International Journal of Mathematical Archive-9(4), 2018, 105-112
Available online through www.ijma.info ISSN 2229 – 5046

MHD FLOW AND SISKO FLUID OVER A STRETCHING CYLINDER IN THE PRESENCE OF VISCOUS DISSIPATION AND CONVECTIVE BOUNDARY CONDITION: KELLER – BOX METHOD

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(Received On: 23-02-18; Revised & Accepted On: 19-03-18)

ABSTRACT

Present statement and mathematical examination of magneto hydrodynamic Sisko fluid flow over linearly stretching cylinder along with mutual effects of temperature depending thermal conductivity, viscous dissipation, and convective boundary condition. The arising set of flow governing equations is bespoke under usual boundary layer hypothesis. A set of variable similarity transforms are employed to shift the governing partial differential equations into ordinary differential equations. The rationalization of attained extremely nonlinear simultaneous equations is computed by a well-organized technique known as Keller-Box method. Numerical computations are accomplished and attractive aspects of flow velocity and temperature are visualized via graphs for special parametric conditions. A wide-ranging discussion is presented to divulge the influence of flow parameters on wall shear stress and local Nusselt number via figures and tables. Furthermore, it is observed that magnetic field has given obvious confrontation to the fluid motion while both material parameter and curvature parameter accelerates it. The making progress values of both Eckert number and convective parameter have qualitatively same effects i.e. they raise the temperature. Additionally, material parameter and curvature parameter increase the coefficient of skin friction enormously and qualitatively similar effects are noticed for Nusselt number against variations in Prandtl number and curvature parameter. Alternatively, local Nusselt number diminishes for larger values of Eckert number and power law index. The present results are compared with existing literature via tables; they have the good covenant with previous results.

Keywords — *Sisko fluid, stretching cylinder, MHD, Viscous dissipation, Convective condition.*

I. INTRODUCTION

The boundary layer flow and heat transfer with stretching precincts conventional extraordinary concentration in modern manufacturing and engineering practice. The attributes of end invention are very much dependent on stretching and rate of heat transfer at final period of indulgence. Due to this real-world significance, attention urbanized among scientists and engineers to understand this phenomenon. Ordinary examples are the extrusion of metals into cooling liquids, food, plastic products, the reprocessing of material in the molten state under elevated temperature. During this phase of the developed process, the material passes into elongation (stretching) and a cooling process. Such type's of processes are very useful in the manufacture of plastic and metallic complete equipment, such as cutting hardware tools, electronic components in computers, rolling and annealing of copper wires. In many engineering and industrial applications, the cooling of a solid surface is a primary tool for minimizing the boundary layer. Appropriate to these helpful and realistic impacts, the problem of cooling of solid moving surfaces has turned out to be an area of apprehension for scientists and engineers. Recently researchers have shown deep attention in analyzing the individuality of flow and heat transfer over stretching surfaces. In this situation, analysis of flow and heat transfer phenomena over a stretching cylinder has its own significance in processes such as fibre and wire drawing, hot rolling. Based on these applications, the boundary

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layer flow and heat transfer due to a stretching cylinder at first studied by Wang [1]. He extended the work of Crane [2] to study the flow of heat transfer analysis of a viscous fluid due to stretching hollow cylinder. MHD is the field of science which addresses the dynamics of electrically conducting fluid. The key fact following the MHD is that the applied magnetic field induces the current; the consequences of this happening produce Lorentz force which affects fluid motion significantly. The dynamics of electrically conducting fluids is mathematically formulated with well-known Navier–Stokes equations along with Maxwell equations. Nature contains a variety of MHD fluids like plasmas, salt water, electrolysis etc. Currently, MHD is a topic of intense research due to its use in many industrial processes like magnetic materials processing, glass manufacturing, magneto hydrodynamics electrical power production. Furthermore, it has applications in astrophysics and geophysics as well, e.g. it is worn in solar structure, geothermal energy extraction, radio propagation etc. Whereas, MHD pumps and MHD flow meters are some products of engineering which utilized the magneto hydrodynamics phenomenon. So, magneto hydrodynamics is freshly practiced a period of great swelling and differentiation of subject matter. Alfven [3] discovered electro magneto hydrodynamic waves in his work. Liao [4] discussed the magneto hydrodynamics power-law fluid flow over continuously stretching sheet. The solution was computed by utilizing HAM. In this analysis, he described effects of magneto hydrodynamics on skin friction coefficient by considering variations in the power-law index. He recommended that effects of MHD are prominent for shear thinning than shear thickening fluids. Power-law fluid flow in the existence of MHD over stretching sheet was studied by Cortell [5]. In this problem, he considered the numerical solution by way of shooting method and analyzed the model for variations in power law index and Hartmann number. He fulfilled that Hartmann number is a source of decrease in both Newtonian and non-Newtonian fluids velocity. Ishak *et al.* [6] investigated the incompressible flow of Newtonian fluid over stretching cylinder under the influence of magneto hydrodynamics. The solution was considered numerically by applying Keller-Box method. They illustrated that MHD causes refuse in velocity profile while enhances the skin friction coefficient. Nadeem *et al.* [7] examined the flow of MHD Casson fluid over a porous stretching sheet in three dimensions. Numerical solution of the problem was established by applying Runge–Kutta Fehlberg numerical scheme. They proved that Hartmann number reduces both horizontal and vertical velocity profiles, but it increases skin friction coefficients. Akbar *et al.* [8] Investigated the Jeffrey fluid in small intestine under the impact of magnetic field and found an exact solution. Ellahi *et al.* [9] discussed the blood flow of two-dimensional Prandtl fluid through tapered parties.

The solution was calculated analytically and variations are established against physical parameters. Mabood *et al.* [10] deliberated the heat transfer study of boundary layer flow of nanofluid over a non-linear stretching sheet with aid of Runge – Kutta fifth order integration scheme. They deduced that the applied magnetic field enhances skin friction coefficient while decreases both Nusselt and Sherwood numbers. Rashidi *et al.* [11] analyzed the Darcy–Brinkman–Forchheimer fluid under the control of the transverse magnetic field and computed the numerical solution via finite element technique. The induced magnetic field on carbon nanotubes through a permeable channel was examined by Akbar *et al.* [12]. The resulting equations are solved exactly and interested quantities are deliberated. Malik and Salahuddin [13] examined the stagnation point flow of Williamson fluid under magneto hydrodynamics effects over stretching cylinder and calculated solution with shooting method. Kandelousi and Ellahi [14] inspected the Fe_3O_4-plasma nanofluid flow in a vessel under the combined influence of ferrohydrodynamic and magnetohydrodynamics. They computed numerical solution via Boltman technique and interpreted that magnetic field substantially affected the fluid movement. Gangadhar *et al.* [15] investigated the influence of MHD effect on micro polar nanofluid over a permeable stretching/shrinking sheet. They considered Newtonian heating boundary condition on energy equation. Mohammed Ibrahim *et al.* [16] investigated the MHD effect on oscillatory flow in a channel filled with porous medium. The effects of radiation, heat generation and viscous dissipation on MHD boundary layer flow for the Blasius and Sakiadis flows with a convective condition was investigated by Gangadhar [17]. Gangadhar [18] studied the impact of convective surface boundary condition on hydromagnetic heat and mass transfer over a vertical plate. Gangadhar and Baskar Reddy [19] investigated the MHD flow of heat and mass transfer over a moving vertical plate. The effect of MHD on a micropolar fluid over a stretching permeable sheet with radiation and thermal slip effects was studied by Gangadhar *et al.* [20]. Gangadhar *et al.* [21] investigated the viscous dissipation and MHD effects on a micropolar fluid with slip effects. The flow of non-Newtonian fluids is one of the large amount influential issues in little current years since they have a wide variety of applications in many fields of daily life such as food engineering, chemical engineering, power engineering and petroleum production. Also, the recent advancement in industry and improved engineering expertise motivated researchers to explore non-Newtonian fluids characteristics in a more systematic way. As non-Newtonian fluids have a lot of varieties in nature, so many constitutive equations were proposed to scrutinize physical properties of these fluids. Most of the non-Newtonian fluids such as lubricating greases, waterborne coatings, multiphase mixers etc. which encountered in chemical engineering obey the Sisko fluid model. This model was obtainable by Sisko [22] he studied the properties of lubricating greases. Nadeem *et al.* [23] also designed hypothetical model of peristaltic motion in the endoscope by using constitutive equations of Sisko fluid model. They computed both analytical and numerical solutions and analyzed the pressure gradient and peristaltic motion of Sisko fluid. In addition, they obtainable comparison between Sisko and Newtonian fluid and found that Newtonian fluid shaves best peristaltic transference. Khan and Shehzad [24] explored the physical features of Sisko fluid flow over the linearly stretching sheet in a radial direction. The analytic solution was calculated by homotopy analysis method. The interesting quantities were discussed by varying power law index. And showed that fluid parameter accelerates the non-Newtonian fluid motion as well as wall shear stress. Also, the contrast of Sisko fluid with both viscous and power-law fluids was presented. The results show that friction of wall is greater for Sisko fluid as compared to both viscous and power-law fluids. Khan and Shehzad [25] also examined Sisko fluid flow over a stretching sheet. In this investigation, velocity profile was described under the influences of power-law index and Sisko parameter. They remarked that the power law index diminishes velocity profiles for non-Newtonian fluids. Recently, Malik *et al.* [26] discussed effects of a transverse magnetic field on Sisko fluid over stretching cylinder. Shooting technique was implemented to solve governing equations.

In spite of all the aforementioned studies, the boundary layer flow of MHD Sisko fluid with viscous dissipation and convective boundary condition has paid less attention. Motivated from above literature and also due to various potential applications of the problem in engineering and industry, authors formulated the mathematical model for boundary layer flow of Sisko fluid in presence of magnetic field and heat transfer problem with the effects of both convective boundary condition and viscous dissipation. The modeled set of partial differential equations is modified to coupled ordinary differential equations via similarity variables. For the numerical solution of similarity equations, Keller – Box method is employed and the problem is analyzed physically by varying governing flow parameters.

II. MATHEMATICAL FORMULATION

Let us assume that two-dimensional axi-symmetric, study state flow of incompressible Sisko fluid along the continuously stretching cylinder. The flow is induced due to stretching of a cylinder along the axial direction which stretching velocity *U(x) = cx*, where *c*>0. The magnetic field of strength B_0 is applied on fluid along the radial direction. The schematic diagram of the present problem is shown in figure 1. The problem of heat transfer consists the effect of viscous dissipation. Additionally, thermal conductivity is considered variable in this investigation.

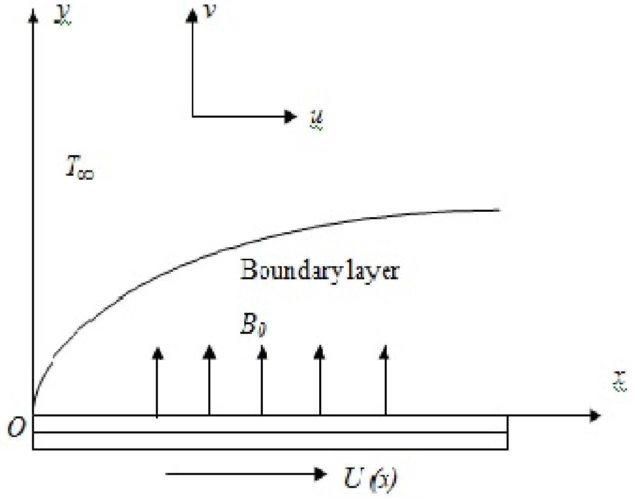

Figure-1: Geometry of the problem

After implying boundary layer approximations on governing equations, these equations are modified to

$$\frac{\partial (ru)}{\partial x}+\frac{\partial (rv)}{\partial r}=0 \tag{1}$$

$$u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial r}=\frac{a}{r\rho}\frac{\partial}{\partial r}\left(r\frac{\partial u}{\partial r}\right)-\frac{b}{r\rho}\left(-\frac{\partial u}{\partial r}\right)^{n}+\frac{nb}{\rho}\left(-\frac{\partial u}{\partial r}\right)^{n-1}\frac{\partial^2 u}{\partial r^2}-\frac{\sigma B_0^2}{\rho}u \tag{2}$$

$$u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial r}=\frac{1}{r}\frac{\partial}{\partial r}\left(\alpha r\frac{\partial T}{\partial r}\right)+\frac{a}{\rho c_\rho}\left(-\frac{\partial u}{\partial r}\right)^{2}+\frac{b}{\rho c_p}\left(-\frac{\partial u}{\partial r}\right)^{n-1} \tag{3}$$

Along with pre-subscribed boundary conditions

$$u=U(x)=cx,\ \ v=0 \text{ At r = } r_0 \text{ and } u\to 0 \text{ at } r\to\infty, \tag{4}$$

$$k\frac{\partial T}{\partial r}=-h_s\left(T-T_\infty\right) \text{ At } r=a \text{ and } T\to T_\infty \text{ as } r\to\infty \tag{5}$$

In the above set of equations, the components of fluid velocity along x and r directions are denoted with u and v. The material constants are n (power law index), a (high shear rate viscosity) and b (consistency index). The density of fluid particles is denoted with ρ and σ called the electrical conductivity of the fluid. In equation (3), T is the temperature of the flow, T_w represents the temperature of the fluid at a wall, T_∞ is ambient temperature, c_p is the specific heat and α shows the thermal diffusivity.

The stream function ψ of flow velocity is defined as

$$u=\frac{1}{r}\frac{\partial\psi}{\partial r},\; v=-\frac{1}{r}\frac{\partial\psi}{\partial x}. \tag{6}$$

The suitable similarity transformations are defined as

$$\eta=\frac{r^2-r_0^2}{2xr_0}\mathrm{Re}_b^{\frac{1}{n+1}},\;\psi=Xr_0U\,\mathrm{Re}_b^{\frac{-1}{n+1}}\;f(\eta),\theta(\eta)=\frac{T-T_\infty}{T_w-T_\infty},\;\alpha=\alpha_\infty(1+\varepsilon\theta), \tag{7}$$

where ε is the thermal conductivity parameter, α_∞ is the extreme thermal diffusivity, Re_b denotes the Reynolds number which is defined as

$$\mathrm{Re}_b=\frac{\rho x^n U^{2-n}}{b}.$$

After employing aforementioned similarity transformations in the governing partial differential equation (1)-(3), the continuity equation is satisfied identically, while the other two governing equations are converted into the following ordinary differential equations

$$A(1+2\gamma\eta)f'''+n(1+2\gamma\eta)^{\frac{n+1}{2}}(-f'')^{n-1}f'''-(n+1)\gamma(1+2\gamma\eta)^{\frac{n-1}{2}}(-f'')^{n} \\ -f'^2+\frac{2n}{n+1}ff''+2A\gamma f''-Mf'=0, \tag{8}$$

$$(1+2\gamma\eta)(\theta''+\varepsilon(\theta\theta''+\theta'^2))+2\gamma(1+\varepsilon\theta)\theta'+\frac{2n}{n+1}\Pr f\theta'+ \\ A(1+2\gamma\eta)Ec\Pr(-f'')^2+Ec\Pr(1+2\gamma\eta)^{\frac{n+1}{2}}(-f'')^{n+1}=0, \tag{9}$$

Boundary conditions of the problem reduce to

$$f(0)=0,\; f'(0)=1,\; \theta'(0)=-Bi(1-\theta(0)),\; f'(\infty)=0,\; \theta(\infty)=0. \tag{10}$$

Curvature parameter γ, Magnetic field parameter M, Eckert number Ec, material parameter A, Prandtl number Pr and local Biot number *Bi* are defined as

$$\left.\begin{aligned}&\gamma=\frac{x}{r_0}\mathrm{Re}_b^{\frac{-1}{n+1}},\; M=\frac{\sigma xB_0^2}{\rho U},\; \mathrm{Re}_a=\frac{\rho Ux}{a},\; A=\frac{\mathrm{Re}_b^{\frac{2}{n+1}}}{\mathrm{Re}_a}\\ &Ec=\frac{U^2}{C_p(T_w-T_\infty)},\; \Pr=\frac{xU}{\alpha}\mathrm{Re}_b^{\frac{-2}{1+n}},Bi=\frac{h_s}{k}\mathrm{Re}_b^{-1/n+1}\end{aligned}\right\} \tag{11}$$

The physical objects which are practically important i.e. skin friction coefficient and local Nusselt number of flow field distribution are defined in the following equation.

$$C_f=\frac{\tau_w}{\frac{1}{2}\rho U^2}\quad and\quad Nu_x=\frac{xq_w}{k(T_W-T_\infty)} \tag{12}$$

In above formulas, skin friction coefficient is expressed with C_f while Nu_x shows Nusselt number. Here τ_w is known as wall shear stress, on the other hand q_w , denotes wall heat fluxes which are defined below.

$$\tau_w=a\left(\frac{\partial u}{\partial r}\right)_{r=r_0}-b\left(-\frac{\partial u}{\partial r}\right)^n_{r=r_0}\quad and\quad q_w=-k\left(\frac{\partial T}{\partial r}\right)_{r=r_0} \tag{13}$$

By inserting similarity transformations in equations (6) and (7), the interesting physical quantities i.e coefficient of skin friction and Nusselt number are converted to

$$\frac{1}{2}C_f\,\mathrm{Re}_b^{\frac{1}{n+1}}=Af''(0)-\left[-f''(0)\right]^n\quad and\quad Nu_x\,\mathrm{Re}_b^{\frac{-1}{n+1}}=-\theta'(0) \tag{14}$$

III. SOLUTION OF THE PROBLEM

"As Equations (8)-(9) are nonlinear, it is not possible to obtain the closed form solutions. As a result, the equations through the boundary conditions (10) are solved numerically by means of a finite-difference scheme recognized as the Keller-box method. The major steps in the Keller-box method to obtain the numerical solutions are the following:

i). Decrease the specified ODEs to a system of first-order equations.
ii). write down the condensed ODEs to finite differences.
iii). Linear zed the algebraic equations by using Newton's method and write down them in vector form.
iv). Solve the linear system through the block tridiagonal elimination technique.

One of the factors so as to be affecting the correctness of the method is the suitability of the preliminary guesses. The accurateness of the method depends on the alternative of the preliminary guesses. The choices of the primary guesses depend on the convergence criteria and the boundary conditions (10) & (11). The subsequent primary guesses are chosen

$$f_0(\eta) = 1 - e^{-\eta}, \;\; p_0(\eta) = e^{-\eta}, g_0(\eta) = \frac{Bi}{Bi+1} e^{-\eta}$$

In this study, a consistent grid of size $\Delta\eta = 0.006$ is found to convince the convergence and the solutions are obtained through an error of tolerance 10^{-5} in all cases. In our study, this gives regarding six decimal places perfect to the majority of the agreed quantities.

IV. RESULTS AND DISCUSSION

The present paper investigates the non-Newtonian Sisko fluid flow over a stretching cylinder is examined under the impact of magnetic fluid in addition viscous dissipation, thermal conductivity and convective heating also considered. Table 1 shows that present results have an excellent agreement with previous results.

Table-1: Comparison of $-\theta'(0)$ by varying *Pr* and considering $\gamma = Ec = M = 0, n = 1, Bi \to \infty$.

Pr	Ali et al. [27]	Hussain et al. [28]	Present results
0.71	------	0.8686	0.8686
1	1.0001	1.0067	1.0068
3	1.9230	1.9260	1.9260
10	3.72028	3.7267	3.7267

Also, for visualizing computed results more clearly, the variations are displayed against single parameters in each figure (while others keeping fixed). Figure 1 shows the behavior of magnetic field parameter on velocity profile. It is observed that the transverse magnetic field reduces the fluid velocity throughout the boundary layer. Because the consequence of electrically conducting fluid dynamics produced Lorentz force. This resisting nature of this force opposes the fluid motion and hence slows down the velocity field. Figure 2 shows the effect of magnetic parameter M on temperature field Θ (η). It is noticed that temperature profiles increases with an increases the values of M.

Figure 3 depicts the nature of curvature parameter γ on velocity profile $f'(\eta)$. As curvature have opponent relation with a radius of the cylinder. So the consequences of increment in curvature led to shrinking the radius and surface area. Hence, fluid motion experiences less resistance which consequently escalates fluid velocity. Figure 4, demonstrates the impact of curvature parameter γ on temperature profile θ (η). Since the curvature parameter γ enlarges fluid viscosity and kinematic energy as a result temperature increases because it is well-known fact that temperature is the average kinematic energy.

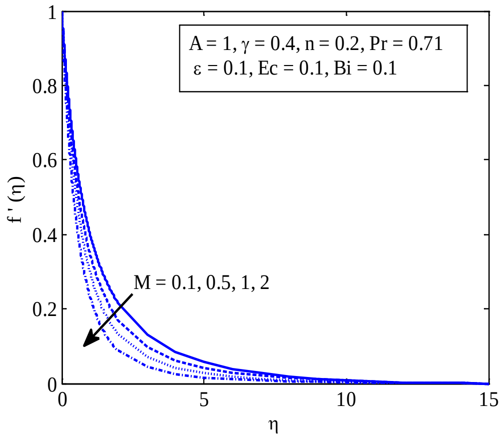

Fig. -1: Dimensionless velocity distribution for different Values of *M*.

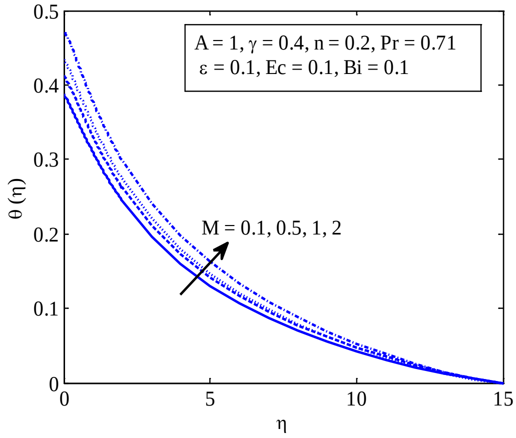

Fig.-2: Dimensionless temperature distribution for different values of *M*

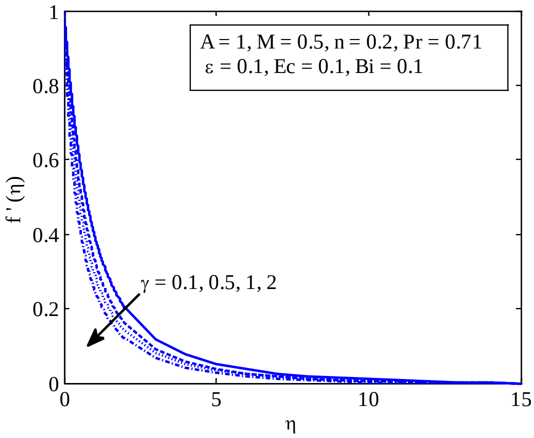

Fig.-3: Dimensionless velocity distribution for different values of γ.

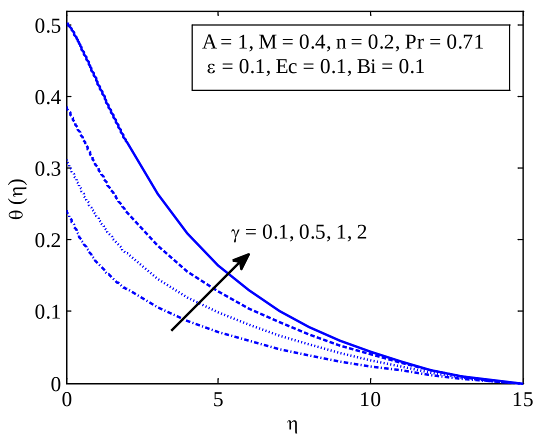

Fig.-4: Dimensionless temperature distribution for different values of γ.

Figure 5 shows the behavior of the fluid parameter *A* on velocity profile $f'(\eta)$. The fluid velocity $f'(\eta)$ enhances for large values of material parameter A, it holds physically because when A has large values viscous force diminishes, so it offers less resistance to fluid motion. Additionally, it increases the boundary layer thickness. Figure 6 display the behavior of material parameter A on temperature profile $\theta(\eta)$. It is clear that fluid temperature increases with an increase in A. Figure 7 reflect the influence of Eckert number Ec on temperature profile $\theta(\eta)$. Since enhancement in Eckert number (Ec) rapids the advective transportation i.e. kinematic energy. As a result fluid particles collide more frequently with each other, the consequences of these collisions transformed kinematic energy into thermal energy. And hence it increases temperature profile $\theta(\eta)$ which can be observed from the figure. Figure 8 depicts the behavior of local Biot number Bi on temperature profiles $\theta(\eta)$. It is observed that temperature distribution increases with an increase in Bi.

Figure 9 and 10 shows the behavior of curvature parameter γ and fluid parameter A on skin friction coefficient and Nusselt number respectively both the local skin friction coefficient and local Nusselt numbers decreases with an increase in A whereas it increases with an increase in γ.

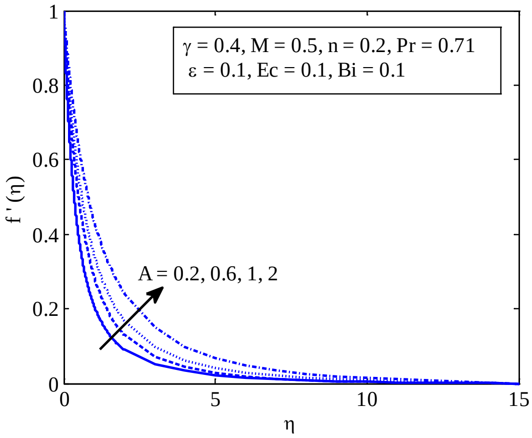

Fig.-5: Dimensionless velocity distribution for different values of *A*.

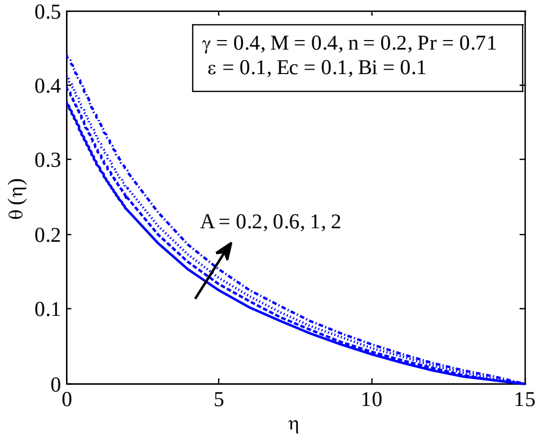

Fig.-6: Dimensionless temperature distribution for different values of *A*.

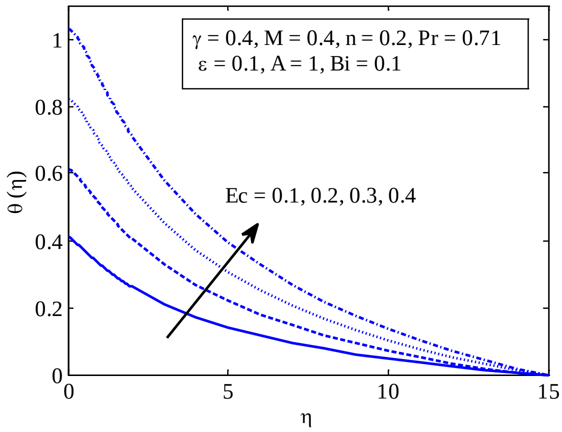

Fig.-7: Dimensionless temperature distribution for different values of *Ec*.

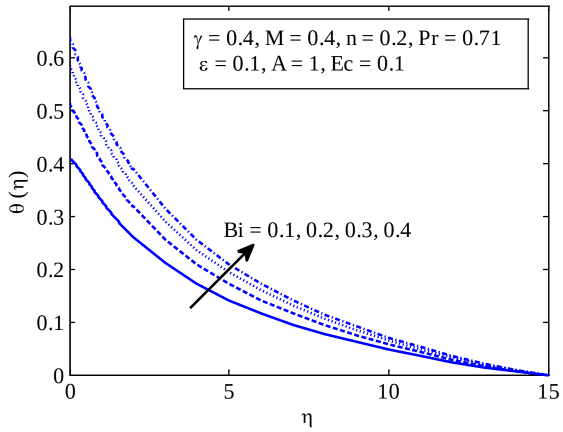

Fig.-8: Dimensionless temperature distribution for different values of *Bi*

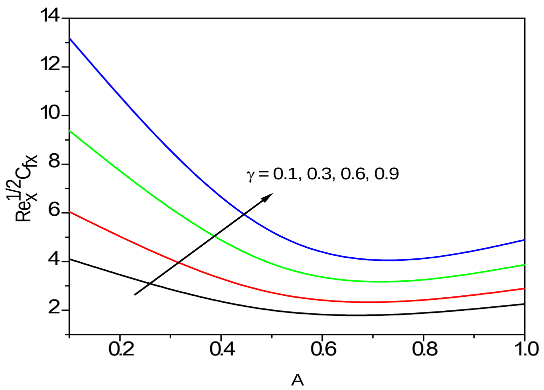

Fig.- 9: Local skin friction coefficient for different values of γ & A.

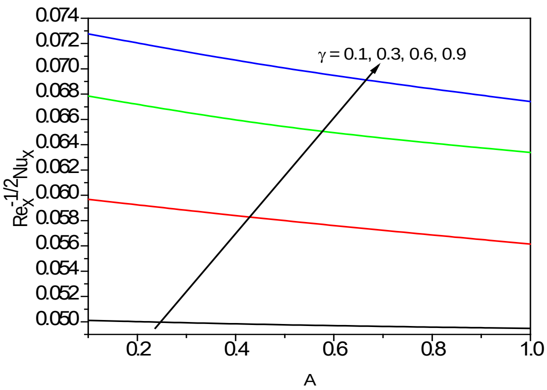

Fig.-10: Local Nusselt number for different Values of γ & A.

V. CONCLUSIONS

In the current investigation, the numerical investigation for simulations of MHD flow of a Sisco fluid past a stretching cylinder with viscous dissipation and convective boundary condition. The modeled non-linear coupled partial differential equations are transformed into ordinary differential equations by employing the self-similar set of transformations, which then solved by the keller-box method. The main findings of current observations are:

1) An increment in fluid parameter A and curvature parameter γ leads to increases fluid velocity while the consequences of the magnetic parameter M on fluid motion are opponent.
2) The effects of all pertinent parameters i.e. M, A, γ, Ec and Bi are increases the fluid temperature.
3) Both skin friction coefficient and local Nusselt numbers are increasing functions of curvature parameter γ.

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Source of support: Nil, Conflict of interest: None Declared.