MHD FLOW IN POROUS MEDIUM THROUGH AN EXPONENTIALLY STRETCHING SHEET WITH SURFACE HEAT AND MASS FLUX UNDER THE IMPACT OF CHEMICAL REACTION

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***Abstract*— The key motive of the present study is to examine the heat and mass transmission process through a sheet that is assumed to be stretching exponentially in porous medium on MHD flow with suction, constant surface heat and mass flux. The governing equations of the problem are first made dimensionless by adopting suitable non-dimensional transformations, there after it is solved by bvp4c, a Matlab inbuilt solver. The solutions are presented by graphs and numerical values are computed for rate of heat transfer, rate of mass transfer and skin-friction coefficient. The validity of the present result is also checked by comparing the result with previously published work. The findings reveal that suction parameter helps in reducing the fluid velocity and heat transfer rate, and mass transfer is boosted by permeability parameter. Other important parameters also showed noticeable consequences on both heat as well as mass transfer process.**

***Keywords*— Stretching sheet, MHD, Viscous dissipation, chemical reaction, radiation, bvp4c**

I. INTRODUCTION

Investigations on thermal and mass transfer have gather significant attention past many decades because of its important applications in engineering. Heat transfer plays a crucial role in designing machineries like solar collectors, radiators of vehicles, important components of thermal power plant, space craft's etc. Mass transfer is another important phenomenon whose applications in food processing, chemical engineering, separations engineering etc. are commonly seen. The consequences of momentum, heat as well as mass transport process in a combined form is very crucial for any chemical reaction because the flow of fluids propels the transfer of heat and mass thereby helping a chemical reaction to proceed further. The study on heat transport along with mass transport in porous medium has been an important research area particularly due to its vast uses in chemical engineering, nuclear reactor, CO_2 storage, pyrolysis etc. Datta (2007) investigated the simultaneous process of thermal and mass transport in food processes in porous medium with special focus on the internal evaporation process. Sahoo (2013) investigated analytically the process of thermal transfer along with mass on the flow of a non-Newtonian fluid above a pervious surface with partial velocity slip effect at the surface.

Many major works in porous medium have been reported on heat and mass transmission process using various numerical and analytical methods. Chamkha (2004) discussed numerically micropolar fluid flow on a semi-infinite surface in a non-Darcian porous medium considering the consequences of chemical reaction effects. Makinde (2005) investigated numerically using superposition method, thermal and mass transmission process on an unsteady natural convection fluid motion above a moving porous surface with thermal radiation. Chamkha *et al.* (2006) inquired numerically the action of thermal and mass transmission with thermophoretic particle deposition on a plane plate inserted in porous medium along with the impact of heat source. Mandal and Mukhopadhyay (2013) investigated heat transmis-sion process through an exponentially elongated porous surface in porous medium assuming constant surface heat flux. Najafabadi and Gorla (2014) investigated the heat transport activity together with mass transmission on a surface that is elongating nonlinearly in a non-Darcy medium in a two-dimensional mixed convective fluid motion with Joule heating and viscous dissipation. Dessie and Kishan (2014) investigated MHD heat process past an exponentially extending sheet considering viscosity to be variable in a porous channel incorporating the impact of internal heat sink. Their findings showed that viscosity hikes the fluid velocity but decreases the fluid temperature. Rashad *et al*. (2014) studied the behavior of thermal transport process by considering the effect of buoyancy on micropolar fluid flow over a flat material in porous medium with radiation and chemical effects assuming that temperature and concentration, both showing sinusoidal variations. Khan *et al*. (2019) investigated the transmission process of heat and mass using Finite element method considering the consequences of viscous dissipation in a porous medium. Swain *et al*. (2020) investigated analytically using HAM, hydromagnetic fluid flow past a stretched surface with Joule heating and viscous dissipation in porous medium. Krishna *et al*. (2020) examined heat as well as mass transmission process on MHD second grade fluid over an extending surface assumed to semi-infinite in extent in porous medium with thermophoresis. Their findings reveal that heat transfer is boosted with the hike in surface convection parameter while thermophoresis boosts mass transmission rate. Verma and Sharma (2022) obtained numerical solution on hydromagnetic flow problem through an exponentially stretching sheet with Ohmic heating and viscous dissipation. Their findings revealed that the Ohmic heating as well as viscous dissipation contribute to the rise of fluid temperature. Other important works reported from the point of view of the current investigation can be looked in the works of Chamkha and Khaled (2001), Ahmed and Mohammad (2008), Motsumi and Makinde (2012), Mohanty *et al*. (2015), Pandey and Kumar (2016), Pandey and Kumar (2017), Mishra *et al*. (2017), Pandey and Kumar (2018), Mishra *et al*. (2019), Singh *et al*. (2019), Verma *et al*. (2020), Singh *et al*. (2020a,b,c), Singh *et al*. (2021a,b), Verma *et al*. (2021a, b) and Upreti *et al*. (2022).

In the present problem, the main motive is to study the process of heat and mass transmission on MHD flow over an exponentially stretching sheet in porous under the impact of viscous dissipation and resistive heating. Abualnaja (2018) and Swain *et al.* (2020) in their works discussed only the heat transfer process assuming constant surface heat flux neglecting the mass transfer process. Therefore, the present work focuses on the goal of analyzing both heat as well as mass transmission process assuming constant heat as well as mass flux taking place at the surface of the sheet. The effect of first order chemical reaction is also incorporated in the problem and its effect on mass transmission process is investigated. The results of the problem have been carried out numerically by using Matlab inbuilt solver bvp4c.

II. MATHEMATICAL FORMULATION OF THE PROBLEM

Consider MHD, steady fluid flow over a sheet, stretching exponentially along x-direction in porous medium. Let the fluid be incompressible, viscous, and Newtonian. The sheet is placed in the direction of $x-$ axis i.e., horizontally and $y-$ axis is drawn normal to it as delineated in Fig. 1. The flow region is assumed to be restricted to $y>0$ and let the surface of the sheet be stretched with a velocity $U=U_0e^{\frac{x}{L}}$, where U_0 and L are the reference velocity and length respectively. Also, we consider a weak magnetic field of unvarying strength B_0 normal to the sheet. The effects of viscous dissipation, internal heat generation/absorption, chemical reaction of first order and Joule heating are further incorporated in the problem. The induced magnetic field as well as the outer electric field are assumed negligible. A constant heat flux q_w and mass flux q_m is acting at the surface of the sheet as well as a variable velocity v_w is also considered which will be defined latter in the problem.

The governing equations of the problem (Abualnaja 2018, Swain *et al.*, 2020) along with the present assumptions are

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

$$u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}=\upsilon\frac{\partial^2 u}{\partial y^2}-\frac{\sigma B_0^2 u}{\rho}-\frac{\upsilon u}{K_p^*}, \tag{2}$$

$$u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}=\alpha\frac{\partial^2 T}{\partial y^2}-\frac{1}{\rho C_p}\frac{\partial q_r}{\partial y}+\frac{q'''}{\rho C_p}+\frac{\mu}{\rho C_p}\left(\frac{\partial u}{\partial y}\right)^2+\frac{\sigma B_0^2}{\rho C_p}u^2. \tag{3}$$

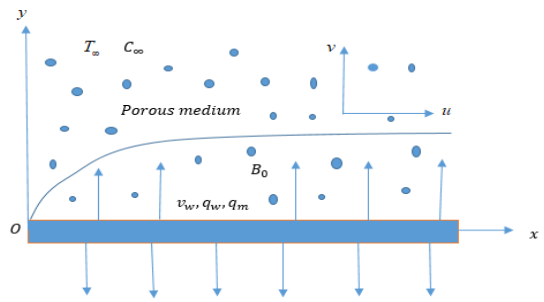

Fig. 1: Flow configuration

$$u\frac{\partial C}{\partial x}+v\frac{\partial C}{\partial y}=D\frac{\partial^2 C}{\partial y^2}-K_1(C-C_\infty). \tag{4}$$

The boundary conditions are given by

$$u=U, v=-v_w, -k\left(\frac{\partial T}{\partial y}\right)=q_w,\ -D\left(\frac{\partial C}{\partial y}\right)=q_m \text{ at } y=0, \tag{5}$$

$$u\to 0, T\to T_\infty, C\to C_\infty \ as\ y\to\infty. \tag{6}$$

where $v_w=v_0e^{\frac{x}{2L}}$, v_0 is a constant. υ, σ, K_p^*, ρ, α, C_p, k, D, K_1 represents kinematic viscosity, electrical conductivity, permeability, density, thermal diffusivity, specific heat at constant pressure, thermal conductivity, mass diffusion rate and rate of reaction respectively.

Heat flux due to radiation (Yih, 1999),

$$q_r=-\left(\frac{4\sigma^*}{3k^*}\right)\frac{\partial T^4}{\partial y}. \tag{7}$$

where

$$T^4\cong 4T_\infty^3T-3T_\infty^*. \tag{8}$$

Non-dimensional transformations (Abualnaja 2018; Swain *et al.*, 2020) and non-dimensional variables are now introduced as follows

$$\psi=\sqrt{2\upsilon LU}f(\eta), \eta=y\sqrt{\frac{U}{2\upsilon L}}, \theta(\eta)=\frac{k}{q_w}(T-T_\infty)\sqrt{\frac{Re}{2L^2}},$$
$$\phi(\eta)=\frac{D}{q_m}(C-C_\infty)\sqrt{\frac{Re}{2L^2}}, Re=\frac{UL}{\upsilon}, M=\frac{2\sigma B_0^2L}{\rho U}, Pr=\frac{\mu C_p}{k},$$
$$R=\frac{16\sigma^*T_\infty^3}{3k^*k}, f_w=v_0\left(\frac{\mu U_0}{2\rho L}\right)^{-\frac{1}{2}}, K_p=\frac{K_p^*U}{2L\upsilon}, Sc=\frac{\upsilon}{D},$$
$$K_c=\frac{2LK_1}{U}, Ec=\frac{U^2k}{C_pq_w}\sqrt{\frac{Re}{2L^2}} \text{ and } J=MEc \tag{9}$$

where $Re, M, Pr, R, f_w, K_p, Sc, K_c$ Ec and J represents Reynolds number, magnetic parameter, Prandtl number, radiation parameter, suction/injection parameter, permeability parameter, Schmidt number, chemical reaction parameter, Eckert number and Joule heating parameter respectively.

Heat generation/absorption (Chamkha and Khaled, 2001),

$$q'''=k\left(\frac{Re}{2L^2}\right)[a^*(T_w-T_\infty)e^{-\eta}+b^*(T-T_\infty)]. \tag{10}$$

where a^* is space dependent internal heat generation/absorption coefficient and b^* is temperature dependent internal heat generation/absorption coefficient.

It is found by solving that $u=Uf'(\eta), v=-\sqrt{\frac{\upsilon U}{2L}}\left(f(\eta)+\eta f'(\eta)\right)$ using the stream function ψ given by $u=\frac{\partial\psi}{\partial y}$ and $v=-\frac{\partial\psi}{\partial x}$.

The dimensionless equations are given by

$$f'''+ff''-2f'^2-\left(M+\frac{1}{K_p}\right)f'=0, \tag{11}$$

$$(1+R)\theta''+\Pr(\theta f'+\theta' f)+a^*e^{-\eta}+b^*\theta+$$

$$EcPrf''^2 + EcMPrf'^2 = 0. \quad (12)$$

$$\phi'' + Scf'\phi' - ScK_c\phi = 0. \quad (13)$$

The boundary conditions are now transformed to

$$f = f_w, f' = 1,\ \theta' = -1, \phi' = -1\ at\ \eta = 0, \quad (14)$$

$$f' \to 0, \theta \to 0, \phi \to 0\ as\ \eta \to \infty. \quad (15)$$

Skin-friction coefficient,

$$C_f = \frac{\tau_w}{\rho U^2}, \tau_w = -\mu\left(\frac{\partial u}{\partial y}\right)_{y=0} \text{ or } \sqrt{2Re_x}C_f = -f''(0) \quad (16)$$

Nusselt number,

$$Nu_x = \frac{Lq_w}{k(T-T_\infty)}$$

$$\text{or } Nu_x = \frac{L\left(\frac{k}{\theta(\eta)}(T-T_\infty)\sqrt{\frac{Re}{2L^2}}\right)_{\eta=0}}{k(T-T_\infty)}$$

$$\text{or } Nu_x = \frac{\sqrt{Re_x}}{\sqrt{2}\theta(0)}$$

$$\text{or } \frac{\sqrt{2}Nu_x}{\sqrt{Re_x}} = \frac{1}{\theta(0)} \quad (17)$$

Sherwood number,

$$Sh_x = \frac{Lq_m}{D(C-C_\infty)}$$

$$\text{or } Sh_x = \frac{L\left(\frac{D}{\phi(\eta)}(C-C_\infty)\sqrt{\frac{Re}{2L^2}}\right)_{\eta=0}}{D(C-C_\infty)}$$

$$\text{or } Sh_x = \frac{\sqrt{Re_x}}{\sqrt{2}\phi(0)}$$

$$\text{or } \frac{\sqrt{2}Sh_x}{\sqrt{Re_x}} = \frac{1}{\phi(0)} \quad (18)$$

where $Re_x = \frac{UL}{\upsilon} = \frac{U_0 e^{\frac{x}{L}}}{\upsilon}$ is the local Reynolds number

III. METHOD OF SOLUTION

The solution of the present problem has been obtained numerically by solving Eqs. (11)-(13) along with boundary conditions (14) and (15) using Matlab solver bvp4c. In order to use bvp4c, Eqs. (11)-(13) are converted to first order differential equations as follows:

Let $f = y_1, f' = y_1' = y_2, f'' = y_2' = y_3, \theta = y_4,$

$\theta' = y_4' = y_5, \phi = y_6, \phi' = y_6' = y_7$

The first order differential equations are given by

$$y_1' = y_2, y_2' = y_3, y_3' = -y_1y_3 + 2y_2^2 + \left(M + \frac{1}{K_p}\right)y_2,$$

$$y_4' = y_5, y_5' = (-\Pr(y_4y_2 + y_5y_1) - a^*e^{-\eta} - b^*y_4 - EcPry_3^2 - EcMPry_2^2)/(1+R)\ , y_6' = y_7,$$

$$y_7' = -Scy_2y_7 + ScK_cy_6$$

The boundary conditions are expressed as follows

$$y_1(0) - f_w, y_2(0) - 1, y_5(0) + 1, y_7(0) + 1,$$

$$y_2(\infty), y_4(\infty), y_6(\infty).$$

With the help of the bvp4c Matlab code, we obtained the solution in graphical form.

IV. RESULTS AND DISCUSSIONS

Equations (11)-(13) with respect to the boundary restrictions (14) and (15) are solved by numerical technique using bvp4c, a Matlab inbuilt solver. The results are illustrated graphically using figures for $f'(\eta), \theta(\eta)$ and $\phi(\eta)$ for different parameters while $f''(0)$, $\frac{1}{\theta(0)}$ and $\frac{1}{\phi(0)}$ are analyzed using the computed values as represented in the table 1. For computation analysis, we put $K_p = 1$, $R = 0.5$, $M = 1$, $Ec = 0.02$, $a^* = b^* = 0.2$, $Sc = 0.22$, $K_c = 1$ and $f_w = 1.5$. The numerical precision is verified by making comparison of our results with Swain *et al.* (2020) and Abualnaja (2018) in Table 2-4.

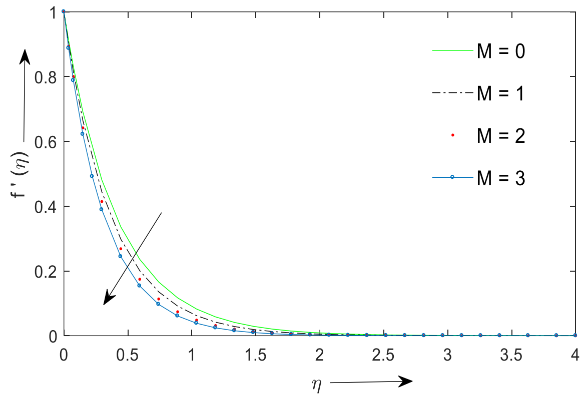

Fig. 2: Change in $f'(\eta)$ due to M

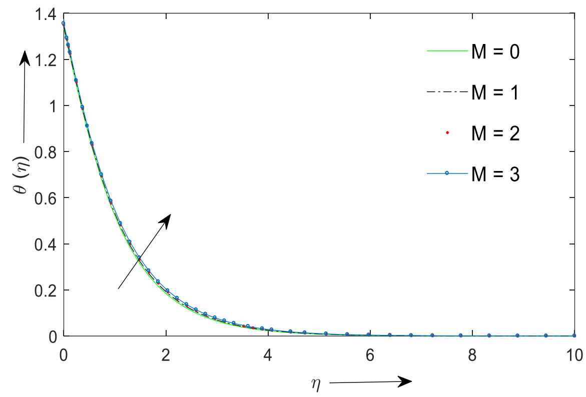

Fig. 3: Change in $\theta(\eta)$ due to M

Figure 2 and Fig. 3 highlights the consequence of magnetic parameter on fluid velocity and temperature. The graphical results show that fluid velocity slows considerably with the hike in magnetic parameter while the temperature shows marginal increase. Magnetic field accounts for the formation of a retarding force called Lorentz force which is opposing in nature. Thus, the fluid velocity declines because of the hindrance provided by Lorentz force. In Fig. 4, it is spotted that permeability parameter accounts for the rise of velocity while a marginal decline in temperature and concentration is perceived with the enhancement of permeability parameter as evident in Fig. 5 and Fig. 6.

The variations caused by chemical reaction parameter on concentration of the fluid is shown in Fig. 7. The result reveals that fluid concentration reduce considerably with the increase in chemical reaction parameter. The effect of chemical reaction directly alters the rate of chemical activity by enhancing the molecular diffusivity. The decrease in fluid concentration close to the sheet informs that molecules diffuse away from the sheet. The variations caused by Schmidt number on fluid concentration is quite similar to that of chemical reaction parameter as evident from Fig. 8. Concentration of the fluid reduces drastically with the hike in Schmidt number. Figure 9 portrays the consequence of Eckert number on fluid temperature. The hike in Eckert number contribute to the rise

Table 1. Computed values of $f''(0)$, $\frac{1}{\theta(0)}$ and $\frac{1}{\phi(0)}$ with $M = 1, K_p = 1, R = 0.5,\ Ec = 0.02, Pr = 1, f_w = 1.5, a^* = b^* = 0.2, Sc = 0.22$ and $K_c = 1$.

M	K_p	Pr	R	Ec	Sc	K_c	$f''(0)$	$\frac{1}{\theta(0)}$	$\frac{1}{\phi(0)}$
0	1	0.71	0.5	0.02	0.22	1	-2.5207	0.7495	0.5006
1							-2.7867	0.7450	0.4981
2							-3.0206	0.7412	0.4963
3							-3.2325	0.7380	0.4948
1	0.1						-4.3810	0.7312	0.4890
	0.5						-3.0208	0.7427	0.4963
	1						-2.7867	0.7450	0.4981
	5						-2.5772	0.7472	0.5000
		0.71					-2.7867	0.4325	0.4981
		1					-2.7867	0.7450	0.4981
		2					-2.7867	1.6641	0.4981
		3					-2.7867	2.4642	0.4981
			0				-2.7867	1.0936	0.4981
			0.5				-2.7867	0.7450	0.4981
			1				-2.7867	0.5492	0.4981
			1.5				-2.7867	0.4242	0.4981
				0			-2.7867	0.7587	0.4981
				0.02			-2.7867	0.7450	0.4981
				0.05			-2.7867	0.7254	0.4981
				0.2			-2.7867	0.6409	0.4981
					0.22		-2.7867	0.7450	0.4981
					0.64		-2.7867	0.7450	0.9274
					0.78		-2.7867	0.7450	1.0504
					1.1		-2.7867	0.7450	1.3166
						0.5	-2.7867	0.7450	0.3548
						1	-2.7867	0.7450	0.4981
						1.5	-2.7867	0.7450	0.6080
						2	-2.7867	0.7450	0.7003

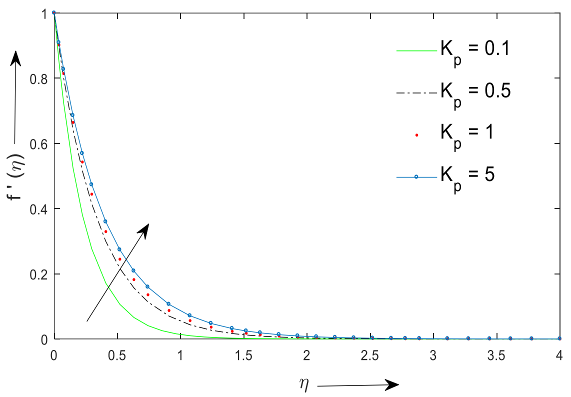

Fig. 4: Change in $f'(\eta)$ due to K_p

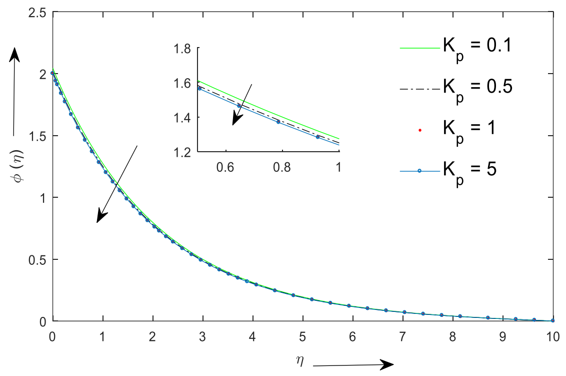

Fig. 6: Change in $\phi(\eta)$ due to K_p

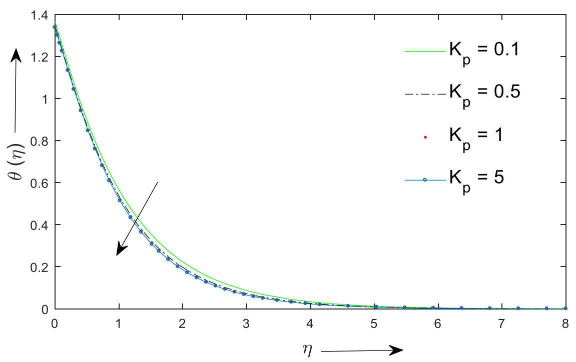

Fig. 5: Change in $\theta(\eta)$ due to K_p

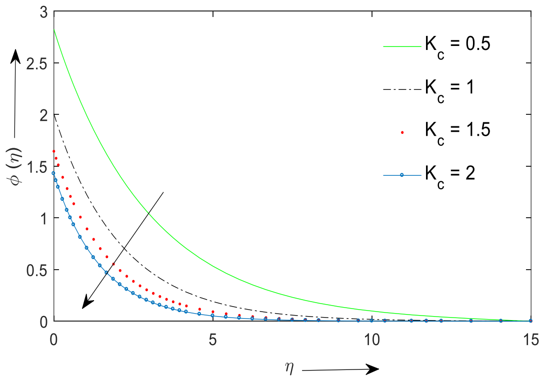

Fig. 7: Change in $\phi(\eta)$ due to K_c.

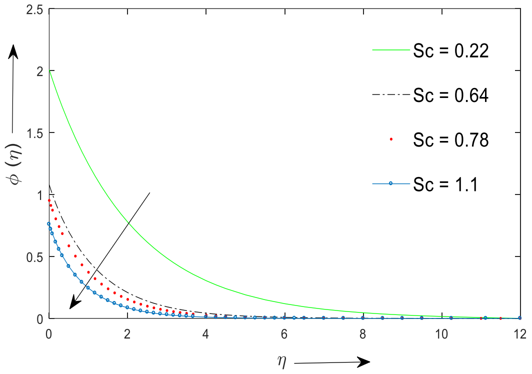

Fig. 8: Change in $\phi(\eta)$ due to Sc

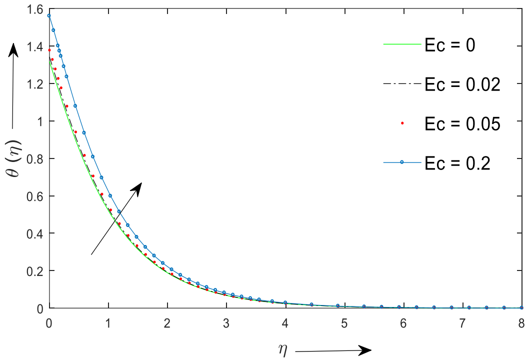

Fig. 9: Change in $\theta(\eta)$ due to Ec

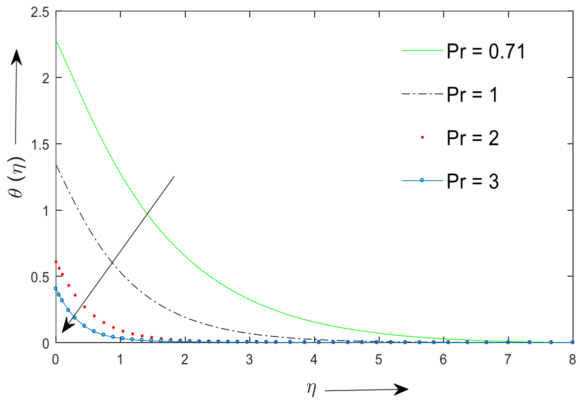

Fig. 10: Change in $\theta(\eta)$ due to Pr

of fluid temperature. Eckert number represents the effect of viscous dissipation, and it can be said that viscous dissipation accounts for rise of fluid temperature.

The consequence of Prandtl number on fluid temperature results in drastic decrease in temperature as well as its boundary layer thickness as seen in Fig. 10. Prandtl number is used in heat transfer operations because it manages the relative thickness of momentum as well as thermal boundary layer. When Pr is low, diffusion of heat is a lot quicker as compared to the fluid's momentum. The reduction in temperature because of increasing Prandtl number i.e. enhancement of the rate of cooling of the fluid near the surface of the sheet, can help in many engineering applications.

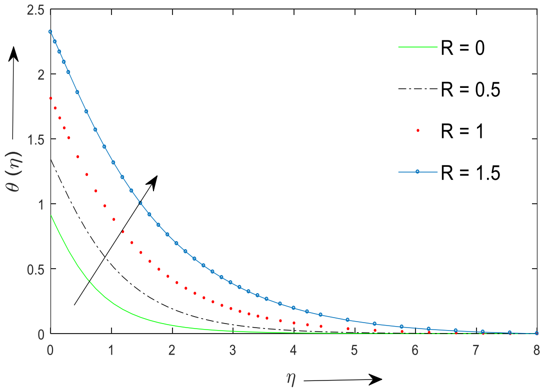

Fig. 11: Change in $\theta(\eta)$ due to R

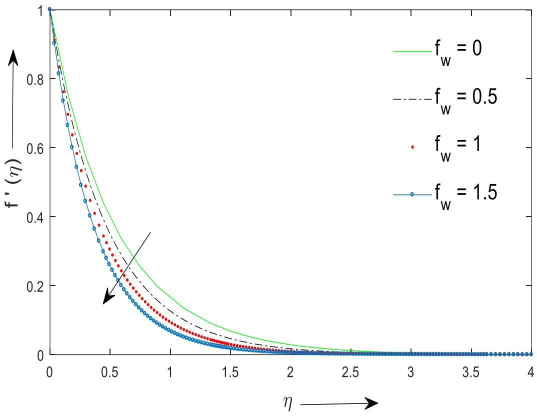

Fig. 12: Change in $f'(\eta)$ due to f_w

The variations in temperature due to radiation parameter is illustrated in Fig. 11. The figure shows that radiation parameter enhances the temperature of the fluid. From mathematical point of view, radiation parameter is indirectly dependent on absorption coefficient and so absorption coefficient gradually decreases with gradual rise in radiation parameter. Thus, less amount of heat is absorbed with the growth of radiation parameter thereby enhancing the fluid temperature. The variations on velocity due to the effect of suction is depicted in Fig. 12. The fluid velocity declines with the growth of suction parameter.

Joule heating parameter is mathematically expressed as the product of Eckert number and magnetic parameter as shown in Eq. (9). The numerical investigation revels that fluid temperature enhances with the rise of both magnetic field and viscous dissipation effects. Therefore, Joule heating parameter $(J = MEc)$ will certainly contribute to the rise of fluid temperature.

In Fig. 13 and Fig. 14, the change in fluid temperature due to a^* and b^* are illustrated. $a^*, b^* > 0$ implies heat generation while $a^*, b^* < 0$ signifies heat absorption. It is interpreted from the graphs that augmenting values of both a^* and b^* causes rise in fluid temperature.

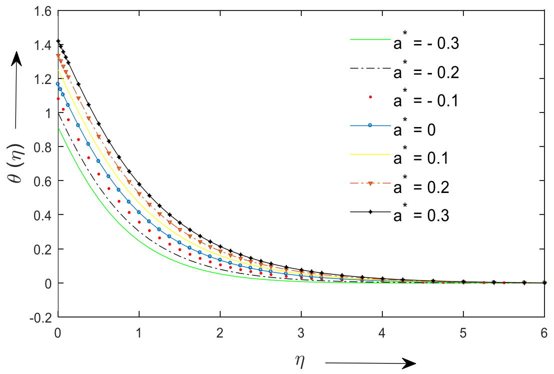

Fig. 13: Change in $\theta(\eta)$ due to a^*

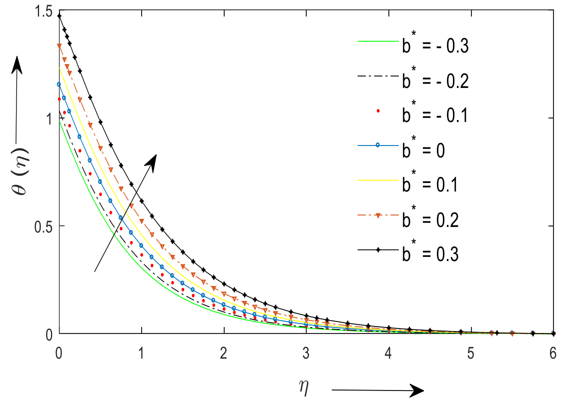

Fig. 14. Change in $\theta(\eta)$ due to b^*

Table 2: Comparison of the present result of $f''(0)$ with Swain et al. (2020) with $R = 0.5,\ Ec = 0.02, Pr = 1, f_w = 1.5, a^* = b^* = 0.2\ Sc = 0$ and $K_c = 0$.

M	K_p	Swain *et al.* (2020) $f''(0)$	Present result $f''(0)$
0	1	-2.52073	-2.5211
0.5		-2.65853	-2.6587
1		-2.78669	-2.7868
1	0.1	-4.38096	-4.3810
	0.5	-3.02082	-3.0208
	10	-2.54918	-2.5492

Table 3. Comparison of the present result of $\frac{1}{\theta(0)}$ with Swain *et al.* (2020) with $M = 1, R = 0.5, K_p = 1, Ec = 0.02, Pr = 1, f_w = 1.5, Sc = 0$ and $K_c = 0$.

a^*	b^*	Swain *et al.* (2020) $\frac{1}{\theta(0)}$	Present result $\frac{1}{\theta(0)}$
-0.1	0.2	1.02445	1.0773
0		1.08437	1.1594
0.3		1.31527	1.4056
	-0.1	1.06830	1.0838
	0	1.12590	1.1477
	0.3	1.27427	1.2516

V. CONCLUSIONS

The present work aims to investigate the changes in the process of thermal transmission as well as mass transmission on MHD flow through a sheet that is stretching exponentially in porous medium assuming constant surface heat and mass flux and variable suction. Many major parameters alter the flow of heat and mass causing its enhancement or decrement while there are some other parameters which could not bring any change. The crucial outcomes are listed below:

1. Fluid velocity declines with growth of magnetic parameter and suction parameter while permeability parameter enhances the velocity.
2. Fluid temperature improves due to M, Ec, R, a^* and b^* while K_p and Pr hinders its growth.
3. The concentration of the fluid near the sheet reduces with the hike in values of K_p, K_c and Sc.
4. Heat transmission rate decreases with the hike of M, R and Ec while on the other hand it enhances due to permeability parameter and Prandtl number. Schmidt number and chemical reaction parameter do not alter the heat transfer rate.
5. Reduction in the rate of mass transfer takes place with the increase in magnetic parameter while K_p, Sc and K_c hikes the rate of mass transfer. Radiation parameter, Prandtl number and Eckert number do not cause any change to mass transfer process.
6. Magnetic parameter decreases the skin-friction coefficient while on the other hand the effect of permeability parameter causes its rise. Skin-friction coefficient remains unaffected by other important parameters like Pr, R, Ec, Sc and K_c.

Table 4. Comparison of the present result of $\frac{1}{\theta(0)}$ with Abualnaja (2018) with $R = 0.5, \frac{1}{K_p} = 0, Ec = 0, Pr = 1, a^* = b^* = 0.2\ Sc = 0$ and $K_c = 0$.

M	f_w	Abualnaja (2018) $\frac{1}{\theta(0)}$ (DTM)	Present result $\frac{1}{\theta(0)}$ (bvp4c)
0	1.5	0.766352	0.771664
1.5		0.763616	0.769941
0.5	1	0.425036	0.449256
	2	1.080237	1.085069

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