CHAPTER 8

EMHD FLUID FLOW WITH SLIP EFFECTS

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Chapter 8

EMHD fluid flow with slip effects

Electromagnetohydrodynamic (EMHD) is the area that concerns the study of dynamics of electrically conducting fluids under the influence of magnetic and electric fields. EMHD has raised quite an interest over the years due to its versatile application in geophysics, engineering, biomedical engineering, magnetic drug targeting, and many others. The non-adherence of the fluid to a solid boundary, known as velocity slip, occurs under certain circumstances. Fluids displaying slip are essential for technologies such as internal cavities and in the artificial cardiac valve polishing.

8.1 Introduction of the Problem

The general goal of electro-MHD, as described in RanjitShit2019 and Ghosh2020, is to improve fluid flows by using electric fields, magnetic fields, or suitable combinations of these fields. Micropumps are frequently used to implement this phenomenon. Several researchers have conducted promising research on magnetohydrodynamic micro pumps; see, for example, [13, 51]. The results of experiments suggest that combined EMHD effects might be used to improve liquid flow in microchannels. EMHD mixed convection flow of fluid over a stretching sheet is discussed by [138].

In circumstances involving wire nettings and perforated plates, lubricated hydrophobic surfaces, porous and abrasive surfaces, and coated surfaces, slip condition must unavoidably be taken into account. The tangential fluid velocity at the surface and the velocity gradient normal to the surface are related by the velocity slip model. Daniel et al. [138] scrutinized the effect of velocity slip on EMHD dual stratified flow of nanofluid. Soomro et al. [32] examined the impect of velocity slip on MHD Williamson fluid along the vertical surface. Eringen [9] introduced the simple micropolar fluids theory. According to his theory, simple micropolar fluids is a fluent medium whose properties and behavior are affected by the local motion of the fluid fundamentals. Keeping this in mind, Eringen [10] simplified micropolar fluids theory and obtained a subclass of these fluids called micro-polar fluids. This theory is one of the best established theories of fluids with microstructure. This theory is useful in explaining the features of certain fluids such as liquid crystals, suspensions and animal blood.

Kataria and Patel [41, 42] explored MHD Casson fluid flow considering radiation, thermal diffusion etc. Anantha Kumar et al. [52] investigated electromagnetic effects on non-Newtonian fluid. Kataria et al. [44] studied a uniform magnetic field in which motion is produced by the buoyancy force of incompressible micropolar fluid. Eringen's proposed mathematical model for examining the flow of conductive fluids was taken into consideration by Lund et al. [63]. The mathematical modelling for Brownian movement and thermophoresis effects on MHD flow with nonlinear thermal radiation was developed by Mittal and Patel [16]. The impact of the electrically driven micropolar fluid through a permeable stretched sheet was studied by Pradhan et al. [125]. Rashad et al. [17] evaluated the influence of chemical reaction impact on mixed convection boundary layer micropolar fluid flow over a constantly moving vertical surface. The differential process was used by Rashidi and Pour [86] to seek a completely analytical solution including radiation. Sheikholeslami et al. [89] examined the unsteady electrically conducting MHD fluid flow. Li et al. [143] investigated the migration of nanofluid through a permeable pipe taking Lorentz forces into account.

8.2 Novelty of the Problem

In this research, the aim of this investigation is to analyze EMHD flow of Micropolar fluid over a stretching sheet. The energy equation includes nonlinear thermal radiation and joule heating effects. Slip condition and convective boundary conditions are considered.

8.3 Mathematical Formulation of the Problem

Two dimensional incompressible Micropolar fluid flow through a horizontal sheet is considered. Figure 8.1 shows velocity of the stretching sheet is taken as $u = ax + U_{Slip}$. A magnetic field of strength $\mathcal{B}$ is normally applied with the conjecture of lower Reynolds number, so that the induced magnetic field may be ignored. Viscous dissipation and Joule heating and nonlinear thermal radiation effects are accounted. The surface of the stretching plate is in contact with another hot plate of temperature T_w and concentration C_w with h_{ft} and h_{fc} are the heat transfer coefficient and mass transfer coefficient. The volume of particle concentration and the temperature of the Micropolar fluid far away from the plate is supposed to be C_∞ and T_∞ respectively.

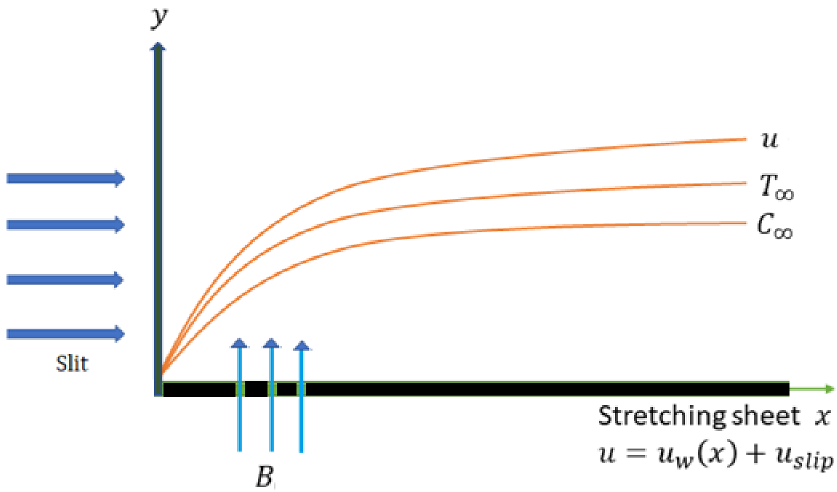

Figure 8.1: Physical Sketch of the Problem

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0, \tag{8.3.1}$$

$$u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} = \left(\frac{\mu + k}{\rho}\right)\frac{\partial^2 u}{\partial y^2} + \frac{k}{\rho}\frac{\partial G}{\partial y} + \frac{\sigma}{\rho}\left(E_0 B_0 - B_0^2 u\right), \tag{8.3.2}$$

$$u\frac{\partial G}{\partial x} + v\frac{\partial G}{\partial y} = \frac{\gamma^*}{\rho j}\frac{\partial^2 G}{\partial y^2} - \frac{k}{\rho j}\left(2G + \frac{\partial u}{\partial y}\right), \tag{8.3.3}$$

$$u\frac{\partial T}{\partial x} + v\frac{\partial T}{\partial y} = \frac{\kappa}{\rho C_P}\left(\frac{\partial^2 T}{\partial y^2}\right) + \frac{\left(uB_0 - E_0\right)^2 \sigma}{\rho C_P} - \frac{1}{\rho C_P}\frac{\partial q_r}{\partial y} + \left(\frac{\mu + k}{\rho}\right)\left(\frac{\partial u}{\partial y}\right)^2, \tag{8.3.4}$$

$$u\frac{\partial C}{\partial x} + v\frac{\partial C}{\partial y} = D_M\frac{\partial^2 C}{\partial y^2}, \tag{8.3.5}$$

The variable formula can also be used here to identify these differential equations because it has a energy integral that is useful for the structure of the solution.

$$\begin{aligned} & u = U_w(x) + U_{slip} = ax + \alpha^*\left[(\mu + k)\frac{\partial u}{\partial y} + kG\right], \; v = \; v_w, G = -n\frac{\partial u}{\partial y}, \\ & -\kappa\frac{\partial T}{\partial y} = h_{ft}\left(T_f - T\right), \; -D_M\frac{\partial C}{\partial y} = h_{fc}\left(C_f - C\right) \text{ at } y = 0, \\ & u(\infty) = G(\infty) = 0, \; T(\infty) = T_\infty, \; C(\infty) = C_\infty. \end{aligned} \tag{8.3.6}$$

Heat flux is given by Rossland [126]:

$$q_r = -\frac{4\sigma^*}{3k^*}\frac{\partial T^4}{\partial y}, \tag{8.3.7}$$

where σ^* and k^* are Stephen Boltzmann's constant and coefficient of mean absorption respectively.

Instance $n = 0,\ G = 0$ on the surface is indicated. It shows a focused particle flow that cannot turn the micro-components nearest to the wall. This situation is often referred to as the high microelement concentration. Because the antisymmetric component of the stress tensor vanishes, the probability $n = 0.5$ implies a low concentration of microelements. The turbulent boundary layer flows are modelled using the case $n = 1$. Consider the following similarity transformation.

$$\left.\begin{aligned} u = axf'(\eta), v = -\sqrt{a\nu}f(\eta), \phi(\eta) = \frac{C - C_\infty}{C_w - C_\infty}, \theta(\eta) = \frac{T - T_\infty}{T_w - T_\infty}, \\ \eta = \sqrt{\frac{a}{\nu}}y, G = ax\sqrt{\frac{a}{\nu}}h(\eta). \end{aligned}\right\} \tag{8.3.8}$$

However, Equations (8.3.2) - (8.3.6) are translated in the following dimensional equations. The completion of the continuity equation (8.3.1) is self-evident.

$$(1 + K) f''' + ff'' - f'^2 + Kh' - M^2 f' + M^2 E = 0, \tag{8.3.9}$$

$$\left(1 + \frac{K}{2}\right) h'' + fh' - f'h - K(2h + f'') = 0, \tag{8.3.10}$$

$$\begin{aligned} \left(1 + \frac{4}{3}Rd\left\{1 + (\theta_w - 1)\theta\right\}^3\right)\theta'' + Prf\theta' + 4Rd\left\{1 + (\theta_w - 1)\theta\right\}^2(\theta_w - 1)\theta'^2 \\ + M^2 EcPr\left(f'^2 + E^2 - 2Ef'\right) + (1 + K)PrEcf''^2 = 0 \end{aligned} \tag{8.3.11}$$

$$\phi'' + Sc\ f\phi' = 0, \tag{8.3.12}$$

Revised boundary conditions now

$$\begin{aligned} f(0) = f_w,\ f'(0) = 1 + \gamma(1 + K(1 - n)) f''(0),\ h(0) = -nf''(0), \\ \theta'(0) = -\lambda_1(1 - \theta(0)), \phi'(0) = -\lambda_2(1 - \phi(0)),\ \text{at}\ \ y = 0, \\ f'(y) \to 0,\ h(y) \to 0,\ \theta(y) \to 0,\ \phi(y) \to 0,\ \text{as}\ \ y \to \infty. \end{aligned} \tag{8.3.13}$$

where $Pr = \frac{\mu C_P}{\kappa},\ K = \frac{k}{\mu},\ M^2 = \frac{\sigma B_0^2}{a\rho},\ f_w = -(av)^{-\frac{1}{2}} v_w,\ Re_x = \frac{ax^2}{\nu},\ \theta_w = \frac{T_w}{T_\infty},$

$Sc = \dfrac{\nu}{D_M}$, $\gamma = \alpha^* \mu \sqrt{\dfrac{a}{\nu}}$, $E = \dfrac{E_0}{U_w B_0}$, $Ec = \dfrac{U_w^2}{C_P(T_w - T_\infty)}$, $\lambda_1 = \dfrac{h_{ft}}{\kappa}\sqrt{\dfrac{\nu}{a}}$, $\lambda_2 = \dfrac{h_{fc}}{D_M}\sqrt{\dfrac{\nu}{a}}$ Coefficient of skin friction, wall couple stress, Nusselt number and Sherwood number in dimensional form are

$$C_{fx} = \frac{2\tau_w}{\rho U_w^2(x)},\ Mw_x = \frac{m_w}{\rho a^2 x^3},\ Sh_x = \frac{x q_m}{D_M(C_w - C_\infty)}, Nu_x = \frac{x q_w}{\kappa\,(T_w - T_\infty)} \quad (8.3.14)$$

where,

$$\tau_w = \left[(\mu + k)\frac{\partial u}{\partial y} + kG\right]_{y=0}, m_w = \gamma^* \left.\frac{\partial G}{\partial y}\right|_{y=0}, q_m = -D_M \left.\frac{\partial C}{\partial y}\right|_{y=0}, q_w = -\kappa \left.\frac{\partial T}{\partial y}\right|_{y=0}, \quad (8.3.15)$$

These quantities of physical interest take on a dimensionless equation

$$Nu_x Re_x^{-\frac{1}{2}} = -\left(1 + \frac{4}{3}Rd\left(\left(\theta_w - 1\right)\theta\left(0\right) + 1\right)^3\right)\theta'\left(0\right),$$
$$Mw_x Re_x = \left(1 + \frac{K}{2}\right)h'\left(0\right),\ \frac{1}{2}C_{fx}Re_x^{\frac{1}{2}} = \left(1 + \left(1 - n\right)K\right)f''\left(0\right),$$
$$Sh_x Re_x^{-\frac{1}{2}} = -\phi'\left(0\right), \quad (8.3.16)$$

8.4 Solution by Homotopy Analysis Method

Liao [120] developed Homotopy analysis method for locating resolution of the governing equations. The initial guess and auxiliary linear operator can be chosen freely in the Homotopy analysis approach.
Initial guesses are

$$f_0\left(\eta\right) = f_w + \frac{1}{1 + \gamma\left(1 + K(1 - n)\right)}\left(1 - e^{-\eta}\right),\ \theta_0\left(\eta\right) = \frac{\lambda_1}{1 + \lambda_1}e^{-\eta},$$
$$h_0\left(\eta\right) = \frac{n}{1 + \gamma\left(1 + K(1 - n)\right)}e^{-\eta},\ \phi_0\left(\eta\right) = \frac{\lambda_2}{1 + \lambda_2}e^{-\eta}, \quad (8.4.1)$$

with auxiliary linear operators

$$\mathcal{L}_f = \frac{\partial^3 f}{\partial \eta^3} - \frac{\partial f}{\partial \eta},\ \mathcal{L}_h = \frac{\partial^2 h}{\partial \eta^2} - h,\ \mathcal{L}_\theta = \frac{\partial^2 \theta}{\partial \eta^2} - \theta,\ \mathcal{L}_\phi = \frac{\partial^2 \phi}{\partial \eta^2} - \phi, \quad (8.4.2)$$

satisfying

$$\mathcal{L}_f\left(k_1 + k_2 e^{\eta} + k_3 e^{-\eta}\right) = 0,\quad \mathcal{L}_h\left(k_4 e^{\eta} + k_5 e^{-\eta}\right) = 0,$$
$$\mathcal{L}_\theta\left(k_6 e^{\eta} + k_7 e^{-\eta}\right) = 0,\quad \mathcal{L}_\phi\left(k_8 e^{\eta} + k_9 e^{-\eta}\right) = 0, \quad (8.4.3)$$

Here $k_i,\ (i = 1,\ 2, \ldots, 9)$ are the arbitrary constants .

8.4.1 Zero-th order deformation

The following is the problem of zeroth order deformation:

$$\left.\begin{array}{r}(1-q)\,\mathcal{L}_f\left[F(\eta;q)-f_0(\eta)\right]=q\hbar_f\mathcal{N}_f\left[F(\eta;q)\right],\\(1-q)\,\mathcal{L}_h\left[H(\eta;q)-h_0(\eta)\right]=q\hbar_h\mathcal{N}_h\left[H(\eta;q)\right],\\(1-q)\,\mathcal{L}_\theta\left[\Theta(\eta;q)-\theta_0(\eta)\right]=q\hbar_\theta\mathcal{N}_\theta\left[\Theta(\eta;q)\right],\\(1-q)\,\mathcal{L}_\phi\left[\Phi(\eta;q)-\phi_0(\eta)\right]=q\hbar_\phi\mathcal{N}_\phi\left[\Phi(\eta;q)\right],\end{array}\right\} \tag{8.4.4}$$

The following is a list of nonlinear operators:

$$\mathcal{N}_f\left[F(\eta;q)\right]=(1+K)\frac{\partial^3F}{\partial\eta^3}+F\frac{\partial^2F}{\partial\eta^2}-\left\{\frac{\partial F}{\partial\eta}\right\}^2+K\frac{\partial H}{\partial\eta}-M^2\frac{\partial F}{\partial\eta}+M^2E, \tag{8.4.5}$$

$$\mathcal{N}_h\left[H(\eta;q)\right]=\left(1+\frac{K}{2}\right)\frac{\partial^2H}{\partial\eta^2}+F\frac{\partial H}{\partial\eta}-H\frac{\partial F}{\partial\eta}-K\left(2H+\frac{\partial^2F}{\partial\eta^2}\right), \tag{8.4.6}$$

$$\begin{aligned}\mathcal{N}_\theta\left[\Theta(\eta;q)\right]=&\left(1+\frac{4}{3}Rd\left\{1+(\theta_w-1)\,\Theta\right\}^3\right)\frac{\partial^2\Theta}{\partial\eta^2}+(1+K)PrEc\left(\frac{\partial^2F}{\partial\eta^2}\right)^2\\&+PrF\frac{\partial\Theta}{\partial\eta}+4Rd\left\{1+(\theta_w-1)\,\Theta\right\}^2(\theta_w-1)\left(\frac{\partial\Theta}{\partial\eta}\right)^2\\&+M^2EcPr\left(\left\{\frac{\partial F}{\partial\eta}\right\}^2+E^2-2E\frac{\partial F}{\partial\eta}\right),\end{aligned} \tag{8.4.7}$$

$$\mathcal{N}_\phi\left[\Phi(\eta;q)\right]=\frac{\partial^2\Phi}{\partial\eta^2}+ScF\frac{\partial\Phi}{\partial\eta}, \tag{8.4.8}$$

Boundary conditions subject to

$$\begin{aligned}&F(0;q)=f_w,\ F'(0;q)=1+\gamma(1+K(1-n))F''(0;q);\ F'(+\infty;q)=0,\\&H(0;q)=-nF''(0;q),\ H(+\infty;q)=0,\Theta'(0;q)=-\lambda_1(1-\Theta(0;q)),\\&\Theta(+\infty;q)=0,\Phi'(0;q)=-\lambda_2(1-\Phi(0;q)),\ \Phi(+\infty;q)=0,\end{aligned} \tag{8.4.9}$$

where $F(\eta;q)$, $H(\eta;q)$, $\Theta(\eta;q)$ and $\Phi(\eta;q)$ are unknown in terms of functions η and q. $\hbar_f$, $\hbar_h$, $\hbar_\theta$ and $\hbar_\phi$ are zero non-auxiliary parameters and N_f, N_h, N_θ and N_ϕ the non-linear operators. Furthermore, where $q \in (0,\ 1)$ is a parameter embedding.

$$\left.\begin{array}{ll} F(\eta;0)=f_0(\eta), & F(\eta;1)=f(\eta), \\ H(\eta;0)=h_0(\eta), & H(\eta;1)=h(\eta), \\ \Theta(\eta;0)=\ \theta_0(\eta), & \Theta(\eta;1)=\ \theta(\eta), \\ \Phi(\eta;0)=\ \phi_0(\eta), & \Phi(\eta;1)=\ \phi(\eta), \end{array}\right\} \tag{8.4.10}$$

If q is 0 to 1, the variation will be $F(\eta;\ q)$, $H(\eta;q)$, $\Theta(\eta;\ q)$ and $\Phi(\eta;\ q)$ differ from $f_0(\eta)$, $h_0(\eta)$, $\theta_0(\eta)$ and $\phi_0(\eta)$ to $f(\eta)$, $h(\eta)$, $\theta(\eta)$, and $\phi(\eta)$. So one can obtain

$$\left.\begin{array}{r} F(\eta;\ q)=f_0(\eta)+\sum_{i=1}^{\infty} f_i(\eta)\,q^i, \\ H(\eta;\ q)=h_0(\eta)+\sum_{i=1}^{\infty} h_i(\eta)\,q^i, \\ \Theta(\eta;\ q)=\theta_0(\eta)+\sum_{i=1}^{\infty} \theta_i(\eta)\,q^i, \\ \Phi(\eta;\ q)=\phi_0(\eta)+\sum_{i=1}^{\infty} \phi_i(\eta)\,q^i, \end{array}\right\} \tag{8.4.11}$$

where

$$\left.\begin{array}{r} f_i(\eta)=\left.\dfrac{1}{i!}\dfrac{\partial^i f(\eta;q)}{\partial\eta^i}\right|_{q=0}, \\ h_i(\eta)=\left.\dfrac{1}{i!}\dfrac{\partial^i h(\eta;q)}{\partial\eta^i}\right|_{q=0}, \\ \theta_i(\eta)=\left.\dfrac{1}{i!}\dfrac{\partial^i \theta(\eta;q)}{\partial\eta^i}\right|_{q=0}, \\ \phi_i(\eta)=\left.\dfrac{1}{i!}\dfrac{\partial^i \phi(\eta;q)}{\partial\eta^i}\right|_{q=0}, \end{array}\right\} \tag{8.4.12}$$

The convergence in the series is largely reliant on $\hbar_f$, $\hbar_h$, $\hbar_\theta$ and $\hbar_\phi$. If non-zero auxiliary parameters are chosen to estimate Equation (8.4.11) at $q = 1$.

Thus, the following can be obtained

$$\left.\begin{array}{r} f(\eta)=f_0(\eta)+\sum_{i=1}^{\infty} f_i(\eta), \\ h(\eta)=h_0(\eta)+\sum_{i=1}^{\infty} h_i(\eta), \\ \theta(\eta)=\theta_0(\eta)+\sum_{i=1}^{\infty} \theta_i(\eta), \\ \phi(\eta)=\phi_0(\eta)+\sum_{i=1}^{\infty} \phi_i(\eta), \end{array}\right\} \tag{8.4.13}$$

8.4.2 i-th order deformation

The deformation equations in i^{th} order can be presented in the form

$$\left.\begin{array}{r} \mathcal{L}_f\left[f_i(\eta)-\chi_i f_{i-1}(\eta)\right]=\hbar_f\mathcal{R}_{f,i}(\eta), \\ \mathcal{L}_h\left[h_i(\eta)-\chi_i h_{i-1}(\eta)\right]=\hbar_h\mathcal{R}_{h,i}(\eta), \\ \mathcal{L}_\theta\left[\theta_i(\eta)-\chi_i \theta_{i-1}(\eta)\right]=\hbar_\theta\mathcal{R}_{\theta,i}(\eta), \\ \mathcal{L}_\phi\left[\phi_i(\eta)-\chi_i \phi_{i-1}(\eta)\right]=\hbar_\phi\mathcal{R}_{\phi,i}(\eta), \end{array}\right\} \tag{8.4.14}$$

under the conditions of the boundary

$$
\begin{aligned}
f_i(0) = 0, f_i'(0) = \gamma\left(1 + K(1-n)\right) f_i''(0), \ f_i'(\infty) = 0, \ h_i(+\infty; q) = 0, \\
h_i(0; q) = -n f_i''(0; q), \ h_i(+\infty; q) = 0, \theta_i'(0; q) = \lambda_1 \theta_i(0; q), \\
\theta_i(+\infty; q) = 0, \phi_i'(0; q) = \lambda_2 \phi_i(0; q), \ \phi_i(+\infty; q) = 0. \quad (8.4.15)
\end{aligned}
$$

where

$$
\mathcal{R}_{f,i}(\eta) = (1+K) f_{i-1}''' + \sum_{j=0}^{i-1} f_j f_{i-1-j}'' - \sum_{j=0}^{i-1} f_j' f_{i-1-j}' + K h_{i-1}' - M^2 f_{i-1}' + M^2 E, \quad (8.4.16)
$$

$$
\mathcal{R}_{h,i}(\eta) = \left(1 + \frac{K}{2}\right) h_{i-1}'' + \sum_{j=0}^{i-1} f_j h_{i-1-j}'' - \sum_{j=0}^{i-1} h_j f_{i-1-j}' - K\left(2h_{i-1} + f_{i-1}''\right). \quad (8.4.17)
$$

$$
\begin{aligned}
\mathcal{R}_{\theta,\ i}(\eta) = \frac{4}{3} Rd\left(\theta_w - 1\right)^3 \left\{ \sum_{j=0}^{i-1} \theta_{i-1-j}'' \sum_{l=0}^{j} \theta_{j-l} \sum_{p=0}^{l} \theta_{l-p} \theta_p \right\} + \left(1 + \frac{4}{3} Rd\right) \theta_{i-1}'' \\
+ 4Rd\left(\theta_w - 1\right)^3 \left\{ \sum_{j=0}^{i-1} \theta_{i-1-j}' \sum_{l=0}^{j} \theta_{j-l}' \sum_{p=0}^{l} \theta_{l-p} \theta_p \right\} + 4Rd\left(\theta_w - 1\right) \sum_{j=0}^{i-1} \theta_{i-1-j}'' \theta_j \\
+ 4Rd\left(\theta_w - 1\right)^2 \sum_{j=0}^{i-1} \theta_{i-1-j}'' \sum_{l=0}^{j} \theta_{j-l} \theta_l + 8Rd\left(\theta_w - 1\right)^2 \sum_{j=0}^{i-1} \theta_{i-1-j}' \sum_{l=0}^{j} \theta_{j-l}' \theta_l \\
+ 4Rd\left(\theta_w - 1\right) \sum_{j=0}^{i-1} \theta_{i-1-j}' \theta_j' + (1+K) Pr Ec \sum_{j=0}^{i-1} f_j'' f_{i-1-j}'' \\
+ M^2 Ec Pr \left(\sum_{j=0}^{i-1} f_j' f_{i-1-j}' + E^2 - 2E f_{i-1}' \right) + Pr \sum_{j=0}^{i-1} f_j \theta_{i-1-j}' \quad (8.4.18)
\end{aligned}
$$

$$
\mathcal{R}_{\phi,i}(\eta) = \phi_{i-1}'' + Sc \sum_{j=0}^{i-1} f_j \phi_{i-1-j}'. \quad (8.4.19)
$$

with

$$
\chi_i = \begin{cases} 0, & i < 1 \\ 1, & i \geq 1 \end{cases} \quad (8.4.20)
$$

The general solutions f_i, h_i, θ_i and ϕ_i comprising the special solution f_i^*, h_i^*, θ_i^* and ϕ_i^* are given by

$$\left.\begin{aligned} f_i(\eta) &= f_i^*(\eta) + k_1 + k_2 e^{\eta} + k_3 e^{-\eta}, \\ h_i(\eta) &= h_i^*(\eta) + k_4 e^{\eta} + k_5 e^{-\eta}, \\ \theta_i(\eta) &= \theta_i^*(\eta) + k_6 e^{\eta} + k_7 e^{-\eta}, \\ \phi_i(\eta) &= \phi_i^*(\eta) + k_8 e^{\eta} + k_9 e^{-\eta} \end{aligned}\right\} \qquad (8.4.21)$$

here f_i^*, h_i^*, θ_i^* and ϕ_i^* are given by the corresponding specific solutions i^{th}-order and constants equations $k_j(\ j = 1, 2,\ \ldots, 9)$ the boundary conditions shall be determined.

8.5 Convergence Analysis

Auxiliary parameters $\hbar_f$, $\hbar_h$, $\hbar_\theta$ and $\hbar_\phi$ significantly affects the convergence and approximation rate of HAM solutions. $\hbar$-curve is plotted taking appropriate order in Figure 8.2, for this purpose. For the auxiliary parameter $\hbar_f$, Figure 8.2 clearly suggests an allowable range of $-1.6 < \hbar_f < -0.1$. We use $\hbar_f = -0.50$ in this case. Similarly, $\hbar_h = -1.17$, $\hbar_\theta = -0.22$ and $\hbar_\phi = -1.84$. Convergence of series solution with varying order of approximation is calculated in Table 8.1.

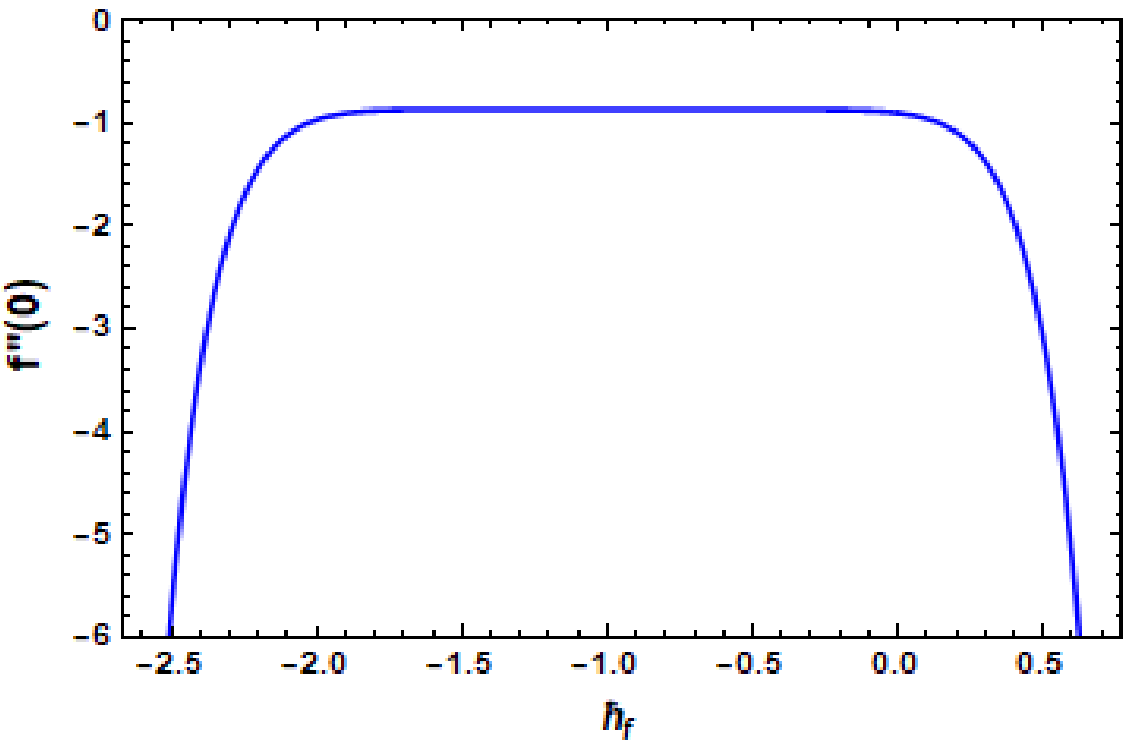

Figure 8.2: $f''(0)$ via $\hbar_f$.

8.6 Result and Discussion

In this section the solutions are found using suitable Mathematica code. Figures 8.3-8.23 show effects on velocity, angular velocity, temperature, and concentration profile of various variables. Graphs are used to describe the findings achieved. This section covers the results of various parameters including Slip parameter γ, Suction parameter f_w, Electric parameter E, Material parameter K, Micro element concentration n, Prandtl number Pr, Radiation parameter Rd, Magnetic parameter M, and Schmidt number Sc on Profiles of velocity, angular velocity, temperature, and concentration. Because of the porous medium, velocity decreases for the higher values of Suction parameter f_w in Figure 8.3. In Figure 8.4 shows velocity decreases for the increasing values of M in the absence of electric fields. Figure 8.6 shows velocity diminishes for the increasing value of concentration of micro elements n. Figure 8.7 shows velocity decreases for the higher values of slip parameter γ. In Figure 8.8, velocity increases for the higher values of Electric parameter E. Figure 8.9 shows velocity enhances for the larger values of Material parameter K.

Figure 8.10 illustrates angular velocity increases for the large amount of Material parameter K. Figure 8.11 shows angular velocity increases for the higher value of concentration of microelements n. For higher value of Magnetic parameter M temperature increases, it can be seen in Figure 8.12. Figure 8.13 shows that temperature enhances when Temperature ratio parameter θ_w has been increased. Figure 8.14 shows an increment in temperature for higher values of radiation parameter Rd. Figure 8.15 shows an increment in temperature for higher values of Electric parameter E. For higher values of thermal Biot number λ_1, temperature enhances, it can be seen in Figure 8.16.

Figure 8.17 shows concentration diminishes for higher values of Schmidt numbers Sc. Figure 8.18 shows concentration is increased for the higher Solutal Biot numbers λ_2. Skin friction coefficient increased for higher values of M, it can be found from Figure 8.19. Figure 8.20 illustrates Local wall couple stress increases for rising values of Material parameter K. Figure 8.22 and Figure 8.21 shows Nusselt number increases with increasing values of θ_w, Rd and γ_1. Figure 8.23 illustrates Sherwood number enhanced by the higher values of Sc. Numerical calculation for Nusselt number can be found in Table 8.2.

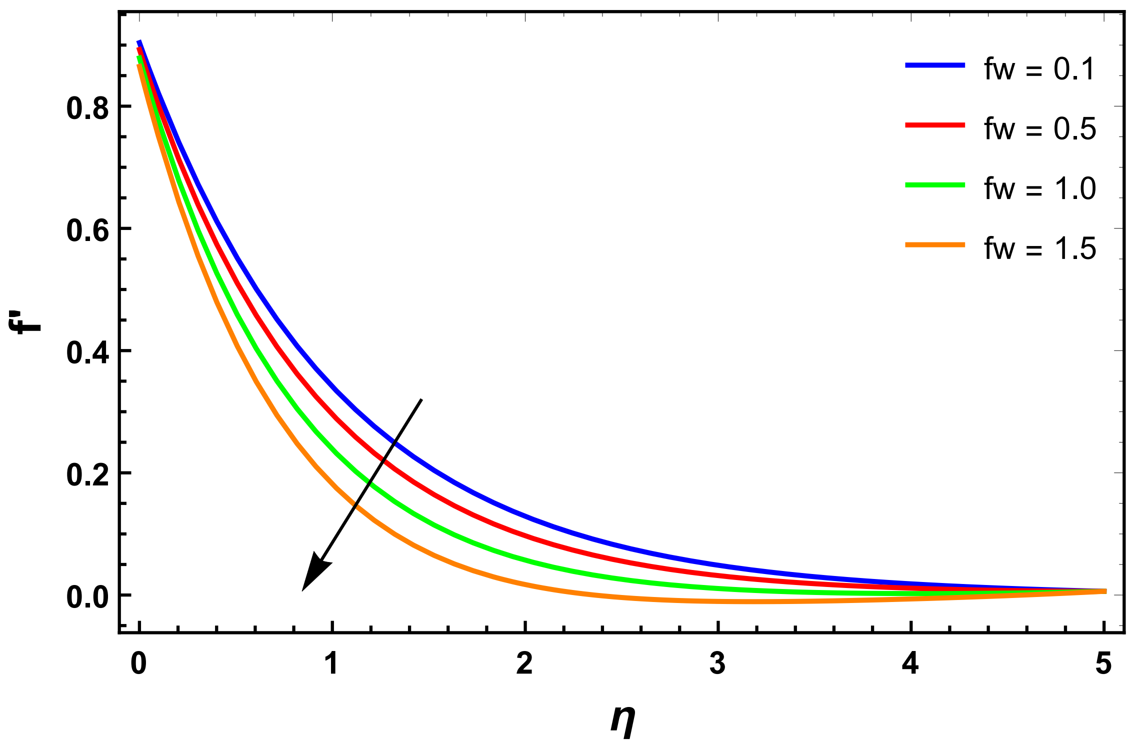

Figure 8.3: $f'(\eta)$ via f_w.

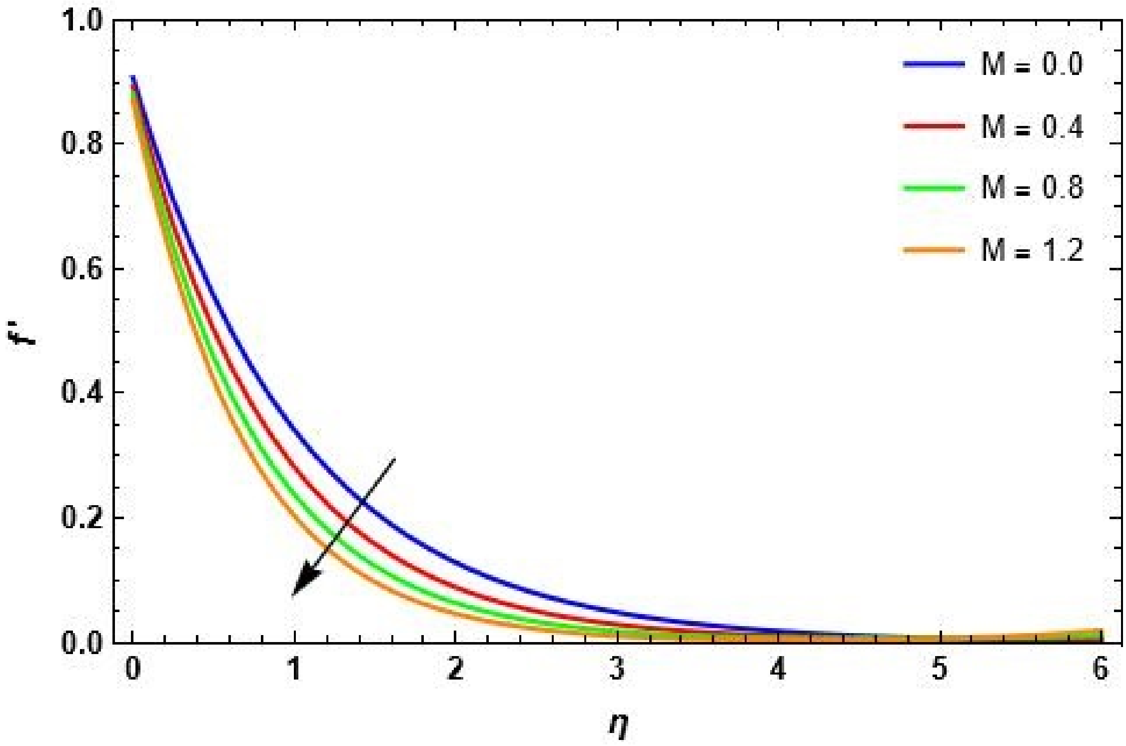

Figure 8.4: $f'(\eta)$ when $E = 0$ via M.

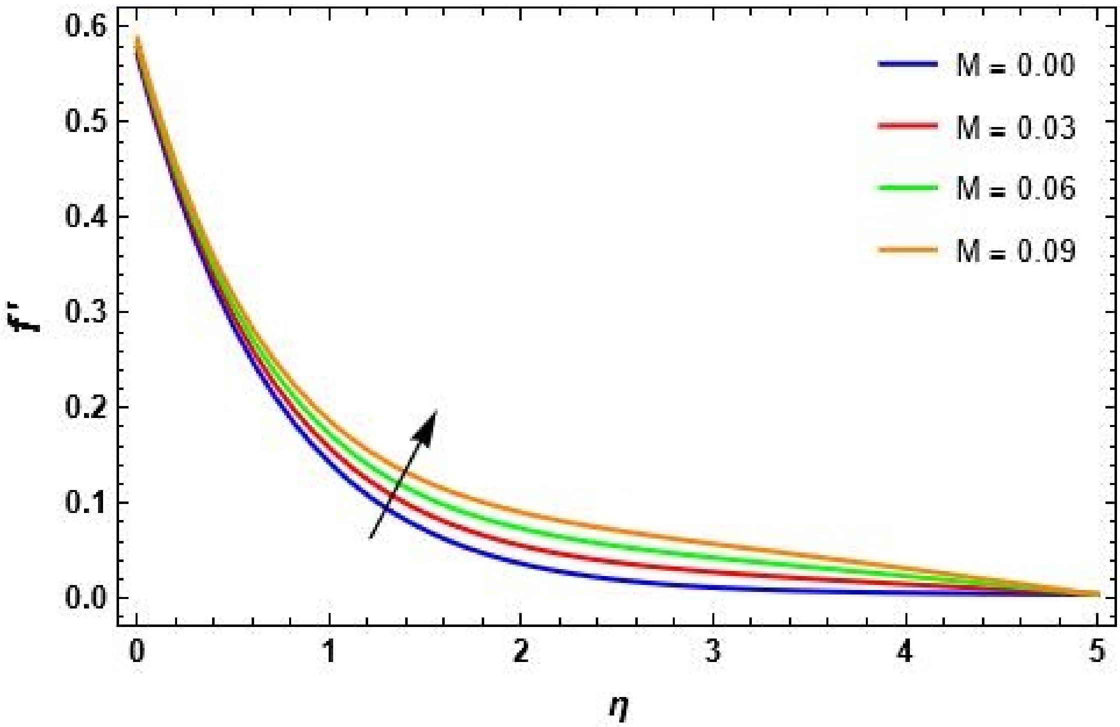

Figure 8.5: $f'(\eta)$ when $E = 0.5$ via M.

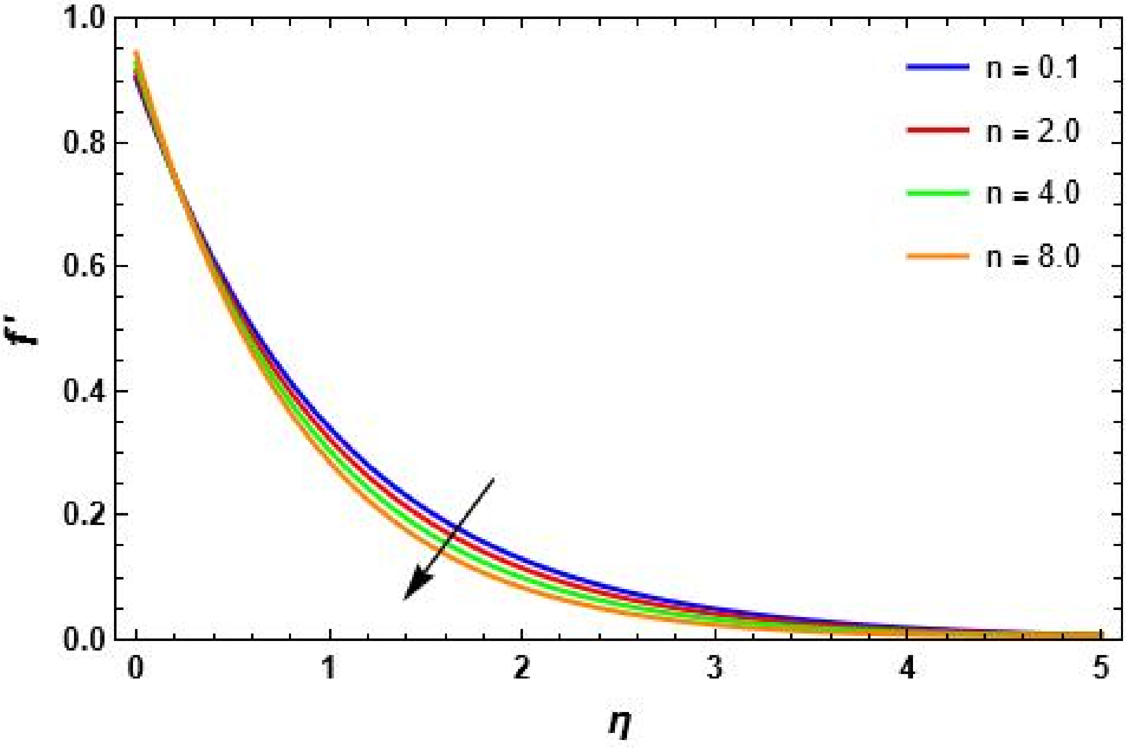

Figure 8.6: $f'(\eta)$ via n.

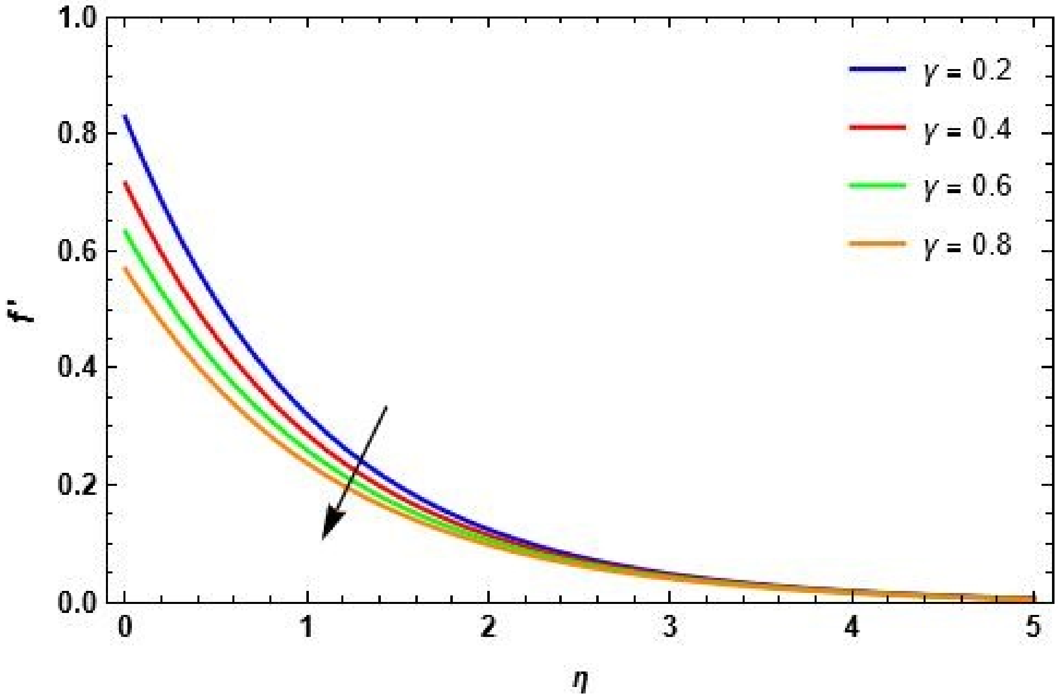

Figure 8.7: $f'(\eta)$ via γ.

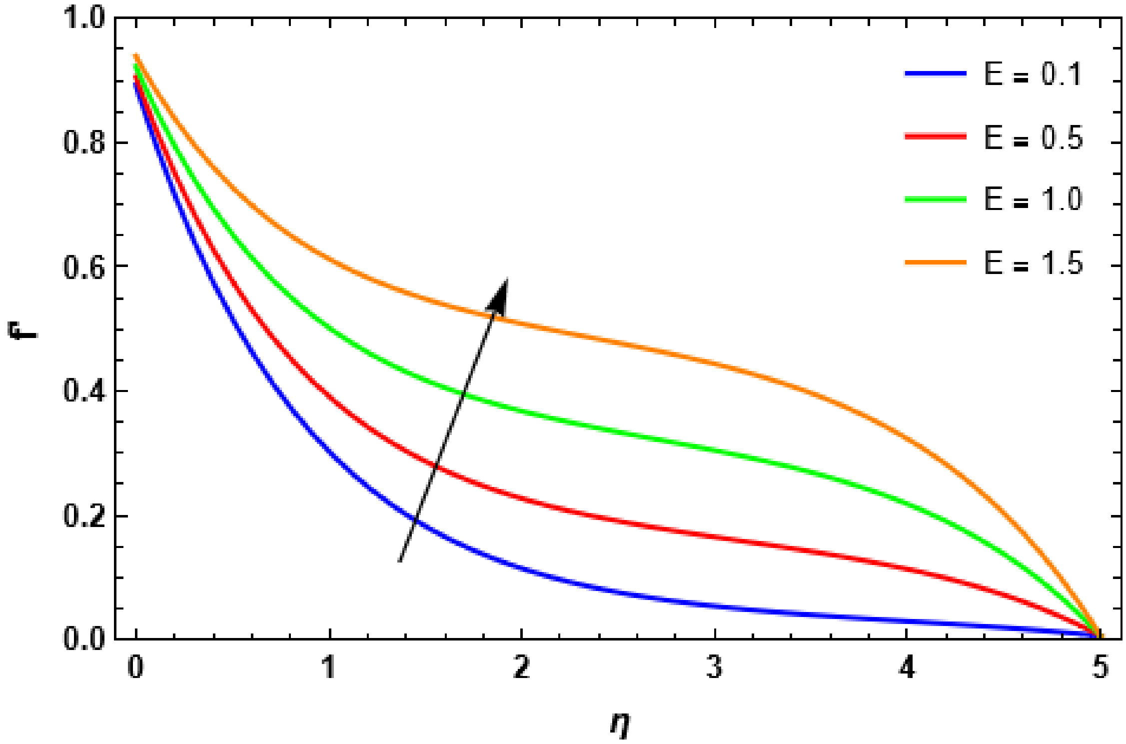

Figure 8.8: $f'(\eta)$ via E.

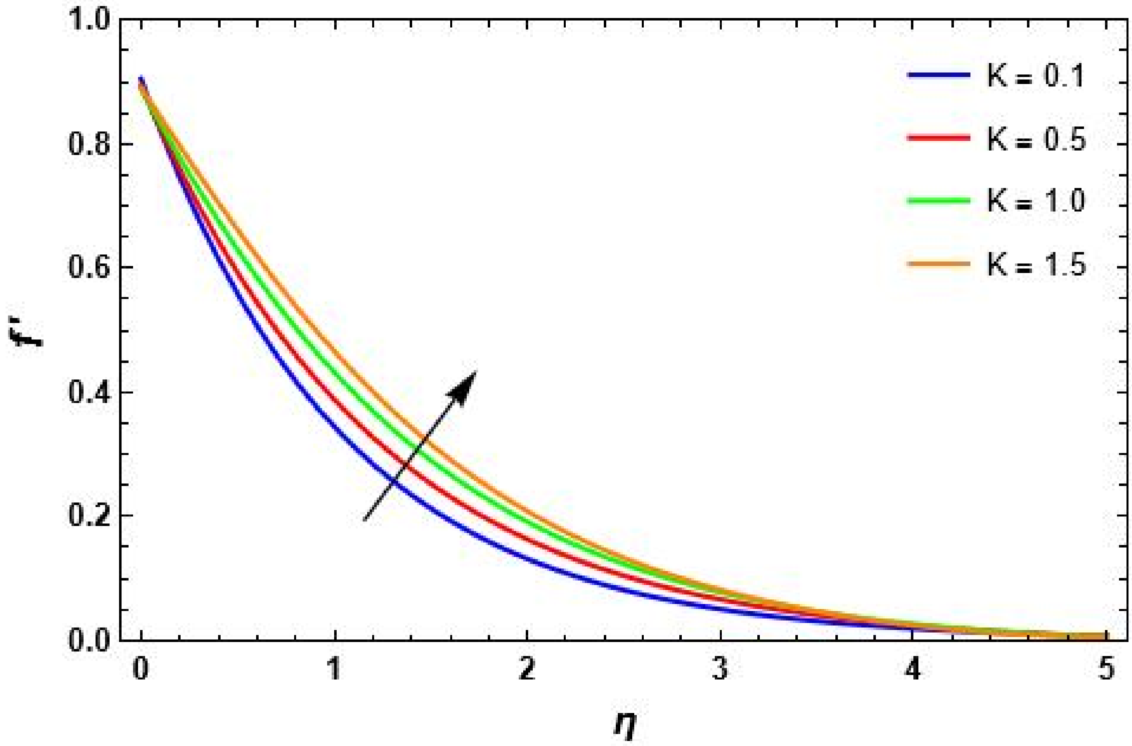

Figure 8.9: $f'(\eta)$ via K.

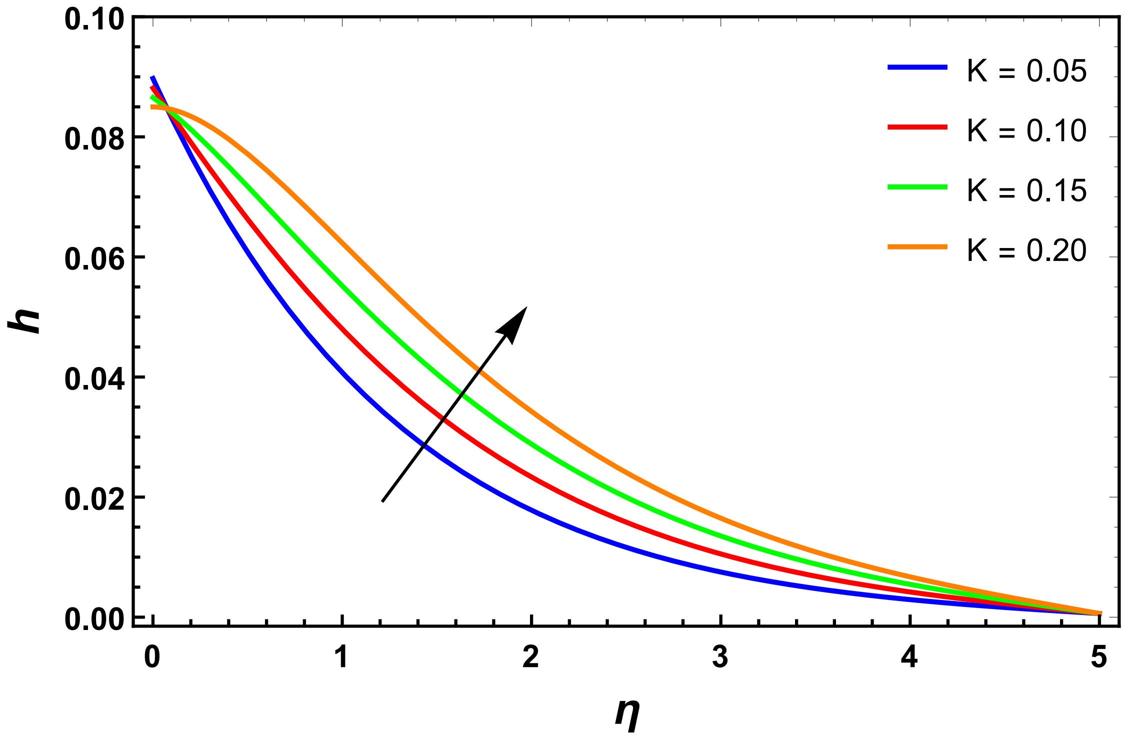

Figure 8.10: $h(\eta)$ via K.

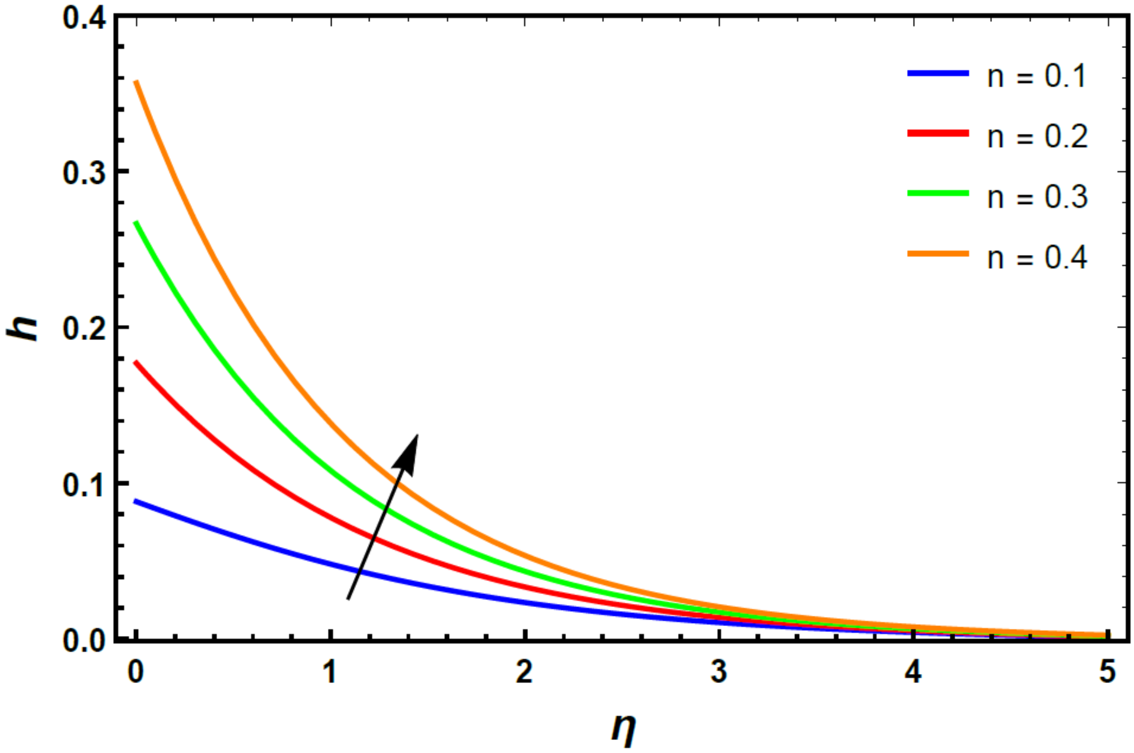

Figure 8.11: $h(\eta)$ via n.

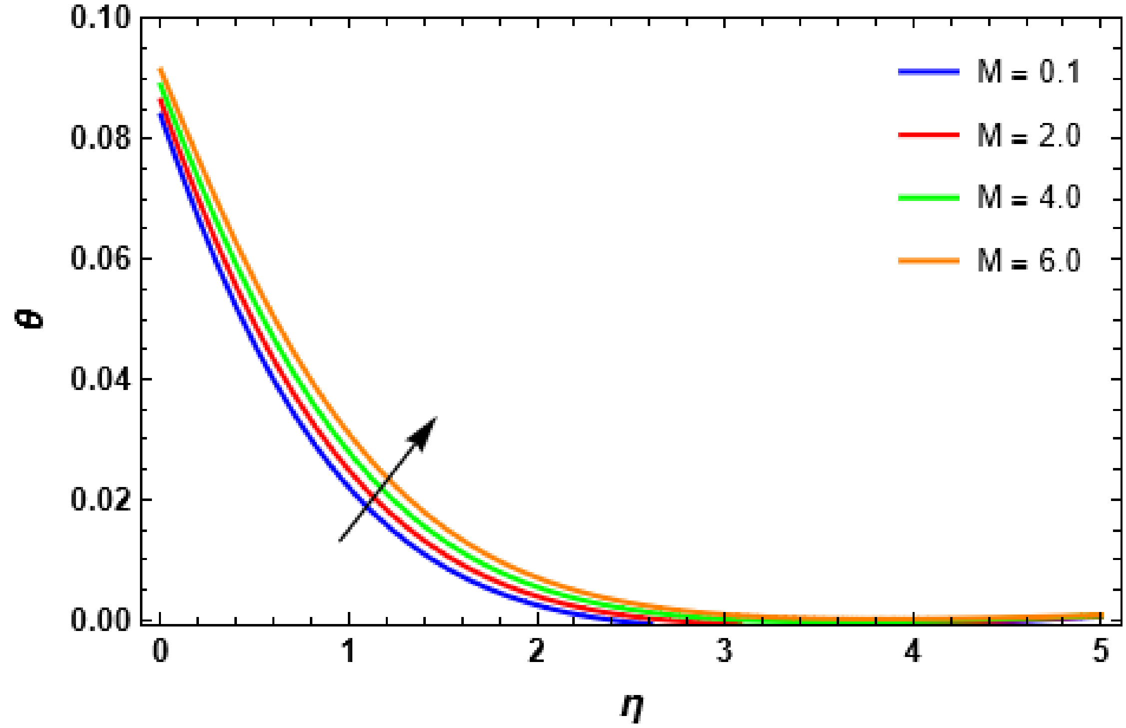

Figure 8.12: $\theta(\eta)$ via M.

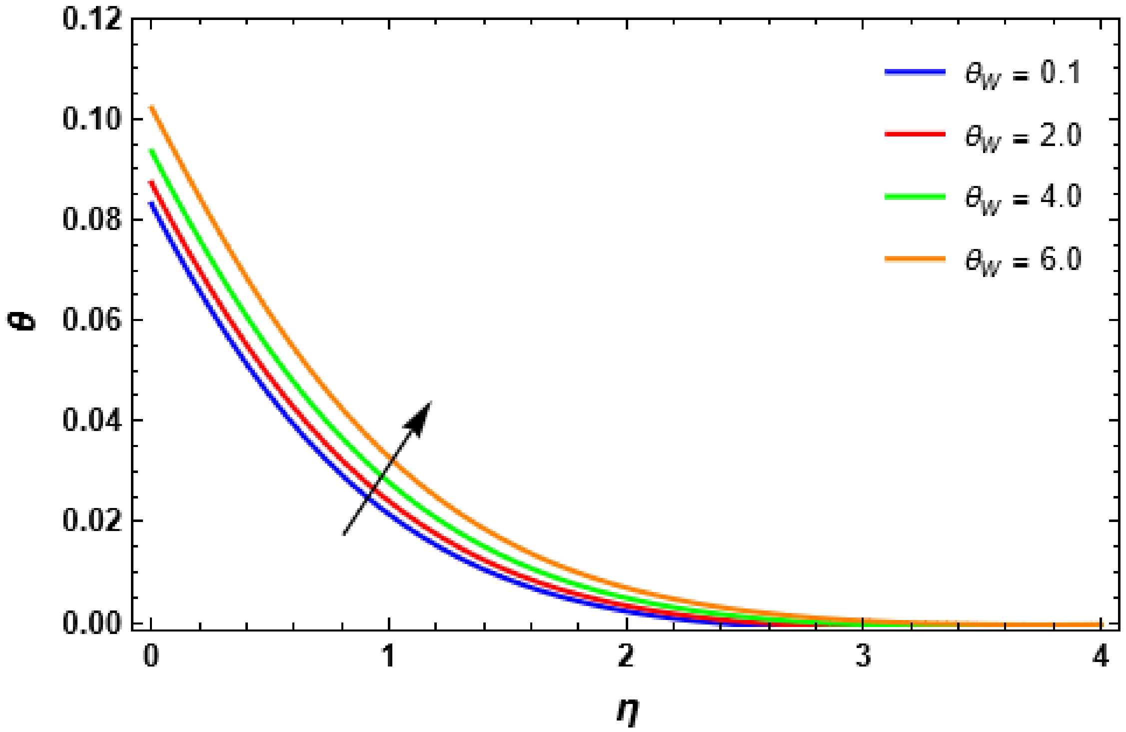

Figure 8.13: $\theta(\eta)$ via θ_w.

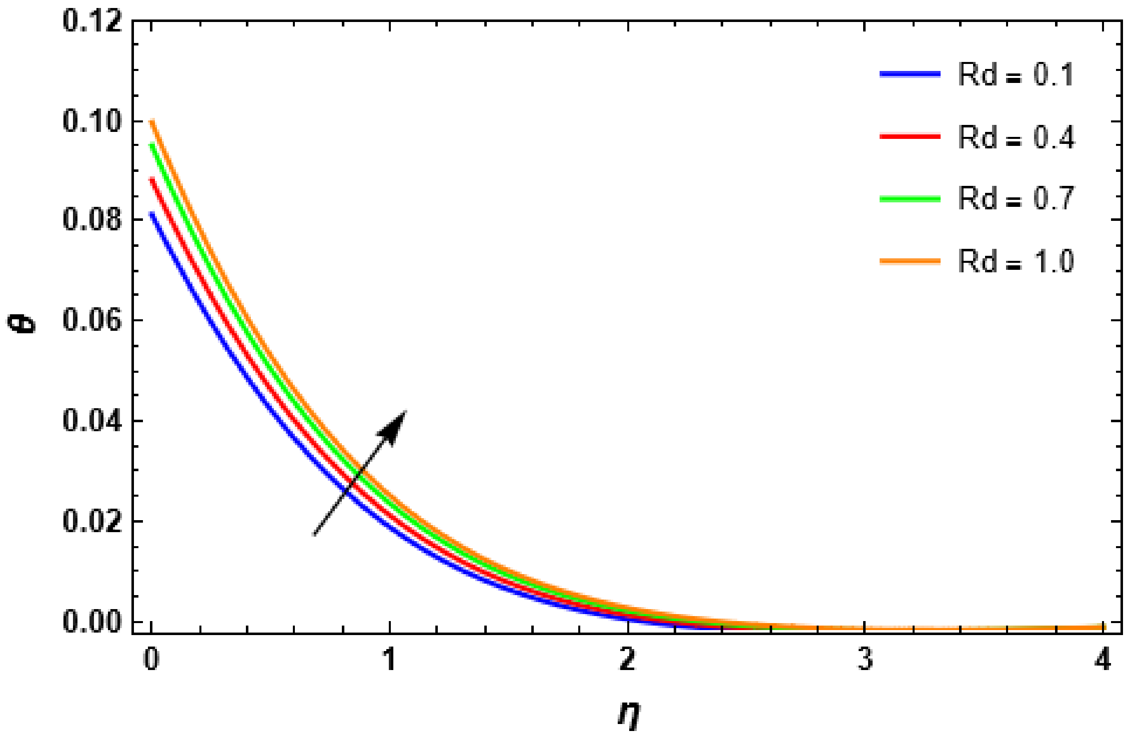

Figure 8.14: $\theta(\eta)$ via Rd.

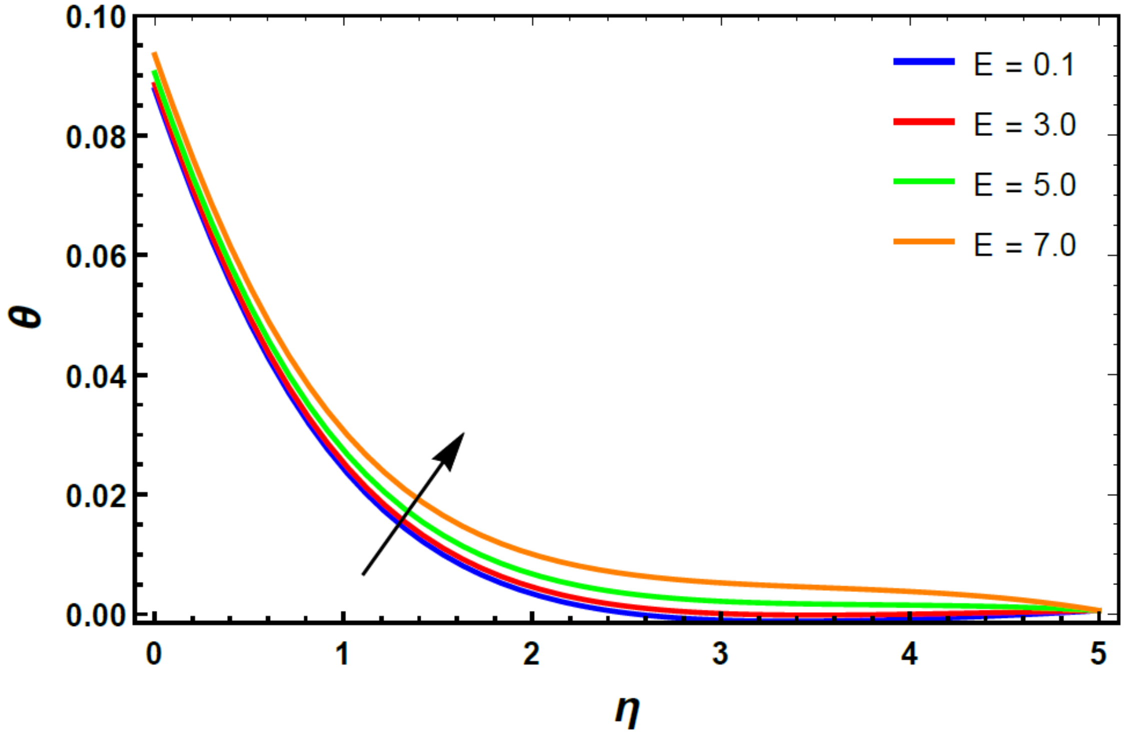

Figure 8.15: $\theta(\eta)$ via E.

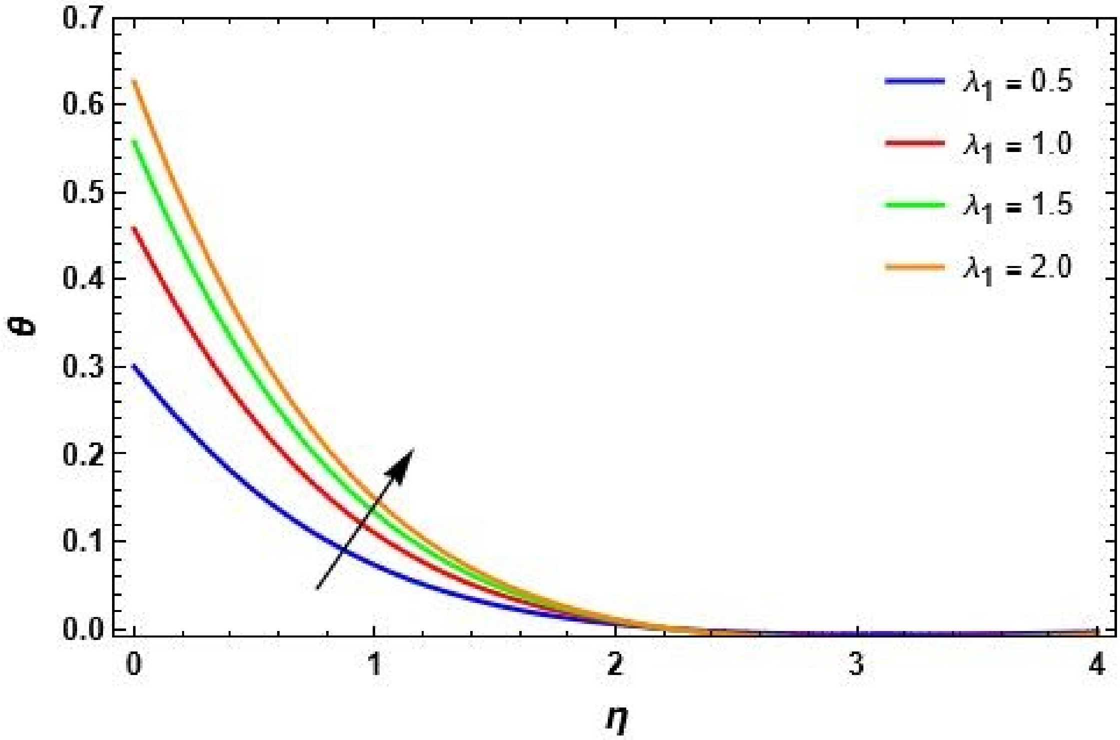

Figure 8.16: $\theta(\eta)$ via λ_1.

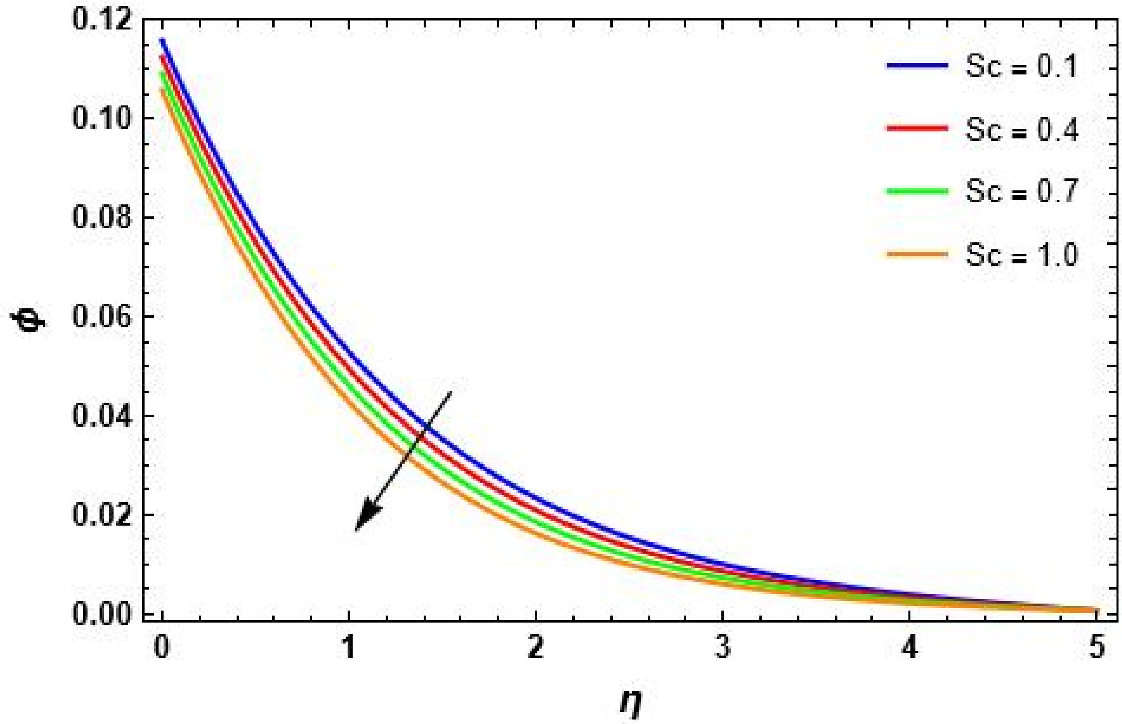

Figure 8.17: $\phi(\eta)$ via Sc.

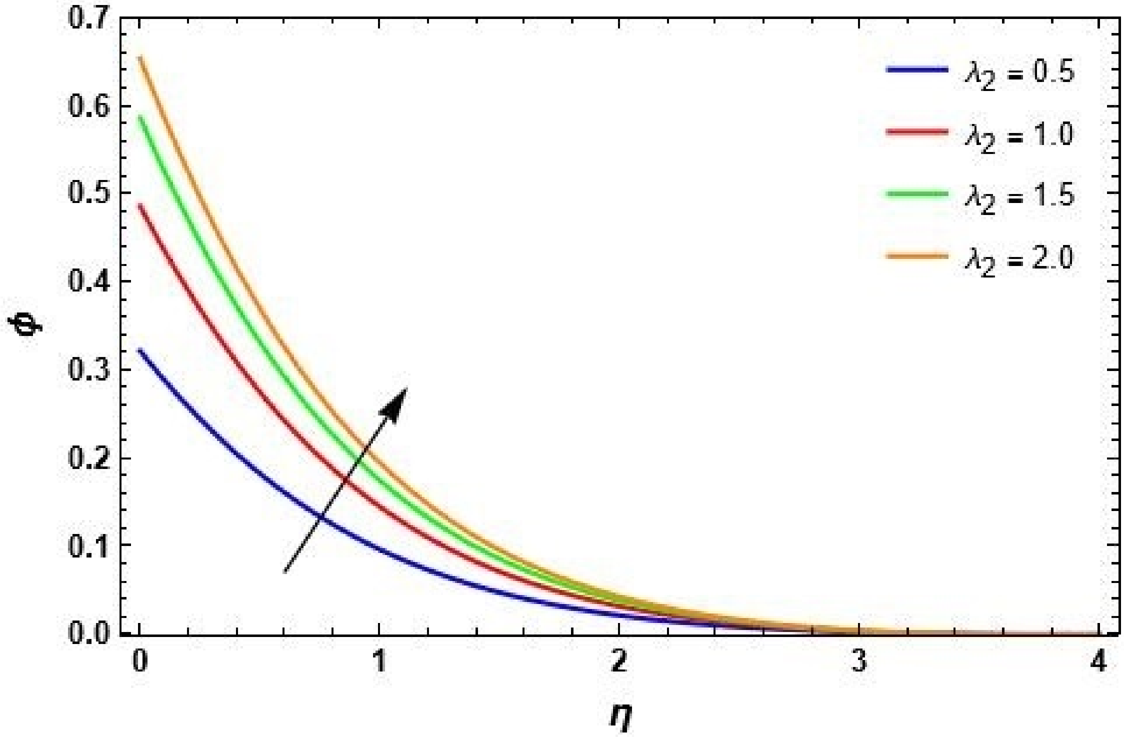

Figure 8.18: $\phi(\eta)$ via λ_2.

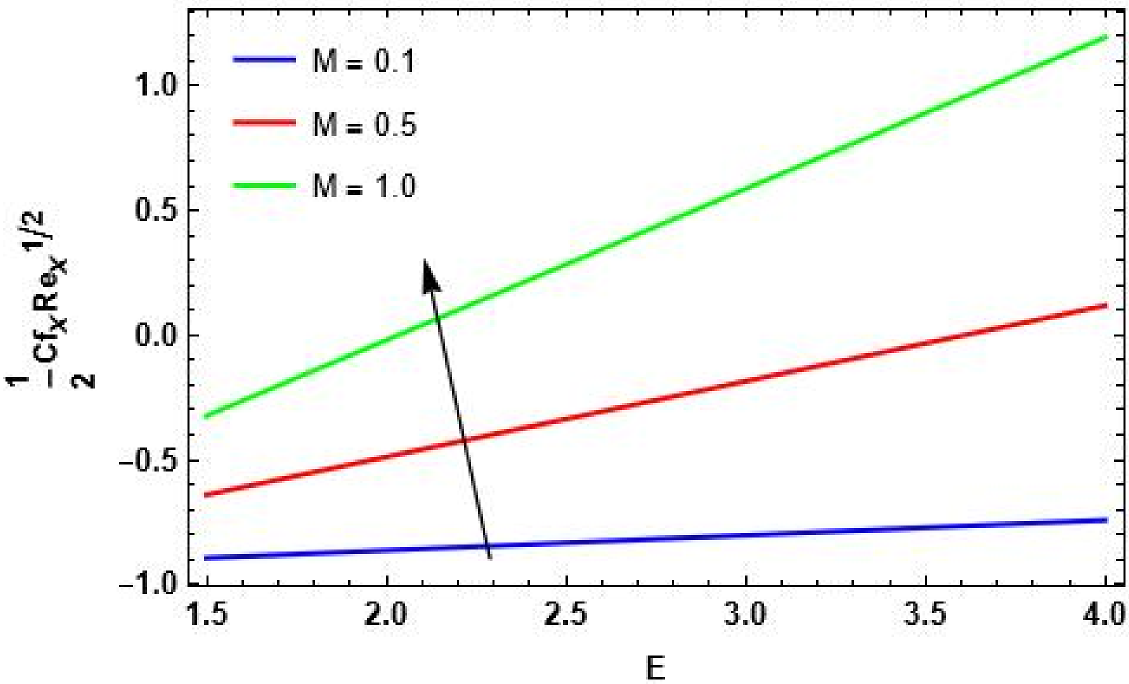

Figure 8.19: $C_{fx}Re_x^{1/2}$ via M.

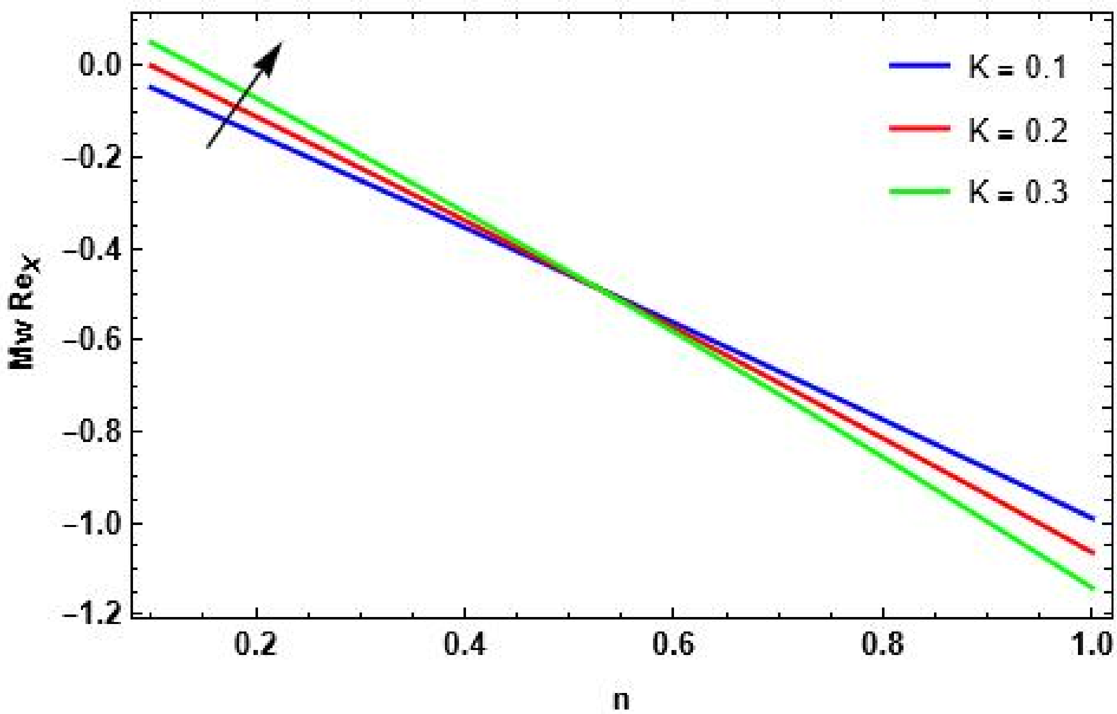

Figure 8.20: $M_{wx}Re_x$ via K.

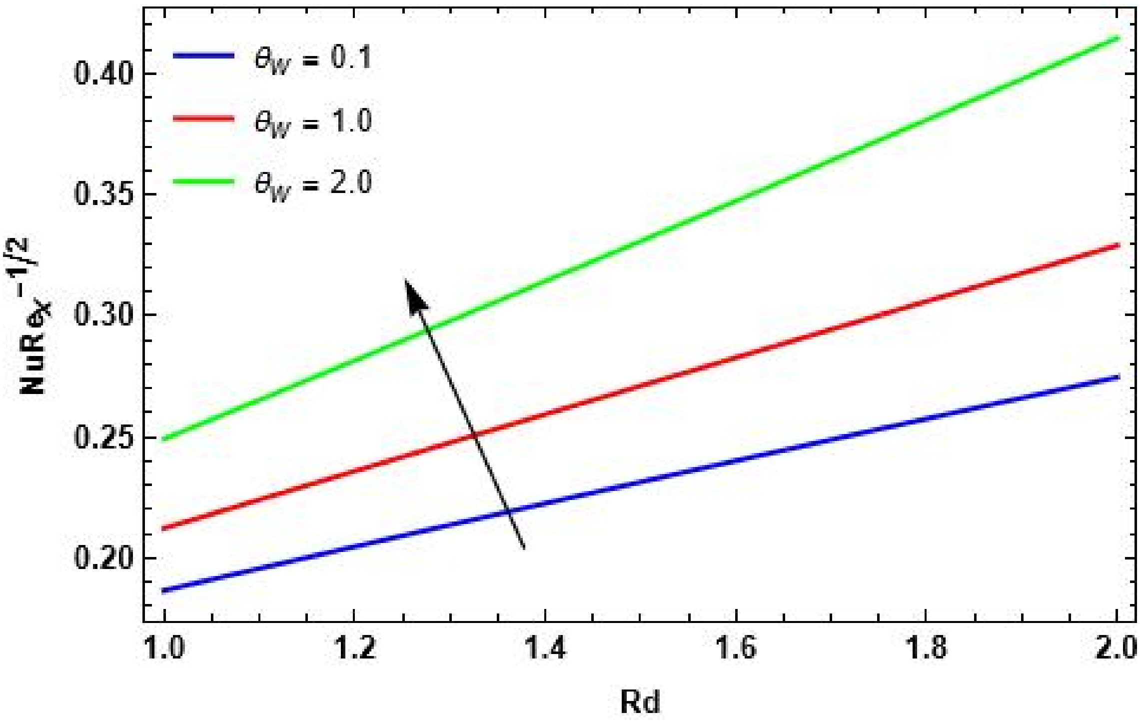

Figure 8.21: $Nu_xRe_x^{1/2}$ via θ_w.

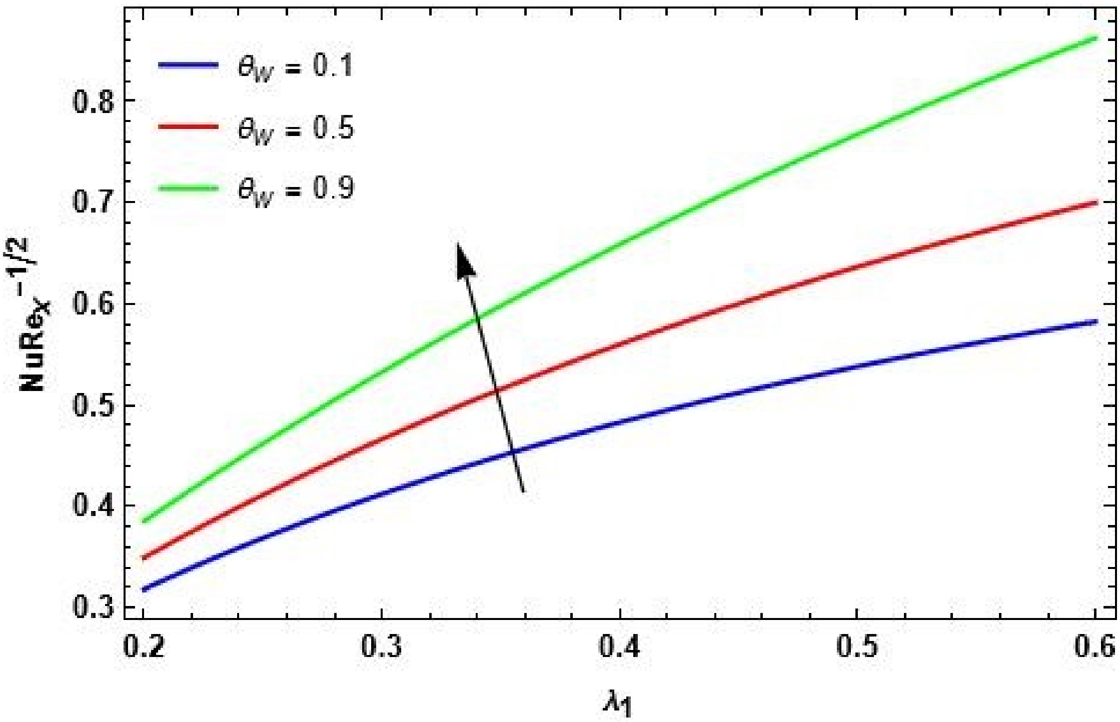

Figure 8.22: $Nu_xRe_x^{1/2}$ via θ_w.

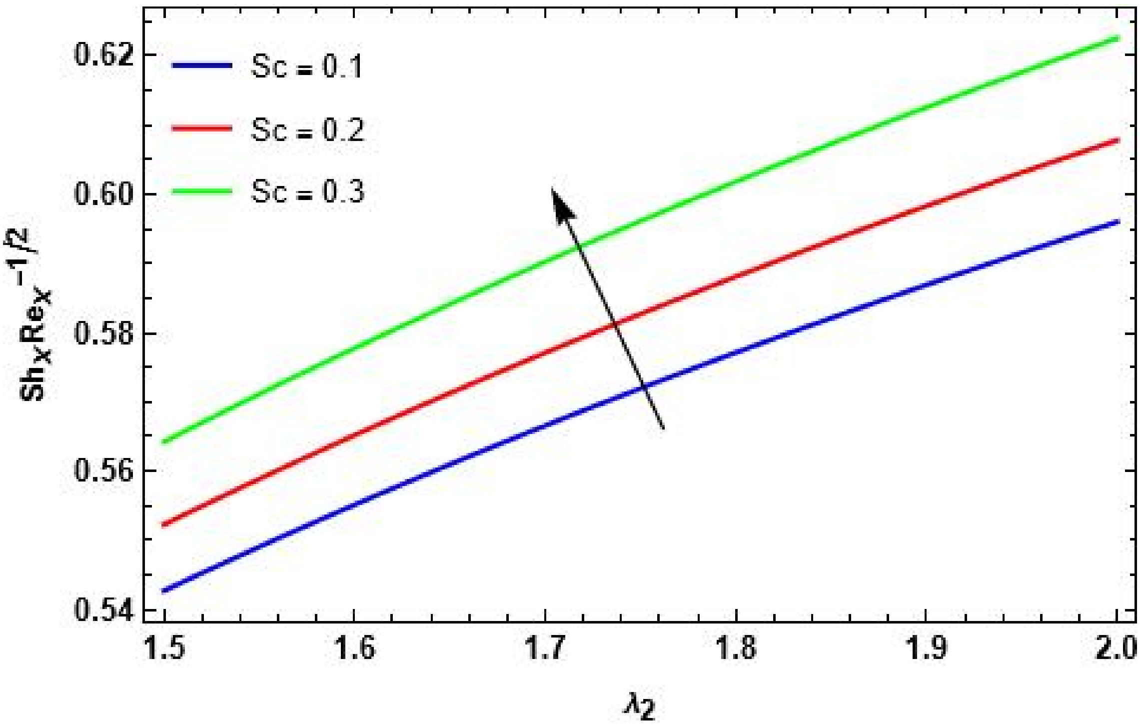

Figure 8.23: $Sh_x Re_x^{1/2}$ via Sc.

Table 8.1: Convergence of series.

Order of Approximations	$-f''(0)$	$-h'(0)$	$-\theta'(0)$	$-\phi'(0)$
1	1.003244	0.066081	0.09101	0.084782
5	0.996594	0.055059	0.09228	0.080484
10	0.996694	0.055061	0.09203	0.079963
15	0.996693	0.055062	0.09201	0.079919
20	0.996693	0.055062	0.09201	0.079919

Table 8.2: Numerical calculation of Nusselt number.

K	M	Rd	θ_w	E	γ	λ_1	Ec	Pr	$Nu_xRe_x^{-1/2}$
0.1	0.2	0.1	0.1	0.1	0.1	0.1	0.2	8.0	0.0886728112312340
0.2									0.0877926621310645
0.3									0.0869460900339288
	0.3								0.0878993228765361
	0.4								0.0871292499113140
		0.2							0.0950280026875549
		0.3							0.1013352240321531
			0.2						0.0890899054572508
			0.3						0.0895248727257786
			1.1						0.0936954842292853
			1.2						0.0943091801034734
			1.3						0.0949447573637243
				0.2					0.0891655414211307
				0.3					0.0894984433810905
					0.2				0.0908204466328325
					0.3				0.092456165624022
						0.2			0.1637989432763814
						0.3			0.2283895299246889
							0.3		0.0819690494354928
							0.4		0.0755037261999629
								9.0	0.0874310327573451
								10.0	0.0861980091535024

8.7 Conclusion

The following are the research's findings:

- For higher values of Electric parameter and Material parameter, both increase velocity.
- With increasing values of Slip parameter, Magnetic parameter and Suction parameter, velocity decreases.
- For increasing values of Material parameter and concentration of microelements, both increase angular velocity.
- With increasing values of Prandtl number, temperature diminishes.
- For increased values of Magnetic parameter, Electric parameter, Thermal Biot number, Temperature ratio parameter, and Non-linear thermal radiation all enhance temperature.
- With higher values of Solutal Biot number raises concentration, while Schmidt number decreases it.
- For a large amount of Magnetic parameter, Skin friction coefficient increases.
- Local wall couple stress rises for a wide number of Material parameter.
- Nusselt number rises during large amount of thermal Biot number.
- Sherwood number increases for large amount of Schmidt number.

- Skin friction factor enhances with increase in Weissenberg number We, velocity slip parameter γ, Thermal Grashof number Gr_T and Solutal Gashof number Gr_C whereas declined for Magnetic parameter M, Variable viscosity parameter ζ and Suction parameter f_w.

- Nusselt number is enhanced against rising values of Prandtl number Pr, temperature ratio parameter θ_w, Thermal Biot number λ_1, Thermal Grashof number Gr_T and Radiation parameter Rd, while decreases for Dufour number Du, Heat generation/absorption coefficient β and Brinkman number Br.

- Skin friction and number of Sherwood decreases for the broad unsteadiness parameter A values.

- Sherwood number is raised for Schmidt number Sc.

- N_G augmented when increment occurs in Magnetic parameter M, Diffusion parameter L^*, Thermal Grashof number Gr_T, temperature difference parmeter α_1 and Brinkman number Br.

- Bejan number has increment for large amount of α_1, L^* and M while decreases for higher values of Br.

Future Works

From studying previous research papers, it is observed that this work can be expanded in three dimensional steady and unsteady flow of Entropy optimized fluid. Also, effects of other physical parameters for different types of non-Newtonian fluids can be carried out. It may also be tried to develop mathematical models of two and three dimensional blood flow with magnetic field which can be used for human life. Study of effects of induced magnetic field for higher dimensional problems is rarely seen previous published works. It can also be tried to find the solutions of magnetic field effects on blood flow with heat transfer in different types of stenosed arteries and also discussed comparative study of different types of blood flow of different type's stenosed arteries.

Published/Accepted Research Articles

1. H. R. Kataria, M. H. Mistry, Effect of Non-linear Radiation on MHD Mixed Convection Flow of a Micropolar fluid Over an Unsteady Stretching Sheet. In **Journal of Physics**, (2021), 1964, p. 022005, ISSN : 1742-6596. doi:10.1088/1742-6596/1964/2/022005, **(Scopus).**

2. H. R. Kataria, M. H. Mistry, A. S. Mittal, Influence of nonlinear radiation on MHD Micropolar fluid flow with viscous dissipation, **Heat Transfer (Wiley)**, (2022), 51(2), 1449-1467, ISSN : 2688-4542. https://doi.org/10.1002/htj.22359, **(Scopus)**.

3. H. R. Kataria, M. H. Mistry, Entropy optimized MHD fluid flow over a vertical stretching sheet in presence of radiation, **Heat Transfer (Wiley)**, (2022), 51(3), 2546-2564, ISSN : 2688-4542. https://doi.org/10.1002/htj.22412, **(Scopus)**.

4. H. R. Kataria, A. S. Mittal, M. H. Mistry, Effect of nonlinear radiation on entropy optimised MHD fluid flow, **International Journal of Ambient Energy (Taylor and Fransis)**, (2022), 1-10, ISSN : 2162-8246. https://doi.org/10.1080/01430750.2022.2059000, **(Scopus).**

5. H. R. Kataria, A. S. Mittal, M. H. Mistry, Consequences of nonlinear radiation, variable viscosity, Soret and Dufour effects on MHD Carreau fluid flow, **International Journal of Applied and Computational Mathematics (Springer)**, (2022), ISSN : 2199-5796, **(Scopus).**

Communicated Research Work

1. H. R. Kataria, M. H. Mistry, A. S. Mittal, Soret and Dufour impact on MHD Williamson fluid flow with non linear radiation and varying viscosity.
2. H. R. Kataria, M. H. Mistry, Entropy optimized unsteady MHD natural convective flow of Williamson fluid including onlinear radiation and viscous dissipation effects.

Presented Research Work in Conferences

1. M. H. Mistry, H. R. Kataria, Mathematical Modelling of two dimensional electrically conducting Williamson fluid considering variable viscosity and radiation, in YOUNG SCIENTIST CONFERENCE as a part of India International Science Festival-2019 held at Biswa Bangla Convention Centre, Kolkata during November 5-8, 2019.

2. M. H. Mistry, H. R. Kataria, Mathematical modelling of two dimensional magnetohydrodynamic fluid flow considering variable viscosity and radiation, at the Science Conclave 2020 organized by Faculty of Science, The Maharaja Sayajirao University of Baroda, Vadodara on 28th February 2020.

3. M. H. Mistry, H. R. Kataria, Magneto-Micropolar electrically conducting fluid flow over a linearly stretching sheet for heat and mass transfer in International conference on Advances in Differential equations and Numerical analysis organized by Department of Mathematics, Indian Institute of Technology, Guwahati, India during October 12-15, 2020.

4. M. H. Mistry, H. R. Kataria, Effect of radiation on two dimensional electrically conducting Williamson fluid considering variable viscosity in the 21st International conference on Science, Engineering and Technology (ISCET-2020), organized by Vellore Institute of Technology, Vellore during November 30, 2020 to December 1, 2020.

5. M. H. Mistry, H. R. Kataria, Influence of Variable Thermal Conductivity and Viscosity on MHD Boundary Layer Flow of Carreau Fluid Over Stretching/Shrinking Sheet in the International Science Symposium on Recent trends in Science and Technology, organized by Christ college, Rajkot on 8th and 9th, April 2021. I stood second in the competition.

6. M. H. Mistry, H. R. Kataria, Entropy optimized MHD natural convective flow of Williamson fluid with nonlinear radiation and viscous dissipation effects,

International Conference on Recent Advances in Fluid Mechanics (ICRAFM-2022) organized Manipal Institute of Technology, MAHE, Manipal on 4th-6th, October 2022.

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