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MHD Casson Fluid Flow, Heat and Mass Transfer in a Vertical Channel with Stretching Walls

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Abstract: *In this paper we analyze the flow, heat and mass transfer characteristics of a magneto hydrodynamic Casson fluid in a parallel plate channel with stretching walls subject to a uniform transverse magnetic field. The governing non linear partial differential equations are solved numerically using Runge – Kutta fourth order shooting method. The influence of the governing parameters on the flow variables are discussed through graphs for several sets of values of these parameters. The skin friction, Nusselt number and Sherwood number are calculated and discussed. The study reveals that with increase in the strength of the magnetic field, the fluid velocity decrease however an enhancement in temperature is noticed. With increase in the Casson parameter the width of the central core region is observed to reduce. The investigation bears potential application in the study of blood flow in the cardiovascular system.*

Keywords: *Magnetohydrodynamics (MHD), Heat and Mass transfer, stretching walls.*

1. INTRODUCTION

MHD problems occur in several situations which include the prediction of space weather, damping of turbulent fluctuations in semiconductor melts in crystal growth, measurement of flow rates of beverages in food industry. MHD channel flows gained significant theoretical and practical importance owing to their applications in MHD generators, accelerators and blood flow measurements. Investigations for studies on MHD flow and heat transfer of non – Newtonian fluid flows generated by a stretching sheet find many applications in engineering and industry. For example, in the extrusion of moulton polymers through a slit die for the manufacture of plastic sheets, the sheet is sometimes stretched. The properties of the final product in such processes mainly depend on the rate of cooling. If such a sheet in an electrically conducting Casson fluid under the influence of a magnetic field is drawn, the rate of cooling can be controlled, so that the end product can be obtained with the desired quality.

Crane [1] investigated the steady two dimensional incompressible boundary layer flow of a viscous fluid generated by an elastic flat sheet which moves in its plane with velocity varying linearly with distance from a fixed point due to the application of a uniform stress and obtained closed form solution. Misra [2] analyzed the study of MHD boundary layer flow of a viscous fluid over a stretching surface in the presence of a uniform transverse magnetic field with Hall currents. The study of mass transfer is significant in problems of convective heat transfer of atoms and molecules. Evaporation of water, separation of chemicals in distillation processes involves the mass transfer phenomenon. On the other hand mass transfer with chemical reaction has applications in chemical and hydrometallurgical industries. Chemical reaction can be considered as homogeneous or heterogeneous processes. It depends on the reaction that takes place at the interface as a single phase volume reaction [3]. Several researchers (Kandasamy et al., [3]; Hayat [4]; Bhattacharyya and Layek [5]; Makinde [6]) studied the problems of mass transfer in the presence of chemical reaction.

Several mathematical models have been developed for the blood flow through arteries modeling blood as a Newtonian viscous incompressible fluid. Blood being a suspension of cells in an aqueous solution called plasma, shows a non – Newtonian character. Experiments conducted on blood revealed that blood has a finite yield stress of 0.04 dynes/cm^2 at 40% hematocrit [7][8]. When blood flows in smaller vessels the effect of yield stress is found to be significant [9][10]. It was shown that [11] for a small shear rate, (less than 10 sec^{-1}) and for hematocrit less than 40% the experimental data on its flow properties were best fitted by the Casson's equation. Various experiments conducted on blood [12][13][14][15] [16] with different hematocrits, anticoagulants, temperature confirmed that the flow of blood could be described by the Casson's fluid model over a wide range of shear rates say (1 - 100, 00 sec^{-1}) and more accurately at low shear rates (less than 20 sec^{-1}) [16].

Elbashbeshy[17] studied the heat and mass transfer along a vertical plate in the presence of a magnetic field. The heat and mass transfer on steady laminar flow along a semi infinite horizontal plate in the presence of chemical reaction have been analyzed by Anjalidevi and Kandasamy [18]. The process of chemical reaction in the transport of solutes has applications in blood flow which enables to understand the rate of dispersion of drugs and nutrients. As blood is electrically conducting, the blood flow in the cardiovascular system is likely to be changed by a magnetic field. It is reported that blood flow [19] affects the thermal response of living tissues. The exchange of heat between living tissues and the blood depends on the geometry of the blood vessels and the variation of blood flow. Craciunescu and Clegg [20] studied the oscillatory flow of heat transfer in blood flow considering the vessels of blood as rigid. Weinbaun [21] and Jiji [22] studied the bio heat transfer by considering different types of blood walls. Cavaliere[23] studied the application of heat to tumors in human being in the extremities by local perfusion with warm blood. They observed that the total regression of melonomas and sarcomas has been achieved due to heat only, and thus increased the survival rate of patients. Shitzer and Eberhart[24] explained various theoretical aspects which will facilitate to estimate heat transfer from an external and internal heat source to a tissue. Their studies also helped to predict the resulting temperature distribution in normal tissues of various mammals in hyperthermia and thus the studies will help in the design of heating protocols for hyperthermia treatment.

Misra [25] investigated the blood flow and heat transfer in a parallel plate channel with stretching walls modeling blood as a viscoelastic fluid. Raftari and Vajravelu [26] analyzed the flow and heat transfer characteristics of a magnetohydrodynamic viscoelastic fluid in a parallel plate channel with a stretching wall. Ashraf [27] discussed the MHD flow and heat transfer of a viscous incompressible electrically conducting micropolar fluid in a channel with stretching walls.

The aim of the present investigation is to study the MHD flow, heat and mass transfer characteristics of an electrically conducting incompressible Casson fluid in a channel with stretching walls in the presence of a chemical reaction subject to a uniform transverse magnetic field in a situation where the surface velocity of the channel varies linearly with distance from the origin. The objective of the study is to analyze the flow of blood in arteries whose walls are stretchable by modeling blood as a Casson fluid. The constitutive equation for the Casson fluid model suggested by Nakamura and sawada [28]; Eldabe and Silwa [29]; Dash [30]; Boyd [31] is employed. The nonlinear coupled equations are very complex to find exact solution hence we employed a numerical method to solve the problem.

2. Mathematical Formulation

Consider the two-dimensional steady laminar flow of a Casson fluid in a parallel plate channel with stretching walls in the presence of a transverse magnetic field. The magnetic Reynolds number is assumed to be small so that the induced magnetic field can be neglected. The constitutive equation for the Casson fluid can be written [29] as

$$\tau_{ij} = \begin{cases} 2\left(\mu_B + \frac{\tau_y}{\sqrt{2\pi}}\right) e_{ij}\ , & \pi > \pi_c\ , \\ 2\left(\mu_B + \frac{\tau_y}{\sqrt{2\pi}}\right) e_{ij}\ , & \pi < \pi_c \end{cases} \tag{1}$$

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

Using equation (1) the governing equations of the flow heat and mass transfer are

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0 \tag{2}$$

$$u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} = -\frac{1}{\rho}\frac{\partial p}{\partial x} + \nu\left(1+\frac{1}{\beta}\right)\frac{\partial^2 u}{\partial y^2} - \frac{\sigma B_0^2}{\rho}u \tag{3}$$

$$u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} = -\frac{1}{\rho}\frac{\partial p}{\partial y} + \nu\left(1+\frac{1}{\beta}\right)\frac{\partial^2 v}{\partial y^2} \tag{4}$$

$$u\frac{\partial T}{\partial x} + v\frac{\partial T}{\partial y} = \frac{k}{\rho_{c_p}}\frac{\partial^2 T}{\partial y^2} - \frac{1}{\rho_{c_p}}\frac{\partial q_r}{\partial y} \tag{5}$$

$$u\frac{\partial C}{\partial x} + v\frac{\partial C}{\partial y} = D\frac{\partial^2 C}{\partial y^2} - k_1 C \tag{6}$$

The boundary conditions are

$$u = bx, \quad v = 0, \quad T = T_1, \quad C = C_1 \quad \text{at } y = -a \qquad 7(a)$$

$$u = bx, \quad v = 0, \quad T = T_2, \quad C = C_2 \quad \text{at } y = a \qquad 7(b)$$

where $b > 0$ is for the stretch of the channel walls. where u and v are the velocity components in x and y directions, respectively, ρ is the density, p is the pressure, ν is the kinematic viscosity, $\beta = \mu_B\sqrt{2\pi_c}/p_y$ is the Casson parameter , σ is the electrical conductivity, B_0 is the strength of the magnetic field, T is the temperature of the fluid, k is the thermal conductivity, c_p is the specific heat and q_r is the radiative heat flux, C is the concentration field, D is the mass duffusivity, k_1 is the reaction rate.

Using Roseland approximation the radiative heat flux can be taken as

$$q_r = \frac{-4\sigma^*}{3k^*}\frac{\partial T^4}{\partial y} \tag{8}$$

where σ^* is the Stephan-Boltzman constant, k^* is the mean absorption coefficient. We assume that the temperature difference within the flow is such that T^4 can be expressed as a linear function of temperature. Giving Taylor series expansion about T_∞ and neglecting high order terms we get

$$T^4 \approx 4T_\infty^3 T - T_\infty^4 \tag{9}$$

We introduce the following similarity variables to convert the governing partial differential equations into ordinary differential equations

$$u = bxf'(\eta), \quad v = -ab\,f(\eta), \quad \eta = \frac{y}{a} \qquad 10(a)$$

$$\theta(\eta) = \frac{T - T_2}{T_1 - T_2}, \quad \varphi(\eta) = \frac{C - C_2}{C_1 - C_2} \qquad 10(b)$$

Eliminating pressure gradient from (2) – (3) and using (8) – (10b), equations (2) – (6) reduce to the following equations

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

$$(1+\mathrm{Nr})\,\theta'' + \mathrm{Re}\ \mathrm{Pr}\ f\ \theta' = 0 \qquad (12)$$

$$\varphi'' - \mathrm{Sc}\,\mathrm{Re}\left(\mathrm{K}\varphi - f\,\varphi'\right) = 0 \qquad (13)$$

The corresponding boundary conditions are

$$f(-1) = 0\ ,\ f'(-1) = 1\ ,\ \theta(-1) = 1\ ,\ \varphi(-1) = 1 \quad as\ \eta = -1 \qquad (14a)$$

$$f(1) = 0\ ,\ f'(1) = 1\ ,\ \theta(1) = 1\ ,\ \varphi(-1) = 0 \quad as\ \eta = 1 \qquad (14b)$$

where $\beta = \mu_B\sqrt{2\pi_c}/p_y$ is the non-Newtonian Casson parameter, $\mathrm{Re} = \frac{a^2 b}{\nu}$ is the stretching Reynolds number, $Nr = \frac{16\,\sigma^* T_\infty^3}{3kk^*}$ is the radiation parameter, $\mathrm{M}^2 = \frac{\sigma}{\mu} B_0^2\, a^2$ is the Hartman number, $\mathrm{Pr} = \frac{\mu c_p}{k}$ is the Prandtl number, $\mathrm{Sc} = \frac{\nu}{D}$, is the Schmidt number, $\mathrm{K} = \frac{k1}{b}$ is the chemical reaction parameter.

The skin friction that arise owing to the viscous drag in the vicinity of the plate is calculated as

$$C_f = \frac{\tau_w}{\mu\frac{bx}{a}} = f''(-1)\,, \quad \text{where} \quad \tau_w = \mu\left(\frac{\partial u}{\partial y}\right)_{y=-a} = \mu\,\frac{bx}{a}\,f''(-1) \qquad (15)$$

The rate of heat transfer between the fluid and the walls is evaluated through the non dimensional Nusselt number. The Nusselt number given by

$$\mathrm{Nu} = \frac{q_w}{\frac{k}{a}(T_1 - T_2)} = \theta'(-1)\,, \quad \text{where} \quad q_w = k\left(\frac{\partial T}{\partial y}\right)_{y=-a} = \frac{k}{a}(T_1 - T_2)\,\theta'(-1) \qquad (16)$$

Similarly the Sherwood number is given by

$$\mathrm{Sh} = \frac{m_w}{\frac{D}{a}(C_1 - C_2)} = \varphi'(-1)\,, \quad \text{where} \quad m_w = D\left(\frac{\partial C}{\partial y}\right)_{y=-a} = \frac{D}{a}(C_1 - C_2)\,\varphi'(-1) \qquad (17)$$

The governing equations (11) - (13) along with the boundary conditions (14a) & (14b) have been solved numerically by using Runge - Kutta fourth order method along with shooting technique.

3. Results and Discussion

Fig. 1 presents the stream function for variation of stretching Reynolds number. It is observed that the stream function is positive in the half region of the channel $-1 \le \eta \le 0$. For increasing values of the Reynolds number it is observed that the stream function decreases. In the upper half of the channel the stream function is negative and its behavior is exactly opposite to that in the lower half channel. In fig.2 it is observed that the velocity profiles are symmetric about $\eta = 0$. In the lower region of the channel as the Reynolds number increases there is a decrease in the velocity up to the point $\eta = 0$. In the mid region $-0.5 \le \eta \le 0.5$ of the channel, the velocity increases and in the remaining portion of the upper half of the channel again the velocity decreases. (Fig. 3) The temperature in the lower half channel decreases to half of the wall temperature and subsequently it approaches zero value on the upper plate. For increasing values of Reynolds number it is noticed that the temperature decreases with Reynolds number in the lower half channel and increases in the upper region. The concentration (Fig. 4) from its peak value prescribed on the lower wall reduces parabolically and attains zero value on the upper wall. Concentration is decrease for increasing values of Re.

The variation of Casson parameter on the flow variables is shown in Figs.5 – 8. Increasing values of the Casson parameter β corresponds to decreasing values of yield stress. It is observed that the stream function increases rapidly in the vicinity of the lower wall and after attaining its maximum value it reduces linearly and attains a minimum value and reaches zero value on the upper half. With increasing values of β it is observed that the stream function increases in the lower half and reduces in the upper half channel. From fig. 6 it is observed that the velocity profiles are blunt in the central core region. We observe that reduction in the yield stress (β increasing) the bluntness in the profiles decrease and the width of the plug flow region also decreases. In the shear flow region the velocity decreases with increasing values of yield stress. The temperature is symmetric about the axis η = 0, with increasing values of β the temperature decreases in the lower half channel while it decreases in upper half channel. It is learnt that the temperature increases with increase in the yield stress owing to the development of inertia in the central core which is responsible for the impedance of the flow and enhancement of temperature. It is observed that the effect of yield stress on concentration is very meager. We learn from the fig. 8 that the concentration increases with increase in the yield stress and asymptotically attains zero value very fast.

The effect of magnetic field is presented in Figs. (9) – (12). The stream function is positive in the lower half region and it increases from zero value to its peak value and then reduces to zero at η = 0 and a reversal behavior in the upper half of the channel is noticed. The presence of magnetic field decreases stream function. Further increase in the strength of the magnetic field results in the reduction of stream function in the lower half while it shows an opposite behavior in upper half channel. From figure 10 we draw the observation that in a pure hydrodynamic flow the velocity profile of blood is parabolic and under the influence of a magnetic field. Reduction in velocity and bluntness in the profiles is observed.

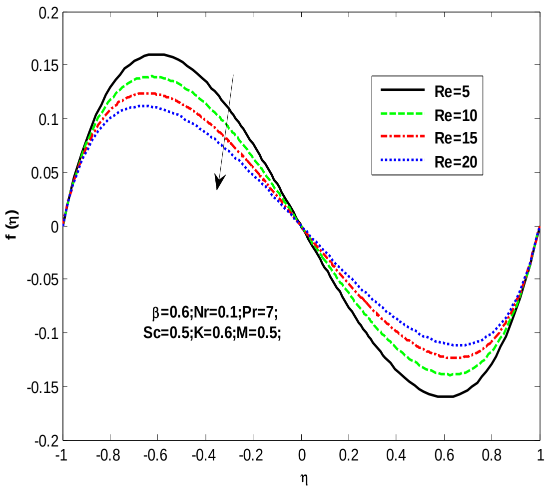

Fig.1. *Stream function for various values of Re*

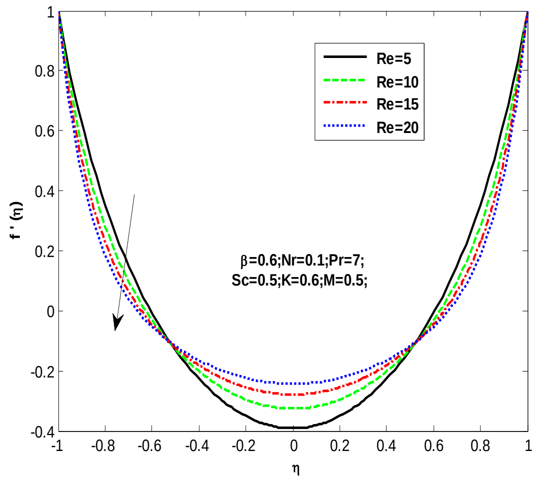

Fig.2. *Velocity profiles for various values of Re*

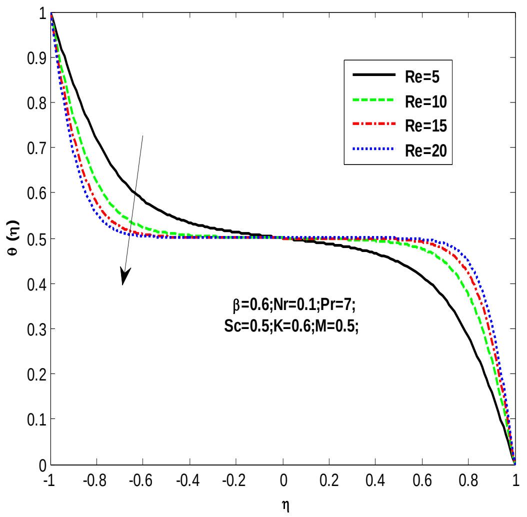

Fig.3. *Temperature profiles for various values of Re*

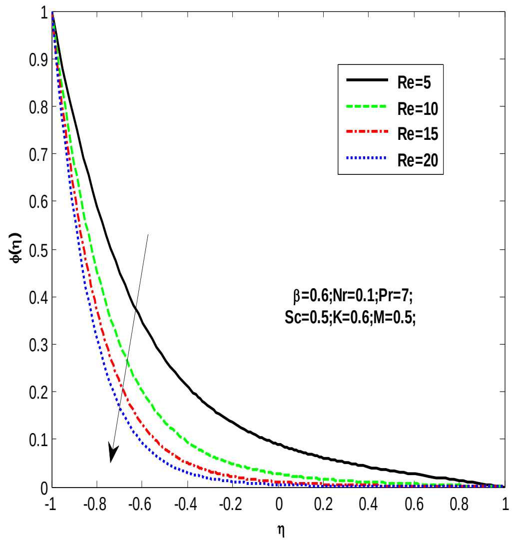

Fig.4. *Concentration profiles for various values of Re*

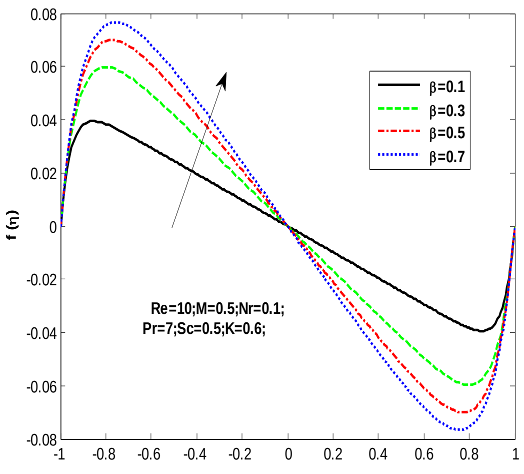

Fig. 5. *Stream function for various values of β*

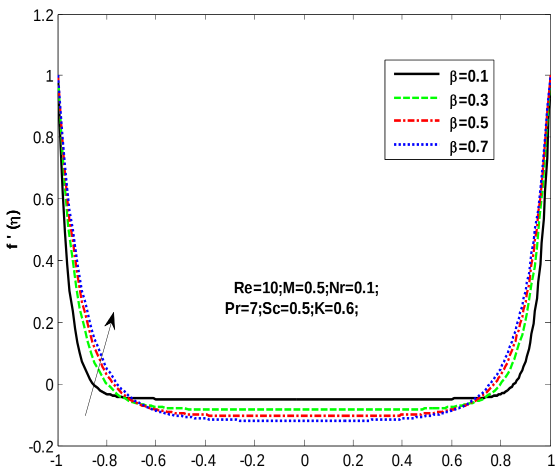

Fig. 6. *Velocity profiles for various values of β*

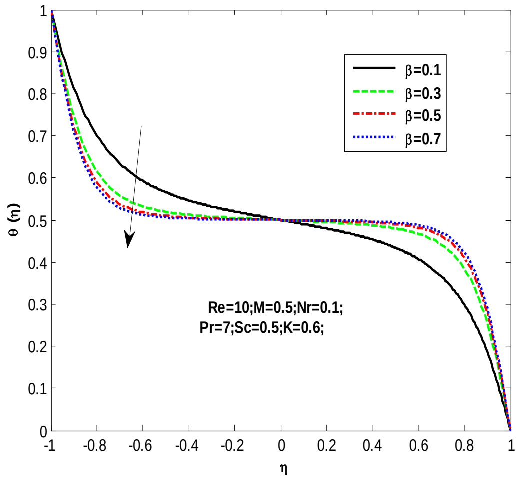

Fig.7. *Temperature profiles for various values of β*

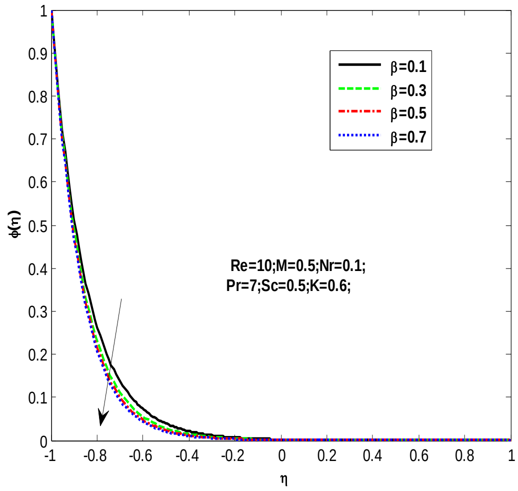

Fig. 8. *Concentration profiles for various values of β*

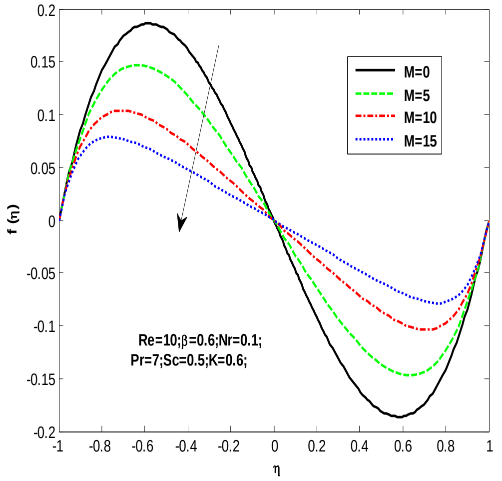

Fig.9. *Stream function for various values of M*

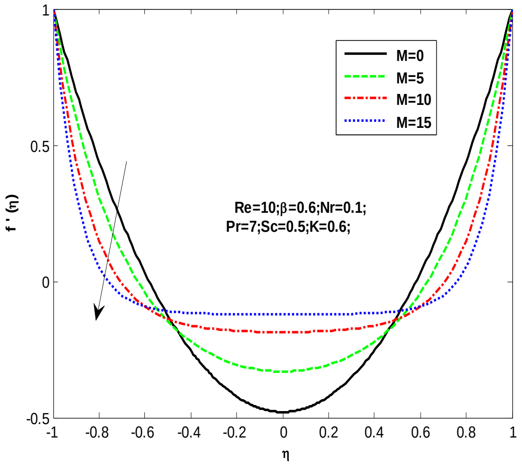

Fig.10. *Velocity profiles for various values of M*

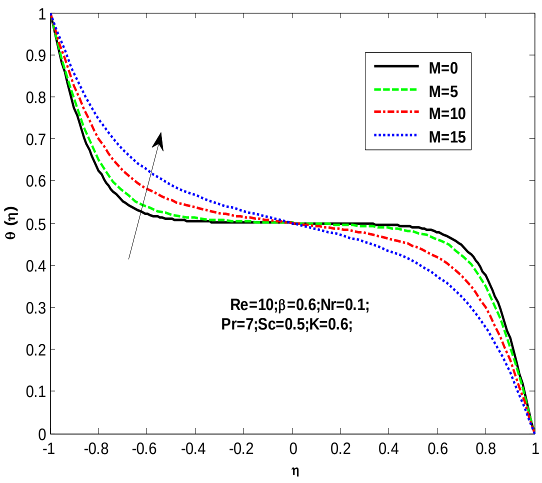

Fig11. *Temperature profiles for various values of M*

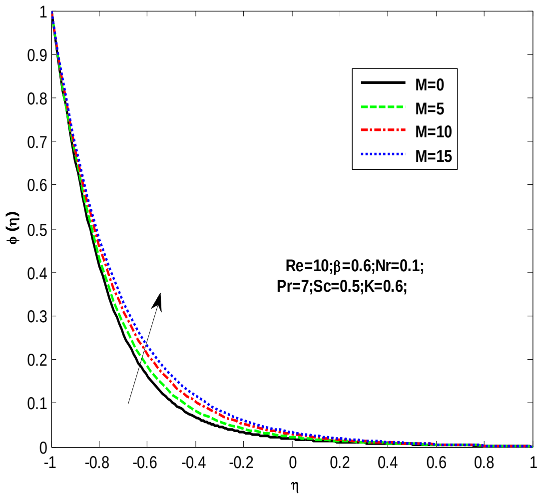

Fig12. *Concentration profiles for various values of M*

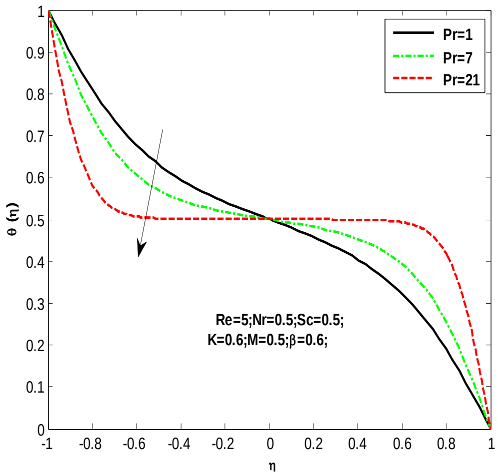

Fig13. *Temperature profiles for various values Pr*

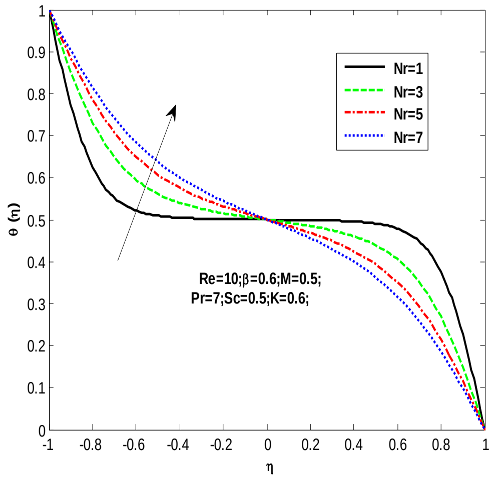

Fig.14. *Temperature profiles for various values of Nr*

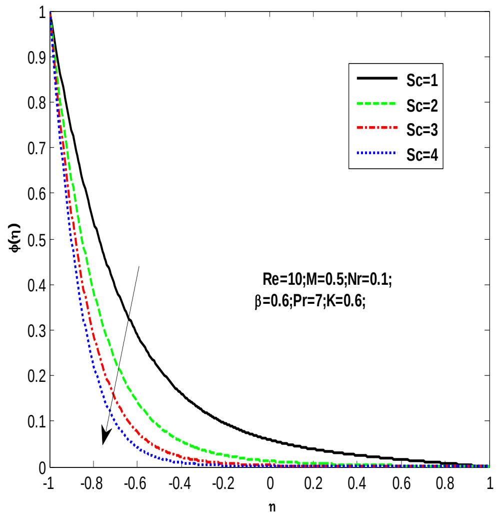

Fig15. *Concentration profiles for various values of Sc*

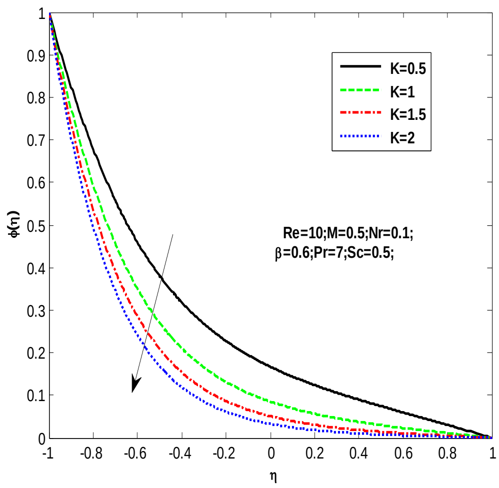

Fig16. *Concentration profiles for various values of K*

We observe that (Fig. 11) temperature increases with increase in the magnetic field strength i.e, under the action of a magnetic field in an electrically conducting fluid a resistive force is developed which causes reduction of flow and an enhancement of temperature. The concentration increases (Fig.12) with increase in the strength of the magnetic field in the upper half region and maintains almost same value in the rest of the channel. Fig. 13 shows a rapid decrease of temperature in the lower half channel while an opposite behavior is observed in the upper region of the channel. It is observed (Fig. 14) that the effect of radiation parameter is to enhance the temperature in the lower half while it decreases in the upper half region. The concentration reduces (Figs. 15 & 16) with increasing values of Schmidt number and chemical reaction parameter.

The skin friction co-efficient, Nusselt number and Sherwood number on the lower wall are tabulated in the following Table 1. From the below table we see that skin friction, Nusselt number and Sherwood number increase numerically for increasing values of the stretching Reynolds number. The magnitude of skin friction decreases with increase in Casson parameter while the Nusselt number and Sherwood number show an increasing tendency. It is observed that with increase in the magnetic field strength, the magnitude of the skin friction decreases, while the magnitude of Nusselt number and Sherwood number decrease. Further for an increase in the radiative heat transfer we observe that the magnitude of the Nusselt number decreases while it increases with an increase in Prandtl number. With increase in the Schmidt number we observe that magnitude of the Sherwood number decreases. It is noticed that lesser the molecular diffusivity greater is the Sherwood number. Increase in the chemical reaction parameter results in the enhancement of magnitude of Sherwood number.

Table1. *The skin friction, Nusselt number and Sherwood number values on the lower wall for different parameters*

Re	β	M	Nr	Pr	Sc	K	$f''(-1)$	Nur $\theta'(-1)$	Shr $\varphi'(-1)$
5 10 15 20	0.6	0.5	0.1	7	0.5	0.6	-4.275966 -5.362679 -6.357377 -7.264072	-1.668632 -2.537333 -3.171309 -3.691860	-1.364909 -1.970266 -2.445388 -2.844208
10	0.1 0.3 0.5 0.7	0.5	0.1	7	0.5	0.6	-10.589260 -6.649383 -5.633181 -5.165314	-1.942551 -2.390420 -2.506769 -2.559501	-1.885249 -1.943785 -1.964319 -1.974742
10	0.6	0 5 10 15	0.1	7	0.5	0.6	-3.323798 -4.811632 -7.539086 -10.474396	-2.760653 -2.569797 -2.195859 -1.834593	-2.023066 -1.974137 -1.913118 -1.873605
10	0.6	0.5	1 3 5 7	7	0.5	0.6	-	-0.674198 -0.583790 -0.555081 -0.541013	-
10	0.6	0.5	0.1	1 7 21	0.5	0.6	-	-0.833677 -2.758384 -3.398644	-
10	0.6	0.5	0.1	7	1 2 3 4	0.6	-	-	-3.003032 -4.429278 -5.529441 -6.456662
10	0.6	0.5	0.1	7	0.5	0.5 1 1.5 2	-	-	-1.874981 -2.510435 -2.993770 -3.401150

4. CONCLUSIONS

The MHD fluid flow of a Casson fluid in a channel with stretching walls and the associated problem of heat and mass transfer have been studied. The investigation is especially motivated towards the flow of blood in a vessel possessing a stretching wall. The study facilitates to examine the variation of blood velocity as the magnetic field strength of the blood, yield value of blood and the stretching Reynolds number. The study reveals that bluntness of the velocity profiles can be decreased with reduction in the magnetic field strength and reduction in the yield value. The temperature is observed to increase as the strength of the magnetic field increases as well as radiation parameter which might be useful in the design and development of new heating methods. It may be noted that investigation shall be useful to clinicians in the cancer therapy. In cancer therapy the objective of hyperthemia is to increase the temperature of the cancerous tissues above a critical therapeutic value 42^0C while simultaneously maintaining Sublethal temperature for the normal tissues around the cancerous tumor.

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