

Transient MHD Natural Convective Flow Past a Heated Vertical Non-porous Surface with Thermal Radiation and Double-Diffusion Effects.

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ABSTRACT

The problem of transient MHD natural convective flow past a vertical plate with thermal radiation, cross-diffusion and zero suction effects is investigated. The governing one-dimensional spatial and non-linear partial differential equations of the Boussineq form are non-dimensionalized to, among others, bring out the necessary parameters. The evolving dimensionless equations are transformed into ordinary differential equations using the similarity transformation, and linearized using the regular perturbation expansion series solutions. The linearization leads to the zeroth and first order equations, and are solved semi-analytically using the Mathematica 11.0 computational software. Expressions for the temperature, concentration, velocity, Nusselt number, Sherwood number and Skin friction are obtained, computed and presented graphically. The analysis of results, amidst others, shows that the increase in the Dufour number increases the temperature, but decreases the Nusselt number; the increase in the Soret number decreases the concentration, but increases the Sherwood number; the increase in the Prandtl number decreases the temperature and concentration, but increases the Nusselt number and Sherwood number; the increase in the Hartmann number decreases the velocity and skin friction. These results are benchmarked with the existing reports in literatures, and are in good agreement.

Keywords: Double-diffusion, MHD, Natural convection, Thermal radiation.

NOMENCLATURE

C - the fluid concentration (quantity of material being transported)

D - the diffusion coefficient

f - the similarity velocity parameter

$\mathbf{g}$ - the gravitational field vector acting in the reverse direction of the flow

s - the suction parameter

t - the time

T - fluid temperature

U - the fluid characteristic velocity

u - the velocity components in the x direction

v - the velocity components in the y directions, and is the velocity with which the fluid is

sucked/injected

(x, y) - the Cartesian coordinates

B_o^2 - the uniform magnetic field strength

C_∞ - the fluid ambient concentration at the wall of the plate

C_w - the plate concentration at the wall

C_p - the specific heat capacity at constant pressure

C_s - the concentration susceptibility

D_r - the Dufour number;

Gr/Gc - the Grashof number due to temperature and concentration differences, respectively

k - the thermal conductivity

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- 37 k_r^2 - the rate of chemical reaction of the fluid
- 38 k_T - the thermal diffusivity ratio of the fluid, and
- 39 M^2 - the magnetic field force
- 40 N - the temperature difference parameter;
- 41 Pr - the Prandtl number;
- 42 q_r - the radiative heat flux
- 43 Sc - the Schmidt number;
- 44 S_r - the Soret number,
- 45 T_∞ - the fluid ambient temperature
- 46 T_m - the mean temperature of the fluid.
- 47 T_w - the plate temperature at the wall
- 48 α - the optical property of the thin medium in which the heat is propagating
- 49 ρ - the fluid density
- 50 η - the independent variable
- 51 ν - the kinematic viscosity
- 52 Θ - the dimensionless temperature
- 53 Θ - the dimensionless concentration
- 54 μ - the viscosity of the fluid
- 55 κ - the permeability parameter of the porous medium
- 56 σ - the Stefan-Boltzman constant;
- 57 ϕ -- a non-constant small temperature correction factor
- 58 β_1 - the volumetric expansion coefficient for temperature
- 59 β_2 - the volumetric expansion coefficient for concentration
- 60 μ_m - the magnetic permeability of the fluid
- 61 σ_e - the electrical conductivity of the fluid
- 62 χ^2 - the porosity parameter

64 **1. INTRODUCTION**

65
 66 MHD convective flow over vertical plates has applications in science and engineering. It is relevant in the new type of
 67 energy conversion devices; stellar and ionospheric phenomena; geophysics; chemical engineering.

68
 69 A lot of reports exist in literature in this domain of study. Some considered the highly interacting flow with diverse
 70 parameters effects, and others the less. For the highly interacting flow, [1] studied the free convective flow with double
 71 diffusive convection over a vertical infinite plate using the successive linearization method;[2] considered a mixed
 72 convective heat and mass transfer flow along a wavy surface in a Darcy porous medium in the presence of cross-diffusion
 73 effects using similarity transformation and numerical method.

74
 75 More so, the flow-modifying impact of magnetic field on the highly interacting flow has been investigated. [3] examined the
 76 Soret and Dufour effects on the steady magneto-hydrodynamic natural convective flow over a semi infinite accelerating
 77 vertical plate in a porous medium with viscous dissipation; [4] considered the thermal radiation, Hall currents, Dufour and
 78 Soret effects on the magneto-hydrodynamic mixed convective flow over a vertical plate in porous media;[5] investigated
 79 the effects of Soret/diffusion thermal on the unsteady MHD natural convective flow over an infinite porous plate with
 80 variable suction. [6] examined the effects of Dufour and Hall currents on an unsteady magneto-hydrodynamic flow over an
 81 infinite vertical plate using a special function $Hh_n(z)$, and observed that injection enhances the flow, Hartmann number
 82 reduces the skin friction, heavier species decreases the velocity in both suction and injection cases; Hall currents slightly
 83 increase the flow velocity in the case of constant temperature and concentration but decreases for time-dependent
 84 temperature and concentration. [7] studied the unsteady MHD free convective flow over a vertical plate with focus on the
 85 effects of chemical reaction, thermal radiation, Dufour, Soret, Hartmann number, Grashof number and constant suction
 86 using similarity transformation and perturbation series solutions methods, and observed that the Hartmann number and
 87 Grashof number increase the velocity; Dufour number increases the temperature, Nusselt number and velocity; chemical
 88 reaction rate decreases the temperature, but increases the concentration, velocity and Nusselt number; Soret number

increases the concentration and velocity; the suction decreases the temperature, concentration and velocity, but increases the Nusselt number.

For the less interacting flow, in which case the thermal diffusion and thermo-phoresic effects are negligible, [8] worked on the two-dimensional unsteady free convective flow over an infinite vertical porous plate with oscillating wall temperature and constant suction. [9] studied the unsteady free convective flow through a porous plate with time-dependent temperature and concentration, and variable suction using the method of similarity transformation, and observed that the velocity increases with the increase in the convection current. [10] investigated unsteady mixed convective flow over an infinite vertical plate with periodic suction; [11] examined the radiation effects on mixed convection flow over an isothermal vertical surface in a saturated porous medium, and obtained self-similar solution; [12] numerically examined the unsteady free convective flow over an accelerating vertical plate with suction and heat transfer flux. [13] examined the unsteady mixed convective flow over a vertical porous plate with heat and mass transfer, periodic suction and oscillatory free stream using separation of variables and successive perturbation techniques, and found that the Stanton number increases as the porosity parameter increases but decreases as the Schmidt number increases.

Furthermore, the effects of MHD on the non-highly interacting flows were also investigated. For example, [14] investigated the flow past a vertical porous plate in the presence of transverse MHD and sinusoidal suction; [15] investigated the unsteady MHD free convective flow over a moving infinite porous vertical plate; [16] considered the MHD free convection flow of an incompressible and optically transparent porous medium with time-dependent suction and radiation heat transfer using asymptotic approximation, and observed that the radiation, porosity and magnetic field parameters affect the flow. [17] considered the MHD free convective flow over a vertical plate in the presence of radiation and surface temperature using numerical approach. [18] examined the unsteady MHD free convective flow through a porous medium with variable suction and constant heat flux. [19] studied the unsteady MHD natural convective flow with heat transfer past a semi-infinite vertical and moving plate with variable suction. [20] studied the unsteady MHD mixed convective flow and mass transfer over an accelerating infinite vertical plate with suction. [21] investigated the effects of mass transfer on MHD flow and heat transfer over a vertical porous plate with oscillatory suction and heat source. [22] worked on unsteady MHD heat and mass transfer with heat source, constant suction and radiation over a vertical porous plate using a perturbation technique, and noticed that unsteadiness is caused by time-dependent surface temperature and concentration. [23] studied the effects of viscous dissipation and thermal radiation on an unsteady MHD free convective flow over an infinite vertical plate constant suction and heat sink. [24] examined the thermal radiation effects on unsteady MHD flow past a vertical porous plate with variable suction using finite element method, and noticed that when velocity function is increased by the increase in the radiation parameter and porosity parameter but is decreased by the increase in Hartmann number, Prandtl number and Schmidt number; the temperature function increases with the increase in the radiation parameter, Hartmann number but is decreased with the increase in the Prandtl number; concentration is increased by the increase in the Schmidt number. [25] studied the transient free convective MHD flow of a viscous incompressible fluid over hot a porous plate under the attendant effects of heat source, viscous dissipation and variable temperature using the method of regular perturbation, and noticed that porosity has influential effect on the flow and viscous dissipation enhances the heating and cooling of the plate due to convective current. [26] considered the unsteady MHD mixed convective flow over a moving infinite vertical porous plate with suction in the presence of radiation and heat absorption/generation using similarity transformation and fourth order Runge-Kutta and shooting methods, and observed that the velocity increases with the increase in Grashof number but decreases through the increase in the suction, magnetic field parameters; the cooling of the plate is faster when the suction, radiation parameters and Prandtl number become large; heat source and sink enhances the temperature field; the skin friction, Nusselt number and Sherwood number increase as the suction parameter increases; the concentration decreases as the Schmidt number or suction parameter increases.

Examining the influence of chemical reaction, [27] investigated the effects of chemical reaction and variable viscosity on hydro-magnetic mixed convective heat and mass transfer for Hiemenz flow through a Darcy porous medium in the presence of radiation and magnetic field; [28] considered the effects of chemical reaction on a flow over an infinite vertical plate with constant suction and heat sink; [29] considered the effects of chemical reaction and radiation on an unsteady MHD free convection flow past a semi-infinite vertical plate with heat source and variable suction. [30] investigated the unsteady MHD heat and mass transfer in a flow over vertical porous plate with chemical reaction and thermal radiation. [31] examined numerically the effects of chemical reaction on an unsteady MHD free convective flow over an infinite vertical plate with constant suction. [32] investigated the chemical reaction effects on an unsteady MHD free convective flow past a semi-infinite porous plate with viscous dissipation; [33] considered the chemically reacting MHD boundary layer flow of convective heat and mass transfer flow over an infinite vertical porous plate with suction. [34] studied numerically the effects of chemical reaction in an unsteady MHD natural convective heat and mass transfer flow over an infinite vertical porous plate whose temperature oscillates with the same frequency as the variable suction, and noticed that the increase in: magnetic field decreases the velocity, skin friction; Prandtl number decreases the velocity, temperature, skin friction and Nusselt number; Schmidt number decreases the velocity, concentration, skin friction and

Sherwood number; chemical reaction rate decreases the velocity, concentration, skin friction and Sherwood number; both thermal and solutal Grashof numbers increase the skin friction.

In [7], we considered the unsteady flow of a chemically reacting fluid over a vertically accelerating plate with constant suction, which is greater than zero using the similarity solution. With the aim of getting the picture of the problem under different suction situations, this paper studies the case when suction is zero.

This paper is organized in the following manner: section 2 is the materials and method; section 3 gives the results and discussion, while section 4 gives the conclusion.

2. METHODOLOGY

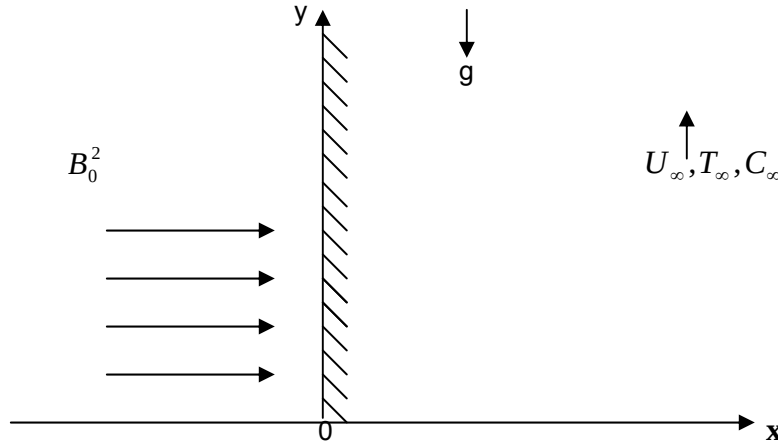


Fig. 1: The schematic model of a moving vertical surface in a fluid

This problem is formulated on the assumptions that the fluid is incompressible, viscous, Newtonian, magnetically susceptible and optically thin; the surface/plate is vertical and is accelerating upwards with the lower edge $y=0$ as the origin; the x -axis is normal to the plate; the pressure does not vary in the axial direction such that it is equal to the hydrostatic pressure (i.e. $p_o(x) = 0$); the flow is naturally convective; the suction is zero such that the plate is impermeable; the magnetic field is constant and is maintained in the x -direction; the problem is highly interactive such that the Dufour and Soret effects are significant. Upon the unsteady one-dimensional flow theory, the physical variables in this model in the Cartesian coordinates system are functions of y and t only. Furthermore, we assumed the plate wall concentration and temperature are sufficiently high to affect radiative heat transfer. So, if the axial velocity of the fluid is u ; the velocity of the fluid in the y -direction is v , and it is the velocity at which the fluid is sucked at the wall, by the Boussinesq approximations, the governing continuity, momentum, energy and diffusion equations are as follows:

$$\frac{\partial v}{\partial y} = 0 \quad (1)$$

$$\rho \left(\frac{\partial u}{\partial t} + v \frac{\partial u}{\partial y} \right) = \mu \frac{\partial^2 u}{\partial y^2} - \frac{\sigma_e B_0^2}{\mu_m} u + \rho g \beta_t (T - T_\infty) + \rho g \beta_c (C - C_\infty) \quad (2)$$

$$\rho C_p \left(\frac{\partial T}{\partial t} + v \frac{\partial T}{\partial y} \right) = k \frac{\partial^2 T}{\partial y^2} - \frac{Dk_t}{C_s} \frac{\partial^2 C}{\partial y^2} - \frac{\partial q_r}{\partial y} \quad (3)$$

$$\frac{\partial C}{\partial t} + v \frac{\partial C}{\partial y} = D \frac{\partial^2 C}{\partial y^2} - \frac{Dk_t}{T_m} \frac{\partial^2 T}{\partial y^2} \quad (4)$$

with the boundary conditions:

$$u = 0, T = T_w, C = C_w \text{ at } y = 0 \quad (5)$$

$$u \rightarrow 0, T \rightarrow T_\infty, C \rightarrow C_\infty \text{ at } y \rightarrow \infty \quad (6)$$

Radiative heat transfer is relevant in a high temperature regime and is equivalent to convective heat transfer. From Vincenti and Kruger [35], the gradient of a radiative heat flux for an optically thin fluid is defined as

$$\frac{\partial q_r}{\partial y} = -4\sigma\alpha \frac{\partial^2}{\partial y^2} (T^4 - T_\infty^4) \quad (7)$$

in which case $\alpha \ll 1$. This is a physical assumption for an optically thin/transparent fluid, and it depicts that the depth of penetration of the radiant rays α is far less than one, and the density is relatively low to allow long photon travel.

More so, we take the difference in temperature within the flow to be sufficiently small that we can state $\phi = T - T_\infty$, where ϕ is a non-constant small temperature correction factor; writing T^4 as a linear function of the temperature, we can express T^4 in a Taylor series about T_∞ as

$$T^4 = 4T_\infty^3 T - 3T_\infty^4 \quad (8)$$

In situations like this, we say the fluid is slowly radiating and as such $Ra < 1$, [see [16]]. Moreover, equation (1) shows that the velocity is not a function of y . But, from [36], the velocity v is prescribed as:

$$v = s \left(\frac{\nu}{t} \right)^{1/2} \quad (9)$$

where s , the suction parameter is a function of time. Motivated to investigate the flow characteristic behaviour when the suction is neither a function of y , t nor constant, in this paper, we assume the suction is zero such that the plate is impermeable and $v = s = 0$.

Introducing the similarity solution, dimensionless quantities, equations (7) and (8) in association with the suction condition into equations (1)-(6), we get

$$f'' + 2\eta f' - M_1^2 f = -Gr\Theta - Gr\Phi \quad (10)$$

$$\Theta'' + 2Pr\eta\Theta' = Ra[3(\Theta + N)^2\Theta'^2 + (\Theta + N)^3\Theta'] + D_r\Phi'' \quad (11)$$

$$\Phi'' + 2Sc\eta\Phi' = S_r\Theta'' \quad (12)$$

with the boundary conditions

$$f(0) = 1, \quad \Theta(0) = 1, \quad \Phi(0) = 1 \quad (13)$$

$$f(\infty) = 0, \quad \Theta(\infty) = 0, \quad \Phi(\infty) = 0 \quad (14)$$

where

$$u = Uf(\eta), \quad \eta = \frac{y}{2\sqrt{\nu t}} \quad (15)$$

are the similarity solutions,

$$\Theta = \frac{T - T_\infty}{T_w - T_\infty}, \quad \Phi = \frac{C - C_\infty}{C_w - C_\infty}, \quad Gr = \frac{4g\beta_t\nu(T_w - T_\infty)}{U}, \quad Gc = \frac{4g\beta_c\nu(C_w - C_\infty)}{U}, \quad M^2 = \frac{\sigma_e B_o^2 \nu}{\mu\mu_m} \quad (16)$$

$$Pr = \frac{\nu}{k_o}, \quad Sc = \frac{\nu}{D}, \quad N = \frac{T_\infty}{(T_w - T_\infty)}, \quad D_r = \frac{Dk_t(C_w - C_\infty)}{k_o C_s(T_w - T_\infty)}, \quad Ra = \frac{16\sigma\alpha(T_w - T_\infty)}{\nu k}$$

are the dimensionless quantities. It is noteworthy that there are many versions of similarity transformation equations. Equation (15) is used when the normal velocity v is assumed to be the suction, which can be a constant (zero or non-zero) or a variable function.

Equations (10)-(12) are nonlinear and highly coupled. So, to obtain analytic solutions we assume the fluid is slowly radiating such that $Ra < 1$ and perturb the equations. We seek for perturbation series solutions of the form

$$n = n_o + Ran_1 + Ra^2 n_2 + \dots \quad (17)$$

where n stands for the flow variables and n_i the order of perturbation.

Substituting equation (17) into equations (10)-(14), then collecting the coefficients of each power of Ra , and equating to zero, we get

$$f_o'' + 2\eta f_o' - M_1^2 f_o = -Gr\Theta_o - Gr\Phi_o \quad (18)$$

$$\Theta_o'' + 2Pr\eta\Theta_o' = -D_r\Phi_o'' \quad (19)$$

$$\Phi_o'' + 2Sc\eta\Phi_o' = S_r\Theta_o'' \quad (20)$$

with the boundary conditions

$$f_o(0) = 1 \quad \Theta_o(0) = 1, \quad \Phi_o(0) = 1 \quad (21)$$

$$f_o(\infty) = 0 \quad \Theta_o(\infty) = 0, \quad \Phi_o(\infty) = 0 \quad (22)$$

for the zeroth order

and

$$f_1'' + 2\eta f_1' - M_1^2 f_1 = -Gr\Theta_1 - Gr\Phi_1 \quad (23)$$

$$\Theta_1'' + 2Pr\eta\Theta_1' = (\Theta_o^3 + 3N\Theta_o^2 + 3N^2\Theta_o + N^2)\Theta_o' + (3N\Theta_o^2 + 6N\Theta_o + 3N^2)\Theta_o'^2 + D_r\Phi_1'' \quad (24)$$

$$\Phi_1'' + 2Sc\eta\Phi_1' = S_r\Theta_1'' \quad (25)$$

with the boundary conditions

$$f_1(0) = 0 \quad \Theta_1(0) = 0, \quad \Phi_1(0) = 0 \quad (26)$$

$$f_1(\infty) = 0 \quad \Theta_1(\infty) = 0, \quad \Phi_1(\infty) = 0 \quad (27)$$

for the first order .

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253 Additionally, we express the rate heat transfer (Nu) and rate mass transfer (Sh) as

$$Nu = k \frac{2q_w \sqrt{ut}}{(T_w - T_\infty)} = -\Theta'|_{\eta=0}, \quad (28)$$

$$Sh = D \frac{2s_w \sqrt{ut}}{(C_w - C_\infty)} = -\Phi'|_{\eta=0}, \quad (29)$$

$$\tau_o = \mu \frac{\partial u}{\partial \eta} \Big|_{\eta=0} = f'|_{\eta=0} \quad (30)$$

257 where

$$q_w = -k \frac{\partial T}{\partial y} \Big|_{y=0}, \quad s_w = -D \frac{\partial C}{\partial y} \Big|_{y=0}$$

259 Equations (18)-(30) are solved and the solutions plotted using the *Mathematica 11.0* computational software. The analysis
 260 of the solutions shows that *Mathematica 11.0* has difficulty in evaluating the definite integrals of the evolving Error and
 261 Hyper-geometric functions, which encase the Grashof numbers, Prandtl number, Schmidt number, Dufour and Soret
 262 number in the zeroth order velocity solution. Upon this, the roles of these parameters on the velocity factor are not
 263 quantifiable. Similarly, the analysis of the solutions shows that the order one equations, that is, equations (23)-(27) has
 264 empty or zero solutions within the specified region $\eta = 0$ and $\eta = \infty$. Therefore, the roles of the heat exchange
 265 parameter (N) and Raleigh number are not feasible in this problem.

266 3. RESULTS AND DISCUSSION

267

269 In this study, the influence of Dufour number, Soret number, Prandtl number, Schmidt number and magnetic field strength
 270 on the flow characteristics when the suction is zero (or the plate impermeable) are investigated and the results are shown
 271 graphically in Fig.2–Fig.15. For positively varied values of $Dr = 0.1, 0.3, 0.5, 0.7, 0.9, 1.2$; $Sr = 0.1, 0.3, 0.5, 0.7, 0.9, 1.2$;

272 $Pr = 0.5, 1.0, 1.5, 2.0, 2.5, 3.0$; $Sc = 0.5, 1.0, 1.5, 2.0, 2.5, 3.0$ and $M^2 = 0.1, 0.3, 0.5, 0.7, 0.9, 1.2$ the distributions are
 273 presented below.

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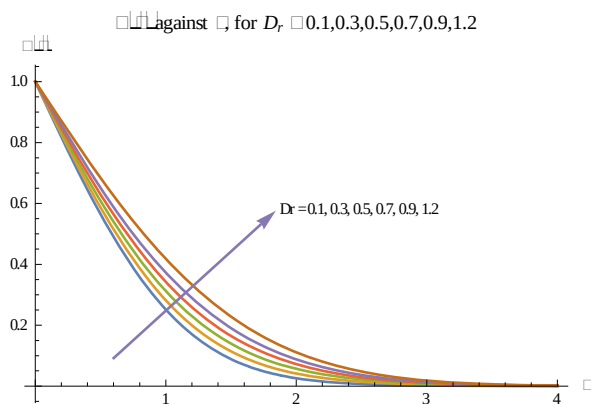


Fig. 2: Temperature $\Theta(\eta)$ -Dufour number (Dr) profiles

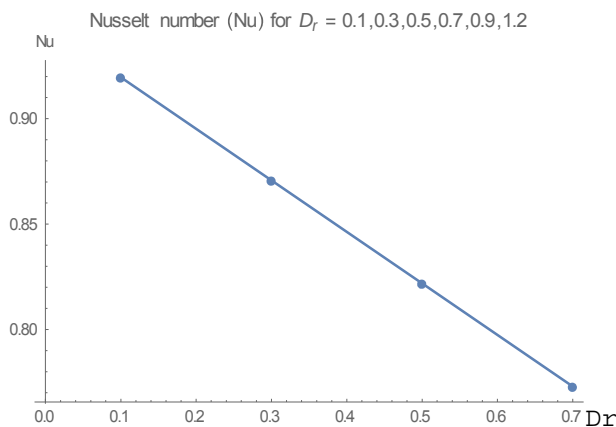


Fig. 3: Nusselt Number (Nu)-Dufour number (Dr) profile

The effects of Dufour number on the flow are shown in Figure 2 and Figure 3. Figure 2 depicts that the increase in the Dufour number increases the fluid temperature. The Dufour number has the potential of driving small fluid particles towards the hot surface. The small fluid particles driven towards the hot surface are energized; their kinetic energy, and of course, their temperature is increased. This may account for the increase in the fluid temperature. This result agrees with [7]. Figure 3 shows that the increase in the Dufour number reduces the rate at which heat is transferred to the fluid mainstream.

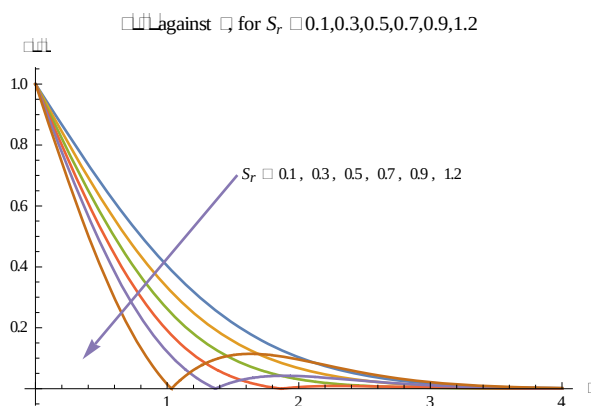


Fig. 4: Concentration $\Phi(\eta)$ -Soret number (Sr) profiles

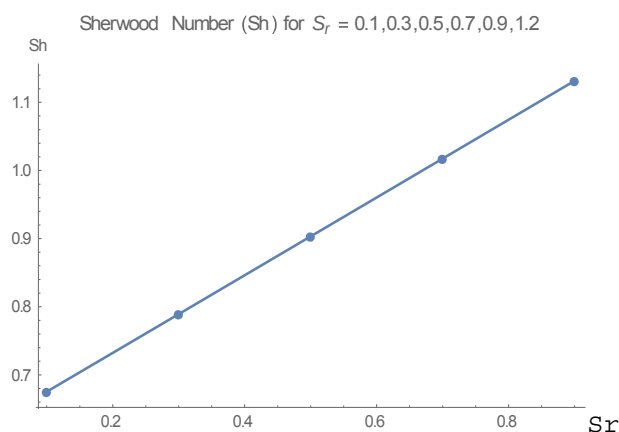


Fig. 5: Sherwood Number (Sh)-Soret number (Sr) profile

The effects of the Soret number on the flow are shown in Figure 4 and Figure 5. Figure 4 show that the increase in the Soret number decreases the fluid concentration. The Soret number has the tendency of drifting small fluid particles away from the hot surface to less hot region; as seen in [25]. This result aligns with [7]. Figure 5 depicts that the increase in the Soret number increases the rate of mass transfer to the main stream of the fluid system.

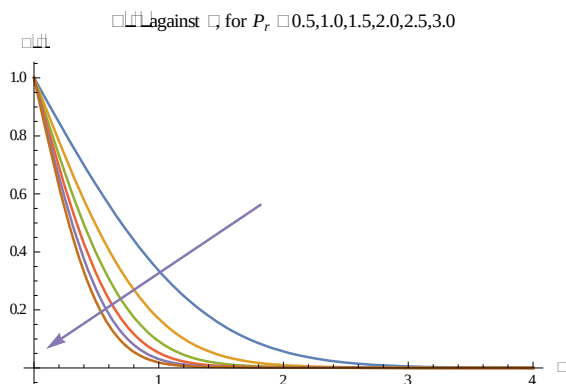


Fig. 6: Temperature $\Theta(\eta)$ -Prandtl number (Pr) profiles

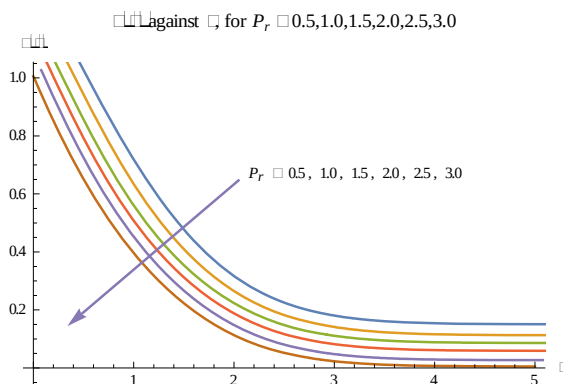


Fig. 7: Concentration $\Phi(\eta)$ -Prandtl number (Pr) profiles

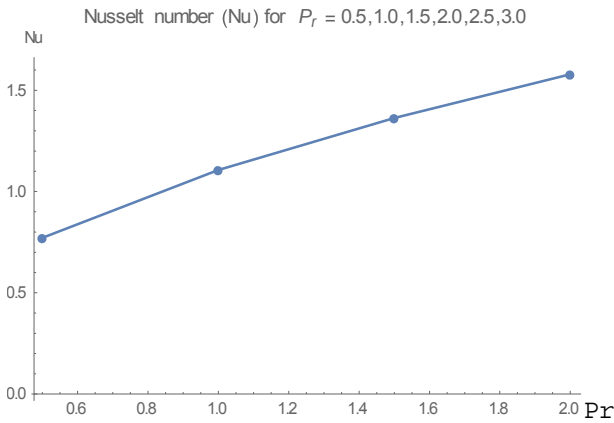


Fig. 8 : Nusselt Number (Nu) -Prandtl number (Pr) profile

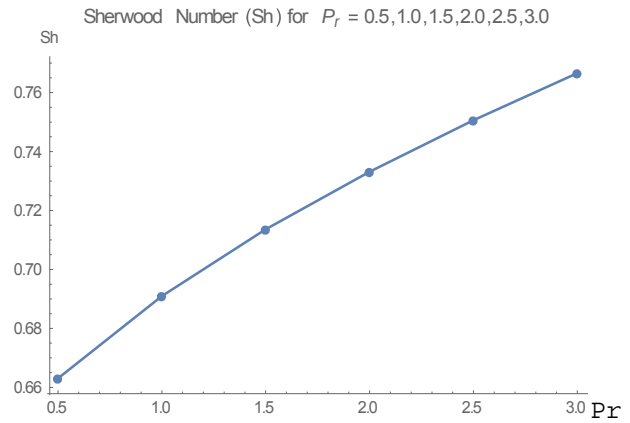


Fig. 9: Sherwood Number (Sh) -Prandtl number (Pr) profile

The roles of the Prandtl number on the flow variables are seen in Figure 6 – Figure 9. As in radiation phenomenon, the effects of the Prandtl number are noticeable when the temperature regime of the flow system is high. Figure 6 and Figure 7 show respectively, that the increase in the Prandtl number decreases the temperature and concentration. Additionally, Figure 8 and Figure 9, respectively, show that the increase in the Prandtl number leads to the increase in the rates of heat and mass transfer. These results are in consonance with [24, 25, 33]

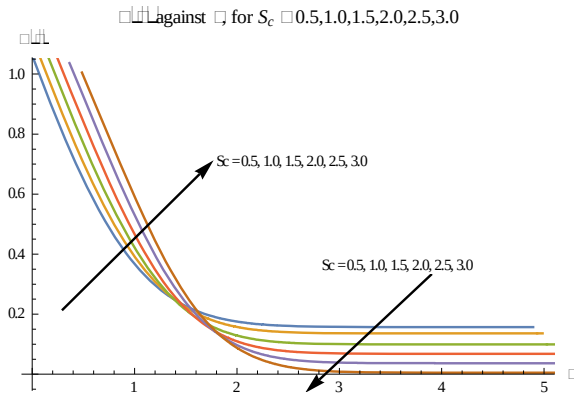


Fig. 10: Temperature $\Theta(\eta)$ -Schmidt number (Sc) profiles

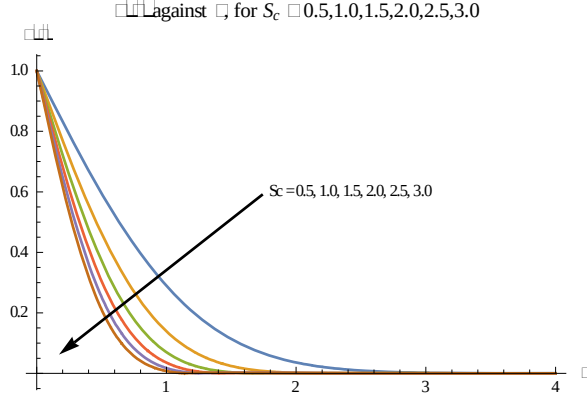


Fig. 11: Concentration $\Phi(\eta)$ - Schmidt number (Sc) profiles

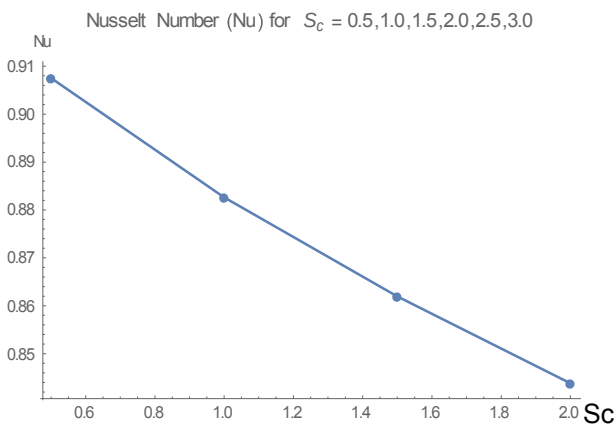


Fig. 12 : Nusselt Number (Nu) -Schmidt number (Sc) p profile

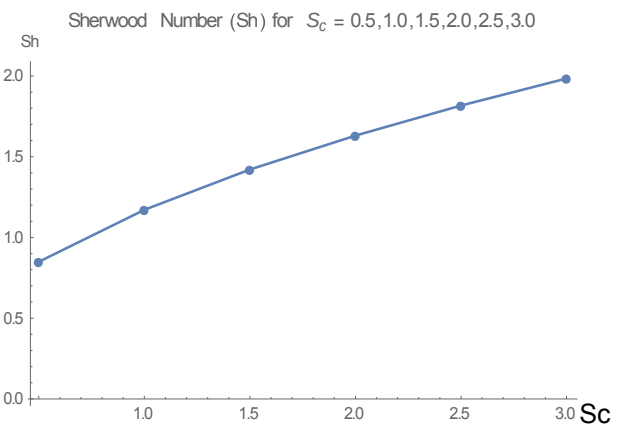


Fig. 13: Sherwood Number (Sh) - Schmidt number (Sc) profile

The influence of the Schmidt number on the flow variables are seen in Figure 10-Figure 13. Figure 10 shows that a twist occurs in the temperature distribution. In the region $\eta < 1.3$, the temperature increases as the Schmidt number increases. At $\eta = 1.3$, the temperature distribution curves converge and a twist occurs. The twist may be due to some adverse temperature gradient effect. And, at $\eta > 1.3$, the temperature decreases as the Schmidt number increases. Figure 11 shows that the concentration decreases as the Schmidt number increases; Figure 12 illustrates that the rate of heat transfer in the fluid decreases as the Schmidt number increases; Figure 13 depicts that the rate of mass transfer increases as the Schmidt number increases. These results are similar to those of [24, 25, 33]

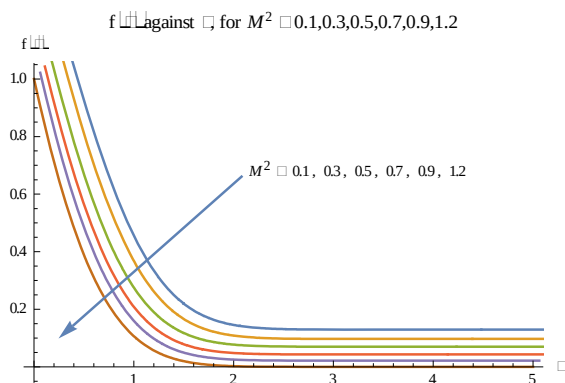


Fig. 14 : Velocity ($f(\eta)$) -Hartmann number (M^2) profiles

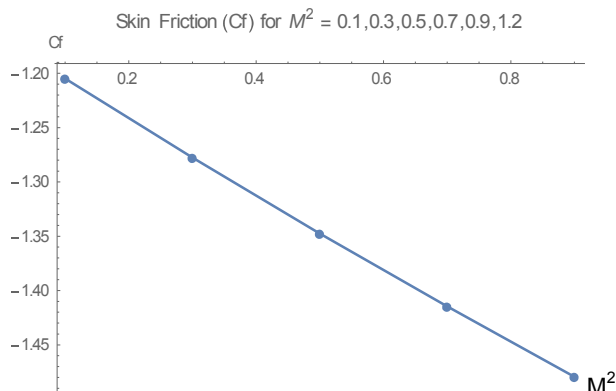


Fig. 15: Skin Friction (C_f) - Hartmann (M^2) number profile

The flow-modifying effects of magnetic field, which may be due to the interaction between the Earth magnetic field or other-wise, and the chemical content of the fluid are seen in Figure 14 and Figure 15. Figure 14 shows that the increase in the Hartmann number decreases the fluid velocity; Figure 15 depicts that the increase in the Hartmann number decreases the skin friction or the force exacted on the plate by the fluid.

4. CONCLUSION

We considered the transient MHD natural convective flow of an incompressible and optically thin fluid past a hot vertical plate in the presence of thermal radiation, thermo-diffusion, diffusion-thermo and zero suction effects using similarity transformation, perturbation series solutions, and Mathematica11.0 software. The analyses of results show that increase in:

- Dr increases the fluid temperature, but decreases the Nusselt number;
- Sr Soret number decreases the concentration, but increases the Sherwood number;
- Pr Prandtl number decreases the temperature and concentration, but increases the Nusselt number and Sherwood number;
- Sc Schmidt number leads to a twist in the temperature distribution, decreases the concentration and Nusselt number, but increases the Sherwood number;
- M^2 Hartmann number decreases the the velocity and skin friction.

REFERENCES

- [1] Awad FG, Sibanda P, Narayana M, Motsa SS. Radiative Convection from a semi-finite plate in a fluid saturated porous medium with cross-diffusion and heat transfer. Int. J. Phys. Sci.2011; 6(21):4910-4923. DOI: 10.5897/IJPS11.295.
- [2] Srinivasacharya D, Mallikarjuna B, Bhuvanavijaya R. Soret and Dufour effects on mixed convection along a vertical wavy surface in a porous medium with variable properties, Ain Shams Eng. J. 2015; 6(2):553-564. <http://dx.doi.org/10.1016/j.asej.2014.11.007>.
- [3] Gnaneshwar Reddy M, Bhaskar Reddy N. Soret and Dufour effects on steady MHD free convection flow past a semi infinite moving vertical plate in a porous medium with viscous dissipation. Int. J. Appl. Math and Mech. 2010; 6(1):1-12.
- [4] Shateyi S, Motsa SS, Sibanda P. The effects of thermal radiation, Hall currents, Soret, and Dufour on MHD flow by mixed convection over a vertical surface in porous media. Math. Problems in Eng. 2010; DOI: 10.1155/2010/627475.
- [5] Seethamahalakshmi BD, Prasad CN, Ramana Reddy GV. MHD free convective mass transfer flow past an infinite vertical porous plate with variable suction and Soret effect. Asian J. Current Eng. and Maths. 2012; 1(2):49-55
- [6] Pattnaik J.R., Dash G.C , Singh S, Diffusion-thermal effects with hall currents on unsteady hydrodynamic flow past an infinite vertical plate. Alexandria Eng. J. 2017; (56):13-25
- [7] Okuyade WIA, Abbey TM, Gimalaabel AT. Unsteady MHD free convective chemically reacting flow over a vertical plate with thermal radiation, cross-diffusion and constant suction effects. Alexander Eng. J. 2018; ID: AEJ-D-17-01044 – (Accepted, in press)

- [8] Soundalgekar VM, Wavre PD. Unsteady free convective flow past an infinite vertical plate with variable suction and mass transfer. *Inter. J. Heat Mass Transf.* 1977; (20):1375-1380
- [9] Sattar Abdus MD. Free convection and mass transfer flow through a porous medium past an infinite vertical plate with time –dependent temperature and concentration. *Indian J. Pure and Applied Math.* 1994; 759-766.
- [10] Singh KD, Verma GN, Kumar S. Effects of mass transfer on a 3-D unsteady forced and free convective flow past an infinite vertical plate with periodic suction. *Proc. Nat. Acad. Sci. India.* 1995; 65(A):293-308.
- [11] Bakier AY. Thermal radiation effects on a mixed convection from a vertical surface in a saturated porous medium. *Inter. Com. Heat and Mass Transf.* 2001; 28(1):119-126
- [12] Das SS, Satapathy A, Das JK., Sahoo SK. Numerical solution of unsteady free convective MHD flow past an accelerated vertical plate with suction and heat flux. *J. Ultra Scienc Phys. Sc.* 2007; 19(1):105-112.
- [13] Halem Ali Attia. On the effectiveness of porosity on the unsteady mixed convective flow along an infinite vertical porous plate with heat and mass transfer, periodic suction and oscillatory free stream velocity. *Tankang J. Sci. and Eng.* 2011;14(4):285-291
- [14] Gersten K, Gross JF. Flow and heat transfer along a plane wall with periodic suction. *ZAMP.* 1974; (25):399-408
- [15] Bansal JL, Dave A, Jat RN. Heat and mass transfer in unsteady hydrodynamic free convective flow past an accelerated vertical plate. *Proc. Nat. Acad. Sc., India.* 1990; 60(A):211-226
- [16] Alagoa KD, Tay G, Abbey TM. Radiative and free convective effects of a MHD flow through a porous medium between infinite parallel plates with time-dependent suction. *Astrophys. Space Sci.* 1998; 260(4):455-468
- [17] Abdel-Naby MA. Finite difference solution of radiation effects on MHD unsteady free convective flow over a vertical plate with variable surface temperature. *J. Applied Math.* 2003; (2):65-86
- [18] Sarangi KC, Jose CB. Unsteady MHD free convective flow and mass transfer through a porous medium with variable suction and constant heat flux. *J. Indian Acad. Math.* 2004; 26:115-126
- [19] Kim YJ. Unsteady MHD convective heat transfer past a semi-infinite vertical porous moving plate with variable suction. *Inter. J. Eng. Sci.* 2008; 38: 833-845.
- [20] Das SS, Mitra M. Unsteady MHD mixed convective flow and mass transfer past an accelerated infinite vertical plate with suction. *Indian J. Sci. and Tech.* 2009; 2(5):18-22
- [21] Das SS, Satapathy A, Das JK, Panda JP. Mass and heat effects on MHD flow past a vertical porous plate through a porous medium under oscillatory suction and heat source. *Inter. J. Heat Mas Transf.* 2009; (52):5962-5969.
- [22] Pal D, Talukdar B. Pertubation analysis of unsteady MHD convective heat and mass transfer in a boundary layer slip flow past a vertical permeable plate with thermal radiation and chemical reaction. *Comm. Non-linear and Num. Simulat.* 2010; 15(7):1813-1830
- [23] Narayana PV, Satya Kesavaiah D, Venkataramana S. Viscous dissipation and thermal radiation effects on an unsteady MHD convection flow past a semi-infinite vertical permeable moving porous plate. *Inter. J. Math. Archives.* 2011; 2(4):476-487
- [24] Gundagani M, Sivaiah S, Babu NVN, Reddy MCK. Finite element solution of thermal radiation effect on unsteady MHD flow past a vertical porous plate with variable suction. *Ameri. Acad. Scholarly Res. J.* 2012; 4(3); www.aasrc.org/aasr
- [25] Acharya AK, Dash GC, Mishra SR. Free Convective Fluctuating MHD Flow Through Porous Media Past a Vertical Porous Plate with Variable Temperature and Heat Source. *Physics Research Inter.* 2014, (2014):1-9. [Http://Dx.Doi.Org/10.1155/2014/587367](http://Dx.Doi.Org/10.1155/2014/587367)
- [26] Dei RLVR, Neeraja A, Reddy NB. Effects of radiation on an unsteady MHD mixed convection flow past an accelerated vertical porous plate with suction and chemical reaction. *Inter. J. Techni. Res. and Applicat.* 2016; 4(2):1-8

- [27] Seddeek MA, Darwish AA, Abdelmeguid, MS. Effects of chemical reaction and variable viscosity on a hydro-magnetic mixed convective heat and mass transfer for Hiemenz flow through porous media with radiation. *Com. Nonlinear Sci. and Numer. Simulat.* 2007;12(2):195-213
- [28] Gireesh Kumar J, Satya Narayana PV, Ramakrishna S. Effects of chemical reaction and mass transfer on MHD unsteady free convective flow past an infinite vertical plate with constant suction and heat sink. *J. Ultra Sci.* 2009; 21(3):12-28
- [29] Sudheer Babu M, Satya Narayana PV. Effects of chemical reaction and thermal radiation on heat and mass transfer through a porous medium with variable suction in the presence of uniform magnetic field. *J. Heat and Mass Transf.* 2009; V: 219-234
- [30] Kesavaiah D Ch, Satya Narayana PV. Venkataramana S. Effects of chemical reaction and radiation absorption on an unsteady MHD free convective heat and mass transfer flow past a semi-infinite vertical permeable moving plate embedded in a porous medium with heat source and suction. *J. Applied Math. and Mech.* 2011; 7(1): 652-699
- [31] Anand RJ, Shivaiah S. Chemical reaction effects on an unsteady MHD flow past a vertical porous plate with constant suction. *Indust. Chem. Eng.* 2011; (17):249-257
- [32] Anand RJ, Shivaiah S. Chemical reaction effects on an unsteady MHD flow past a vertical porous plate with viscous dissipation. *J. Applied Math. and Mech. (Engineering Edition).* 2012; 32(8):1065-1078
- [33] Gangadhar K., Reddy BN. Chemically reacting MHD boundary layer flow of heat and mass transfer over a moving vertical plate with suction in a porous medium with suction. *J. Applied Fluid Mech.* 2013; 6(1):107-114
- [34] Sarada K, Shanker B. The effect of chemical reaction on an unsteady MHD free convective flow past an infinite vertical porous plate with a variable suction. *Inter. J. Modern Eng. Res.* 2013; 3(2):725-735
- [35] Vincenti WG, Krugger GH. *Introduction to physical gas-dynamics*, New York, 1965.
- [36] Singh AK., Soundalgekar VM. Transient Free convection in cold water past a vertical porous plate. *Int. J. Energy Res.* 1990; (14): 413-42