AN UNSTEADY MHD FLOW OF CASSON FLUID PAST AN EXPONENTIALLY ACCELERATED VERTICAL PLATE

U. J. DAS

Department of Mathematics, Gauhati University, Guwahati-781014, Assam, India.
Email: utpaljyotidas@yahoo.co.in

***Abstract*— An unsteady, magnetohydrodynamic, incompressible, radiative Casson fluid flow past an infinite vertical permeable plate, which is accelerated exponentially, in presence of heat sink parameter and first-order chemical reaction taking account of Soret effect, is considered. Governing equations are solved for the profiles of velocity, temperature and concentration with the help of Laplace transform. The effects of various physical parameters on velocity, temperature and concentration profiles are discussed with the help of graphs. It is seen that the Casson parameter increases the fluid velocity near the plate, but away from the plate it is opposite. Also, an increase in Casson parameter has a significant increase in skin friction. Velocity has a significant increase with increase in the accelerating parameter, Soret number and chemical reaction parameter, while heat sink parameter, radiation parameter reduces the fluid velocity.**

***Keywords*— Casson fluid, Soret effect, Magnetohydrodynamic, Laplace transform**

I. INTRODUCTION

The study of heat and mass transfer problems of non-Newtonian Casson fluid with porous medium is prevalent in polymer industries and medical applications. Casson fluid is a non-Newtonian shear thinning fluid in which viscosity is assumed to be infinity at zero shear rate. The constitutive equation of the Casson fluid model was developed by Casson (1959) in his investigation on flow equations for pigment oil suspensions of printing ink type. Significant studies on Casson fluid flow have been conducted by several authors (Scott Blair, 1959; Merrill *et al.*, 1965; Nadeem *et al.*, 2012; Mukhopadhyay, 2013; Immanuel *et al.*, 2015; Subba Rao *et al.*, 2015; Ibrahim and Makinde, 2016; Oyelakin *et al.*, 2016; Animasaun *et al.*, 2016) in different fluid flow situations.

Magnetohydrodynamic convective flow past an accelerating plate with heat and mass transfer has wide applications in different technological fields. Gupta (1960) studied the magnetohydrodynamic, transient free convective flow past a vertical plate. Muthucumaraswamy *et al.* (2008) studied the flow past an exponentially accelerated infinite vertical plate in the presence of variable surface temperature. Modather *et al.* (2009) studied the MHD oscillatory flow of a micropolar fluid over a vertical permeable plate. Ahmed *et al.* (2015) studied the MHD radiating flow of Newtonian fluids over an infinite vertical permeable plate with variable temperature and concentration. Das (2016) studied mixed convective MHD flow of an elastico-viscous fluid past a vertical plate in the presence of thermal radiation and chemical reaction with an induced magnetic field. Seth *et al.* (2017) examined an unsteady magneto-hydrodynamic double diffusive natural convective flow over exponentially accelerated plate. Das (2019) studied three dimensional MHD flow past an infinite inclined plate. Chamkha and Aly (2010), Gorla and Chamkha (2011), Krishna and Chamkha (2019) investigated the MHD flow of nanofluid past an infinite vertical plate with different physical conditions. Gudekote and Choudhari (2018) and Rajashekhar *et al.* (2018) studied the peristaltic transport of Casson fluid in a tube. Divya *et al.* (2020) studied the hemodynamics of variable liquid properties on MHD peristaltic mechanism of Jeffrey fluid.

To the best of the author's knowledge, unsteady MHD flow of Casson fluid past an exponentially accelerated vertical plate with variable temperature and concentration through a permeable medium never considered in the literature. The objective of the present study is concerned to an unsteady free convective MHD flow of an incompressible, radiative Casson fluid past an ex-ponentially accelerated infinite vertical permeable plate through porous medium in presence of heat sink and first-order chemical reaction parameter taking account of Soret effect. This type of study may find applications in material processing and geothermal energy systems.

II. MATHEMATICAL FORMULATION

An unsteady free convective MHD flow of an incompressible, radiative Casson fluid past an infinite vertical permeable plate through porous medium in presence of heat sink parameter and first-order chemical reaction taking account of Soret effect is considered. The x-axis is considered along the vertical plate and y-axis is considered along the normal to the vertical plate. The fluid is considered slightly conducting so that the magnetic Reynolds number is very small and thus the induced magnetic field can be neglected

The rheological equation of a Casson fluid model (Mustafa *et al.*, 2011) can be written as

$$\sigma_{ij} = \begin{cases} 2\left\{\mu_B + \left(\frac{P_y}{\sqrt{2\pi}}\right)\right\} e_{ij}, \pi \geq \pi_c \\ 2\left\{\mu_B + \left(\frac{P_y}{\sqrt{2\pi_c}}\right)\right\} e_{ij}, \pi < \pi_c \end{cases},$$

where σ_{ij} is stress tensor, e_{ij} is deformation rate, π is product of the component of the deformation rate with itself, π_c is a critical value which is based on the non-Newtonian model, μ_B is plastic dynamic viscosity and P_y is the yield stress of the fluid. If shear stress is greater than yield stress then it starts to move, whereas if a shear stress is less than yield stress it behaves likes a solid.

https://doi.org/10.52292/j.laar.2021.588

Here, the plate is accelerated exponentially with velocity $u = u_0\exp(\bar{b}\bar{t})$ at time $\bar{t} > 0$ along its own plane and variations in temperature and concentration are considered to be of similar nature. The flow variables are dependent only on y, t and independent of x because of the infinite plate assumption and hence the flow reduces to one dimensional and the convective term reduces to zero. Thus, the governing equations of the flow are (Mustafa *et al.*, 2011 and Ahmed *et al.*, 2015):

$$\frac{\partial u}{\partial \bar{t}} = \upsilon\left(1+\frac{1}{\beta}\right)\frac{\partial^2 u}{\partial y^2} + g\beta_T(T-T_\infty) + g\beta_c(C-C_\infty) - \frac{\sigma B_0^2 u}{\rho} - \frac{\upsilon u}{\bar{K}}, \quad (1)$$

$$\frac{\partial T}{\partial \bar{t}} = \frac{\kappa}{\rho C_p}\frac{\partial^2 T}{\partial y^2} - \frac{1}{\rho C_p}\frac{\partial q_r}{\partial y} - \frac{Q_0}{\rho C_p}(T-T_\infty), \quad (2)$$

$$\frac{\partial C}{\partial \bar{t}} = D\frac{\partial^2 C}{\partial y^2} - \bar{K}_r(C-C_\infty) + D_t\frac{\partial^2 T}{\partial y^2}. \quad (3)$$

The initial and boundary conditions are

$$u = 0, T = T_\infty, C = C_\infty \text{ for all } y \text{ when } \bar{t} = 0;$$
$$u = u_0\exp(\bar{b}\bar{t}), T = T_\infty + (T_w - T_\infty)A\bar{t},$$
$$C = C_\infty + (C_w - C_\infty)A\bar{t} \text{ for } y = 0, \bar{t} > 0;$$
$$u \to 0, T \to T_\infty, C \to C_\infty \text{ for } y \to \infty, \bar{t} > 0, \quad (4)$$

where $\beta = \mu_B\sqrt{2\pi_c}/P_y$ is Casson parameter and $A = u_0^2/\upsilon$.

For optically thin fluid,

$$\frac{\partial q_r}{\partial y} = -4\bar{a}\bar{\sigma}(T_\infty^4 - T^4), \quad (5)$$

Using Taylor series about T and neglecting the higher-order terms, we get

$$T^4 = -4T_\infty^3 T - 3T_\infty^4. \quad (6)$$

Non-dimensional quantities introduced are

$$U = \frac{u}{u_0}, Y = \frac{yu_0}{\upsilon}, t = \frac{\bar{t}u_0^2}{\upsilon}, \theta = \frac{T-T_\infty}{T_w-T_\infty}, \phi = \frac{C-C_\infty}{C_w-C_\infty},$$
$$\Pr = \frac{\mu c_p}{\kappa}, M = \frac{\sigma B_0^2\upsilon}{\rho u_0^2}, Gr = \frac{g\beta_t\upsilon(T_w-T_\infty)}{u_0^3}, R = \frac{16\bar{a}\upsilon^2\sigma\bar{T}_\infty^3}{\kappa u_0^2},$$
$$Gc = \frac{g\beta_c\upsilon(C_w-C_\infty)}{u_0^3}, Q = \frac{Q_0\upsilon}{\rho C_p u_0^2}, Sc = \frac{\upsilon}{D}, S_r = \frac{D_t(T_w-T_\infty)}{\upsilon(C_w-C_\infty)},$$
$$K_r = \frac{\bar{K}_r\upsilon}{u_0^2}, K = \frac{\bar{K}u_0^2}{\upsilon^2}, a = \frac{\bar{b}\upsilon}{u_0^2}, \quad (7)$$

where Pr, M, Q, Sc, K, R, S_r and K_r are Prandtl number, Hartmann number, heat sink parameter, Schmidt number, non dimensional porosity parameter, radiation parameter, Soret number and chemical reaction parameter, respectively.

The Eqs. (1)-(3), using (5)-(7), in non-dimensional form become

$$\frac{\partial U}{\partial t} = \left(1+\frac{1}{\beta}\right)\frac{\partial^2 U}{\partial Y^2} + Gr\theta + Gc\phi - \left(M+\frac{1}{K}\right)U, \quad (8)$$

$$\Pr\frac{\partial \theta}{\partial t} = \frac{\partial^2\theta}{\partial Y^2} - R\theta - \Pr Q\theta, \quad (9)$$

$$Sc\frac{\partial \phi}{\partial \bar{t}} = \frac{\partial^2\phi}{\partial Y^2} - K_r Sc\phi + S_r Sc\frac{\partial^2\theta}{\partial Y^2}. \quad (10)$$

with

$$U = 0, \theta = 0, \phi = 0 \text{ for all } Y \text{ when } t = 0;$$
$$U = \exp(at), \theta = t, \phi = t \text{ for } Y = 0, t > 0;$$
$$U \to 0, \theta \to 0, \phi \to 0 \text{ for } Y \to \infty, t > 0. \quad (11)$$

III. SOLUTION OF THE PROBLEM

The unsteady coupled partial differential Eqs. (8)–(10) under the boundary condition (11) have been solved analytically by using Laplace transform technique and the solutions are obtained as:

$$U = \exp(at)\, f_1(A_8, Y, z+b_{26}, t) + b_{13}f_1(A_8, Y, b_{26}, t) + b_{14}f_2(A_8, Y, b_{26}, t) + b_{15}\exp(-A_3t)\, f_1(A_8, Y, b_{26}, t) + b_{16}\exp(A_{10}t)\, f_1(A_8, Y, b_{26}, t) + b_{17}\exp(A_{11}t)\, f_1(A_{11}, Y, b_{26}, t) + b_{18}f_1(\Pr, Y, R+\Pr Q, t) + b_{19}f_2(\Pr, Y, R+\Pr Q, t) + b_{20}\exp(-A_3t)\, f_1(\Pr, Y, R+\Pr Q-A_3, t) + b_1\exp(A_{10}t)\, f_1(\Pr, Y, R+\Pr Q-A_{10}, t) + b_{22}f_1(Sc, Y, Kr, t) + b_{23}f_2(Sc, Y, Kr, t) + b_{24}\exp(-A_3t)\, f_1(Sc, Y, Kr-A_3, t) + b_{25}\exp(A_{11}t)\, f_1(Sc, Y, Kr-A_{11}, Y, t),$$

$$\theta = \frac{1}{2}\{\psi_1\operatorname{erfc}(\psi_2) + \psi_3\operatorname{erfc}(\psi_4)\},$$

$$\phi = (1+B_2)f_2(Sc, K_r, Y, t) - (B_1+B_2)f_1(Sc, Y, K_r, t) + (B_1+B_2)\exp(-A_3t)\, f_1(Sc, Y, K_r-A_3, t) - B_2f_1(\Pr, Y, R+\Pr Q, t) + B_2f_2(\Pr, R+\Pr Q, Y, t) + B_2\exp(-A_3t)\, f_1(\Pr, Y, R+\Pr Q-A_3, t).$$

Skin friction is given by

$$-\left[\left(1+\frac{1}{\beta}\right)\frac{\partial u}{\partial y}\right]_{y=0} = \exp(at)\, F_1(A_8, a+b_{26}, t) + b_{13}F_1(A_8, b_{26}, t) + b_{14}F_2(A_8, b_{26}, t) + b_{15}\exp(-A_3t)\, F_1(A_8, b_{26}-A_3, t) + b_{16}\exp(A_{10}t)\, F_1(A_8, b_{26}+A_{10}, t) + b_{17}\exp(A_{11}t)\, F_1(A_{11}, b_{26}+A_{11}, t) + b_{18}F_1(\Pr, R+\Pr Q, t) + b_{19}F_2(\Pr, R+\Pr Q, t).$$

Heat transfer is given by

$$Nu = -\left[\frac{\partial\theta}{\partial y}\right]_{y=0} = F_2(\Pr^2, R+\Pr Q, t).$$

Sherwood number is given by

$$Sh = -\left[\frac{\partial\phi}{\partial y}\right]_{y=0} = (1+B_2)F_2(Sc, K_r, t) - (B_1+B_2)F_1(Sc, K_r, t) + (B_1+B_2)\exp(-A_3t)\, F_1(Sc, K_r-A_3, t) - B_2F_1(\Pr, R+\Pr Q, t) + B_2F_2(\Pr, R+\Pr Q, t) + B_2\exp(A_3t)\, F_1(\Pr, R+\Pr Q-A_3, t).$$

where

$$f_1(x, y, z, t) = \frac{1}{2}\left[\exp(y\sqrt{xz})\operatorname{erfc}\left(\frac{y}{2}\sqrt{\frac{x}{t}} + \sqrt{zt}\right) + \exp(-y\sqrt{xz})\operatorname{erfc}\left(\frac{y}{2}\sqrt{\frac{x}{t}} - \sqrt{zt}\right)\right],$$

$$f_2(x, y, z, t) = \frac{1}{2}[\psi_5\operatorname{erfc}(\psi_6) + \psi_7\operatorname{erfc}(\psi_8)],$$

$$\psi_1 = \left(t + \frac{Y\Pr}{2\sqrt{R+\Pr Q}}\right)\exp\left(Y\sqrt{R+\Pr Q}\right),$$

$$\psi_2 = \frac{Y}{2}\sqrt{\frac{\Pr}{t}} + \sqrt{\left(\frac{R+\Pr Q}{\Pr}\right)t},$$

$$\psi_3 = \left(t - \frac{Y\Pr}{2\sqrt{R+\Pr Q}}\right)\exp\left(-Y\sqrt{R+\Pr Q}\right),$$

$$\psi_4 = \frac{Y}{2}\sqrt{\frac{\Pr}{t}} - \sqrt{\left(\frac{R+\Pr Q}{\Pr}\right)t},$$

$$\psi_5 = \left(t + \frac{x}{2}\sqrt{\frac{x}{y}}\right)\exp(z\sqrt{xy}), \psi_6 = \frac{z}{2}\sqrt{\frac{x}{t}} + \sqrt{yt},$$

$$\psi_7 = \left(t - \frac{z}{2}\sqrt{\frac{x}{y}}\right)\exp(-z\sqrt{xy}), \psi_8 = \frac{z}{2}\sqrt{\frac{x}{t}} - \sqrt{yt},$$

$$\psi_9 = \frac{1}{2}\sqrt{\frac{x}{y}}\operatorname{erf}(\sqrt{yt}),$$

$$\psi_{10} = \left[\sqrt{xy}\operatorname{erf}(\sqrt{yt}) + \sqrt{\frac{x}{\pi t}}\exp(-yt)\right],$$

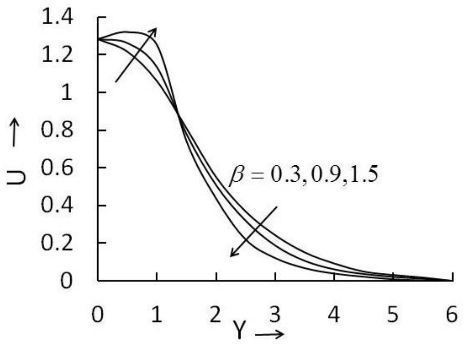

Fig. 1. Effect of β on velocity.

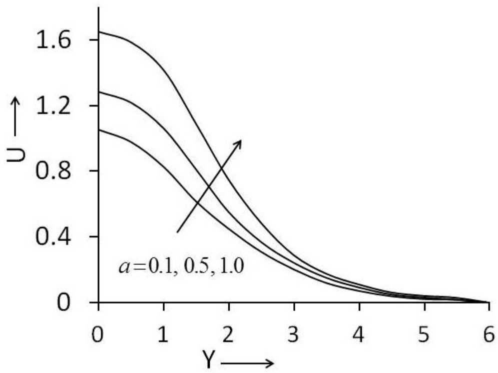

Fig. 1. Effect of a on velocity.

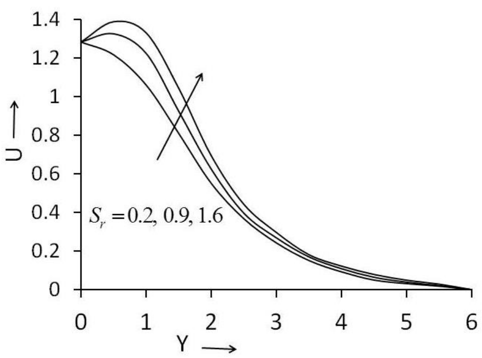

Fig. 3. Effect of S_r on velocity.

$$F_1(x,z,t) = \sqrt{xz}\,\mathrm{erf}\big(\sqrt{zt}\big)\sqrt{\frac{x}{\pi t}}\exp(-zt)\ ,$$

$$F_2(x,z,t) = \psi_9 + t\psi_{10}.$$

Constants A´s, b´s and c´s are not presented here for brevity.

IV. RESULTS AND DISCUSSIONS

Numerical calculations have been carried out to analyze the effects of various flow parameters with the following parameter values: $\Pr = 1$, $a = 0.5$, $t = 0.5$, $M = 1$, $R = 2$, $Gr = 2$, $Sc = 2$, $K = 0.5$, $Gc = 0.2$, $S_r = 0.2$, $K_r = 0.2$, $\beta = 0.2$ and $Q = 0.2$.

Figures 1-6 represent the velocity against Y for different values of Casson parameter (β), accelerating parameter (a), Soret number (S_r), chemical reaction parameter (K_r), heat sink parameter (Q), and radiation parameter (R), respectively. Figure 1 reveals that velocity profile increases with the increasing values in Casson parameter

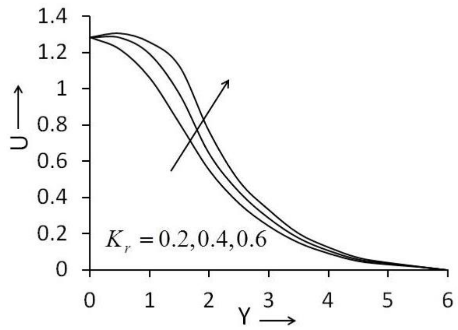

Fig. 4. Effect of K_r on velocity.

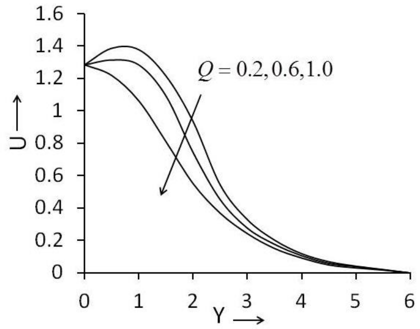

Fig. 5. Effect of Q on velocity.

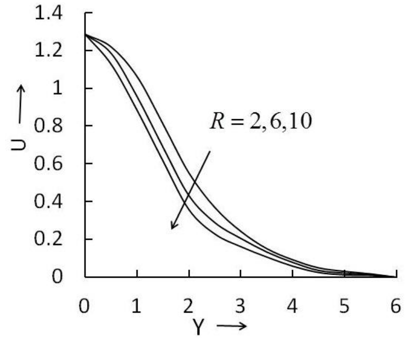

Fig. 6. Effect of R on velocity.

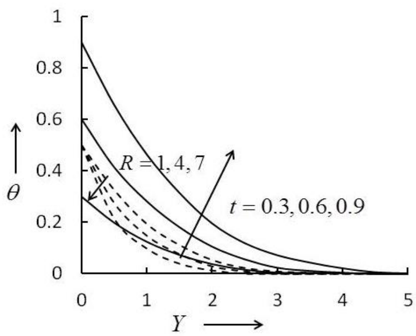

Fig. 7. Effect of t on temperature.

for $0 \le y \le 1.4$, but thereafter when $y \ge 1.4$ opposite result is seen. As expected, it is seen from Fig.2 that an increase in accelerating parameter a enhances the fluid velocity. Figures 3-6 show that fluid velocity enhances due an increase in Soret number, chemical reaction parameter, while opposite effect is seen for heat sink pa-

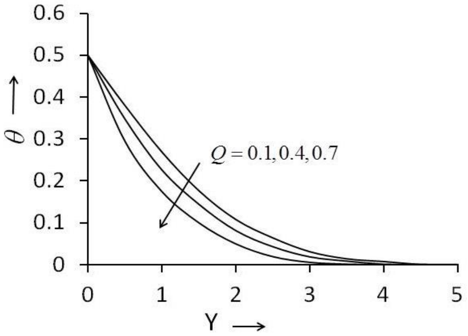

Fig. 8. Effect of Q on temperature.

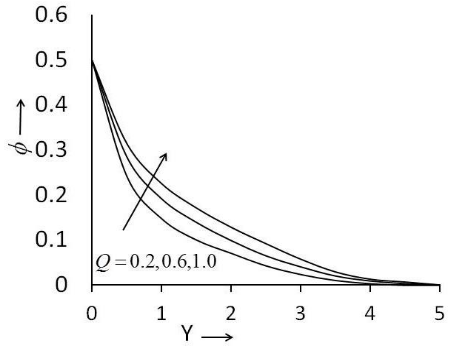

Fig. 9. Effect of Q on concentration.

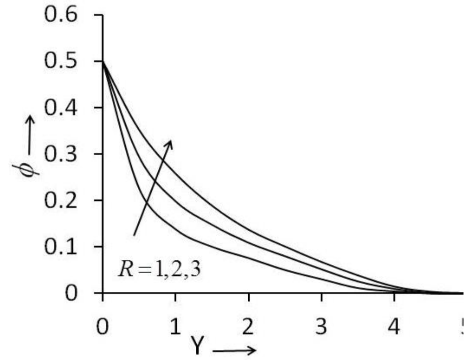

Fig. 10. Effect of R on concentration.

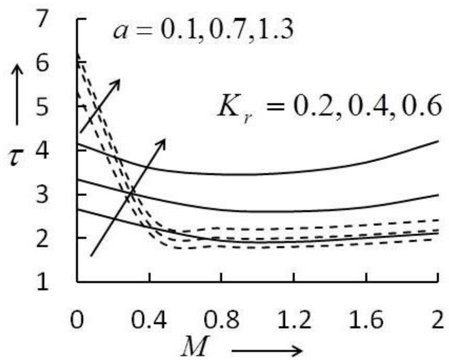

Fig. 11. Effect of K_r on skin friction.

rameter and radiation parameter. Soret number expresses the ratio of temperature difference to the concentration. So, the thermal diffusion factor which enhances the fluid velocity. Introduction of heat sink parameter and radiation parameter reduces the temperature of the fluid and thus reduces the fluid velocity.

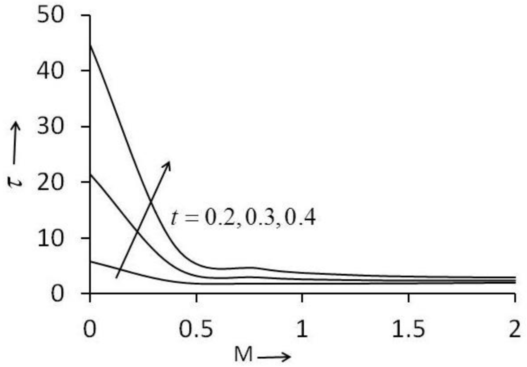

Fig. 12. Effect of t on skin friction.

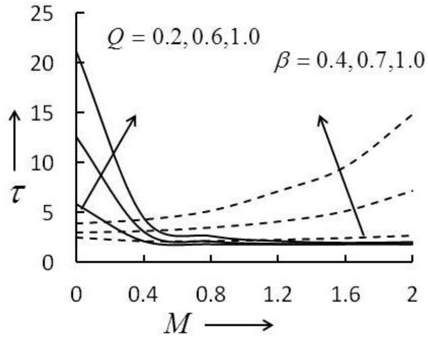

Fig. 13. Effect of Q on skin friction.

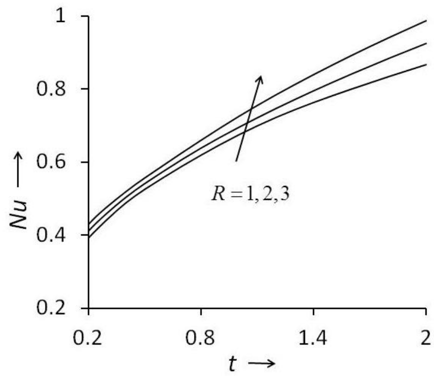

Fig. 14. Effect of R on Nusselt number.

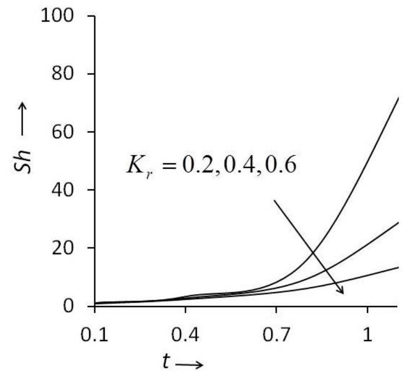

Fig. 15. Effect of K_r on Sherwood number.

By setting $\beta \to \infty$, $K_r = 0$, $Q = 0$ and $S_r = 0$, the results obtained for temperature and concentration profiles are compared with the results obtained by Ahmed *et al.* (2015) and that are found in good agreement.

Figures 7 represent temperature profile against Y for different values of time and radiation parameter. It is observed that temperature increases with the increasing values of time whereas it decreases with increasing radiation parameter. Figure 8 shows that temperature reduces due to an increase in the strength of heat sink parameter. Thus the heat sink parameter or radiation parameter reduces the thickness of the thermal boundary layer and in fact provides an additional factor for diffusing energy.

Also, it is seen that temperature decreases sharply near the plate and then steadily diminishes to zero at far away due to the introduction of heat absorption parameter.

Figures 9-10 represent the concentration profiles against Y for different values of heat sink parameter and radiation parameter respectively, and observed that concentration increases with the increasing values of heat sink parameter or radiation parameter. Thus the presence of heat sink parameter and radiation parameter thickens the thickness of concentration boundary layer. Figures 11-13 represent the expressions for skin friction against M for different values of K_r, a, t, Q and β, respectively. It is observed that skin friction increases with the increasing values of K_r or a or t or Q or β.

Figure 14 illustrate the effect of radiation parameter on Nusselt number against time t. It depicts that Nusselt number increase with an increase in radiation parameter with time. Figure15 illustrate the effect of chemical reaction parameter on Sherwood number against time and observed that Sherwood number decrease with an increase in chemical reaction parameter with time.

V. CONCLUSIONS:

The above study led to the following conclusions

1. Casson parameter increases the fluid velocity near the plate, but away from the plate it is opposite. Also, accelerating parameter (a), Soret and chemical reaction effects enhances the fluid velocity, while heat sink parameter, radiation parameter reduces the fluid velocity.
2. Temperature of the system reduces with increasing radiation and heat sink parameter, while it decreases with increasing time.
3. Concentration can be increased by increasing radiation and heat sink parameter.
4. Skin friction increases with increasing accelerating parameter (a), heat sink parameter, Casson parameter, chemical reaction parameter and time.
5. Rate of heat transfer increases with increasing radiation parameter, while mass transfer decreases with increasing chemical reaction parameter.

NOMENCLATURE

a: accelerating parameter; $\bar{b}$: a constant; B_0: strength of transverse magnetic field; C: concentration of fluid; C_p: specific heat at constant pressure; D: molecular diffusivity; D_t: thermophoresis coefficient; g: acceleration due to gravity; Gc: Grashof number for mass transfer; Gr: Grashof number for heat transfer; K: non-dimensional porosity parameter; $\overline{K}$: dimensional porosity parameter; $\overline{K}_r$: chemical reaction rate; M: Hartmann number; Nu: Nusselt number; K_r: chemical reaction parameter; Pr: Prandtl number; Q: heat sink parameter; Q_0: heat suction parameter; q_r: thermal radiative heat flux; R: radiation parameter; S_r: Soret number; Sc: Schmidt number; Sh: Sherwood number; t: non-dimensional time; $\bar{t}$: dimensional time; T: temperature; U: non-dimensional fluid velocity; u: fluid velocity; u_0: characteristic velocity; X: distance along the plate; Y: distance perpendicular to the plate; β: Casson parameter; β_t: coefficient of thermal expansion; β_c: coefficient of mass expansion; ϕ: non-dimensional concentration; κ: thermal conductivity; ρ: density; σ: electrical conductivity; $\bar{\sigma}$: Stefan Boltzmann constant; θ: non-dimensional temperature; τ: skin friction coefficient; υ: kinematic viscosity; w: conditions on the surface; ∞: conditions on the free stream.

REFERENCES

Ahmed, S., Batin, A. and Chamkha, A.J. (2015) Numerical/Laplace transform analysis for MHD radiating heat/mass transport in a Darcian porous regime bounded by an oscillating vertical surface. *Alexandria Engineering Journal*. **54**, 45–54.

Animasaun, I.L, Adebile, E.A. and Fagbade, A.I. (2016) Casson fluid flow with variable thermo-physical property along exponentially stretching sheet with suction and exponentially decaying internal heat generation using the homotopy analysis method. *Journal of the Nigerian Mathematical Society.* **35**, 1–17.

Casson, N.A. (1959) Flow equation for pigment oil-suspensions of the printing ink type. *Rheology of disperse systems.* Ed. Mill, C.C. Pergamon Press. 84-102.

Chamkha, A.J. and Aly, A.M. (2010) MHD free convection flow of a nanofluid past a vertical plate in the presence of heat generation or absorption effects. *Chemical Engineering Communications*. **198,** 425-441.

Das, U.J. (2016) Mixed convective flow of an elastico-viscous fluid past a vertical plate in the presence of thermal radiation and chemical reaction with an induced magnetic field. *Journal of Engineering Physics and Thermophysics.* **89**, 117-126.

Das, U.J. (2019) Soret and Dufour effects on three dimensional mixed convective hydromagnetic flow of a visco-elastic fluid past an infinite inclined plate. *Latin American Applied Research*. **49**, 7-12.

Divya, B.B., Manjunatha, G., Rajashekhar, C., Vaidya, H. and Prasad, K.V. (2020) The hemodynamics of variable liquid properties on the MHD peristaltic mechanism of Jeffrey fluid with heat and mass transfer. *Alexandria Engineering Journal*. **59**, 693-706.

Gorla, R.S. and Chamkha, A. (2011) Natural Convective Boundary Layer Flow Over a Nonisothermal Vertical Plate Embedded in a Porous Medium Saturated With a Nanofluid. *Nanoscale and Microscale Thermophysical Engineering*. **15**, 81-94.

Gudekote, M and Choudhari, R. (2018) Slip Effects on Peri staltic Transport of Casson Fluid in an Inclined Elastic Tube with Porous Walls. *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences.* **43**, 67-80.

Gupta, A.S. (1960) Steady and transient free convection of an electrically conducting fluid from a vertical plate in the presence of a magnetic field. *Applied Scientific Research*. **9**, 319–333.

Ibrahim, W. and Makinde, O.D. (2016) Magnetohydrodynamic stagnation point flow and heat transfer of Casson nanofluid past a stretching sheet with slip and convective boundary condition. *J. Aero sp. Eng*. **29**, 04015037.

Immanuel, Y., Pullepu, B. and Kirubhashankar, C.K. (2015) Casson flow of MHD fluid moving steadily with constant velocity. *Appl. Math. Sci.* **9**, 1503–1508.

Krishna, M.V. and Chamkha, A.J. (2019) Hall and ion slip effects on MHD rotating boundary layer flow of nanofluid past an infinite vertical plate embedded in a porous medium. *Results in Physics*. **15,** 102652.

Merrill, E.W., Benis, A.M., Gilliland, E.R., Sherwood, T.K. and Salzman, E.W. (1965) Pressure-flow relations of human blood in hollow fibers at low flow rates. *Journal of Applied Physiology*. **20**, 954-967.

Modather, M., Rashad, A.M. and Chamkha, A.J. (2009) An analytical study of MHD heat and mass transfer oscillatory flow of a micropolar fluid over a vertical permeable plate in a porous medium. *Turkish J. Eng. Env. Sci.* **33**, 245–257.

Mukhopadhyay, S. (2013) Casson fluid flow and heat transfer over a nonlinearly stretching surface. *Chin. Phys*. B. **22.** 074701.

Mustafa, M., Hayat, T., Pop, I. and Aziz, A. (2011) Unsteady boundary layer flow of a Casson fluid due to an impulsively started moving flat plate. *Heat Transfer- Asian Res.* **40**, 563-576.

Muthucumaraswamy, R., Sathappan, K. and Natarajan, R. (2008) Heat transfer effects on flow past an exponentially accelerated vertical plate with variable temperature. *Theoretical and Applied Mechanics*. **35**, 323–331.

Nadeem, S., Haq, R.U. and Lee, C. (2012) MHD flow of a Casson fluid over an exponentially shrinking sheet. *Sci. Iran*. **19**, 1550–1553.

Oyelakin, I.S., Mondal, S. and Sibanda, P. (2016) Unsteady Casson nanofluid flow over a stretching sheet with thermal radiation, convective and slip boundary conditions. *Alexandria Eng. J. Faculty of Engineering*. **55**, 1025–1035.

Rajashekhar, C., Manjunatha, G., Vaidya, H., Divya, B.B. and Prasad, K.V. (2018) Peristaltic flow of Casson liquid in an inclined porous tube with convective boundary conditions and variable liquid properties. *Frontiers in Heat and Mass Transfer*. **11**, 35.

Scott Blair, G.W. (1959) An Equation for the Flow of Blood, Plasma and Serum through Glass Capillaries. *Nature.* **183**, 613–614.

Seth, G.S., Tripathi, R., Sharma, R. and Chamkha, A.J. (2017) MHD double diffusive natural convection flow over exponentially accelerated inclined plate. *Journal of Mechanics*. **33**, 87-99.

Subba Rao, A., Ramachandra Prasad, V., Bhaskar Reddy, N. and Anwar Bég, O. (2015) Heat Transfer in a Casson Rheological Fluid from a Semi-infinite Vertical Plate with Partial Slip. *Heat Transfer-Asian Research*. **44**, 272-291.

Received: May 27, 2020
Sent to Subject Editor: July 7, 2020
Accepted: July 21, 2021
Recommended by Subject Editor Fabio Giannetti