

# Three Dimensional Flow of a Casson Fluid over a Stretching Surface with Convective Boundary Conditions

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**ABSTRACT:** In this paper, the effects of thermal radiation, heat source, viscous dissipation and Joule heating in the presence of thermophoresis and chemical reaction on the flow of a Casson fluid over a stretching sheet embedded in a porous medium under the influence of a magnetic field is investigated. Using a similarity transformation, the time dependent boundary-layer equations are reduced to a set of non-linear ordinary differential equations. The resulting multi parameter problem is solved numerically in Matlab. The effects of all the parameters on the flow variables are explored and discussed through graphs. A comparison of our numerical analysis with the results of already published works is made which indicates very close agreement between the two.

**KEYWORDS:** Three dimensional flow, Casson fluid, Viscous dissipation, Thermophoresis.

## I. INTRODUCTION

Wang [1] studied the three-dimensional flow of a viscous fluid caused by the stretching of a flat surface in two lateral directions and obtained exact similar solutions. Surma Devi et al. [2] extended the study of Wang [1] to study the flow, heat and species concentration due to the unsteady, three-dimensional flow induced by a stretching surface in two lateral directions and obtained a self similar solution for the nodal point region of flow. Takhar et al. [3] examined the development of velocity and temperature fields of a viscous fluid due to the impulsive stretching of the surface in two lateral directions by suddenly increasing the surface temperature from that of the surrounding fluid. Ariel [4] obtained an approximate analytical solution of the steady, laminar three-dimensional flow for an incompressible, viscous fluid past a stretching sheet using homotopy perturbation method. Liu and Andersson [5] considered the heat transfer in three-dimensional flow due to a non-isothermal stretching sheet. Nazar and Latip [6] made a numerical study of the three-dimensional boundary layer flow over a stretching surface in a viscoelastic fluid. Ashraf et al. [7] explored the heat and mass transfer characteristics in a three-dimensional flow of a Maxwell fluid over a stretching surface with convective boundary conditions. Sarojamma et al. [8] discussed the influence of radiative heat transfer on steady three-dimensional flow of an electrical conducting chemically reactive Casson fluid induced by an elastic surface embedded in a porous medium by stretching the surface in two lateral directions under convective boundary conditions on temperature and concentration.

In all the above investigations the effect of thermophoresis is not studied. In this paper we analyse the steady three-dimensional flow of a viscous electrical conducting fluid induced by an elastic surface embedded in a porous medium by stretching the surface in two lateral directions under convective boundary conditions on temperature and concentration.

## II. MATHEMATICAL FORMULATION

We consider a highly elastic membrane immersed in a viscous fluid through a porous medium which is continuously stretched in the  $x$  and  $y$ - directions. A constant magnetic field  $B$  is applied in a direction normal to the fluid flow. The magnetic Reynolds number is assumed to be small and thus the induced magnetic field is neglected. The fluid velocities on the surface are given by  $U_w = ax$ ,  $V_w = by$  and  $w = 0$  along the  $xy$ -plane, where  $a$  and  $b$  are constants.

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The fluid has no lateral motions at  $z \rightarrow \infty$ . The effects of viscous dissipation, Joule heating, thermal radiation and thermophoresis are taken into consideration.

The steady boundary layer equations governing the flow, heat and diffusion transport can be expressed as:

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0 \tag{1}$$

$$u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} + w \frac{\partial u}{\partial z} = \nu \frac{\partial^2 u}{\partial z^2} - \frac{\sigma B^2}{\rho} u - \frac{\nu}{K_p} u \tag{2}$$

$$u \frac{\partial v}{\partial x} + v \frac{\partial v}{\partial y} + w \frac{\partial v}{\partial z} = \nu \frac{\partial^2 v}{\partial z^2} - \frac{\sigma B^2}{\rho} v - \frac{\nu}{K_p} v \tag{3}$$

$$u \frac{\partial T}{\partial x} + v \frac{\partial T}{\partial y} + w \frac{\partial T}{\partial z} = \frac{k}{\rho c_p} \frac{\partial^2 T}{\partial z^2} + \frac{16\sigma^* T_\infty^3}{3\rho c_p k^*} \frac{\partial^2 T}{\partial z^2} + \frac{2\mu}{\rho c_p} \left[ \left( \frac{\partial u}{\partial z} \right)^2 + \left( \frac{\partial v}{\partial z} \right)^2 \right] + \frac{\sigma B^2}{\rho c_p} [u^2 + v^2] + \frac{Q}{\rho c_p} (T - T_\infty) \tag{4}$$

$$u \frac{\partial C}{\partial x} + v \frac{\partial C}{\partial y} + w \frac{\partial C}{\partial z} = D \frac{\partial^2 C}{\partial z^2} - K(C - C_\infty) - \frac{\partial}{\partial z} [V_T (C - C_\infty)] \tag{5}$$

Here  $u$ ,  $v$  and  $w$  are the fluid velocity components along  $x$ ,  $y$  and  $z$ -directions respectively,  $\nu$  is the kinematic viscosity,  $\rho$  is the density of the fluid,  $B$  is magnetic induction,  $T$  and  $T_\infty$  are the fluid and ambient temperatures,  $K_p$  is the permeability of the porous medium,  $k^*$  is the mean absorption coefficient,  $C$  and  $C_\infty$  are the fluid and ambient concentrations,  $\sigma$  is the electrical conductivity,  $c_p$  is the specific heat at constant pressure,  $\sigma^*$  is the Stefan-Boltzmann constant,  $k$  is the thermal conductivity of the medium,  $Q$  is the uniform volumetric heat generation and absorption,  $D$  is the mass diffusivity,  $K$  is the chemical reaction, and  $V_T$  is the thermophoresis velocity, following Talbot et al. (1980) given by  $V_T = -\frac{k_t \nu}{T_{ref}} \frac{\partial T}{\partial z}$ , where  $T_{ref}$  is some reference temperature, the value of  $k_t \nu$  represents the thermophoretic diffusivity.

The associated boundary conditions of equations (2) – (5) are as follows:

$$u = U_w(x) = ax, v = V_w(x) = by, w = 0, -k \frac{\partial T}{\partial z} = h_f (T_f - T), -D \frac{\partial C}{\partial z} = h_s (C_f - C) \quad \text{at } z = 0 \tag{6}$$

$$u \rightarrow 0, v \rightarrow 0, T \rightarrow T_\infty, C \rightarrow C_\infty \quad \text{as } z \rightarrow \infty \tag{7}$$

where  $h_f$  is the convective heat transfer coefficient and  $T_f$  is the convective fluid temperature below the sheet,  $h_s$  is the mass transfer coefficient and  $C_f$  is the fluid concentration below the sheet.

### III. METHOD OF SOLUTION

Exemplar Introducing the following similarity transformations

$$u = axf'(\eta), v = ayg'(\eta), w = -\sqrt{av}(f(\eta) + g(\eta))$$

$$\eta = z\sqrt{a/\nu}, \theta(\eta) = \frac{T - T_\infty}{T_f - T_\infty}, \phi(\eta) = \frac{C - C_\infty}{C_f - C_\infty} \tag{8}$$

We see that  $u$ ,  $v$  and  $w$  satisfy equation (1), and equations (2) – (5) take the form

$$f''' - (f')^2 + (f + g)f'' - (M^2 + \lambda)f' = 0 \tag{9}$$

$$g''' - (g')^2 + (f + g)g'' - (M^2 + \lambda)g' = 0 \tag{10}$$

$$\theta'' \left( 1 + \frac{4}{3}Nr \right) + Pr \left( (f + g)\theta' + 2Ec(f''^2 + L^2g''^2) \right) + M^2Ec(f'^2 + L^2g'^2) + \delta\theta = 0 \tag{11}$$

$$\phi'' + Sc(f + g)\phi' - \tau(\theta'\phi' + \theta''\phi) - \gamma\phi = 0 \tag{12}$$

with the boundary conditions

$$f = 0, g = 0, f' = 1, g' = c, \theta' = -Bi_1(1 - \theta(0)), \phi' = -Bi_2(1 - \phi(0)), \quad \text{at } \eta = 0 \tag{13}$$

$$f' \rightarrow 0, g' \rightarrow 0, \theta \rightarrow 0, \phi \rightarrow 0, \quad \text{as } \eta \rightarrow \infty \tag{14}$$

where,

$M^2 = \sigma B^2 / \rho a$  is the magnetic parameter,  $\lambda = \nu / aK_p$  is the porosity parameter,  $c = b/a$  is the stretching parameter,

$Pr = \rho c_p \nu / k$  is the Prandtl number,  $Nr = 4\sigma^* T_\infty^3 / k k^*$  is the thermal radiation parameter,  $Ec = U_w^2 / c_p (T_f - T_\infty)$

is the Eckert number,  $L = y/x$  is the dimensionless parameter,  $\delta = Q / \rho c_p a$  is the heat source/sink parameter,

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$Sc = \nu/D$  is the Schmidt number,  $\gamma = K/a$  is the Chemical reaction parameter,  $\tau = -\frac{k_t(T_f - T_\infty)}{T_{ref}}$  is the thermophoretic parameter,  $Bi_1 = \frac{h_f}{k} \sqrt{\frac{\nu}{a}}$  is the heat transfer Biot number,  $Bi_2 = \frac{h_s}{D} \sqrt{\frac{\nu}{a}}$  is the mass transfer Biot number.

The physical quantities of engineering interest are the skin friction and heat transfer coefficients. The local skin friction coefficients in the x and y directions, local Nusselt number and Sherwood number are expressed as:

$$\begin{aligned} C_{fx} &= -2(Re_x)^{-1/2} f''(0), & C_{fy} &= -2c^{1/2} (Re_y)^{-1/2} g'(0) \\ Nu_x &= -(Re_x)^{1/2} \theta'(0), \\ Sh_x &= -(Re_x)^{1/2} \phi'(0), \end{aligned} \tag{15}$$

where  $Re_x = \frac{U_w x}{\nu}$  and  $Re_y = \frac{V_w y}{\nu}$  are the local Reynolds numbers,  $\mu$  is the coefficient of viscosity,  $C_{fx}$  and  $C_{fy}$  are the local skin friction coefficients along x and y directions (i.e.,  $C_{fx}$  and  $C_{fy}$  are the local skin friction coefficients for the primary and secondary flows, respectively),  $Nu_x$  is the local Nusselt number and  $Sh_x$  is the local Sherwood number.

The ordinary differential equations (9)–(12) are coupled and highly non-linear. These equations with the boundary conditions (13) and (14) are solved using Runge-Kutta fourth order method with shooting technique and obtained numerical solutions. In order to confirm the accuracy of our numerical procedure, we compared our results, namely, surface shear stress and surface temperature gradient [ $f''(0), g''(0), \theta'(0)$ ]. with those evaluated by Wang [1], Lakshmisha et al. [9] and Rajeswari et al. [10] in the absence of magnetic field, porous medium, thermal radiation, viscous dissipation, joule heating, heat source/sink and diffusion equation with prescribed wall temperature and concentration ( $M = \lambda = Nr = Ec = \delta = Sc = \tau = \gamma = 0, Bi_1, Bi_2 \rightarrow \infty, Pr = 0.7$ ) for different values of stretching parameter when  $Pr = 0.7$ . Table 1 shows that our results are in excellent agreement.

**Table 1:** Comparison of various results ( $M = \lambda = Nr = Ec = \delta = Sc = \tau = \gamma = 0, Bi_1, Bi_2 \rightarrow \infty, Pr = 0.7$ )

c		Wang [1]	Lakshmisha et al. [9]	Rajeswari et al. [10]	Present results
0.0	$f''(0)$	-1.000000	-0.999974	-0.999818	-1.000063
	$g''(0)$	0.000000	0.000000	0.000000	0.000000
	$\theta'(0)$	-	-0.454461	-0.454585	-0.456051
0.25	$f''(0)$	-1.048813	-1.048803	-1.048585	-1.048835
	$g''(0)$	-0.194564	-0.194576	-0.194574	-0.194577
	$\theta'(0)$	-	-0.521113	-0.521012	-0.521121
0.5	$f''(0)$	-1.093097	-1.093105	-1.093059	-1.093106
	$g''(0)$	-0.465205	-0.465221	-0.465313	-0.465213
	$\theta'(0)$	-	-0.465313	-0.576033	-0.576209
0.75	$f''(0)$	-1.134485	-1.134495	-1.134549	-1.134492
	$g''(0)$	-0.794622	-0.794640	-0.794769	-0.794620
	$\theta'(0)$	-	-0.623835	-0.624132	-0.624048
1.0	$f''(0)$	-1.173720	-1.173741	-1.173866	-1.173861
	$g''(0)$	-1.173720	-1.173741	-1.173866	-1.173861
	$\theta'(0)$	-	-0.667341	-0.667683	-0.667667

## IV. RESULTS AND DISCUSSION

In this section we discuss the effects of different physical parameters on the velocities, temperature and concentration fields. Also the values of surface drag coefficients, Nusselt number and Sherwood number are tabulated and discussed for different variations of the physical parameters.

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**Fig. 1** are the plots of the velocities ( $f'$  and  $g'$ ) in the x and y directions illustrating the influence of magnetic field. The presence of magnetic field reduces the velocities in both directions. This reduction is due to the Lorentz force arising due to the magnetic field acts a decelerating force in reducing velocity of the flow. As a result there is a decrease in the thickness of the boundary layer in both the directions. **Fig. 2** shows that the stretching parameter ( $c$ ) has a significant influence on velocity component in the y – direction. When the parameter  $c = 0$  the problem reduces to flow in the neighbourhood of the two dimensional stagnation point and when  $c = 1$  the problem represents axisymmetric flow. The stretching parameter has an increasing influence on the y-component of velocity for an increase in  $c$  whereas it has a decreasing effect on the corresponding x-component. The effect of  $c$  on the x-component of velocity is small compared to its component in y-direction. An increase in  $c$  implies that the velocity in the y-direction dominates the velocity in x-direction and hence the velocity in the y-direction enhances with a decrease in the x–component. **Fig. 3** depicts that as the porous parameter ( $\lambda$ ) increases, the velocities in both directions reduce. This is due to the resistance offered by the porous medium. Higher values of porous parameter amount to more resistance to flow and hence velocities are reduced. This is in conformity of the fact that porosity stabilizes the growth of the boundary layer.

**Fig. 4** reveals that increasing values of Biot number ( $Bi_1$ ) elevate the temperature. Physically an increase in Biot number amounts to an enhancement in the heat transfer coefficient and higher values of heat transfer coefficient cause the fluid to be hotter and thus higher temperatures are obtained. **Fig. 5** depicts that the temperature significantly increase for increasing values of Eckert number. As  $Ec$  increases, for  $Ec > 0.2$  we notice an overshoot of the temperature on the boundary. Further increase in  $Ec$  increases the overshoot. Consequently the thickness of the thermal boundary layers increase. Physically, increase in  $Ec$  implies heat energy is stored in the fluid owing to the frictional heating.

**Fig. 6** presents the effect of solutal Biot number ( $Bi_2$ ) which is the ratio of convective mass transfer to molecular diffusion. When a solutal gradient is applied on the surface the concentration at the surface varies predominantly. It is observed that as the Biot number increases from 0.1 to 0.4. There is a threefold enhancement in the mass concentration. **Fig. 7** illustrates the influence of the thermophoresis parameter ( $\tau$ ) on concentration. The effect of the thermophoresis parameter is to reduce the concentration steadily. **Fig. 8** shows the effect of chemical reaction parameter ( $\gamma$ ) on species concentration. In the presence of the chemical reaction parameter the species concentration decreases asymptotically along  $\eta$ .

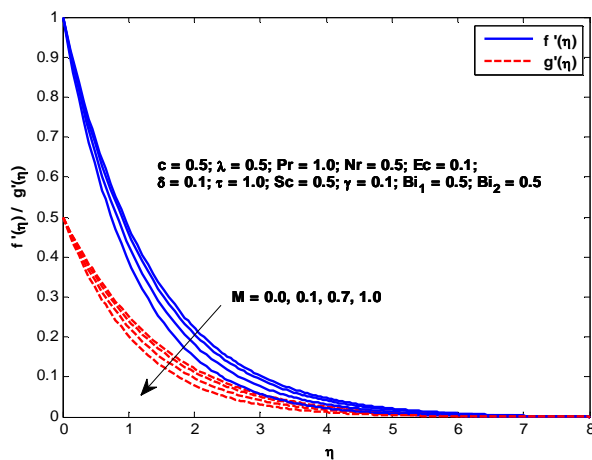


Fig. 1: Variation of  $M$  on  $f'$  and  $g'$

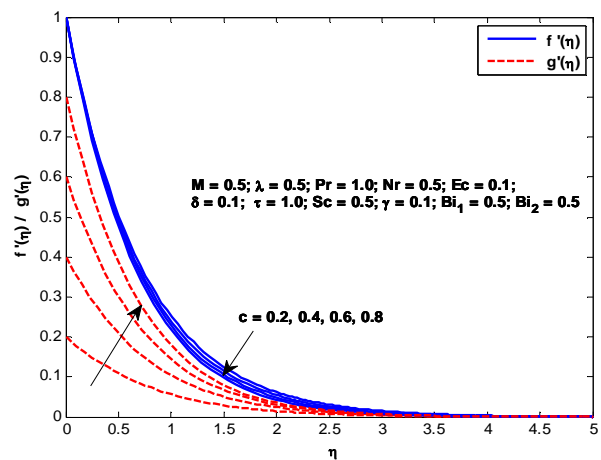


Fig. 2: Variation of  $c$  on  $f'$  and  $g'$

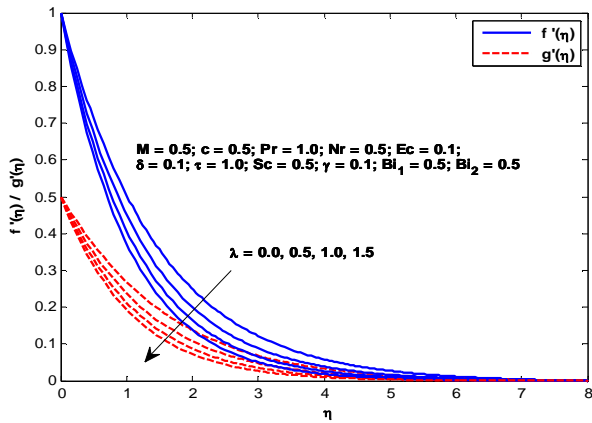


Fig. 3: Variation of  $\lambda$  on  $f'$  and  $g'$

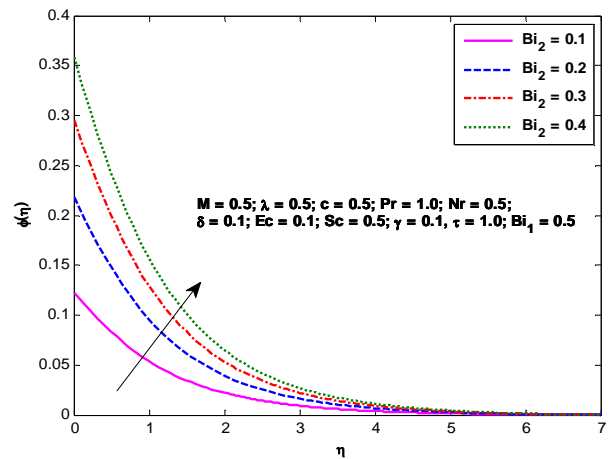


Fig. 6: Variation of  $Bi_2$  on  $\phi$

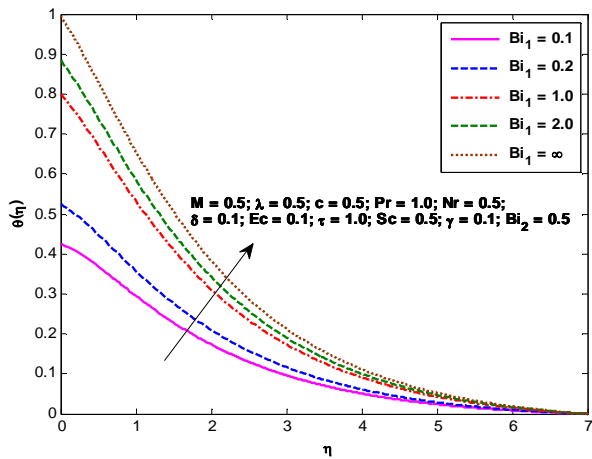


Fig. 4: Variation of  $Bi_1$  on  $\theta$

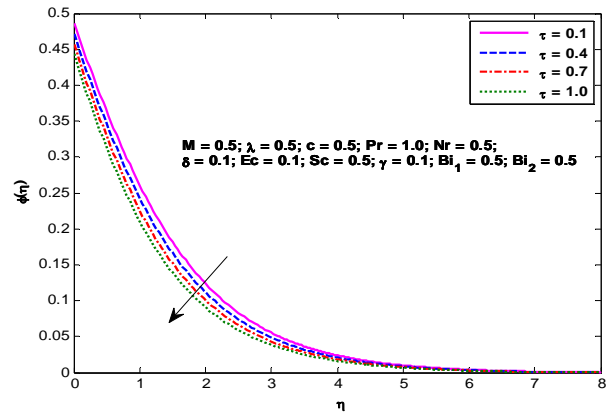


Fig. 7: Variation of  $\tau$  on  $\phi$

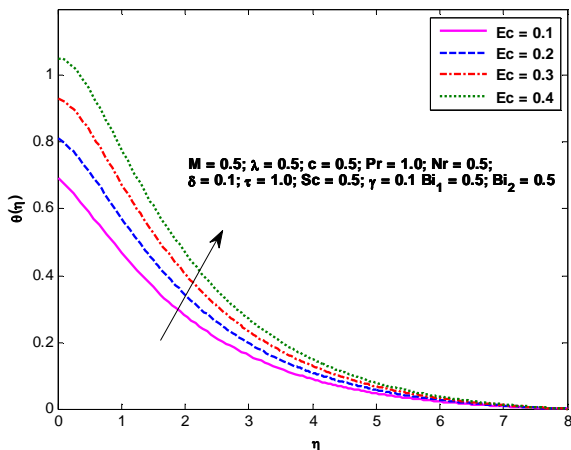


Fig. 5: Variation of  $Ec$  on  $\theta$

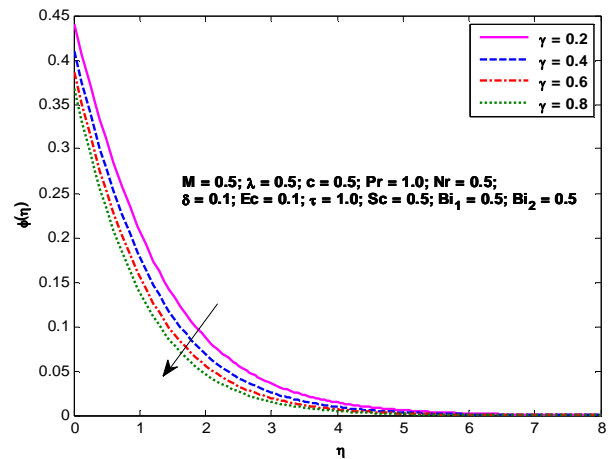


Fig. 8: Variation of  $\gamma$  on  $\phi$

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**Table 2:** Skin friction coefficient, Nusselt number and Sherwood number for various values of pertinent parameters

M	c	$\lambda$	Pr	Nr	Ec	$\delta$	Sc	$\tau$	$\gamma$	Bi <sub>1</sub>	Bi <sub>2</sub>	f''(0)	g''(0)	- $\theta'(0)$	- $\phi'(0)$
0.0												-0.728655	-0.324127	0.221842	0.273696
0.4	0.2	0.5	1.0	0.5	0.1	0.1	0.5	1.0	0.1	0.5	0.5	-0.764125	-0.343908	0.215032	0.271859
0.7												-0.832672	-0.381587	0.201656	0.268267
1.0												-0.928891	-0.433546	0.182367	0.263134
0.5	0.2	0.5	1.0	0.5	0.1	0.1	0.5	1.0	0.1	0.5	0.5	-1.350509	-0.227335	0.133689	0.243236
	0.4											-1.377224	-0.489610	0.149380	0.252541
	0.6											-1.403165	-0.783083	0.156965	0.259827
	0.8											-1.428433	-1.104970	0.157889	0.265606
0.5	0.2	0.0	1.0	0.5	0.1	0.1	0.5	1.0	0.1	0.5	0.5	-1.199732	-0.526475	0.178020	0.264252
	0.5											-1.390285	-0.632638	0.154076	0.256398
	1.0											-1.558609	-0.724008	0.131835	0.249435
	1.5											-1.710833	-0.805320	0.111077	0.243135
0.5	0.2	0.5	2.0	0.5	0.1	0.1	0.5	1.0	0.1	0.5	0.5	-0.785122	-0.355693	0.258048	0.275869
			3.0									-0.785122	-0.355693	0.279705	0.277622
			4.0									-0.785122	-0.355693	0.292478	0.278657
			5.0									-0.785122	-0.355693	0.300906	0.279334
0.5	0.2	0.5	1.0	0.5	0.1	0.1	0.5	1.0	0.1	0.5	0.5	-0.783360	-0.354544	0.211089	0.270782
				1.0								-0.783360	-0.354544	0.184677	0.268695
				1.5								-0.783360	-0.354544	0.165287	0.267171
				2.0								-0.783360	-0.354544	0.151111	0.266063
0.5	0.2	0.5	1.0	0.5	0.1	0.1	0.5	1.0	0.1	0.5	0.5	-1.390285	-0.632638	0.154076	0.256398
				0.2								-1.390285	-0.632638	0.094109	0.248813
				0.3								-1.390285	-0.632638	0.034141	0.240751
				0.4								-1.390285	-0.632638	-0.025827	0.232164
0.5	0.2	0.5	1.0	0.5	0.1	-0.2	0.5	1.0	0.1	0.5	0.5	-0.783398	-0.354569	0.258421	0.275476
						-0.1						-0.783398	-0.354569	0.246099	0.274266
						0.0						-0.783398	-0.354569	0.230907	0.272776
						0.1						-0.783398	-0.354569	0.211301	0.270855
						0.2						0.783398	-0.354569	0.184130	0.268185
0.5	0.2	0.5	1.0	0.5	0.1	0.1	0.5	1.0	0.1	0.5	0.5	-0.783398	-0.354569	0.211301	0.270855
						1.0						-0.783398	-0.354569	0.211301	0.325351
						1.5						-0.783398	-0.354569	0.211301	0.353901
						2.0						-0.783398	-0.354569	0.211301	0.372375
0.5	0.2	0.5	1.0	0.5	0.1	0.1	0.5	0.1	0.1	0.5	0.5	-0.783398	-0.354569	0.309679	0.256821
								0.4				-0.783398	-0.354569	0.309679	0.264336
								0.7				-0.783398	-0.354569	0.309679	0.271513
								1.0				-0.783398	-0.354569	0.309679	0.278367
0.5	0.2	0.5	1.0	0.5	0.1	0.1	0.5	1.0	0.2	0.5	0.5	-0.783398	-0.354569	0.211301	0.280206
									0.4			-0.783398	-0.354569	0.211301	0.295070
									0.6			-0.783398	-0.354569	0.211301	0.306609
									0.8			-0.783398	-0.354569	0.211301	0.315991
0.5	0.2	0.5	1.0	0.5	0.1	0.1	0.5	1.0	0.1	0.1	0.5	-1.390285	-0.632639	0.057550	0.247738
									0.2			-1.390285	-0.632639	0.095317	0.251371
									0.3			-1.390285	-0.632639	0.122003	0.253886
									0.4			-1.390285	-0.632639	0.141862	0.255731
0.5	0.2	0.5	1.0	0.5	0.1	0.1	0.5	1.0	0.1	0.5	0.5	-1.390285	-0.632639	0.157217	0.087725
											1.0	-1.390285	-0.632639	0.157217	0.156269
											1.5	-1.390285	-0.632639	0.157217	0.211303
											2.0	-1.390285	-0.632639	0.157217	0.256462

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Table 2 presents the values of the surface skin friction, Nusselt number and Sherwood number obtained for different variations of the governing parameters. The surface stresses in both directions are negative. As the magnetic field increases the rate of heat transfer and mass transfer are observed to increase. The effect of increasing values of stretching ratio has a decreasing influence on the  $x$ -component of surface shear stress and an opposite effect on the corresponding  $y$ -component. This is in conformity with the behavior of the two components of velocity with  $c$ . The Nusselt number and Sherwood number are observed to enhance with increasing  $c$ . The effect of porous parameter on the skin friction coefficient in both the directions, Nusselt number and Sherwood number is qualitatively similar to that of the magnetic field. As Prandtl number and heat transfer Biot number increase, the Nusselt number increases. It is observed that the rate of heat transfer is enhanced with increase in the radiation parameter, heat source and Eckert number. The Schmidt number, chemical reaction parameter and thermophoresis parameter are found to have an increasing influence on the Sherwood number.

## V. CONCLUSION

The steady three-dimensional MHD flow of a viscous fluid over a stretching surface embedded in a porous medium is investigated by taking the effects of thermophoresis, viscous dissipation and Joule heating into account with convective boundary conditions on temperature and concentration.

- The increasing values of stretching parameter enhance the  $y$ -component of the velocity while an opposite effect on the  $x$ -component is observed. The temperature and concentration are decreased with increasing values of  $c$ .
- The magnetic field and porous parameter decelerated flow and enhanced the temperature and concentration.
- The temperature is raised by the thermal radiation, viscous dissipation and Joule heating.
- The thermophoretic parameter, Schmidt number and chemical reaction parameter have a decreasing influence on species concentration.
- The rate of heat transfer is enhanced by Eckert number, thermal radiation parameter, magnetic field parameter and porous parameter.
- The Sherwood number is enhanced by solutal Biot number and Schmidt number.

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