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Theoretical Investigation of Magnetohydrodynamic Radiative Non-Newtonian Fluid Flow over a Stretched Surface

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Abstract
The aim of this study is to investigate the heat and mass transfer in magnetohydrodynamic Newtonian and non-Newtonian fluid flow over a stretched domain in the presence of thermal radiation, chemical reaction, Soret and Dufour effects. In addition to this, we also considered the aligned magnetic field (i.e. the magnetic field applied at different angles) along the flow direction and dual solutions are executed for the transverse and aligned magnetic field cases. The governing system of equations is transformed as the system of ODEs with the help of suited similarity transforms. The resulting equations are solved numerically with the aid of the shooting process. The graphical and tabular results are explored to discuss the flow, thermal and concentration behavior along with the heat and mass transfer rate.
Keywords: MHD, Aligned Magnetic field, Soret and Dufour effects, Radiation, Chemical reaction.

1. Introduction

The heat and mass transfer in non-Newtonian liquids have prevailed because of their applications in science, industrial and building territories. Liquids which don't obey the Newton's law of viscosity are known as the non-Newtonian liquids. The cases of non-Newtonian liquids are blood, nourishment items, gels, slurries, unrefined oils, restorative items, tooth glue and waste liquids. The 2D unsteady magnetohydrodynamic incompressible convective flow over a vertical plate in the presence of cross diffusion and radiation was studied by Sudhakar et al. [1]. Mallikarjuna et al. [2] used the R-K method to discuss the heat and mass transfer flow towards a rotating cone with magnetic field. The influence of thermo diffusion and diffusion thermo on 2D flow of viscous fluid over a vertical porous wavy plate in the presence of chemical reaction and heat generation are solved by utilizing a finite difference method has been analyzed by Aruna et al. [3]. Srinivasa Raju et al. [4] studied heat source and thermal radiation effects on menetohydrodynamic flow over a vertical plate in the presence of cross diffusion effects. Time dependent MHD convective viscous fluid towards a stretching sheet was discussed by Shehzad et al. [5]. They found that the thermal distribution enhances by rising te Dufour parameter. Sharma et al. [6] numerically analyzed the heat source and Joule effects on mixed convective flow over a plate in the presence of cross diffusion and ohmic dissipation. Hayat et al. [7] investigated the effects of thermophoretic motion in 2-dimensional magnetohydrodynamic flow past a stretching sheet in the presence of chemical reaction and concluded that Prandtl number increases when the temperature decreases. Dursunkaya and Worek [8] investigated cross diffusion on transient neutral convective flow towards a perpendicular stretching sheet. Kafoussias [9] also discussed the cross diffusion impacts on mixed convective frontier layer flow in the presence of viscosity variation and found that flow field is significantly affected by the temperature-viscosity variation. Alam and Rahman [10] discussed the behavior of Soret and Dufour effects in the mixed convective flow past a perpendicular plate and concluded that the velocity and nanoparticle concentration boundary layer rises with wall suction. The laminar 3D MHD non Newtonian fluid flow over a permeable stretching surface was investigated by Mahanta and Shaw [11] using Spectral Relaxation method. The impact of cross diffusion and radiation on 3D unsteady laminar flow past a stretching sheet by assuming viscous dissipation with magnetic field have been discussed by Zaib and Shafie [12]. The 2D MHD flow of a non-Newtonian fluid past a permeable shrinking sheet and they analyzed solution by using R-K with shooting scheme was discussed by Akber et al. [13].

The dual solution of non-Newtonian fluid flow towards a shrinking surface was discussed by Kameswaran et al. [14]. Pop et al. [15] investigated the effects of radiation on near the stagnation point flow over a stretching surface. The thermal radiation influence of magnetohydrodynamic flow, heat and blood transfer in porous stretching motion with slip parameter was studied numerically by Misra and Sinha [16]. Hayat et al. [17] examined the influence of viscous dissipation on non Newtonian fluid flow towards a stretching cylinder with thermal radiation and found the result that improvement in radiation influences corresponds to a superior fluid thermal distribution. The 2D laminar magenetohydrodynamic heat transfer flow past stretching surface with permeable medium in the presence of chemical reaction and viscous dissipation was studied by Hunegnaw and Kishan [18]. The Soret and Dufour effects on convective fluid flow over a circular annulus in permeable medium with magnetic field has been investigated by Reddy and Rao [19]. Reddy et al. [20] examined the heat transfer in Casson fluid past a stretching sheet in the presence of aligned magnetic field and radiation are solved by using R-k based shooting scheme. The effects of thermophoesis and Brownian motion on MHD nanofluid flow past a heated stretching surface with thermal radiation using R-K-F method was studied by Khan et al.[21]. Gireesha et al. [22] investigate the steady 2D stagnation-point flow of nanofluid over a stretching sheet in the presence of melting effect. And found the result that the effect of thermophoresis ratio is to enhance the thermal distribution at the flow surface. Numerically studied the heat transfer of a nanofluid flow past in a channel in the presence of chemical reaction and thermal radiation has been discussed by Narayana and Babu [23]. Mass transfer influence in 3D free convective MHD flow of incompressible viscous fluid towards a stretching sheet along with cross diffusion effects was studied by Ashraf et al. [24]. The effects of thermo diffusion and diffusion thermo on the unsteady MHD flow of non Newtonian fluid past a stretching surface with viscous dissipation are solved by using Kellor-Box method was discussed by Ullah et al. [25]. Very recently, the researchers [26-31] studied the heat and mass transfer nature of the magnetic flows through various geometries.

In all the above considerations researchers' focused on the heat and mass transfer of MHD flows by presumptuous one or two physical aspects with the geometries like plate, sheet, cone, etc. From this study, we discussed the heat and mass in the magnetohydrodynamic Casson flow past a stretched surface by assuming the different physical effects by considering the transverse and aligned magnetic fields. Numerical solutions are obtained by making use of the shooting process. Results are investigated through tables and graphs.

2. Formulation of the problem

A two-dimensional, steady, incompressible flow of Casson fluid is considered along the stretched domain. The sheet is placed along the *x*-axis and *y*-axis is normal to it. An inclined magnetic field $B(x) = B_0 x^{1/3}$ is applied to the flow as shown in the Fig.1. It is assumed that the the magnetic field is acts like transverse magnetic field if the aligned angle is 90^0. If aligned angle is less than 90^0 then the magnetic field is acts like aligned one. The velocity of the sheet is denoted as $u_x(x) = cx^{1/3}$ (c is constant). Thermal radiation, cross-diffusion and chemical reaction effects are taken into account and induced magnetic field is neglected in this study.

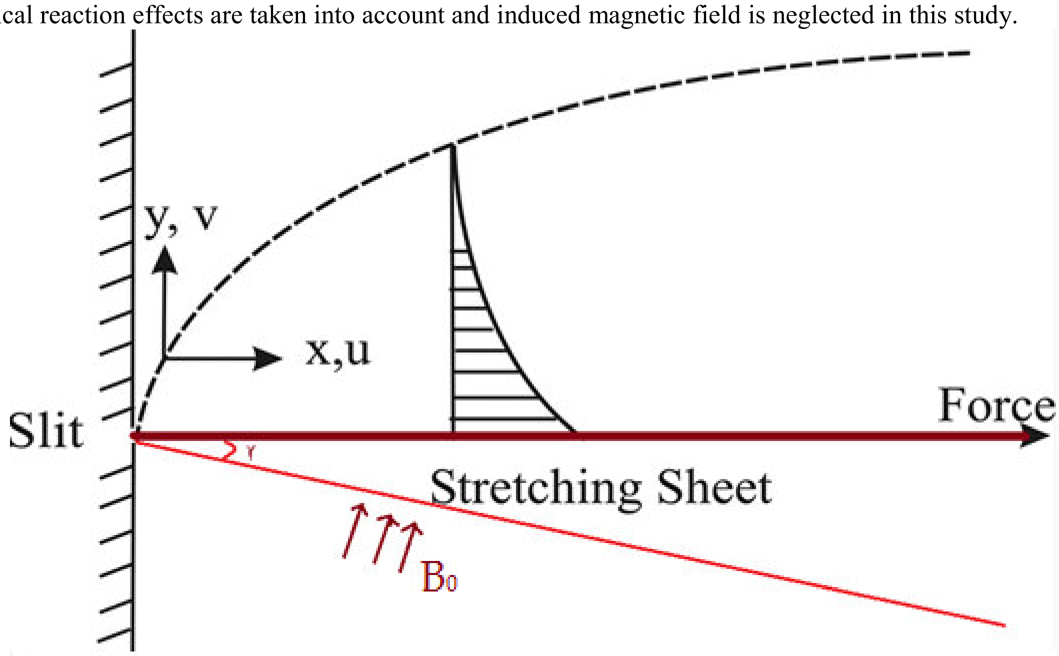

Fig.1 Physical model of the problem

With the assumptions specified above, the governing equations can be written as:

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

$$u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} = \upsilon\left(1+\frac{1}{\delta}\right)\frac{\partial^2 u}{\partial y^2} - \frac{\sigma \sin^2 \gamma B^2(x)}{\rho}u + g\left(\beta_T(T-T_\infty) + \beta_c(C-C_\infty)\right), \tag{2}$$

$$u\frac{\partial T}{\partial x} + v\frac{\partial T}{\partial y} = \alpha\frac{\partial^2 T}{\partial y^2} + \frac{D_m k_T}{c_s c_p}\frac{\partial^2 C}{\partial y^2} - \frac{1}{\rho c_p}\frac{\partial q_r}{\partial y}, \tag{3}$$

$$u\frac{\partial C}{\partial x}+v\frac{\partial C}{\partial y}=D_m\frac{\partial^2 C}{\partial y^2}+\frac{D_m k_T}{c_s c_p}\frac{\partial^2 T}{\partial y^2}-k_i(C-C_\infty), \tag{4}$$

With the conditions

$$u=u_w(x),\ \ v=0,\ -k\frac{dT}{dy}=h_f(x)(T_w-T),\ C_w=C_\infty+bx,\ \text{at}\ y=0,$$

$$u\to 0,\ T\to T_\infty,\ C\to C_\infty,\ \text{as}\ \ y\to\infty \tag{5}$$

Where u and v are the velocity components in the directions of x and y respectively, υ is the kinematic viscosity, δ is the Casson parameter, ρ is the fluid density , σ is the electrical conductivity, g is the acceleration due to gravity , β_T and β_c are the coefficient of thermal and volumetric expansions, α is the thermal conductivity, c_p is specific heat capacitance, q_r is the radiative heat flux, c_s is the concentration susceptibility. D_m is the mass diffusivity, K_T is the thermal diffusion ratio, k_l is the chemical reaction coefficient and T_m is the mean fluid temperature.

By using Roseland approximation, the radiative heat flux q_r is given by

$$q_r=-\frac{4\sigma^*}{3k^*}\frac{\partial T^4}{\partial y} \tag{6}$$

where σ^* is the Steffen Boltzmann constant and k^* is the mean absorption coefficient. Considering the temperature differences within the flow sufficiently small such that T^4 may be expressed as the linear function of temperature. Then expanding T^4 in Taylor series about T_∞ and neglecting higher-order terms takes the form

$$T^4\cong 4T_\infty^3 T-3T_\infty^4 \tag{7}$$

In view of equations 6) & (7), equation (3) reduces to

$$u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}=\alpha\frac{\partial^2 T}{\partial y^2}+\frac{D_m k_T}{c_s c_p}\frac{\partial^2 C}{\partial y^2}+\frac{16\sigma^* T_\infty{}^3}{3\rho c_p k^*}\frac{\partial^2 T}{\partial y^2}, \tag{8}$$

The similarity solutions of equations (2) to (4) subject to the boundary conditions (8) by introducing the following similarity transforms

$$\eta=y\left(c/\upsilon\right)^{0.5}x^{-1/3},\ \ u=cx^{1/3}f'(\eta),\ v=\frac{1}{3}\left[cyx^{-2/3}f'(\eta)-2\upsilon\eta f(\eta)\right]$$

$$\theta(\eta)(T_w-T_\infty)=T-T_\infty,\ \ \phi(\eta)(C_w-C_\infty)=C-C_\infty, \tag{9}$$

Substituting equation (9) into equations (2), (4) and (7), where equation (1) is identically satisfied, we obtain the following ordinary differential equations:

$$\left(1+\frac{1}{\delta}\right)f'''-\frac{1}{3}f'^2+\frac{2}{3}ff''-M\sin^2\gamma f'+Gr\theta+Gc\phi=0, \tag{10}$$

$$(1+Ra)\theta''+\frac{2}{3}\Pr f\theta'+Du\Pr\phi''=0, \tag{11}$$

$$\phi''+SrSc\theta''+\frac{2}{3}Scf\phi'-Kr\phi=0, \tag{12}$$

with the transformed conditions

$$f(\eta)=0,\quad f'(\eta)=1,\quad \theta'(\eta)=-Bi[1-\theta(0)],\quad \phi(\eta)=1,\ \text{at}\ \eta=0,$$

$$f(\eta)=0,\quad \theta(\eta)=0,\quad \phi(\eta)=0,\quad \eta\to\infty, \tag{13}$$

Where $M=\dfrac{\sigma B_0{}^2}{\rho c}$ is the magnetic field parameter , $Gr=\dfrac{g\beta_T(T_w-T_\infty)x^{1/3}}{c^2}$ and

$Gc = \dfrac{g\beta_c (C_w - C_\infty) x^{1/3}}{c^2}$ are the thermal and concentration Buoyancy parameters, $D_f = \dfrac{D_m k_T (C_w - C_\infty)}{c_s c_p (T_w - T_\infty)}$ and $Sr = \dfrac{D_m k_T ((T_w - T_\infty)}{T_m \upsilon (C_w - C_\infty)}$ are the Soret and Dufour numbers, $R = \dfrac{16\sigma^* T_\infty^{\ 3}}{3kk^*}$ is the thermal radiation parameter , $\Pr = \dfrac{\upsilon}{\alpha}$ is the Prandtl number, $Kr = \dfrac{k_l}{c}$ is the chemical reaction parameter and $Sc = \upsilon / D_m$ is the Schmidt number .

The physical quantities of engineering interest, the skin friction at the surface C_{fx} , local Nusselt number Nu_x and local Sherwood number Sh_x are given by

$$\begin{aligned} \mathrm{Re}_x^{\,0.5} C_{fx} &= (1+\delta^{-1}) f''(0), \\ \mathrm{Re}_x^{\,-0.5} Nu_x &= -\theta'(0), \\ \mathrm{Re}_x^{\,-0.5} Sh_x &= -\phi'(0), \end{aligned} \tag{14}$$

where $\mathrm{Re}_x = \dfrac{u_w x}{\upsilon}$ is the local Reynolds number.

3. Results and Discussion

The reduced nonlinear ODE's Eqs. (10)-(12) with the boundary restrictions Eq. (13) are resolved by utilizing shooting technique for the different parameters viz. magnetic field, $Sr, Du, Gr, Ra, \delta, Kr, Bi$ on the velocity, temperature and concentration profiles. In this study, we considered the pertinent parameter values as $Gr = Ra = Du = Sr = 0.5 = Gc, M = 5,\ \Pr = 7, Sc = 0.6, Kr = 0.2, Bi = 0.3$. These values are fixed for the complete study unless otherwise particularized in the corresponding tables and plots.

Figs. 2-4 displayed the impact of M on flow, temperature and concentration distributions respectively. We noticed that the boosting values of M enhances the velocity, thermal and concentration profiles. Generally, rising in magnetic field parameter gives an opposite force to the flow is known as Lorenz force. The Lorenz force may be control to the flow and lessen the velocity distribution as well as it helps to enhance the temperature and concentration boundary layers. Figs. 5 and 6 display that the influence of Ra on temperature and concentration profiles. We found that the rising values of radiation parameter increasing the thermal profile and depreciates the concentration profile. It is also noticed that the aligned magnetic field highly affected by the buoyancy forces when compare with a transverse magnetic field. Figs. 7-9 depict the impact of Gr on velocity, temperature and concentration profiles. We noticed that the improving value of Gr depreciates the flow, thermal and concentration distribution profiles. Physically, boosting the values of Grashof number enhance the buoyancy force of the flow field, these causes to decline the fluid motion and rise in the thermal boundary layer thickness due to internal heat generation.

Figs. 10 and 11 display the impact of Sr on thermal and concentration profiles respectively. It is clear that the rising value of Soret number with increase both the thermal and concentration profiles. The influence of Soret number gives the mass flux from low to high concentration distribution driven by thermal gradient. Figs. 12-14 shows that the influence of Du on velocity, thermal and concentration distributions. We noticed that the rising value of Du enhanced the both momentum and thermal profiles and also reverse behavior in concentration profile. Generally, the impact of Dufour number solutal and thermal buoyancy forces enhances the thermal and concentration filed. Figs. 15 and 16 display the impact of δ on velocity, thermal distribution. It is clear that boosting value of δ enhancing the thermal profile and opposite behavior in flow profile. Fig. 17 illustrates the effect of Bi on temperature profile. It is clear that the thermal distribution is increasing for rising values of Bi .This may happen due to reduced viscosity nature for increasing values of Biot number. Figs. 18 and 19 display the impact of Kr on thermal and concentration profiles respectively. It is clear that the rising value of with Kr increase thermal distribution and lessen the concentration profile.

Tables 1and 2 demonstrates the variations in the flow, local Nusselt and Sherwood number. It is found that the rising values of M and δ depreciates the flow, Nusselt Shearwood numbers. Improving values of Ra and Bi increases both the friction factor and reduced the Nusselt number and depreciates mass transfer rate.

Rising values of Gr increases both the friction factor and reduced Nusselt number. Boosting values of Sr, Du and Kr with enhances the flow heat transfer rate and opposite in Shearwood number in Casson fluid.

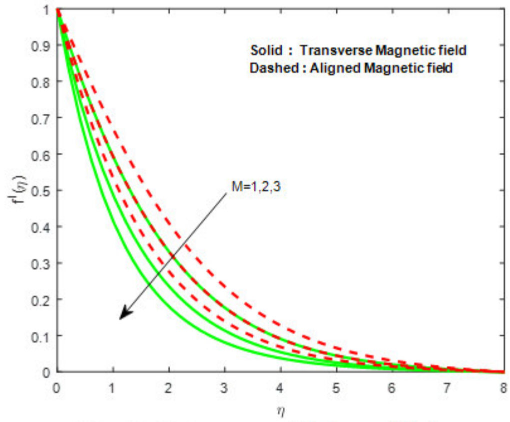

Fig. 2. Influence of M on $f'(\eta)$

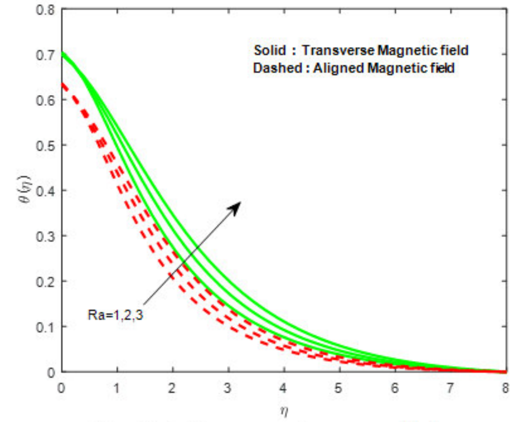

Fig. 5. Influence of Ra on $\theta(\eta)$

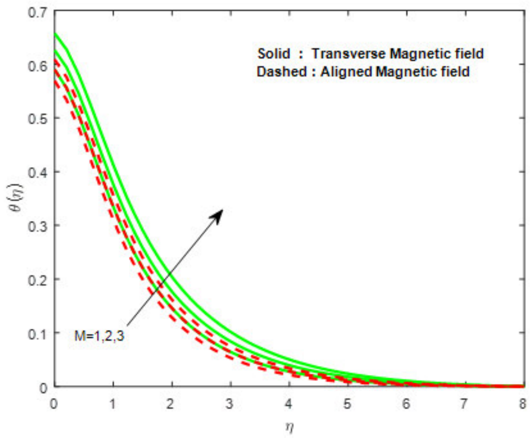

Fig. 3. Influence of M on $\theta(\eta)$

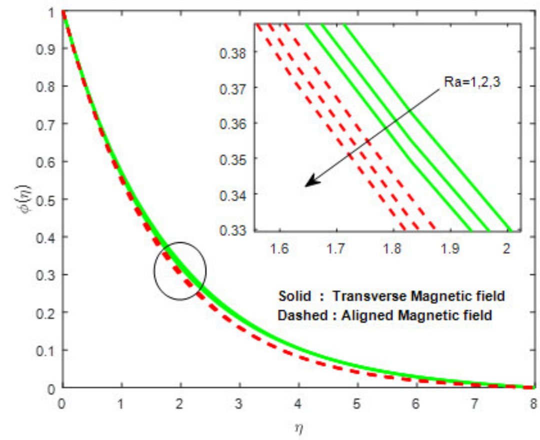

Fig. 6. Influence of Ra on $\phi(\eta)$

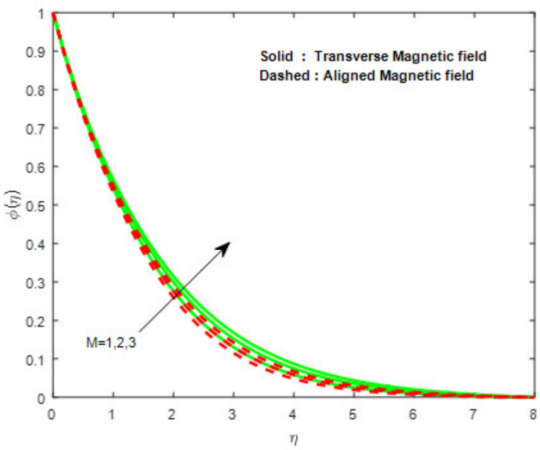

Fig. 4. Influence of M on $\phi(\eta)$

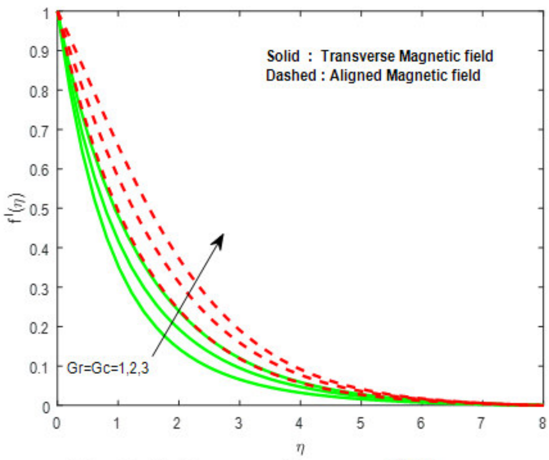

Fig. 7. Influence of Gr on $f'(\eta)$

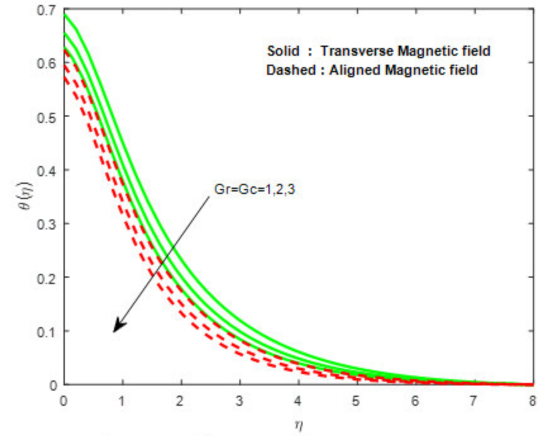

Fig. 8. Influence of Gr on $\theta(\eta)$

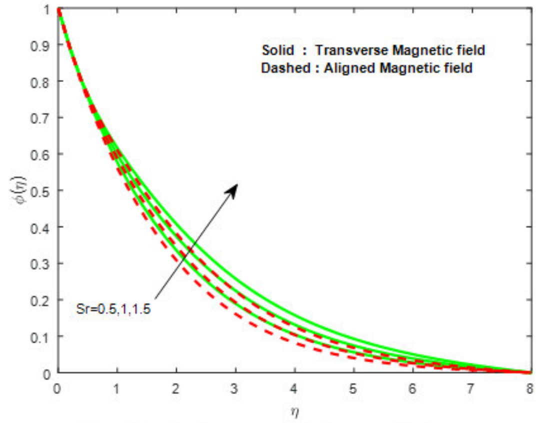

Fig. 11. Influence of Sr on $\phi(\eta)$

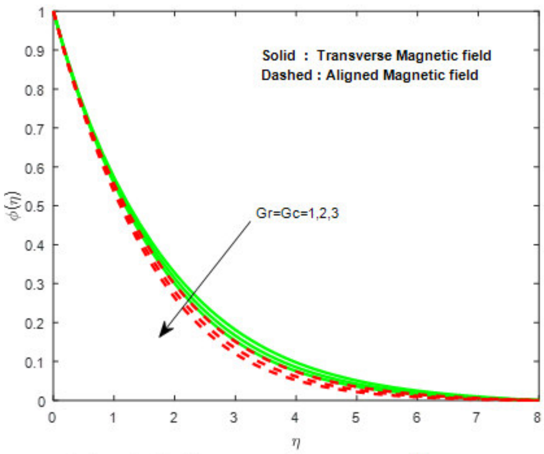

Fig. 9. Influence of Gr on $\phi(\eta)$

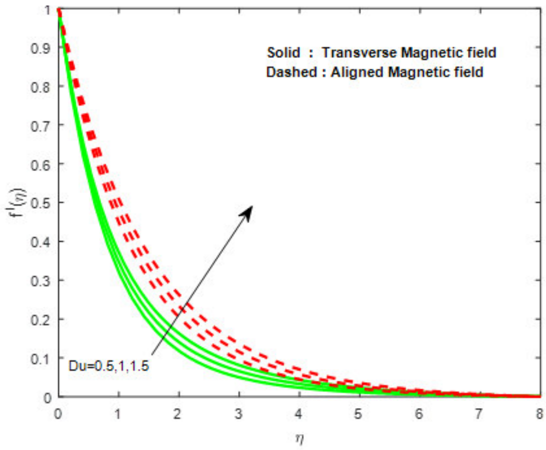

Fig. 12. Influence of Du on $f'(\eta)$

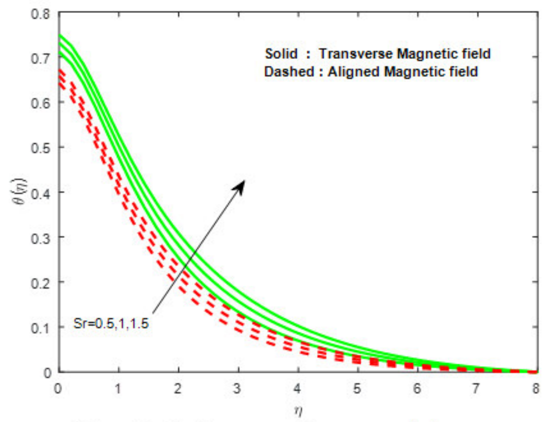

Fig. 10. Influence of Sr on $\theta(\eta)$

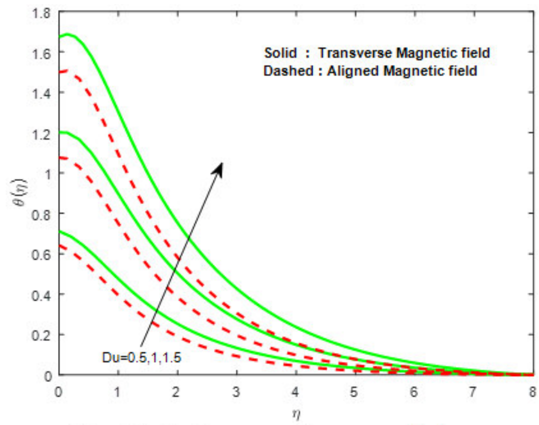

Fig. 13. Influence of Du on $\theta(\eta)$

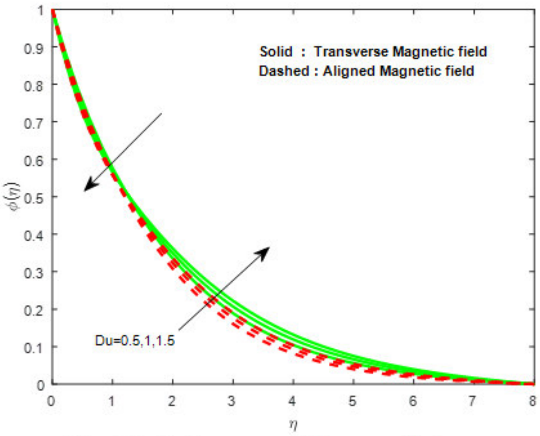

Fig. 14. Influence of Du on $\phi(\eta)$

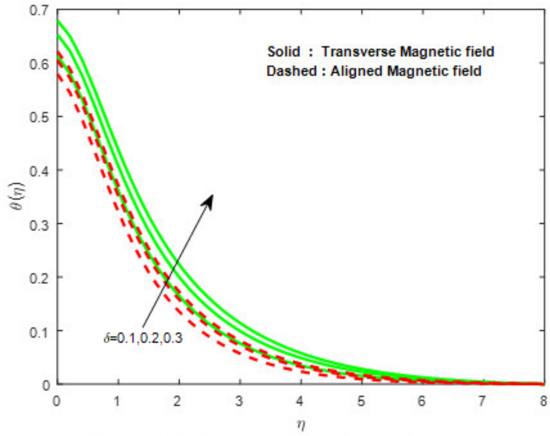

Fig. 16. Influence of δ on $\theta(\eta)$

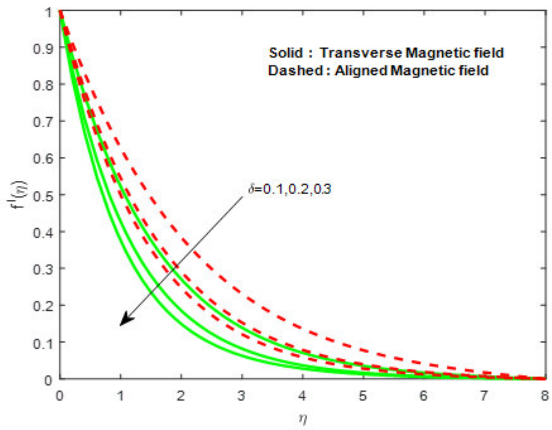

Fig. 15. Influence of δ on $f'(\eta)$

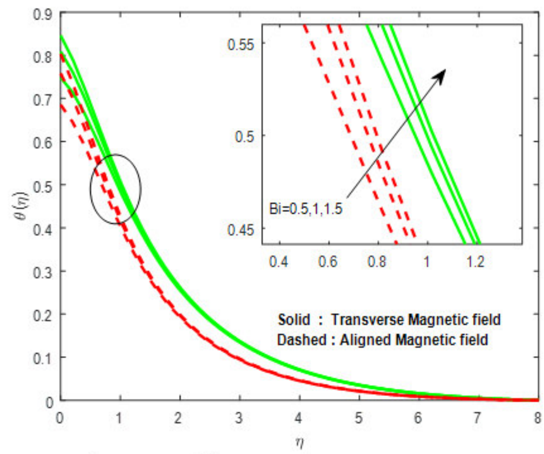

Fig. 17. Influence of Bi on $\theta(\eta)$

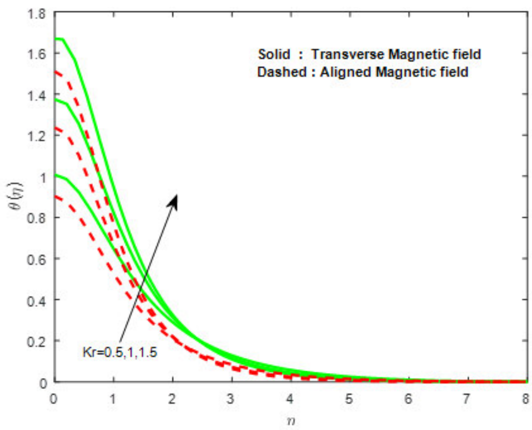

Fig. 18. Influence of Kr on $\theta(\eta)$

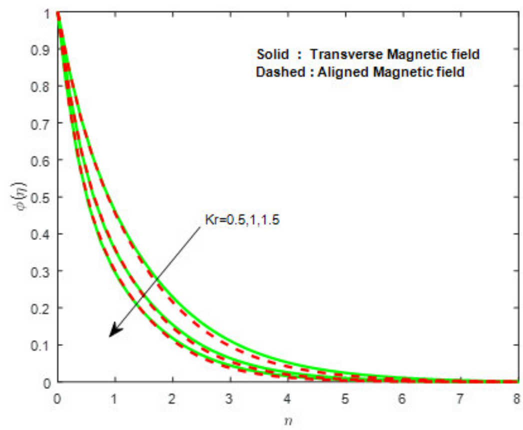

Fig. 19. Influence of Kr on $\phi(\eta)$

Table 1 Variations in $C_{f_x}R_{e_x}, -\theta'(0)$ and $-\phi'(0)$ in transverse magnetic field case

M	*Ra*	*Gr*	*Sr*	*Du*	δ	*Bi*	*Kr*	$C_{f_x}R_{e_x}$	$-\theta'(0)$	$\phi'(0)$
1								-0.491673	0.122963	0.606232
2								-0.715953	0.112109	0.592581
3								-0.896693	0.102677	0.583940
	1							-1.188630	0.088712	0.570962
	2							-1.187440	0.090268	0.567794
	3							-1.186216	0.090206	0.566095
		1						-1.104215	0.092940	0.577138
		2						-0.935580	0.103358	0.584313
		3						-0.768854	0.111393	0.591753
			0.5					-1.189091	0.086423	0.573790
			1.0					-1.184661	0.080518	0.596704
			1.5					-1.180712	0.075169	0.622265
				0.5				-1.189091	0.086423	0.573790
				1.0				-1.134287	-0.060137	0.643813
				1.5				-1.081202	-0.202128	0.711337
					0.1			-0.646594	0.116185	0.597136
					0.2			-0.859460	0.104184	0.585199
					0.3			-1.000994	0.096358	0.579453
						0.5		-1.186460	0.125778	0.565846
						1.0		-1.182106	0.191063	0.552666
						1.5		-1.179444	0.231069	0.544588
							0.5	-1.171786	-0.002475	0.871556
							1.0	-1.149429	-0.112338	1.230443
							1.5	-1.130935	-0.200834	1.514415

Table 2 Variations in $C_{f_x}R_{e_x}, -\theta'(0)$ and $-\phi'(0)$ for aligned magnetic field case

M	*Ra*	*Gr*	*Sr*	*Du*	δ	*Bi*	*Kr*	$C_{f_x}R_{e_x}$	$-\theta'(0)$	$-\phi'(0)$
1								-0.350463	0.129218	0.616546
2								-0.491673	0.122963	0.606232
3								-0.611090	0.117313	0.598544
	1							-0.809476	0.109228	0.585334
	2							-0.807487	0.110318	0.582726
	3							-0.805433	0.109812	0.581514
		1						-0.708613	0.112848	0.593354
		2						-0.509125	0.121558	0.604207
		3						-0.314678	0.128132	0.614572
			0.5					-0.810319	0.107252	0.587821
			1.0					-0.804006	0.102607	0.603062
			1.5					-0.798201	0.098319	0.620408
				0.5				-0.810319	0.107252	0.587821
				1.0				-0.750725	-0.022904	0.652810
				1.5				-0.692606	-0.149626	0.715834
					0.1			-0.456019	0.126268	0.611433
					0.2			-0.597141	0.118580	0.600126
					0.3			-0.689393	0.113582	0.594164
						0.5		-0.806836	0.157233	0.577711
						1.0		0.800960	0.241775	0.560608
						1.5		-0.797298	0.294621	0.549916
							0.5	-0.796917	0.028937	0.872965
							1.0	-0.777364	-0.071122	1.224684
							1.5	-0.760214	-0.152985	1.505776

4. Conclusions

Numerical investigation is carried out to investigate the the heat and mass transfer in magnetohydrodynamic Newtonian and non-Newtonian fluid flow over a stretched domain in the presence of thermal radiation, chemical reaction, Soret and Dufour effects. In addition to this, we also considered the aligned magnetic field (i.e. the magnetic field applied at different angles) along the flow direction and dual solutions are executed for the transverse and aligned magnetic field cases. Numerical observations are as follows:

- Rising values of M decreases the both heat and mass transfer rate.
- Boosting values of Ra suppressing the local Nusselt number.
- Dual solutions are observed for transverse and aligned magnetic field cases.
- An improved Soret number enhances both temperature and concentration distribution**.**
- Du *and* Kr regulates the concentration boundary layer.

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