), Eqs. (45) and (46) reduce to

$$v_{11}''+\mathrm{Re}v_{11}'-\pi^2v_{11}=-\frac{\mathrm{Re}}{\pi}p_{11}', \quad (52)$$

$$v_{11}'''+\mathrm{Re}v_{11}''-(\pi^2+M\mathrm{Re}^2)v_{11}'=-\pi\mathrm{Re}p_{11}, \quad (53)$$

With boundary conditions:

$$y=0: v_{11}=1/\pi, v_{11}'=0 \quad (54)$$

$$y\to\infty: v_{11}\to 0, v_{11}'\to 0, p_{11}\to 0. \quad (55)$$

The solutions of the equations of (52) and (53) under the conditions (54) and (55) are as follow:

$$v_{11}=\frac{1}{\pi(\bar{\eta}-\eta)}\left[\bar{\eta}e^{-\eta y}-\eta e^{-\bar{\eta}y}\right] \quad (56)$$

$$p_{11}=\frac{\eta\bar{\eta}}{\pi^2\mathrm{Re}(\bar{\eta}-\eta)}\left[\bar{\eta}_1e^{-\bar{\eta}y}-\eta_1e^{-\eta y}\right] \quad (57)$$

where

$$\bar{\lambda}=\frac{1-\sqrt{1+4M}}{2},\ \eta=\frac{\mathrm{Re}\lambda+\sqrt{\mathrm{Re}^2\lambda^2+4\pi^2}}{2},\ \bar{\eta}=\frac{\mathrm{Re}\bar{\lambda}+\sqrt{\mathrm{Re}^2\bar{\lambda}^2+4\pi^2}}{2},$$

$$\eta_1=\pi^2+M\mathrm{Re}^2+\mathrm{Re}\eta-\eta^2,\ \bar{\eta}_1=\pi^2+M\mathrm{Re}^2+\mathrm{Re}\bar{\eta}-\bar{\eta}^2$$

The expressions for v_1, w_1 and p_1 are:

$$v_1=\frac{1}{(\eta-\bar{\eta})}\left[\bar{\eta}e^{-\eta y}-\eta e^{-\bar{\eta}y}\right]\cos\pi z \quad (58)$$

$$w_1=\frac{\eta\bar{\eta}}{\pi(\eta-\bar{\eta})}\left[e^{-\eta y}-e^{-\bar{\eta}y}\right]\sin\pi z \quad (59)$$

$$p_1=\frac{\eta\bar{\eta}\mathrm{Re}}{\pi^2(\eta-\bar{\eta})}\left[\eta_1e^{-\eta y}-\bar{\eta}_1e^{-\bar{\eta}y}\right]\cos\pi z \quad (60)$$

Solutions for first order

Based on sinusoidal suction, u_1, θ_1 and ϕ_1 are assumed as,

$$u_1=u_{11}(y)\cos\pi z \quad (61)$$

$$\theta_1=\theta_{11}(y)\cos\pi z \quad (62)$$

$$\phi_1=\phi_{11}(y)\cos\pi z \quad (63)$$

Substituting (61)-(63) in Eqs. (37), (40) and (41), we obtain the ordinary differential equations as:

$$\theta_{11}''+\mathrm{PrRe}\theta_{11}'-\pi^2\theta_{11}=-\pi\mathrm{PrRe}v_{11}\theta_0'-\mathrm{PrDu}(\phi_{11}''-\pi^2\phi_{11}). \quad (64)$$

$$\phi_{11}''+\mathrm{ScRe}\phi_{11}'-\pi^2\phi_{11}=-\pi\mathrm{ScRe}v_{11}\phi_0'-\mathrm{ScSr}(\theta_{11}''-\pi^2\theta_{11}). \quad (65)$$

$$u_{11}''+\mathrm{Re}u_{11}'-(\pi^2+M\mathrm{Re}^2)u_{11}=-\mathrm{GrRe}\theta_{11}-\mathrm{GmRe}\phi_{11}-\pi\mathrm{Re}v_{11}u_0'. \quad (66)$$

With boundary conditions:

$$y=0: u_{11}=0, \theta_{11}'=0, \phi_{11}=0 \quad (67)$$

$$y \to \infty: u_{11} \to 0,\ \theta_{11} \to 0,\ \phi_{11} \to 0 \tag{68}$$

The solutions of (64)-(66) with the help of (67) and (68) are:

$$\theta_{11} = A_6 e^{-\xi_1 y} + B_6 e^{-\bar{\xi}_1 y} + F_{13} e^{-(\eta+\xi)y} + F_{14} e^{-(\eta+\bar{\xi})y} + F_{15} e^{-(\bar{\eta}+\xi)y} + F_{16} e^{-(\bar{\eta}+\bar{\xi})y} \tag{69}$$

$$\phi_{11} = \Omega\left[-\frac{F_{18}}{\xi_1} e^{-\xi_1 y} - \frac{F_{19}}{\bar{\xi}_1} e^{-\bar{\xi}_1 y} - F_{24} e^{-(\eta+\xi)y} - F_{25} e^{-(\eta+\bar{\xi})y} - F_{26} e^{-(\bar{\eta}+\xi)y} - F_{27} e^{-(\bar{\eta}+\bar{\xi})y}\right] \tag{70}$$

$$u_{11} = He^{-hy} + H_1 e^{-\xi_1 y} + H_2 e^{-\bar{\xi}_1 y} + H_3 e^{-(\eta+\lambda\mathrm{Re})y} + H_4 e^{-(\bar{\eta}+\lambda\mathrm{Re})y} + H_5 e^{-(\eta+\xi)y} + H_6 e^{-(\eta+\bar{\xi})y} + H_7 e^{-(\bar{\eta}+\xi)y} - H_8 e^{-(\bar{\eta}+\bar{\xi})y} \tag{71}$$

where:

$$\xi_1 = \frac{\xi+\sqrt{\xi^2+4\pi^2}}{2},\ \bar{\xi}_1 = \frac{\bar{\xi}+\sqrt{\bar{\xi}^2+4\pi^2}}{2},\ A_5 = \frac{\bar{\eta}}{\pi(\bar{\eta}-\eta)},\ B_5 = -\frac{\eta}{\pi(\bar{\eta}-\eta)}$$

$$F_1 = -\bar{M}A_2A_5\xi,\ F_2 = -\bar{M}B_2A_5\bar{\xi},\ F_3 = -\bar{M}A_2B_5\xi,$$

$$F_4 = -\bar{M}B_2B_5\bar{\xi},\ \bar{M} = \mathrm{PrDuReSc},\ F_5 = -NA_1A_5\xi,$$

$$F_6 = -NB_1A_5\xi, F_7 = -NA_1B_5\xi, F_8 = -NB_1B_5\xi, N = \pi\mathrm{RePr},$$

$$F_9 = \mathrm{ScRe}(\eta+\xi)F_5 + (\eta+\xi)^2F_1 - (\eta+\xi)^2F_5 - \pi^2F_1 + \pi^2F_5$$

$$F_{10} = \mathrm{ScRe}(\eta+\bar{\xi})F_6 + (\eta+\bar{\xi})^2F_2 - (\eta+\bar{\xi})^2F_6 - \pi^2F_2 + \pi^2F_6$$

$$F_{11} = \mathrm{ScRe}(\bar{\eta}+\xi)F_7 + (\bar{\eta}+\xi)^2F_3 - (\bar{\eta}+\xi)^2F_7 - \pi^2F_3 + \pi^2F_4$$

$$F_{12} = \mathrm{ScRe}(\bar{\eta}+\bar{\xi})F_8 + (\bar{\eta}+\bar{\xi})^2F_4 - (\bar{\eta}+\bar{\xi})^2F_8 - \pi^2F_4 + \pi^2F_8$$

$$F_{13} = \frac{KF_9}{F(-\eta-\xi)},\ F_{14} = \frac{KF_{10}}{F(-\eta-\bar{\xi})},\ F_{15} = \frac{KF_{11}}{F(-\bar{\eta}-\xi)},\ F_{16} = \frac{KF_{12}}{F(-\bar{\eta}-\bar{\xi})}$$

$$F(D) = D^4 + \mathrm{Re}K(\mathrm{Pr}+\mathrm{Sc})D^3 + K(\mathrm{PrScRe}^2 + 2\mathrm{PrDuScSr}\pi^2 - 2\pi^2)D^2 - \pi^2K\mathrm{Re}(\mathrm{Sc}+\mathrm{Pr})D + \pi^4$$

$$F_{17} = (\eta+\xi)F_{13} + (\eta+\bar{\xi})F_{14} + (\bar{\eta}+\xi)F_{15} + (\bar{\eta}+\bar{\xi})F_{16}$$

$$F_{18} = A_6\xi_1^2 - \pi^2A_6 - \mathrm{PrRe}K\xi_1A_6, F_{19} = B_6\bar{\xi}_1^2 - \pi^2B_6 - \mathrm{PrRe}K\bar{\xi}_1B_6$$

$$F_{20} = K(F_5-F_1) + (\eta+\xi)^2F_{13} - \pi^2F_{13} - \mathrm{PrRe}K(\eta+\xi)F_{13}$$

$$F_{21} = K(F_6-F_2) + (\eta+\bar{\xi})^2F_{14} - \pi^2F_{14} - \mathrm{PrRe}K(\eta+\bar{\xi})F_{13}$$

$$F_{22} = K(F_7-F_3) + (\bar{\eta}+\xi)^2F_{15} - \pi^2F_{15} - \mathrm{PrRe}K(\bar{\eta}+\xi)F_{15}$$

$$F_{23} = K(F_8-F_3) + (\bar{\eta}+\bar{\xi})^2F_{16} - \pi^2F_{16} - \mathrm{PrRe}K(\bar{\eta}+\bar{\xi})F_{16}$$

$$F_{24} = \frac{F_{20}}{\eta+\xi},\ F_{25} = \frac{F_{21}}{\eta+\bar{\xi}},\ F_{26} = \frac{F_{22}}{\bar{\eta}+\xi},\ F_{27} = \frac{F_{23}}{\bar{\eta}+\bar{\xi}},\ \Omega = \frac{1}{K\mathrm{PrDuScRe}}$$

$$F_{28} = F_{24}+F_{25}+F_{26}+F_{27}, A_6 = \frac{\bar{\xi}_2F_{17}-\bar{\xi}_1F_{28}}{\xi_2\bar{\xi}_1-\bar{\xi}_2\xi_1}, B_6 = \frac{\xi_1F_{28}-\xi_2F_{17}}{\xi_2\bar{\xi}_1-\bar{\xi}_2\xi_1}$$

$$A_7 = -\frac{\Omega F_{18}}{\xi_1},\ B_7 = -\frac{\Omega F_{19}}{\bar{\xi}_1},\ F_{29} = -\Omega F_{24},\ F_{30} = -\Omega F_{25},\ F_{31} = -\Omega F_{26}$$

$$F_{32} = -\Omega F_{27},\ h = \frac{\mathrm{Re}+\sqrt{\mathrm{Re}^2+4(M\mathrm{Re}^2+\pi^2)}}{2},$$

$$G_1 = \pi\mathrm{Re}^2A_5(1+\mathrm{Re}A_4+\mathrm{Re}B_4)\lambda,\ G_3 = -\pi\mathrm{Re}^2A_5\xi A_4,$$

$$G_2 = \pi\mathrm{Re}^2B_5(1+\mathrm{Re}A_4+\mathrm{Re}B_4)\lambda,\ G_4 = -\pi\mathrm{Re}^2A_5\bar{\xi}B_4,$$

$$G_5 = -\pi\mathrm{Re}^2B_5\xi A_4,\ G_6 = -\pi\mathrm{Re}^2B_5\bar{\xi}B_4,\ G_7 = -\mathrm{GrRe}A_6,$$

$$G_8 = -\mathrm{GrRe}B_6,\ G_9 = -\mathrm{GrRe}F_{13},\ G_{10} = -\mathrm{GrRe}F_{14},$$

$$G_{10} = -\mathrm{GrRe}F_{14},\ G_{11} = -\mathrm{GrRe}F_{15},\ G_{12} = -\mathrm{GrRe}F_{16},$$

$$G_{13} = -\mathrm{GrRe}A_7,\ G_{14} = -\mathrm{GrRe}B_7,\ G_{15} = -\mathrm{GmRe}F_{29},$$

$$G_{16} = -\mathrm{GmRe}F_{30},\ G_{17} = -\mathrm{GmRe}F_{31},\ G_{18} = -\mathrm{GmRe}F_{32},$$

$$G_{19} = G_3+G_9+G_{15},\ G_{20} = G_4+G_{10}+G_{16},\ G_{21} = G_5+G_{11}+G_{17},$$

$$G_{22} = G_6+G_{12}+G_{18},\ G_{23} = G_7+G_{13},\ G_{24} = G_8+G_{14},$$

$$\psi(D) = D^2 + \mathrm{Re}D - (\pi^2 + M\mathrm{Re}^2),\ H_1 = \frac{G_{23}}{\psi(-\xi_1)},\ H_2 = \frac{G_{24}}{\psi(-\bar{\xi}_1)},$$

$$H_3 = \frac{G_1}{\psi(-\eta-\lambda\mathrm{Re})},\ H_4 = \frac{G_2}{\psi(-\bar{\eta}-\lambda\mathrm{Re})},\ H_5 = \frac{G_{19}}{\psi(-\eta-\xi)},\ H_6 = \frac{G_{20}}{\psi(-\eta-\bar{\xi})},$$

$$H_7 = \frac{G_{21}}{\psi(-\bar{\eta}-\bar{\xi})},\ H_8 = \frac{G_{22}}{\psi(-\bar{\eta}-\bar{\xi})},\ H = -\sum_{\alpha=1}^{8} H_\alpha$$

Skin Friction: The co-efficient of skin friction is a dimensionless quantity obtained from the shear stress at the wall given by Newton's law of viscosity

$$\vec{\tau}_0 = -\mu\vec{\nabla}u'$$

where τ_0 is the shear stress.

The coefficient of friction at the plate is defined as,

$$\tau = \left.\frac{\partial u}{\partial y}\right|_{y=0} = \tau_0 + \varepsilon\tau_{11}\cos\pi z$$

where:

$$\tau_0 = -u_0'(0) \text{ and } \tau_{11} = -u_{11}'(0) \tag{72}$$

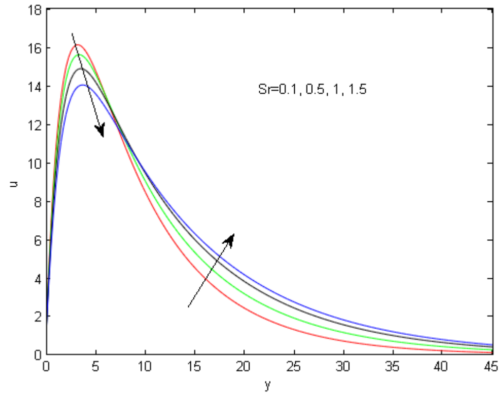

Figure 2. Velocity profile for Gr = 5; Gm = 3; Du = 0.5; Sc = 0.6; M = 6; Pr = 0.71; Re = 0.2; $z = \pi/4$; ε = 0.001.

Plate temperature: The dimensionless temperature field is given by,

$$\theta(y,z) = \theta_0(y) + \varepsilon\theta_1(y,z) = \theta_0(y) + \varepsilon\theta_{11}(y)\cos\pi z$$

The non-dimensional plate temperature is given by,

$$\theta_w = \theta_0(y) + \varepsilon\theta_{11}(0)\cos\pi z \tag{73}$$

Sherwood number: Sherwood number represents the ratio of the convective mass transfer to the rate of diffusive mass transport. It is a dimensionless quantity obtained from Fick's law of diffusion:

$$\vec{J} = -D_M\vec{\nabla}C'$$

where J is the diffusion flux.

Sherwood number is defined as,

$$\mathrm{Sh} = \left.\frac{\partial\phi}{\partial y}\right|_{y=0} = \mathrm{Sh}_0 + \varepsilon\mathrm{Sh}_{11}\cos\pi z$$

where:

$$\mathrm{Sh}_0 = -\phi_0'(0) \text{ and } \mathrm{Sh}_{11} = -\phi_{11}'(0) \tag{74}$$

IV. RESULTS AND DISCUSSION

The expressions describing the velocity distribution, temperature distribution, concentration profile, skin-friction, rate of mass transfer and plate temperature are already obtained. To get a physical insight of the problem, the effects of the applied magnetic field on velocity distribution and on coefficient of skin friction have been studied graphically when other parameters do not vary. Also, the effects of other important parameters like Schmidt number (Sc), Reynolds number (Re), Soret number (Sr), Prandtl number (Pr) and Dufour number (Du) on velocity distribution, temperature profile and concentration profile are studied graphically while keeping other parameters as constants.

The variation in the velocity distribution of the flow field with respect to y for four specific values of Soret parameter (Sr) is shown in Fig. 2. It is evident in the figure that the velocity profile diminutions near the plate due to the Soret effect, but at far away from the plate, Soret effect can be used to boost the fluid velocity. Figure 3 presents the effect of Hartmann number parameter (M) on the velocity profile against the normal co-ordinate y. The fluid velocity is found to reduce with rising values of M. This result is consistent with the physical reality of the fact that when a magnetic field is applied to an electrically conducting fluid, a resistive type of force known

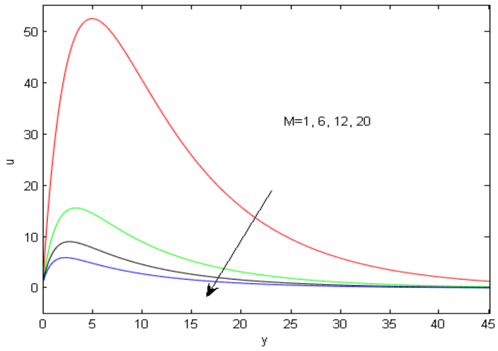

Figure 3. Velocity profile for Gr = 5; Gm = 3; Du = 0.5; Sc = 0.6; Pr = 0.71; Re = 0.2; Sr = 0.5; $z = \pi/4$; $\varepsilon = 0.001$.

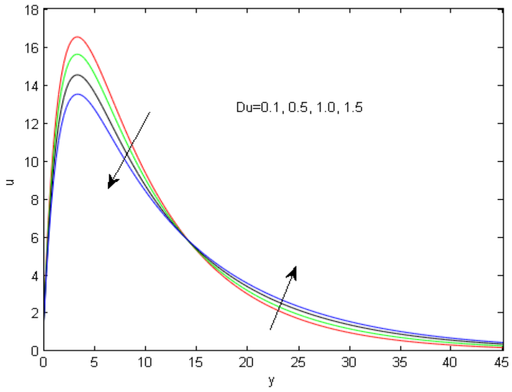

Figure 4. Velocity profile for Gr = 5; Gm = 3; Sc = 0.6; $M = 6$; Pr = 0.71; Re = 0.2; Sr = 0.5; $z = \pi/4$; $\varepsilon = 0.001$.

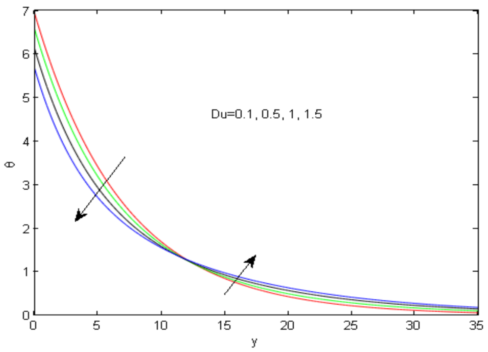

Figure 5. Temperature profile for Sc = 0.6; Pr = 0.71; Re = 0.2; Sr = 0.5; $z = \pi/4$; $\varepsilon = 0.001$.

as Lorentz force is generated which has the tendency to retard the fluid motion. Figure 4 is a plot of the velocity profile with respect to y for various values of Dufour number (Du). The figure explains that because of the Dufour effect, the velocity shrinkages near the plate up to a certain distance and then growths away from the plate. The Dufour number Du signifies the contribution of the concentration gradients to the thermal energy flux in the flow. As Du upsurges, an escalation in the fluid velocity can be seen in the Fig. 4.

Figures 2, 3, and 4 together establish that velocity upsurges with respect to y up to a certain distance and then shrinkages continuously.

Figure 5 is a plot of the temperature profile for four different values of Dufour number (Du). As can be ob-

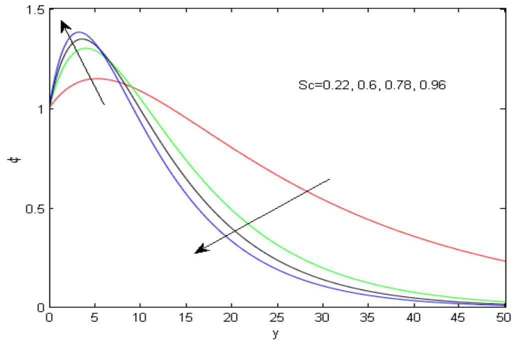

Figure 6. Concentration ϕ versus y for Du = 0.5; Pr = 0.71; Re = 0.2; Sr = 0.5; $z = \pi/4$; $\varepsilon = 0.001$.

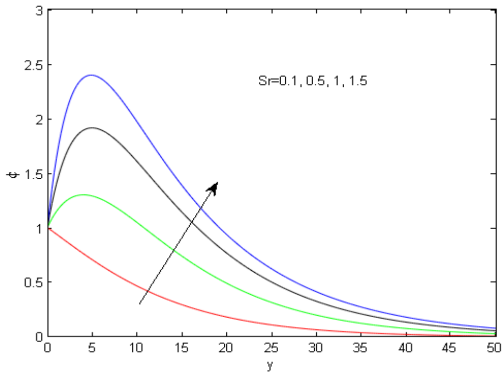

Figure 7. Concentration ϕ versus y for Du = 0.5; Sc = 0.6; Pr = 0.71; Re = 0.2; $z = \pi/4$; $\varepsilon = 0.001$

served from this figure that the Dufour effect drops the temperature profile close to the plate, but far away from the plate, it raises the fluid temperature.

Figure 6 elucidates the effect on the concentration profile due to the variation of Schmidt number Sc. Sc causes the concentration level of the fluid to grow near the plate. But, away from the plate, concentration level of the fluid falls with surge in the value of Sc. This observation is compatible with the physical reality that an increase in Sc results in a diminution in mass diffusivity, which leads to a decrease in fluid concentration. The fluid concentration for various values of Sr is plotted in Fig. 7. Observing the plotted curves in Fig. 7, it is inferred that the Soret parameter elevations the concentration profile of the fluid in flow.

Figure 8 represents the graphical relationship of the skin friction coefficient with the Reynolds number for four different strength magnetic fields. It is noticed that the viscous drag at the plate diminution with increasing values of magnetic parameter. Figure 9 displays the effect of the Schmidt number on the Sherwood number against the Reynolds number. The inference drawn from it is that the surge of Schmidt number reduces the mass diffusivity which slows down the mass transfer rate. But, as the Reynolds number upsurges, Schmidt number enhances the rate of mass transfer. Figure 10 presents the plate temperature against the Reynolds number at four different values of Dufour number (Du). The figure indicates that fluid temperature at the plate upsurges due to diffusion-thermo effect.

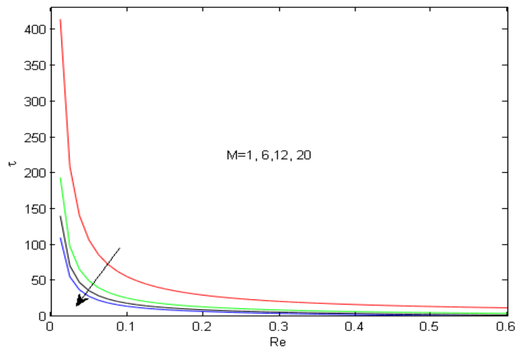

Figure 8: Skin friction τ versus Re for Gr $= 5$; Gm $= 3$; Du $= 0.5$; Sc $= 0.6$; Pr $= 0.71$; Sr $= 0.5$; $z = \pi/4$; $\varepsilon = 0.001$.

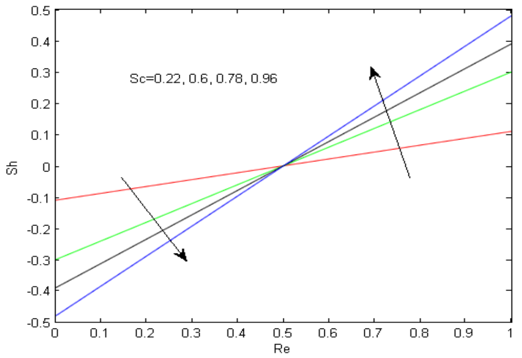

Figure 9: Sherwood number versus Re for Du $= 0.5$; Pr $= 0.71$; Sr $= 0.5$; $z = \pi/4$; $\varepsilon = 0.001$.

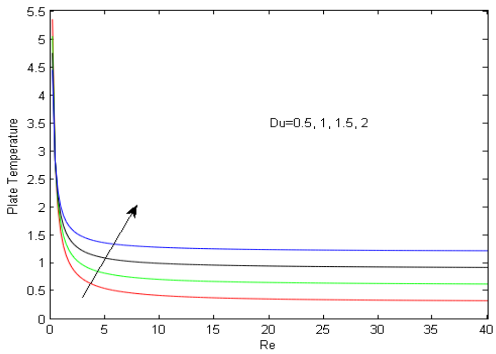

Figure 10: Plate temperature for Sc $= 0.6$; Pr $= 0.71$; Sr $= 0.5$; $z = \pi/4$; $\varepsilon = 0.001$.

V. CONCLUSIONS

We have formulated the problem of three dimensional MHD flow with Soret and Dufour effects in presence of constant heat flux. Perturbation technique is used to solve the resulting coupled equations. The outcome of the investigation is summarized by the following significant conclusions:

A. Velocity is decelerated with greater Hartmann number and Reynolds number. And far away from the plate, fluid velocity can be augmented by familiarizing Soret or Dufour effects.
B. Temperature drops with the rise of Prandtl number. Dufour effect also drops the fluid temperature near the plate.
C. Concentration level of the fluid rises because of thermal diffusion. But, far away from the plate, Schmidt number lowers the fluid concentration.
D. The shear stress decreases with stronger magnitude of the applied magnetic field.
E. For smaller Reynolds number, mass transfer is accelerated with increase in the Schmidt number, but the rate of mass transfer is slowed down due to Schmidt number for large Reynolds number.
F. The plate temperature escalations due to the diffusion-thermo effect.

COMPARISON

Table 1 and 2 are plotted to make a comparison of the current work with the previously published result of Choudhury *et al.* (2022b). Table 1 displays the variations in Skin friction due to various parameters in absence of Soret effect i.e. Sr $= 0$. It is seen that both the tables are almost identical. This validates the accuracy of our work.

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Table 1: Skin friction τ at the plate in absence of Soret

Sc	M	Du	τ
0.60	6	0.5	0.04521
0.78	6	0.5	0.00441
0.99	6	0.5	0.00182
0.60	**2**	0.5	2.11821
0.60	**4**	0.5	0.46285
0.60	**6**	0.5	0.23187
0.60	6	**6**	0.03732
0.60	6	**8**	0.05642
0.60	6	**10**	0.12835

Table 2: Scan copy of Choudhury *et al.* (2022b) "Skin friction τ at the plate for the values of $M = 1.5$, $Gr = 10$, $Gm = 5$, $Sc = 0.3$, $Pr = 0.71$, $R = 5$, $Q = 5$, $K = 1$, $Du = 0.1$, $K_c = 1$, $E = 0.01$"

Sc	M	R	Q	Du	τ
0.60	1.5	5	5	0.1	0.0482
0.78	1.5	5	5	0.1	0.0044
0.99	1.5	5	5	0.1	0.0018
0.30	**2**	5	5	0.1	2.1081
0.30	**4**	5	5	0.1	0.4528
0.30	**5**	5	5	0.1	0.2118
0.30	1.5	**5**	5	0.1	0.0550
0.30	1.5	**10**	5	0.1	0.0088
0.30	1.5	**15**	5	0.1	0.0085
0.30	1.5	5	**5**	0.1	0.0550
0.30	1.5	5	**10**	0.1	0.0559
0.30	1.5	5	**15**	0.1	0.0563
0.30	1.5	5	5	**6**	0.0363
0.30	1.5	5	5	**8**	0.0551
0.30	1.5	5	5	**10**	0.1272

Note: Bold values are variations and the others are fixed.

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LIST OF SYMBOLS

$\vec{B}$: Magnetic flux density

B_0: Intensity of the externally applied magnetic field, Weber/m^2

C: Molar species concentration, k mol/m^3

C_p: Specific heat at constant pressure, J/kg K

C_∞: Concentration far away from the plate, k mol/m^3

C_s: Concentration susceptibility, (k mol)^2 s^2/m^2

C_w: Concentration at the plate, k mol/m^3

D_M: Mass diffusivity, m^2/s

Du: Dufour number

$\vec{E}$: Electric field vector
$\vec{g}$: Acceleration due to gravity
g: Magnitude of the acceleration due to gravity, m/s^2
Gr: Thermal Grashof number
Gm: Grashof number for mass transfer
$\vec{J}$: Current density vector
K_T: Thermal diffusion ratio, m (k mol)
L: Wavelength of the periodic suction, m
M: Magnetic parameter
p: Fluid pressure, N/m^2
Pr: Prandtl number
p_∞: Fluid Pressure in the free stream, N/m^2
$\vec{q}$: Velocity of fluid
Re: Reynolds number
Sc: Schmidt number
q^*: Heat flux, W/m^2
T: Fluid temperature, K
T_m: Mean fluid temperature, K
T_∞: Fluid temperature in the free stream, K
(u', v', w'): Fluid velocity components, (m/s, m/s, m/s)
U_0: Plate velocity, m/s
(x', y', z'): Cartesian coordinates, (m, m, m)

Greek symbols
σ: Electrical conductivity, 1/(Ohm m)
ρ: Density of the fluid, kg/m^3
ρ_∞: Density of the fluid in the free stream, kg/m^3
μ: Coefficient of viscosity, kg/(m s)
κ: Thermal conductivity, W/(m K)
β: Volumetric coefficient of thermal expansion, 1/K
$\bar{\beta}$: Volumetric coefficient of solutal expansion,1/k mol
υ: Kinematic viscosity. m^2/s

Subscripts
w: Refers to the physical quantity at the plate
∞: Refers to the physical quantity in the free stream far away from the plate

Received: February 25, 2022
Sent to Subject Editor: March 2, 2022
Accepted: October 19, 2022
Recommended by Subject Editor Gianfranco Caruso