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Numerical study of chemically reacting unsteady Casson fluid flow past a stretching surface with cross diffusion and thermal radiation

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Abstract: The problem of an unsteady MHD Casson fluid flow towards a stretching surface with cross diffusion effects is considered. The governing partial differential equations are converted into a set of nonlinear coupled ordinary differential equations with the help of suitable similarity transformations. Further, these equations have been solved numerically by using Runge-Kutta fourth order method along with shooting technique. Finally, we studied the influence of various non-dimensional governing parameters on the flow field through graphs and tables. Results indicate that Dufour and Soret numbers have tendency to enhance the fluid velocity. It is also found that Soret number enhances the heat transfer rate where as an opposite result is observed with Casson parameter. A comparison of the present results with the previous literature is also tabulated to show the accuracy of the results.

Keywords: thermal radiation; MHD; unsteady; chemical reaction; cross diffusion effects; stretching surface

1 Introduction

The problems of heat and mass transfer effects on MHD flow have become more important in many engineering processes. The effect of radiation can be quite significant at high operating temperature.The fluid not fulfilling the Newton's rule of cooling is termed as non-Newtonian. A few of them comprise shampoos, sauce, pastes, paints, colloidal solutions,ketchup etc. Casson fluid is also a non-Newtonian fluid. Presently, most of the researchers of fluid mechanics are concentrating their research on this type of fluids due to their rheological applications in chemical and mechanical engineering. The unsteady free convection of non-Newtonian flows over a stretching surface have received much attention in recent days due to its wide applications in many studies like geophysical, geothermal, oil reservoir engineering and astrophysical.

Ibrahim *et al.* [1] discussed the effects of radiation and chemical reaction on an unsteady hydrodynamic free convection flow over an oscillating vertical plate with heat source. Ishak *et al.* [2] investigated the heat transfer characteristics of the boundary layer flow past an unsteady vertical stretching sheet. Through this study, it is found that increase in unsteadiness parameter decreases the velocity, temperature profiles. Furthermore, Bhargava *et al.* [3] studied the Soret and Dufour effects on MHD free convection flow past a semi infinite vertical plate in the presence of thermal radiation. The influence of mass transfer and radiation on MHD unsteady flow past a stretching sheet was reported by Hayat *et al.* [4]. Vempati and Laxmi-Narayana-Gari [5] analyzed cross-diffusion effects on unsteady hydrodynamic flow over an infinite vertical flat plate with thermal radiation. Chamkha and Aly [6] studied the stagnation point flow of a polar fluid over a stretching surface in a porous medium with thermo diffusion and diffusion thermo effects. Pal and Mondal [7] discussed the unsteady MHD non-Darcy mixed convective flow towards a stretching surface with heat and mass transfer effects. In this study, they concluded that temperature profiles increases with Dufour number. The stagnation point flow of a micropolar fluid past a stretching sheet with Soret and Dufour effects was investigated by Hayat *et al.* [8]. Mustafa *et al.* [9] studied the unsteady boundary layer flow of a Casson fluid due to an impulsively oscillating flat plate. From this paper, it is found that an increase in Casson parameter reduces the velocity. The influence of thermal radiation on chemically reacting MHD free convective flow past a vertical plate was studied by Sandeep *et al.* [10].

The boundary layer flow of non-Newtonian fluids over a stretching surface in presence of Lorentz force has mag-

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netized the attention of many authors owing to its significance in many engineering processes like oil exploration, nuclear reactors, plasma studies, MHD generators and boundary layer control in aerofoil. In view of this, Hayat *et al.* [11] reported the cross-diffusion effects on MHD steady flow of a Casson fluid past a stretched surface. The study of an unsteady magneto hydrodynamic mixed convection flow through a radiative vertical plate in a porous medium with Dufour and Soret and effects was carried out by Sharma *et al.* [12] and concluded that velocity and concentration profiles decreases with increasing values of chemical reaction parameter. Zheng *et al.* [13] analyzed the unsteady MHD flow over a moving stretching surface with Soret and Dufour effects. Mukhopadhyay [14] studied the flow characteristics of Casson fluid towards an unsteady stretching surface with thermal radiation. Further, similar type of study on the stagnation point flow was carried out by Bhattacharya [15].

The flow due to stretching of a sheet has countless scientific and industrial applications such as spinning of fiber, glass blowing, metal continuous casting, manufacturing of plastic covers, paper plates production, cooling of a big magnetite plates in a bath and suspension of particles and so on.The impact of cross-diffusion on unsteady MHD mixed convection flow past a stretching surface was discussed by Alsaadi *et al.* [16]. Abbasi *et al.* [17] reported the Soret and Dufour effects on peristaltic transport of magneto hydrodynamic fluid with variable viscosity and found that an increase in Soret number reduces the concentration profiles.The effect of thermo diffusion on chemically reacting dusty viscous flow was studied by Reddy *et al.* [18]. In that paper, it is found that increasing values of Soret number enhances the fluid velocity. Sugunamma *et al.* [19] analyzed the influence of magnetic field and thermal radiation on heat transfer of the nanofluid flow towards a rotating frame. Pramanik [20] investigated the heat transfer effects on the Casson fluid past an exponentially stretching surface with suction/blowing and found that friction factor is higher for suction than that of blowing. Mean while, the unsteady free convection flow of MHD Casson fluid over a moving vertical plate in a porous medium was studied by Khalid *et al.* [21]. Krishna *et al.* [22] studied the influence of chemical reaction and thermal radiation on free convective MHD flow through a permeable stretching sheet with Soret and Dufour effects. The study of mixed convection flow of incompressible Eyring-Powell nanofluid past a stretching surface was carried out by Malik *et al.* [23]. The presence of Soret and Dufour effects on nanofluid flow past an exponentially stretching sheet under the influence of aligned magnetic field was discussed by Sulochana *et al.* [24].

Raju *et al.* [25] reported the unsteady MHD flow of a nanofluid towards an oscillating vertical plate embedded in a porous medium with radiation and Soret effects. Mythili *et al.* [26] investigated the effect of chemical reaction on Casson fluid flow through a permeable vertical cone with non-uniform heat source/sink using the finite difference method of Crank-Nicolson type. In that paper they concluded that temperature dependent heat source/sink parameters play a pivotal role in controlling the heat transfer. The influence of thermal radiation and variable permeability on mixed convective flow of MHD fluid over a vertical wavy channel with travelling thermal waves was analyzed by Narayana [27]. Recently, Raju and Sandeep [28] discussed the Soret and Dufour effects on bio-convection flow of a non-Newtonian fluid past a rotating cone with heat and mass transfer. Very recently, the influence of non uniform heat source/sink on nanofluid due to an unsteady permeable stretching surface was reported by Raju *et al.* [29].

The main aim behind the present study is to analyze the effects of cross diffusion on Casson fluid over an unsteady stretching surface. To the best of author's knowledge none of the researchers carried out this type of study. So, by making use of all the references mentioned above we make an attempt to study the unsteady flow behavior of Casson fluid over a stretching surface with buoyancy effects.

2 Mathematical modeling

Consider an unsteady two dimensional laminar flow of electrically conducting non-Newtonian Casson fluid over a stretching surface. It is assumed that the unsteady fluid flow, heat and mass transfer begins at $t = 0$. It is also assumed that the surface is being stretched with velocity $U_w(x, t) = ax/1 - ct$ along the x -axis as shown Figure 1. Here a is the initial stretching rate and $B = B_0/\sqrt{1 - ct}$ is the magnetic field applied along the $y-$ axis, which is perpendicular to the $x-$ axis. Here B_0 is the strength transverse magnetic field. The mass transfer $v_w(t)$ assumed to be perpendicular to the stretching surface. When the sheet starts to move with velocity $U_w(x, t)$ the surface temperature $T_w(x, t)$ and concentration $C_w(x, t)$ will suddenly raise to T_∞, C_∞ respectively. Also, it is assumed that $T_w > T_\infty$, which corresponds to an assisting flow.

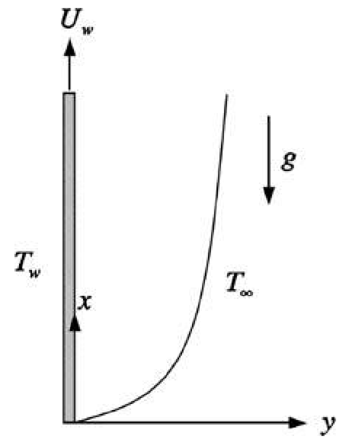

Figure 1: Physical configuration and coordinate system

The rheological equation of state for the Cauchy stress tensor of Casson fluid can be written as [20, 21]

$$\tau_{ij} = \begin{cases} 2\left(\mu_B + p_y/\sqrt{2\pi}\right) e_{ij}, & \pi > \pi_c \\ 2\left(\mu_B + p_y/\sqrt{2\pi_c}\right) e_{ij}, & \pi < \pi_c \end{cases}$$

Where $\pi = e_{ij}e_{ij}$ and e_{ij} is the $(i,j)^{th}$ component of the deformation rate with itself, π_c is the critical value of this product based on the non-Newtonian model, μ_B is the plastic dynamic viscosity of the non –Newtonian fluid and p_y is yield stress of the fluid.

Under above made assumptions the governing equations of the flow are given by,

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

$$\rho\left(\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y}\right) = \mu\left(1 + \frac{1}{\beta}\right)\frac{\partial^2 u}{\partial y^2} + g(\rho\beta_T)(T - T_\infty) + g(\rho\beta_C)(C - C_\infty) - \sigma B^2 u, \tag{2}$$

$$\left(\frac{\partial T}{\partial t} + u\frac{\partial T}{\partial x} + v\frac{\partial T}{\partial y}\right) = \alpha\frac{\partial^2 T}{\partial y^2} - \frac{1}{\rho c_p}\frac{\partial q_r}{\partial y} + \frac{D_m K_T}{c_s c_p}\frac{\partial^2 C}{\partial y^2}, \tag{3}$$

$$\frac{\partial C}{\partial t} + u\frac{\partial C}{\partial x} + v\frac{\partial C}{\partial y} = D_m\frac{\partial^2 C}{\partial y^2} - k_l(C - C_\infty) + \frac{D_m K_T}{T_m}\frac{\partial^2 T}{\partial y^2}, \tag{4}$$

With the boundary conditions

$$u = U_w(x,t),\ v = v_w(t),\ T = T_w(x,t),\ C = C_w(x,t) \quad \text{at } y = 0, \tag{5}$$

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

where u and v are the velocity components in the x, y directions, t refers to the time, $\beta = \mu_B\sqrt{2\pi_c}/p_y$ is the Casson parameter, ρ and μ are density and the dynamic viscosity of the Casson fluid respectively, β_T and β_C are the coefficients of volumetric expansion due to temperature and concentration differences respectively, g is the acceleration due to gravity, T, C are the fluid temperature and concentration, σ is the electrical conductivity, α is the thermal diffusivity, D_m is the species diffusivity, K_T is the thermal diffusion ratio, c_s is the concentration susceptibility, c_p is the specific heat at constant pressure, k_l is the chemical reaction parameter and T_m is the mean fluid temperature.

The quantity q_r on the right hand side of temperature equation (3) represents the radiative flux and is given by,

$$q_r = \frac{-16\sigma^* T_\infty^*}{3k^*}\frac{\partial T}{\partial y}, \tag{7}$$

In eqn. (7), σ^* is the Stephan-Boltzmann constant, k^* is the mass absorption coefficient, T_∞ is the free stream temperature.

Also,

$$U_w(x,t) = \frac{ax}{1-ct},\ v_w(t) = \frac{v_0}{(1-ct)^{1/2}}, \quad T_w(x,t) = T_\infty + \frac{bx}{(1-ct)^2},\ C_w(x,t) = C_\infty + \frac{bx}{(1-ct)^2}, \tag{8}$$

Here a, c are constants ($a > 0$ and $c \geq 0$ with $ct < 1$). Also, b is a constant and has dimension temperature/concentration length ($b = 0$ refers to absence of buoyancy forces).

We now introduce the similarity transformation as,

$$\eta = \left(\frac{a}{v(1-ct)}\right)^{1/2} y,\ \psi(x,y) = \left(\frac{va}{1-ct}\right)^{1/2} x f(\eta), \quad T = T_\infty + \frac{bx}{(1-ct)^2}\theta(\eta),\ C = C_\infty + \frac{bx}{(1-ct)^2}\phi(\eta), \tag{9}$$

Here $\psi(x,y)$ is the stream function that satisfies the continuity equation (1) with

$$u = \frac{\partial\psi}{\partial y} = \frac{ax}{1-ct}f'(\eta), \quad v = \frac{-\partial\psi}{\partial x} = -\left(\frac{va}{1-ct}\right)^{1/2} f(\eta), \tag{10}$$

Using equations (7)–(10) the equations (2)–(5) can be transformed into

$$\left(1 + \frac{1}{\beta}\right)f''' - f'\left(f' + A\right) - f''\left(\frac{1}{2}A\eta - f\right) + \lambda\theta + \lambda^*\phi - Mf' = 0 \tag{11}$$

$$\frac{1}{\Pr}\left(1+\frac{4R}{3}\right)\theta''+Du\phi''-\theta\left(2A+f'\right) \tag{12}$$
$$-\theta'\left(\frac{1}{2}A\eta-f\right)=0,$$

$$\frac{1}{Sc}\phi''-Kr\phi+Sr\theta''-\phi\left(2A+f'\right) \tag{13}$$
$$-\phi'\left(\frac{1}{2}A\eta-f\right)=0,$$

The transformed boundary conditions are

$$f(\eta)=f_w, f'(\eta)=1, \theta(\eta)=1, \phi(\eta)=1, \tag{14}$$
$$f'(\eta)=1, \phi(\eta)=1, \theta(\eta)=1 \quad \text{at } \eta=0$$

$$f'(\eta)\to 0, \theta(\eta)\to 0, \phi(\eta)\to 0 \quad \text{as } \eta\to\infty \tag{15}$$

Where primes denotes differentiation with respect to η, here η is the similarity variable, $A = c/a$ is the unsteadiness parameter, $M = \sigma {B_0}^2/\rho a$ is the magnetic field parameter, $\lambda = g\beta_T b/a^2$ is the thermal buoyancy parameter, $\lambda^* = g\beta_C b/a^2$ is concentration buoyancy parameter, $R = \frac{4\sigma^* T_\infty^3}{kk^*}$ is the radiation parameter, $Du = \frac{D_m K_T}{c_s C_p \upsilon}$ is the Dufour number, $\Pr = \frac{\rho c_p \upsilon}{k}$ is the Prandtal number, $Sc = \upsilon_f/D_m$ is the Schmidt number, $Kr = k_l(1-ct)/a$ is the chemical reaction parameter and $Sr = \frac{D_m K_T}{T_m \upsilon}$ is the Soret number.

The physical quantities of engineering interest are Skin friction coefficient (Cf_x), local Nusselt number (Nu_x) and Sherwood number (Sh_x).These are given by,

$$Cf_x {\mathrm{Re}_x}^{1/2} = \left(1+\frac{1}{\beta}\right) f''(0), Nu_x {\mathrm{Re}_x}^{-1/2} \tag{16}$$
$$= -\left(1+\frac{4R}{3}\right)\theta'(0), Sh_x {\mathrm{Re}_x}^{-1/2} = -\phi'(0),$$

In the above equation $\mathrm{Re}_x = xU_w(x,t)/\upsilon$ is the Reynolds number.

3 Results and discussion

Equations (11)–(13) subject to the boundary conditions (14)–(15) have been solved numerically by adopting Runge-Kutta fourth order method along with shooting technique. Further, the effects of a few pertinent parameters on velocity, temperature and concentration fields have been discussed through figures 2–11.

Then after, we presented the effects of same parameters on skin friction coefficient, Nusselt and Sherwood numbers in table 1. Table 2 depicts the comparison of present results within the existed literature (Ishak*et al.* [2]). This shows the correctness of our results and the numerical technique we adopted. For the results, we con-

Table 1: The influence of various physical parameters on skin friction, heat and mass transfer coefficients.

Du	Sr	β	R	A	$f''(0)$	$-\theta'(0)$	$-\phi'(0)$
0.5					−0.6527	0.8556	1.4484
3.0					−0.6033	0.0273	1.6373
6.0					−0.5348	−1.5818	2.0287
	0.2				−0.6574	0.8481	1.5076
	1.8				−0.6318	0.8920	1.1655
	4.0				−0.5933	0.9724	0.5505
		0.1			−0.4495	0.8713	1.4631
		0.2			−0.5735	0.8613	1.4538
		0.3			−0.6527	0.8556	1.4484
			0.5		−0.6668	1.0141	1.4158
			2.5		−0.6261	0.6287	1.4906
			5.0		−0.6021	0.4740	1.5157
				1.0	−0.6527	0.8556	1.4484
				2.0	−0.8188	1.0963	1.7615
				3.0	−0.9528	1.2904	2.0234

Table 2: Comparison of the values of ($-\theta'(0)$) with the previous work Ishak *et al.* [2], When $\lambda^* = Du = Sr = Sc = R = 0$ and $\beta \to \infty$.

A	λ	Pr	$-\theta'(0)$ Ishak *et al.* [2]	$-\theta'(0)$ Present values
0	0	0.72	0.8086	0.808871
0	0	1.0	1.0000	1.000010
0	1	1.0	1.0873	1.087641
0	3	1.0	1.1853	1.185812
1	0	1.0	1.6820	1.682101
1	1	1.0	1.7039	1.703990

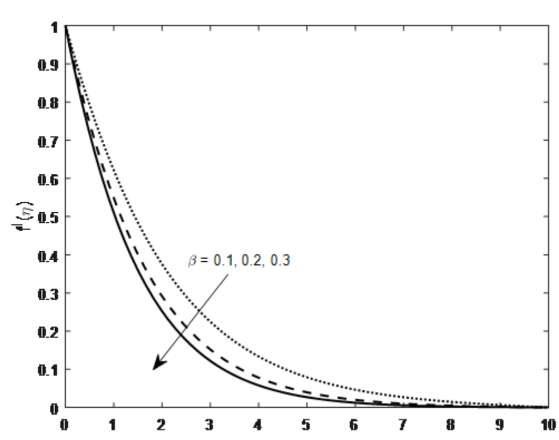

Figure 2: Velocity profiles for different values of Casson parameter β

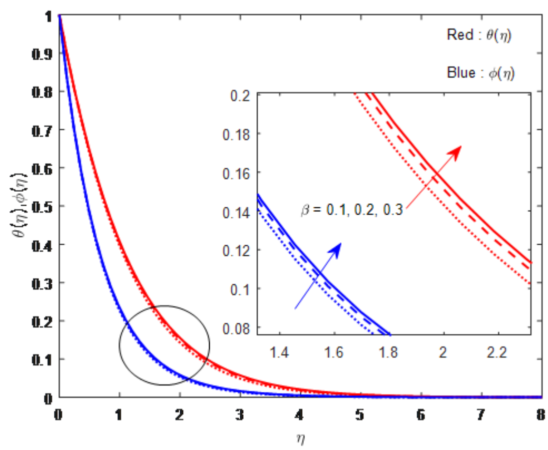

Figure 3: Temperature and concentration profiles for different values of Casson parameter β

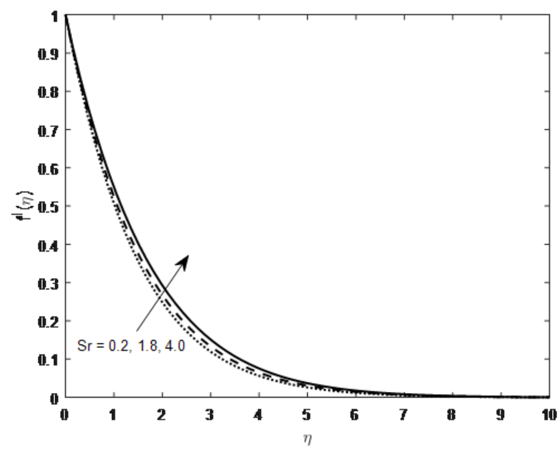

Figure 6: Velocity profiles for different values of Soret number Sr

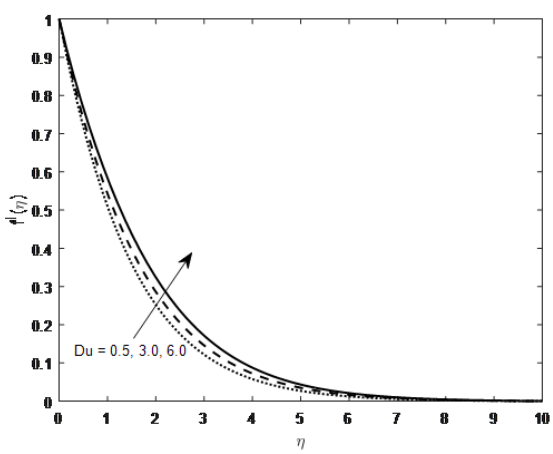

Figure 4: Velocity profiles for different values of Dufour number Du

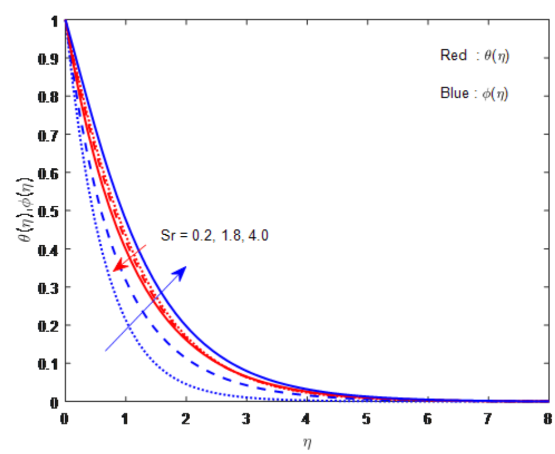

Figure 7: Temperature and concentration profiles for different values of Soret number Sr

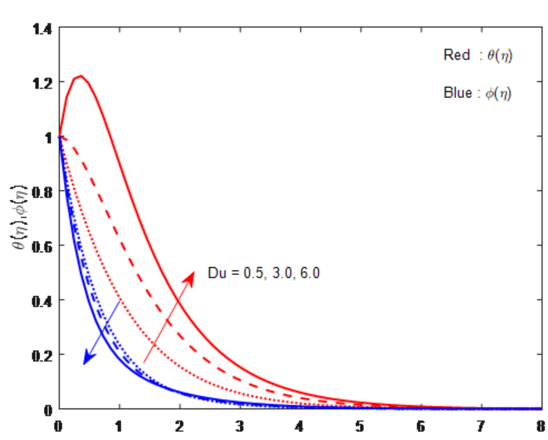

Figure 5: Temperature and concentration profiles for different values of Dufour number Du

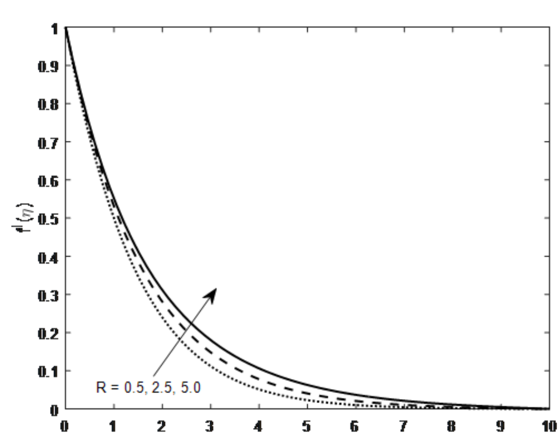

Figure 8: Velocity profiles for different values of radiation parameter R

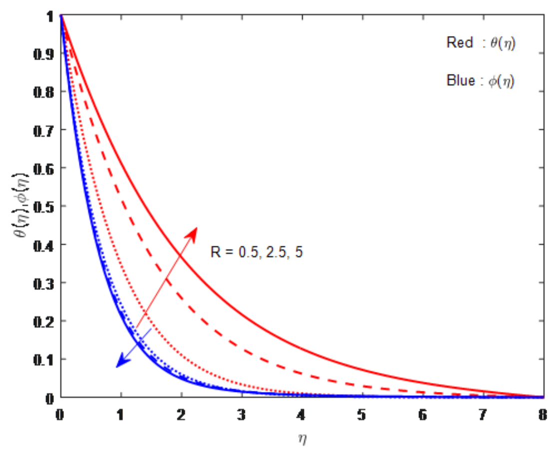

Figure 9: Temperature and concentration profiles for different values of radiation parameter R

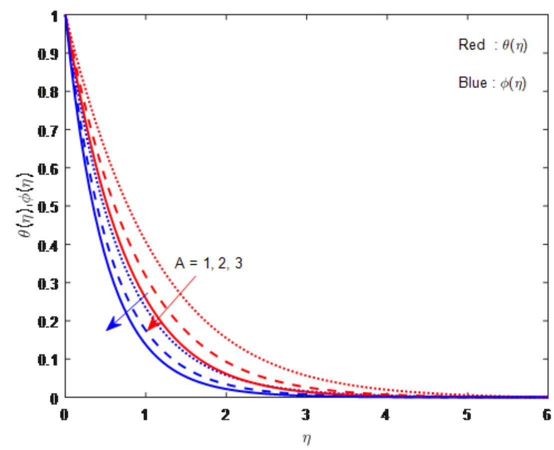

Figure 11: Temperature and concentration profiles for different values of unsteadiness parameter A

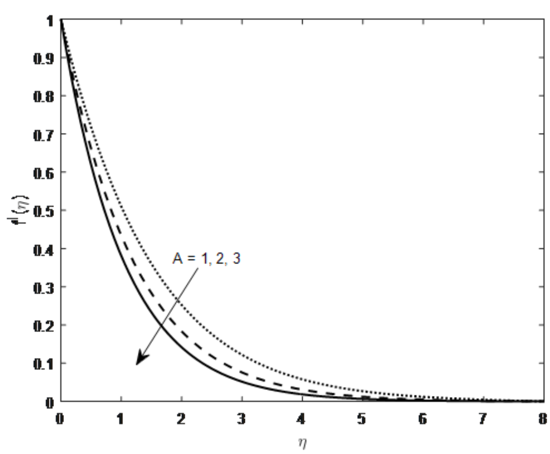

Figure 10: Velocity profiles for different values of unsteadiness parameter A

sidered the values of physical parameters as $\beta = 0.3$, $\eta = 0.1$, $f_w = 0.2$, $R = 1$, $M = 2$, $\Pr = 0.7$ (air), $Sr = Du = 0.5$, $A = 1$, $\lambda = \lambda^* = 1.5$, $Sc = 0.6$ and $Kr = 0.5$. These values have been kept in common for the complete study of results unless otherwise specified in respective figures and tables.

Figures 2–3 are plotted to examine the influence of Casson parameter (β) on velocity, temperature and concentration profiles. In figure 2, we see that velocity increases with β, because, an increase in β increases in plastic dynamic viscosity, which creates a resistance in the fluid motion. From figure 3, one can easily say that increasing values of Casson parameter (β) enhances the temperature as well as concentration distribution. The reason behind this is Casson parameter enhances the thermal and concentration boundary layer thicknesses. Also, it is worth to mention that β significantly affects the temperature profiles while compared with concentration profiles.

The effect of Dufour number (Du) on velocity, temperature and concentration profiles ispresented in figures 4–5. From figure 4, we may conclude that Dufour number enhances the fluid velocity. We observe the same behavior in temperature profiles. But reverse trend is followed by concentration profiles with an increase in the values of Du. Generally, increase in Dufour number produces heat flux in the fluid. This leads to an enhancement in the thermal boundary layer thickness. Figures 6–7 illustrate the influence of Soret number (Sr) on the flow field. From figure 6, we observe that velocity is an increasing function of Soret number (Sr). One can say from figure 7 that increasing values of Soret number reduces the temperature distribution but increases the concentration distribution.

Figures 8–9 disclose the impact of radiation parameter (R) on velocity, temperature and concentration fields. From these figures, we found that velocity and temperature profiles increase with an increase in R. This may happen due to the fact that increase in radiation parameter releases heat energy in the flow. From figure 9, we notice that radiation parameter depreciates the concentration profiles. It is important to mention that temperature profiles are more effected by R while compared with concentration profiles. Figs. 10–11 exhibit the impact of unsteadiness parameter (A) on the velocity, temperature and concentration profiles respectively. It is clear from these figures that an increase in unsteadiness parameter slowdowns the fluid motion but suppress the temperature and concentration profiles. This agrees with the results obtained by Ishak *et al.* [2]. From Fig. 11, it can be also noted that A shows same amount of variation on temperature and concentration distribution.

From table 1, it is interesting to note that Soret and Dufour numbers have the tendency to enhance the friction factor. A rise in the values of Soret number or unsteadiness parameter enhances the heat transfer rate. Meanwhile, increasing values of either Dufour number or radiation parameter decreases the rate of heat transfer but increase the mass transfer rate significantly.

4 Concluding remarks

This paper deals with the study of thermo diffusion and diffusion thermo effects on Casson fluid flow over an unsteady stretching surface in presence of thermal radiation and magnetic field. The influence of various governing parameters has been examined with the help of graphs and tables. The conclusions are summarized below.

- Casson parameter and unsteadiness parameter have tendency to depreciate the velocity distribution.
- Temperature and concentration profiles have been significantly affected by Dufour and Soret numbers respectively.
- A raise in Soret number or unsteadiness parameter increases the heat transfer rate.
- Dufour number significantly suppresses the rate of heat transfer.
- Sherwood number increases with an increase in the values of Dufour number or radiation parameter.

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