European Journal of Mechanical Engineering Research, 12(1),62-89, 2025

Print ISSN: 2055-6551(Print)

Online ISSN: 2055-656X(Online)

Website: https://www.eajournals.org/

Publication of the European Centre for Research Training and Development-UK

The Impact of Viscosity, Viscous Dissipation, Porosity and Chemical Reaction on Heat and Mass Transfer Flow of Mhd Micropolar Fluid Along a Permeable Stretching Sheet in a Non-Darcian Porous Medium

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doi: https://doi.org/10.37745/ejmer.2014/vol12n16289 Published September 10, 2025

Citation: Areo, A. O., Olajide,. A.O., Aworinde, A., Odebiyi O. A., and Adetunde, I. A. (2025) The Impact of Viscosity, Viscous Dissipation, Porosity and Chemical Reaction on Heat and Mass Transfer Flow of Mhd Micropolar Fluid Along a Permeable Stretching Sheet in a Non-Darcian Porous Medium, *European Journal of Mechanical Engineering Research,* 12(1),62-89

Abstract: *The study of Newtonian and Non-Newtonian fluid in porous medium is very important owing to its wide area of practical applications. The applications are in engineering practices, particularly in applied geophysics, geology, food technology, filtration and oil recovery processes. Several studies involving heat and mass transfer in Newtonian fluid flow through porous media have been undertaken. This study, evaluated the effects of variable viscosity, viscous dissipation, porosity and chemical reaction on heat and mass transfer flow of MHD micro polar fluid along a permeable stretching sheet in a non-Darcian porous medium. Dimensionless parameters were used to non-dimensionalize the governing equations and the resulting sets of equations were analyzed and solved numerically by using Runge Kutta with shooting method. The effects of the various physical parameters entering into the problem on velocity, micro rotation, temperature and concentration profiles are presented graphically. Also, the effects of pertinent parameters on local skin-friction coefficient, local Nusselt number and local Sherwood number are also presented graphically and discussed. It was concluded that variable porosity and viscosity increased velocity and reduced temperature of MHD flow. Increment in viscous dissipation decreased the temperature of the flow while the physical parameters had significant effect on the velocity, temperature and concentration profiles of the flow.*

Keywords: micro polar fluid, Magneto hydrodynamics (MHD), chemical reaction, Darcian porous medium, viscous dissipation and physical parameter.

INTRODUCTION

Physically, the fluids consisting of the spherical rigid and randomly oriented micro particles suspended in a viscous medium are called micro polar fluids Ghanbari & Rezazadeh, (2020). Micro polar fluids as a complex non-Newtonian fluid belong to a class of fluids with microstructures assuming that their internal micro particles may rotate independently of the fluid vorticity Ding *et al.* ,(2017); Weng *et al.*, (2009). Due to the simplicity, this model has been widely used in numerous applications of science and technology to describe the rheological behavior of certain real fluids, such as exotic lubricants, liquid crystals, synovial joint lubricants, slurry dynamics, blood and biological fluid flows in thin vessels (Allen & Kline, (1971); Khonsari, (1990); Khonsari & Brewe, (1989); Nisar et al., (2022). This class of fluids exhibits a wrapped constitutive relationship dealing with a couple stress tensor in addition to a non-symmetric stress tensor (Hayakawa, (2000)). The nonlinear relations governing between the stress and strain tensor and also between the temperature gradient and the heat flux, distinguish micro polar fluids from Newtonian fluids in rheology and thermodynamics Sui et al., (2017). One of the most significant and important fluids that due to the characteristic of suspensions in it can be considered as a micro polar fluid is the blood of humans or animals. Blood plays an important role in regulating the body's system and maintaining homeostasis. However, blood is a bodily fluid in animals that delivers necessary substances such as nutrients and oxygen to the cells and transports metabolic waste products away from those same cells Ghanbari & Rezazadeh, (2020). In chemical industries, lubricants are examples of the important micro polar fluids. Lubrication is one of the most important aspects of any rotating equipment reliability program. Lubricants can reduce friction between the rotating and stationary components, absorb shocks, and damp the noises Shram et al., (2016). The basic idea of micro polar fluid, revealed by Eringen, (1966), was used to study different flux conditions and framed the fundamental continuum theory for the fluids with microstructures and rotating microscopic crystals Nisar et al., (2022). Recently, micro polar fluids have been investigated in various aspects. Among them, heat transfer of micro polar fluids due to its importance in several engineering applications has been discussed numerously. The mass and heat transfer magneto hydrodynamic (MHD) flows have a substantial use in heat exchangers, electromagnetic casting, X-rays, the cooling of nuclear reactors, mass transportation, magnetic drug treatment, energy systems, fiber coating, etc. The effect of MHD can be observed in several natural and artificial flows. MHD is the study of the interaction of conducting fluids with electromagnetic phenomena. Electrically conducting fluids in the presence of a magnetic field are of importance in many areas of technology and engineering such as MHD flow meters, MHD power generation, and MHD pumps. It is generally accepted that various astronomical bodies e.g., Earth, the sun, Jupiter, magnetic stars, and pulsars acquire fluid interiors and magnetic fields T. Hayat et al., (2008); Sheikh et al., (2017). In the recent past, extensive consideration has been given to applications of MHD and heat transfer such as MHD generators, metallurgical processing, and geothermal energy extraction. The MHD flow with combined effects of heat and mass transfer has wide applications in science and technology, for example, quasi-solid bodies such as earth and in buoyancy induced flows in the atmosphere Khan et al., (2014). Prakash et al., (2015) analyzed the effects of thermal diffusion and chemical reaction on MHD boundary layer flow of electrically conducting dusty fluid between two vertical heated plates. Shahid, (2015) obtained the exact solutions for MHD free convection flow of generalized viscous fluid over an oscillating plate. Raju & Sandeep,(2016) investigated the MHD flow of non-Newtonian fluid over a rotating cone with cross-diffusion. Therefore, the MHD flow with combined effect of heat and mass transfer has been a subject of concern of several researchers including Areo et al (2011); Bakr, (2011); Mohyud-Din et al., (2015); Pal & Chatterjee, (2010); Srinivas & Kothandapani, (2009).This study of heat and mass transfer flow of an electrically conducting micro polar fluid has attracted many researchers due to its enormous applications in many industry and engineering problems, such as MHD generators, nuclear reactors, geothermal energy extractions, design of chemical processing equipment, food processing, cooling towers and the boundary layer control in the field of aerodynamics.

In this paper, a fully developed MHD flow in a rhombus micro polar fluid in the presence of variable viscosity, viscous dissipation, heat and mass transfer flow past a porous stretching sheet in a non-Darcian medium with chemical reaction is investigated. The governing equations were reduced to similarity boundary layer equations using suitable transformations and then solved using the runge –Kutta numerical integration with a modified version of shooting technique. Numerical results are obtained. The velocity, angular velocity temperature and concentration distributions as well as the local Sherwood number are presented graphically.

Mathematical Problem Formulation

The study considered two-dimensional steady flow of a magneto hydrodynamic heat and mass transfer of a viscous incompressible micro polar fluid over a continuously moving stretching surface embedded in a non-darcian porous medium. The surface is stretched in the x direction such that the x component of the velocity varies nonlinearly along it, that is $\boldsymbol{\mu_w(x) = ax^n}$, where a (>0) is constant and n is a power index. The positive x coordinate is measured along the direction of motion with the slot as the origin, and the positive y coordinate is measured normal to the porous plate. Here, magnetic Reynolds number of the fluid is assumed to be small, so that the induced magnetic field is neglected. Within the framework of these assumptions the magneto-hydrodynamic flow relevant to the problem is governed by the set of equations.

$$\frac{1}{\mu} = \frac{1}{\mu}[1+\gamma(T-T_\infty)], \qquad \text{that is} \qquad \frac{1}{\mu_0} = A(T-T_r)\,, \qquad (1)$$

Where $A = \frac{\gamma}{\mu_\infty}$ and $T_r = T_\infty - \frac{1}{\gamma}$ are constants, and their values depends on the reference state on the fluid. Under the above assumption and using the Boussinesq approximation, the boundary layer equations for this problem is given as follows

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}=0 \qquad (2)$$

$$u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}=\frac{1}{\rho_\infty}\frac{\partial}{\partial y}[(\mu_n(T)+\mu_r)\frac{\partial u}{\partial y}]+\frac{\mu_r}{\rho_\infty}\frac{\partial \omega}{\partial y}-[\frac{\mu_n(T)+\mu_r}{\rho_\infty}]\frac{\varphi}{K_1}u$$

$$-c\varphi u^2-\frac{\sigma B_0^2}{\rho_\infty}u+g\beta(T-T_\infty)+g\beta^*(c-c_\infty) \qquad (3)$$

$$G_1\frac{\partial^2 \omega}{\partial y^2}-2\omega-\frac{\partial u}{\partial y}=0 \qquad (4)$$

$$u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}=\frac{K}{\rho_\infty c_p}\frac{\partial^2 T}{\partial y^2}$$

$$+\frac{Q_0}{\rho_\infty c_p}(T-T_\infty)+\frac{\mu_n(T)+\mu_r}{\rho_\infty c_p}(\frac{\partial u}{\partial y})^2 \qquad (5)$$

$$u\frac{\partial C}{\partial x}+v\frac{\partial C}{\partial y}=D\frac{\partial^2 C}{\partial y^2}-K(C-C_w) \qquad (6)$$

Subject to the boundary conditions

$$u=u_w=ax^n, \quad v=\pm v_w$$
$$T=T_w(x)=T_\infty+Ax, \quad \omega=0,$$
$$C=C_w \quad at \quad y=0,$$
$$u\to 0 \quad T\to T_\infty \quad N\to 0,$$
$$C\to C_\infty \quad as \quad y\to\infty \qquad (7)$$

Where x and y are the coordinate directions, u, v, ω, T, and C are t5he fluid velocity components in the x and y directions, the component of micro rotation, temperature and concentration, respectively $\mu_n, \mu_r, K_1, \omega,$ and ρ_∞ are Newtonian fluid viscosity, micro polar viscosity, the permeability of the porous medium, the porosity of the porous medium and the density of the ambient fluid σ is the electrical conductivity of the fluid, B_0 is the strength of applied magnetic field , β and β^* are coefficient of thermal and concentration expansions, respectively , G_1 is the micro rotation constant, C_p is the specific heat of the fluid at constant pressure, K is the thermal conductivity, Q_0 is the volumetric heat generation/absorption rate, D is the molecular diffusivity of the species concentration, K is the rate of chemical reaction, T_∞ is the temperature of the ambient fluid, and v_0 is the permeability of the porous surface.

The governing equations (2) - (6) can be expressed in a simple form by introducing the following similarity transformations:

$$\eta=\sqrt{\frac{a(n+1)}{2v_\infty}}x^{(n-1)/2}y$$

$$\omega=ax^{\frac{3n-1}{2}}\sqrt{\frac{a(n+1)}{2v_\infty}}\,g(\eta)$$

$$\psi=x^{(n+1)/2}\sqrt{\frac{2av_\infty}{n+1}}\,f(\eta)$$

$$u=\frac{\partial\psi}{\partial y},\qquad v=-\frac{\partial\psi}{\partial x},$$

$$\theta=\frac{T-T_\infty}{T_\omega-T_\infty},\qquad \varphi=\frac{C-C_\infty}{C_\omega-C_\infty}\tag{8}$$

Where $\boldsymbol{\psi}$ is the stream function, $\boldsymbol{\theta}$ and $\boldsymbol{\varphi}$ are the nondimensional temperature and concentration parameters Substituting (8) into (3)- (6) produces the following differential equations:

$$\left(\frac{\theta_r}{\theta\ -\theta}+L\right)f'''+\left(\frac{\theta_r\theta'}{(\theta_{r_r}-\theta)^2}+f\right)f''-2\left(\frac{n+a_1}{n+1}\right)f'^2+Lg'$$

$$-\tag{9}$$

$$-\left[\frac{2}{Da(n+1)}\left(\frac{\theta_r}{\theta_r-\theta}+L\right)+\frac{2M}{n+1}\right]f'+\frac{2\Delta}{n+1}(\theta+N\varphi')=0$$

$$G(n+1)g''-2(g+f'')=0\tag{10}$$

$$\theta''+\Pr_\infty\left(\frac{2}{n+1}E\theta+\left(\frac{\theta_r}{\theta_r-\theta}+L\right)Ecf''^2\right)=0\tag{11}$$

$$\psi''+Sc\left(f\psi'-\frac{2\Delta}{n+1}\psi\right)=0\tag{12}$$

And the boundary condition (7) becomes

$$f(\eta)=\pm F_\omega,\qquad f'(\eta=1),$$
$$\theta(\eta)=1,\quad g(\eta)=0,\quad \varphi(\eta)=1\qquad at\ \eta=0,$$
$$F'(\eta)\to 0,\qquad \theta(\eta)\to 0,\tag{13}$$
$$\varphi(\eta)\to 0,\quad g(\eta)\to 0\qquad as\ \eta\to\infty$$

Where $\boldsymbol{M} = \frac{\sigma B_o{}^2}{a\rho_\infty x^{n-1}}$ is the local magnetic field parameter, $\boldsymbol{Da^{-1}} = \frac{\varphi v_\infty}{a k_{1x}{}^{n-1}}$ is the inverse Darcy number, $\boldsymbol{\epsilon} = \frac{x}{k(n+1)}$ is the porosity parameter, $\boldsymbol{Sc} = \frac{v_\infty}{D}$ is the Schmidt number, $\boldsymbol{Pr}_\infty = \frac{\mu_\infty c_p}{k_\infty}$ is the ambient Prandtl number, $\boldsymbol{Ec} = \frac{a^2 x^{2n}}{\rho_\infty (T_w - T_\infty)}$ is the local Eckert number (characterizing viscous dissipation), $\boldsymbol{E} = \frac{Q_\circ x^{1-n}}{\rho_\infty c_p a}$ is the local heat generation/ absorption parameter, $\boldsymbol{G} = \frac{G_1 a}{v_\infty x^{1-n}}$ is the microrotation parameter and $\boldsymbol{\Delta} = \frac{k}{a x^{n-1}}$is the chemical reaction parameter.

A prime denotes differentiation with respect to η in the above equations. $\theta_r \to \infty$ (Uniform viscosity), L=0 (Newtonian fluid), n=1 (linear surface velocity), $\lambda = 0$ (without buoyancy force), (9), together with the boundary conditions $f(0) = f_w f'(0) = 1$ *and* $f'(\infty) = 0$ has an exact closed form solution in the form.

$$f(\eta) = \frac{1}{Z}(1 - \exp(\frac{1}{\eta}Z) + \frac{1}{2}F_w Z),$$
$$Z = F_w + 2\sqrt{1 + (M + Da^{-1}) + \frac{F_w^2}{4}} \tag{14}$$

The physical quantities of interest are the skin friction coefficient, the Nusselt number and the Sherwood number. These are defined by

$$C_f = \frac{2\tau_w}{\rho_\infty u_0^2} \qquad Nu_x = \frac{x q_w}{k(T_{w-} T_\infty)}$$

$$Sh = \frac{x m_w}{\rho_\infty D(C_w - C_\infty)}$$

Where

$$\tau_w = [(\mu_0(T) + \mu_\tau)\frac{\partial u}{\partial y} + \mu_\tau \omega]_{y=0}$$
$$q_w = -K[\frac{\partial T}{\partial y}]_{y=0} \tag{15}$$
$$m_w = -\rho_\infty D(\frac{\partial u}{\partial y})_{y=0}$$

Are shear, surface heat flux, and surface mass flux, respectively. Using the new similarity variables in (8) gives

$$c_f \sqrt{Rc} = \sqrt{2(n+1)}[(\frac{\theta_r}{\theta(\theta)-\theta_r} + L) f''(0) + Lg(0)]$$

$$Nu \operatorname{Re}_x^{-\frac{1}{2}} = -\sqrt{\frac{n+1}{2}\theta'(0)} \qquad (16)$$

$$sh \operatorname{Re}_x^{-\frac{1}{2}} = -\sqrt{\frac{n+1}{2}\varphi'(0)}$$

DISCUSSION OF RESULTS

The influence of variable viscosity parameter θ_r, and the magnetic field parameter M on the velocity, micro rotation, temperature and concentration profiles are shown in figures 3, 4 and 5. It shows from these figures that the velocity, micro rotation, and temperature profiles of the micro polar fluid decrease, whereas the concentration of the micro polar fluid increases as θ_r increases in the absence/presence of the magnetic field. ($M \neq 0$), varying the temperature dependent viscosity becomes more effective on the velocity, micro rotation and temperature fields than in the nonmagnetic case (M=0) Further, the temperature dependent viscosity has only very slight influence on the concentration profiles whenever no magnetic field is applied, while the increase in the concentration due to variable viscosity is recognized at a certain nonzero value of Mgraphical representation for velocity, micro rotation, temperature and concentration profiles for different values of Darcy number Da in the absence and presence of the Eckert number Ec. The presence of a porous medium in the flow presents the resistance to the flow and in the limiting case when Da $\rightarrow \infty$ value, the porosity disappears.

Therefore, as the inverse Darcy number $\boldsymbol{Da^{-1}}$ increases, the resistance due to porous medium increases and the velocity profiles decreases as shown in figure 5. Also, from this figure the velocity increases with increasing viscous dissipation parameter Ec. This effect is more pronounced in the case of a purely fluid region (infinite Da) than in the case of flow through a porous medium. Figure 6 shows that the micro rotation velocity decreases with an increase in the inverse Darcy number which means that the presence of porous medium decelerates the rotatory motion of the microelements near the surface. Figure 7 shows that the temperature and concentration distribution of the fluid increases due to the increase in the inverse Darcy number $\mathbf{Da^{-1}}$. In the presence of viscous dissipation, Ec$\neq \mathbf{0}$, the effect of $\mathbf{Da^{-1}}$ is to increase the temperature more than the case of Ec = 0 as a result of viscous dissipation effects which acts as a heat source. Also, the viscous dissipation parameter has only very slight influence on the concentration profiles in the case of highly porous medium.
Figures 8 – 11 depicts the influence of the chemical reaction parameter Δ with different values of Sc on the behavior of the velocity, microrotation, temperature and concentration profiles.

Increasing the chemical reaction parameters Δ produces a decrease in the species concentration for both hydrogen and ammonia. This is due to the fact that destructive chemical reaction reduces the solutal boundary layer thickness. This, in turn, causes the concentration buoyancy effect to decrease as Δ increases.

Figure 10 shows that with increasing Δ and Sc, the microrotation profiles increases near the porous plates while the situation is reversed far away from the porous plates, that is, the microrotation profiles increases as Δ and Sc increases. Also, we noticed that, the effects of Δon the microrotation profiles in the case of micropolar fluids with small Schmidt number is stronger than its effect in the case of micropolar fluid with large Schmidt number.

The variation of the velocity, temperature and concentration profiles as shown in figures 12, 13, 14 for various values of the suction/blowing parameter $\boldsymbol{F_w}$ and microrotation parameter L. Here, $\boldsymbol{F_w}$ is greater than 0 corresponding to suction and $\boldsymbol{F_w}$ is less than 0 corresponding to injection at the plate. It is clear that for all values of suction/blowing parameter $\boldsymbol{F_w}$, the temperature and concentration profiles within the boundary layer increases, while the velocity component decreases as L increases (the micro rotation increases).

Figure 15 displays the influence of the coupling parameter L and suction/injection parameter $\boldsymbol{F_w}$ on the microrotation profiles. It is seen from this figure that increasing values of the microrotation parameter L results in increasing the micro rotation profile near the plate but a reverse process has occurred as one moves away from the porous plate. From these figures, it is observed the effect of micro rotation parameter L on the velocity, temperature and concentration is more pronounced in the case of injection than in the case of the impermeable plate. $(\mathbf{F_w = 0})$ and suction $(\boldsymbol{F_w = 1})$.

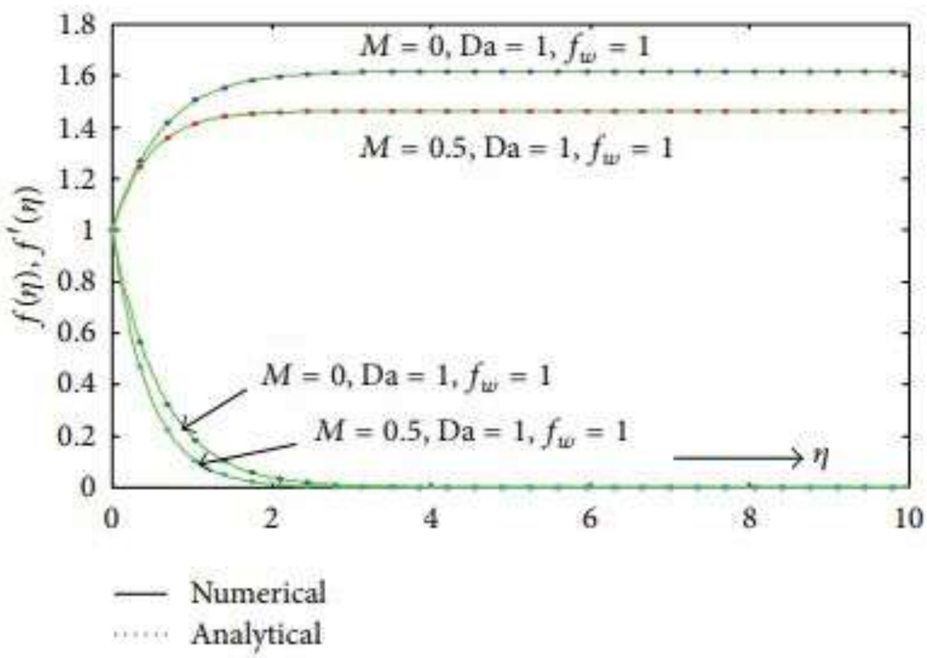

Figure 1: Comparison of the exact solution on numerical solution for various value of M.

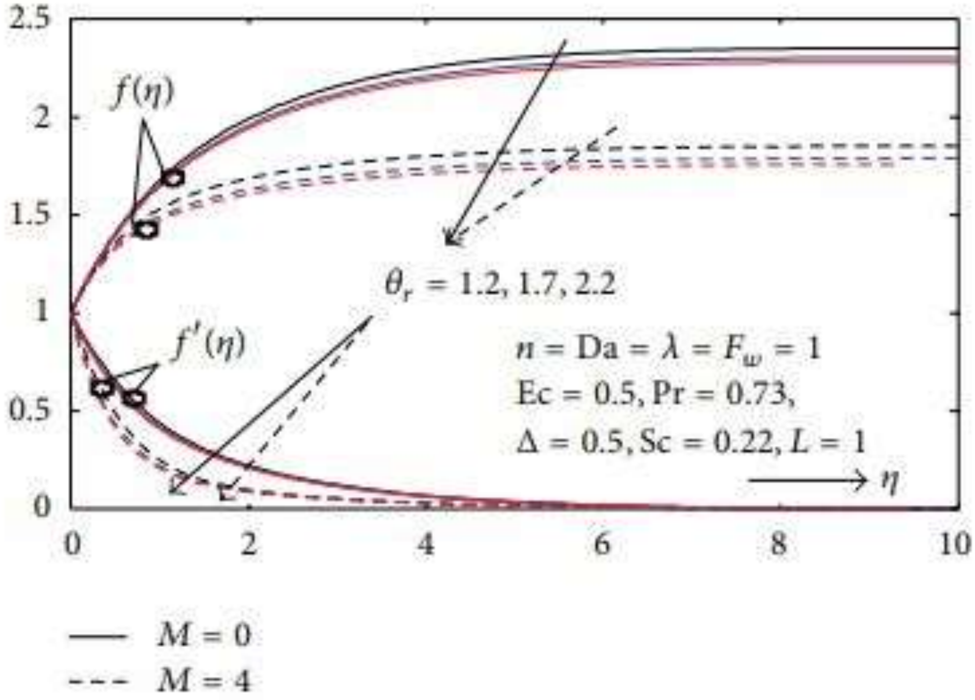

Figure 2: Velocity profile for different values of $\boldsymbol{\theta_r}$ and M.

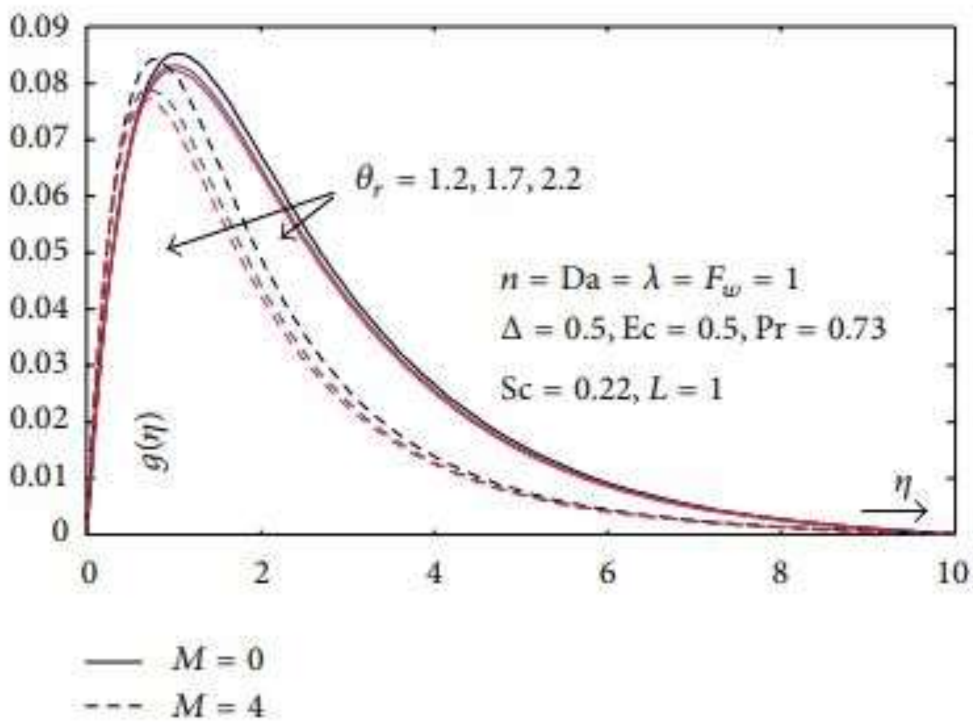

Figure 3: Angular velocity profile for different values of $\boldsymbol{\theta_r}$ and M.

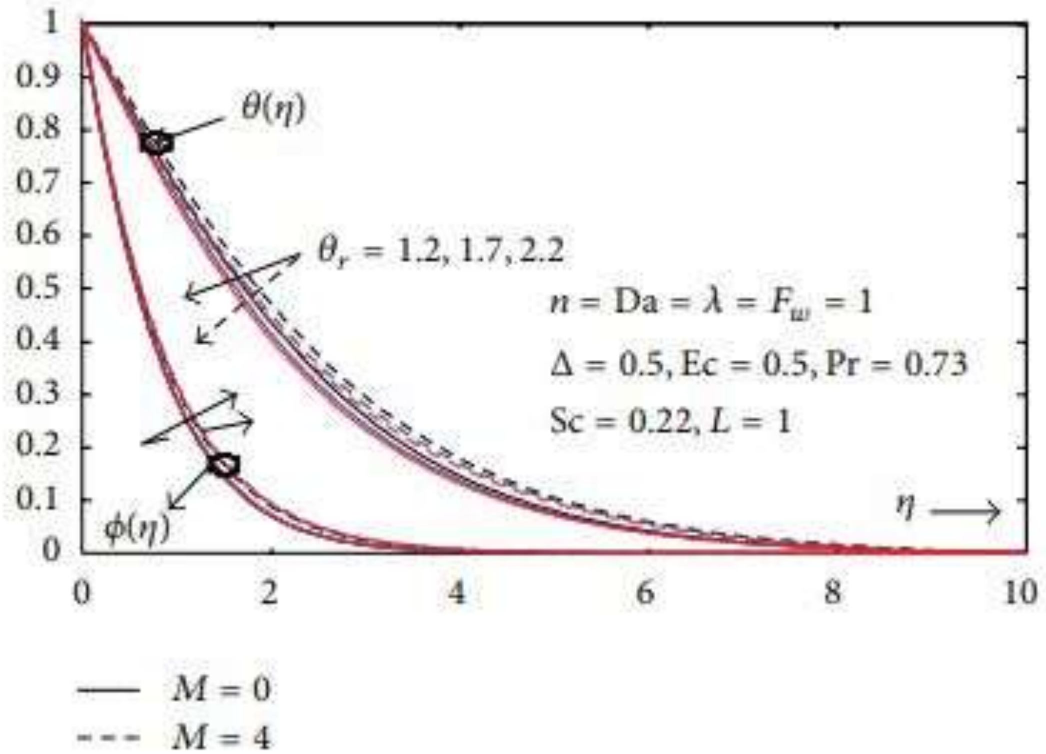

Figure 4: Temperature and profile different values of $\boldsymbol{\theta_r}$ and M.

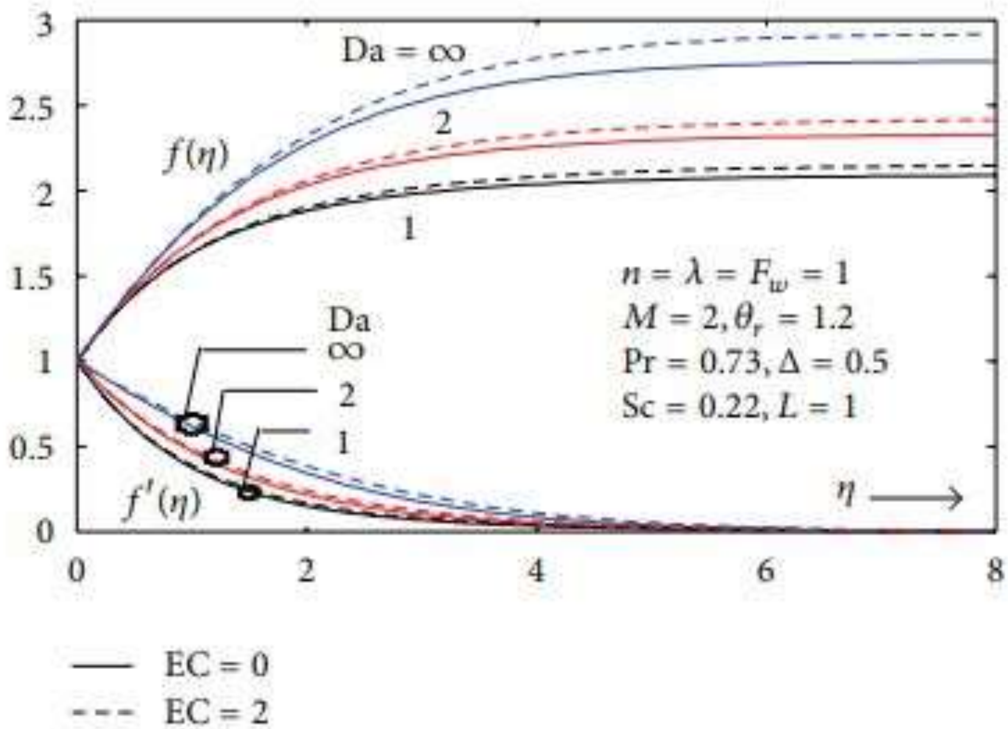

Figure 5: Velocity profile for different values of Da and Ec.

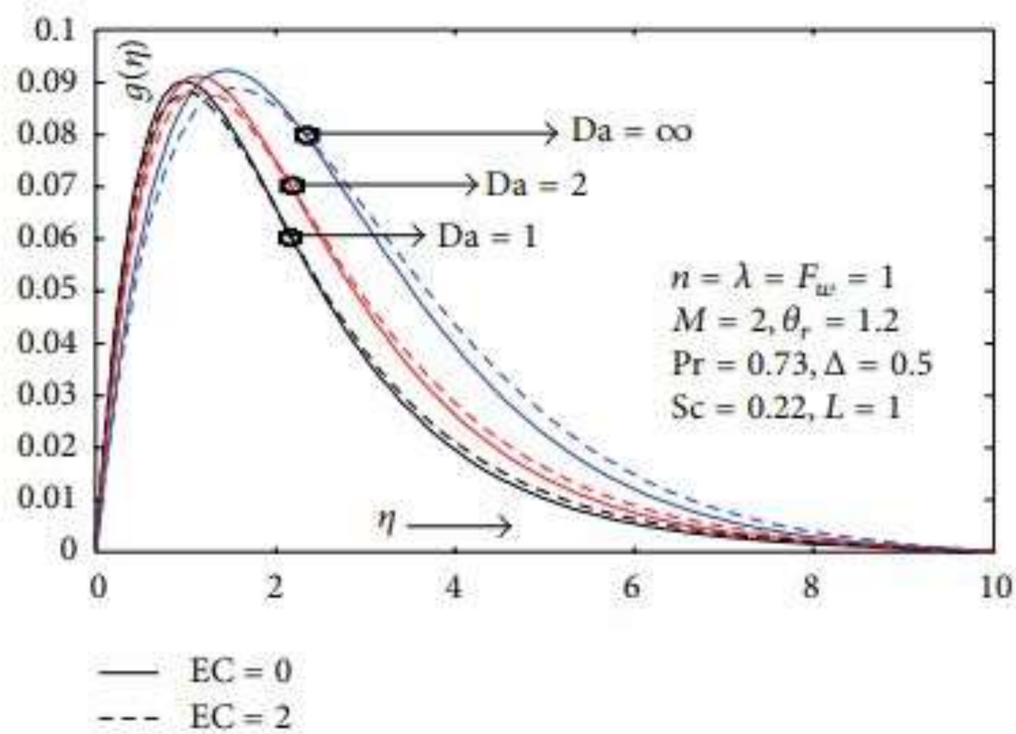

Figure 6: Angular velocity profile for different values of Da and Ec.

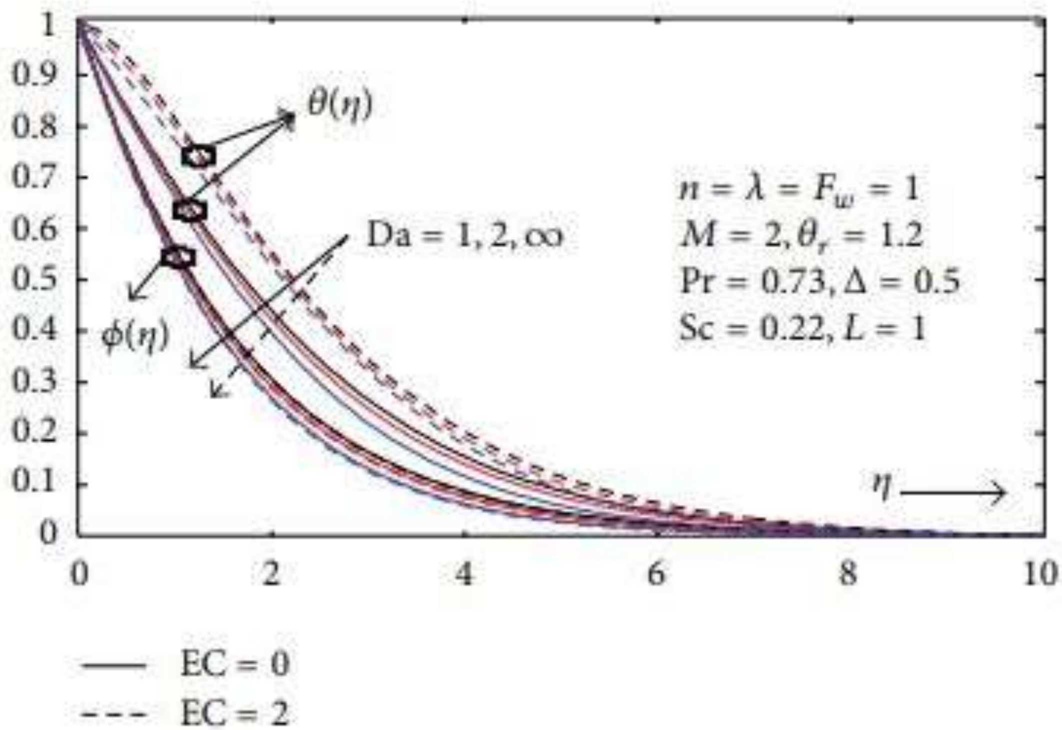

Figure 7: Temperature and concentration profile for different values of Da and Ec.

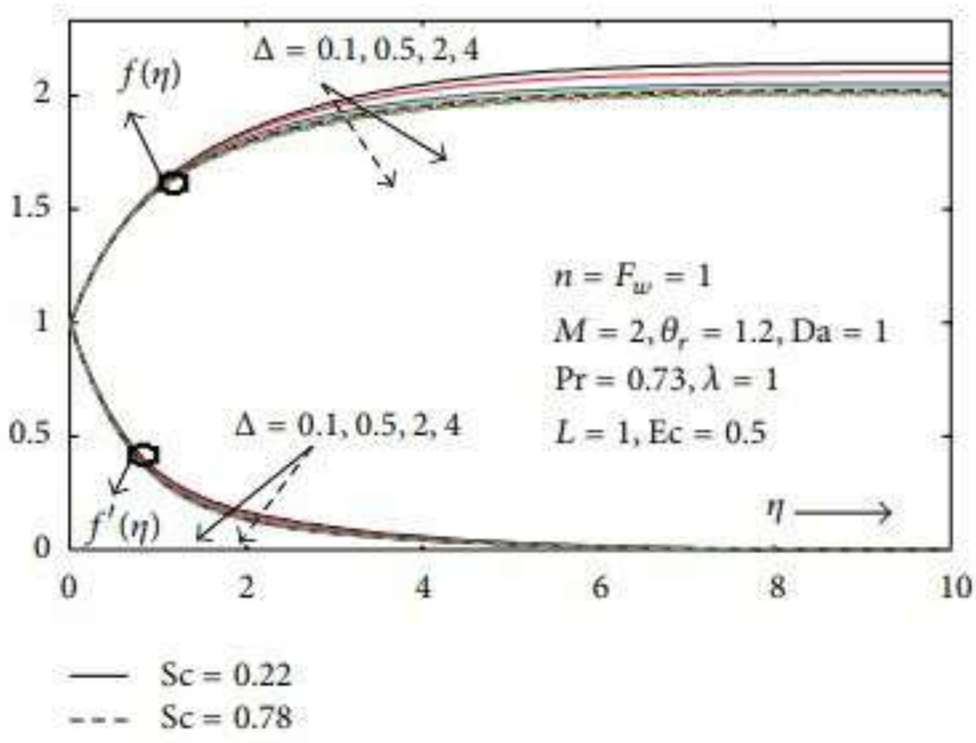

Figure 8: Velocity profile for different values of Δ and Sc.

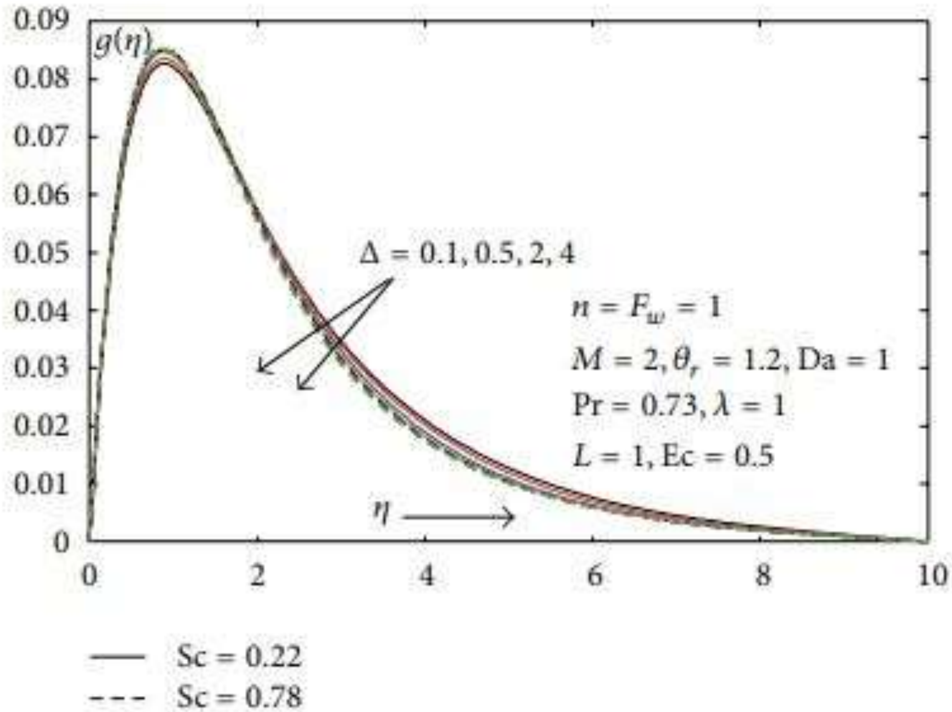

Figure 9: Angular velocity profile for different values of Δ and Sc.

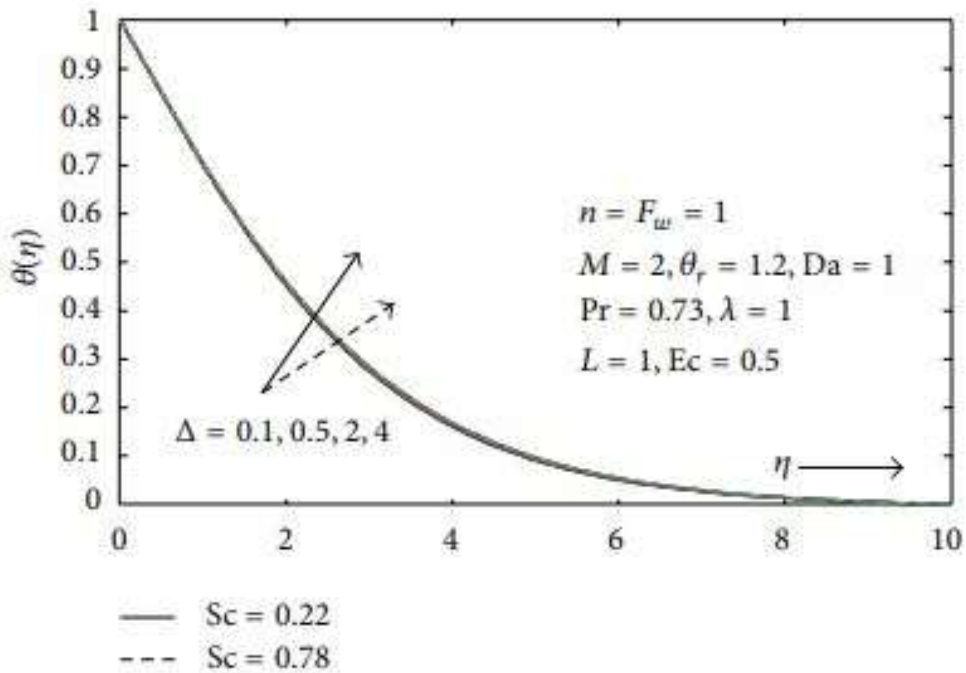

Figure 10: Temperature profile for different values of Δ and Sc.

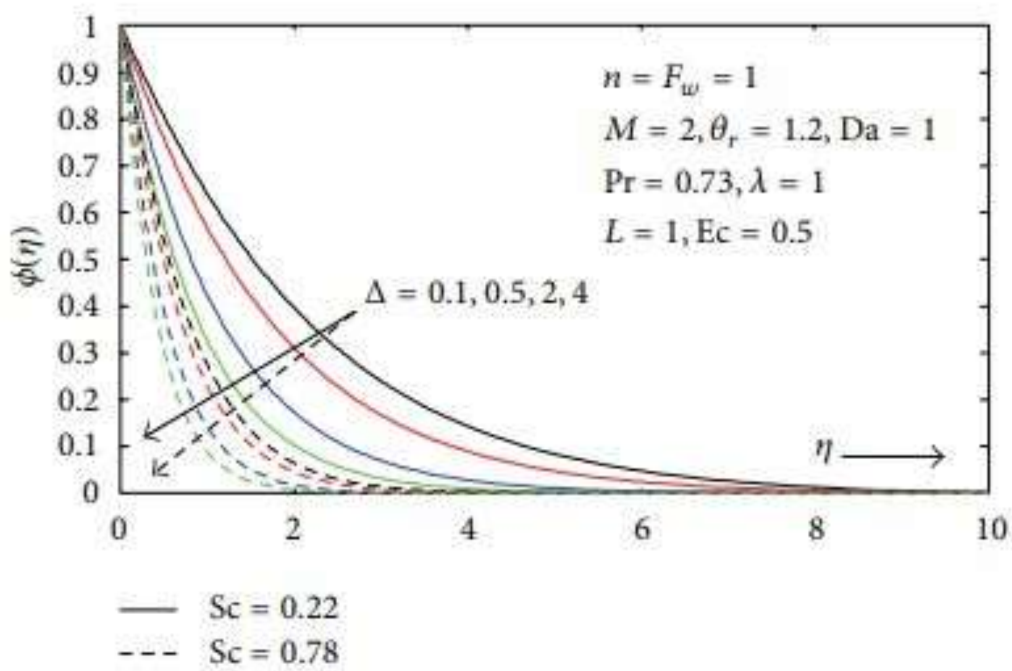

Figure 11: Concentration profile for values of Δ and Sc.

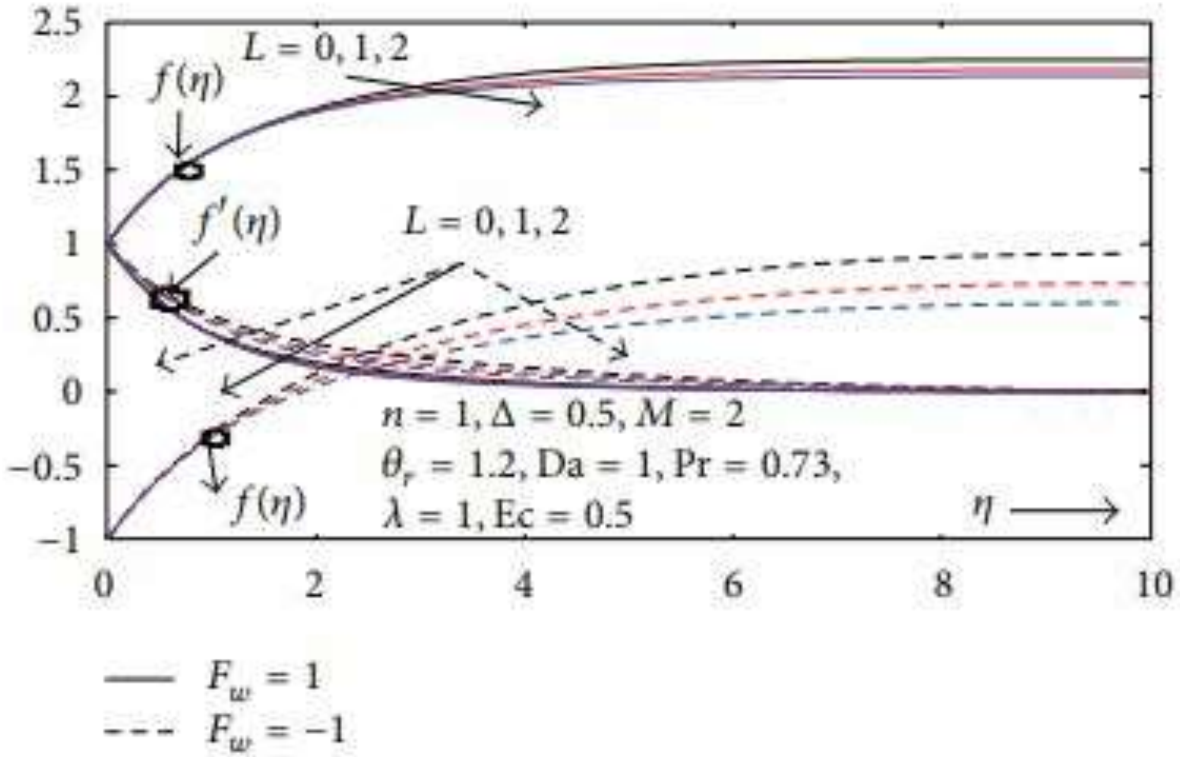

Figure 12: Velocity profile of different values of $\boldsymbol{F_w}$ and L.

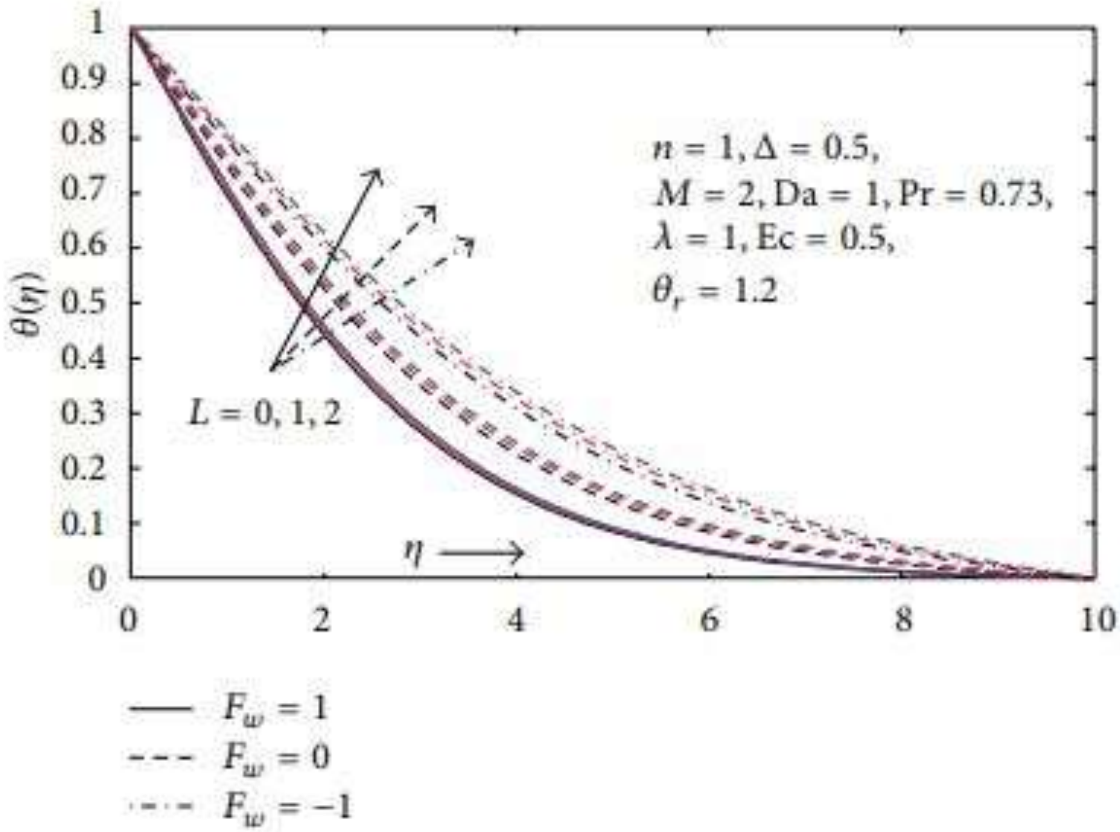

Figure 13: Temperature profile for different values $\boldsymbol{F_w}$ and L.

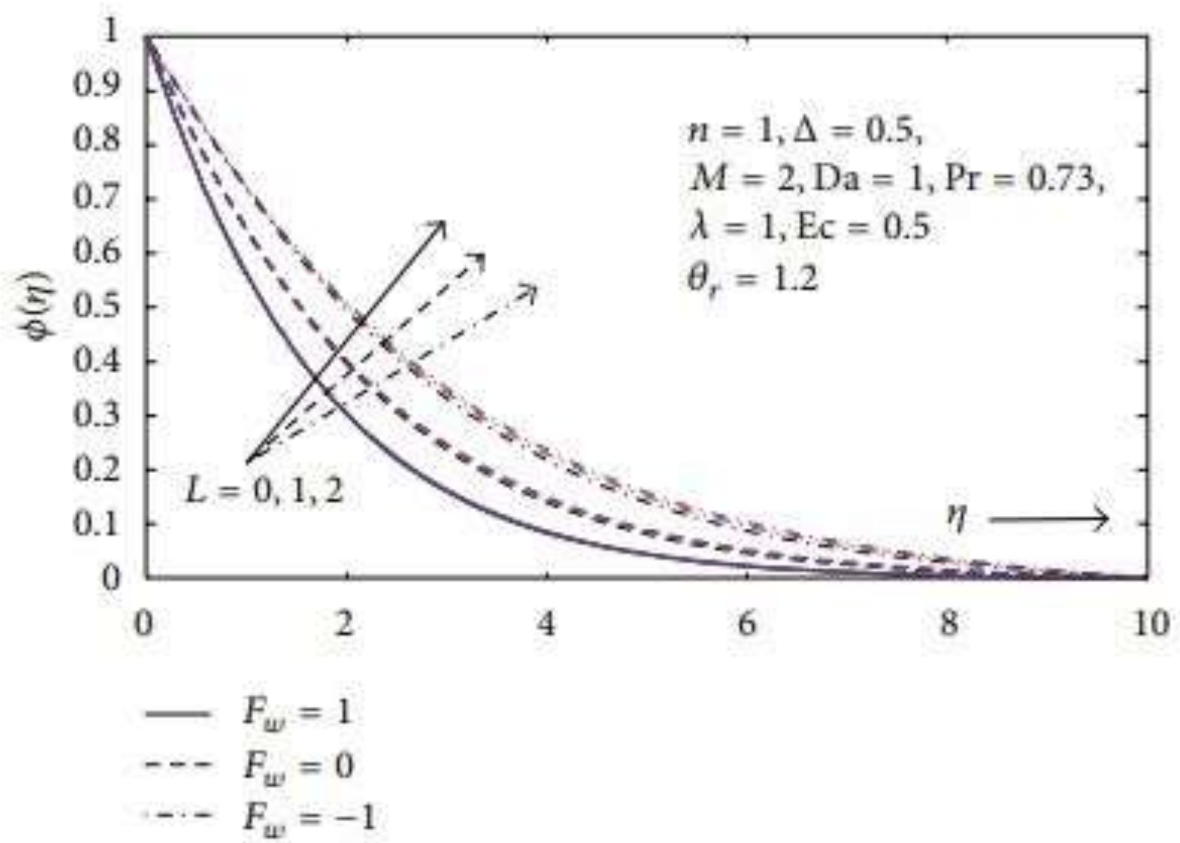

Figure 14: Concentration profile for different values of $\boldsymbol{F_w}$ and L.

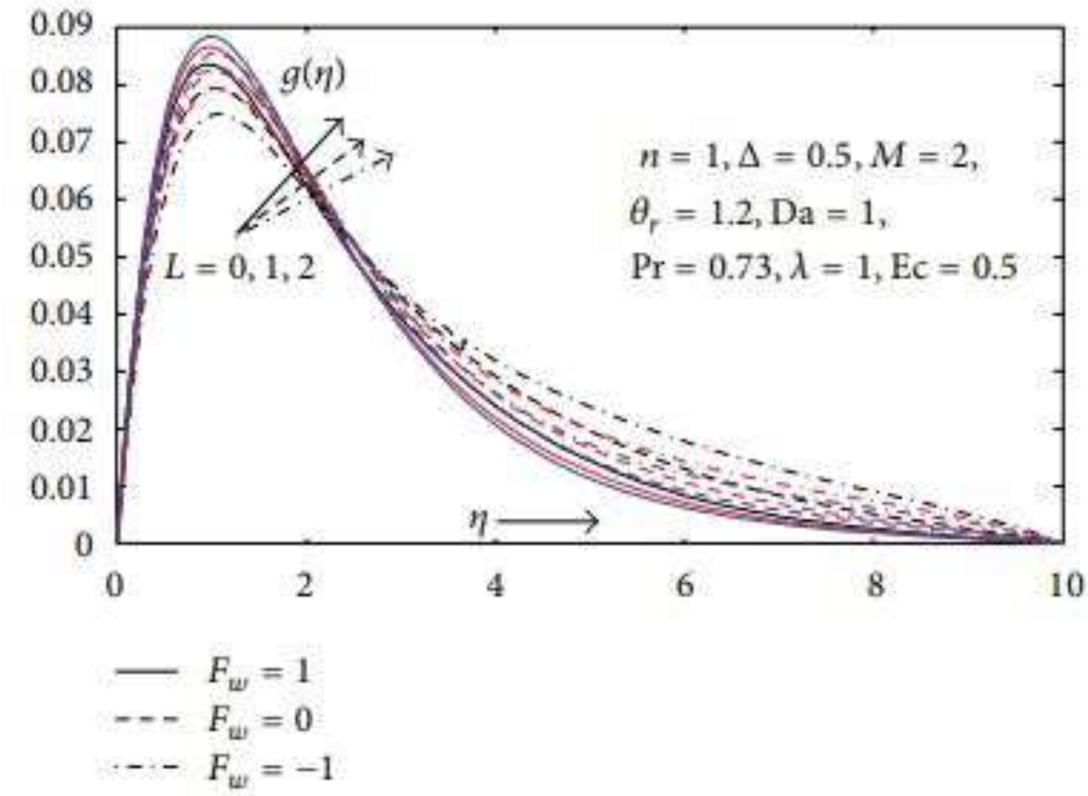

Figure 15: Angular velocity distribution for different values of $\boldsymbol{F_w}$ and L.

Print ISSN: 2055-6551(Print)

Online ISSN: 2055-656X(Online)

Website: https://www.eajournals.org/

Publication of the European Centre for Research Training and Development-UK

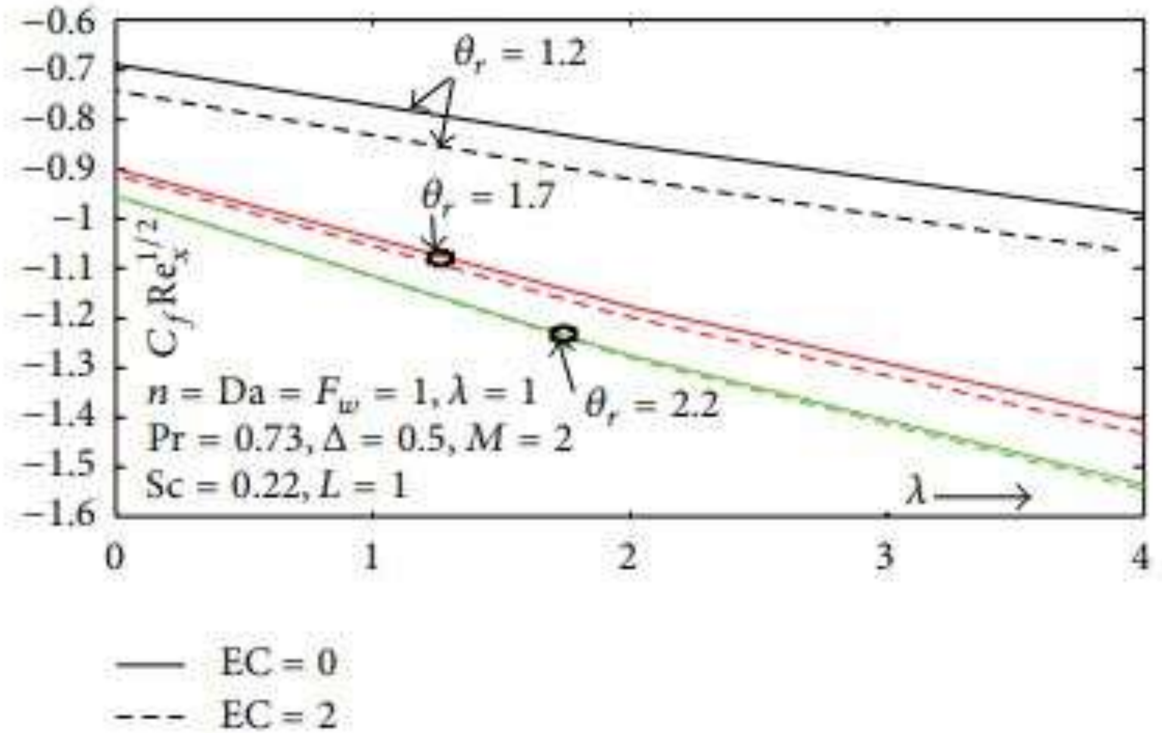

Figure 16: Local skin friction for different values of Ec and $\boldsymbol{\theta_r}$.

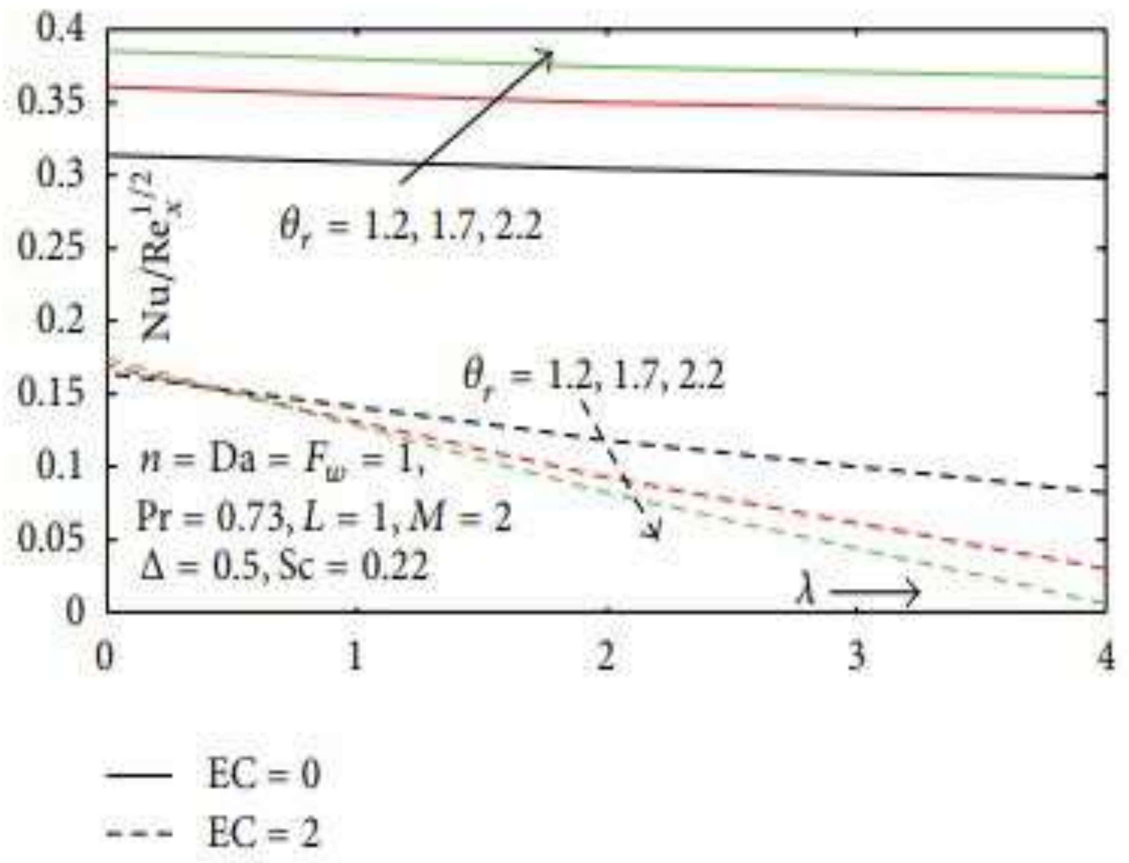

Figure 17: Local Nusselt number for different values of Ec and $\boldsymbol{\theta_r}$.

CONCLUSION

The mathematical analysis has been carried out to study the MHD boundary layer flow of a micro polar fluid with medium molecular weight along a permeable stretching surface embedded in a non-Darcian porous medium with viscous dissipation, porosity and chemical reaction. The fluid viscosity is assumed to vary as an inverse linear function of temperature. The resulting partial differential equations, which describe the problem, are transformed into ordinary differential equations by using a similarity transformation and then solved numerically by shooting method. A comparison between the analytical and the numerical solutions has been included, and the results are found to be in excellent agreement. A representative set of numerical results for velocity, temperature and concentration profiles as well as the local skin-friction coefficient, the local Nusselt number and the local Sherwood number is presented graphically and discussed. It is found that the momentum boundary thickness as well as thermal boundary layer thickness decrease with increasing in the variable viscosity parameter $\boldsymbol{\theta_r}$.

It is of interest to note that the heat transfer strongly depends on the viscous dissipation Ec. In the presence of the latter, the effect of increasing values of $\boldsymbol{\theta_r}$ is seen to increase the rate of heat transfer near surface and to decrease the same significantly away from the surface. This reduction of heat transfer away from the boundary would be more for large values of buoyancy force parameter λ.

The ability of the microelements of the fluid to rotate decreases as the variable viscosity parameter $\boldsymbol{\theta_r}$ increases, and it increases away from the plate due to the presence of viscous dissipation.

The local friction coefficient is highly affected by the viscous dissipation for small values of $\boldsymbol{\theta_r}$. However, for large $\boldsymbol{\theta_r}$, the local friction coefficient is slightly influenced by the viscous dissipation effect. Therefore, we conclude that for a micro polar fluid of hydrogen-air mixtures, the variable viscosity and viscous dissipation effects should not be neglected. Increasing the coupling parameter tends to increase the local friction coefficient but tends to decrease the heat transfer rate and slightly increase the local Sherwood number. Increasing the Schmidt number tends to increase the local Sherwood number but tends to decrease the local friction coefficient. Finally, our numerical computations also indicate that the local skin-friction and the local Sherwood number are lower for the case of Newtonian fluids ($L = 0$) as compared with the micro polar fluids ($L > 0$). Also, the rate of heat transfer for the micro polar fluid is considerably less than that for the Newtonian fluid.

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