ENTROPY GENERATION ANALYSIS OF MAGNETIZED MICROPOLAR FLUID STREAMING ABOVE AN EXPONENTIALLY EXTENDING PLANE

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Abstract**––An effort has been made to study the irreversibilies caused by magnetized micropolar fluid streaming above an extending surface. In the meantime, important physical characteristics in the form of magnetic field, vortex viscosity, thermal transmission and mass diffusion are implemented. The MATLAB routine bvp4c solver scheme are employed to solve the boundary value problem (ODEs). The entropy generation rates and the other flow behaviors like velocity, temperature etc are shown pictorially through some figures and irreversibilities are shown in tabular form. The major founding of this investigation is that the material parameter (responsible for micropolar fluid) enhances the motion of the fluid and reduces the entropy generation of the fluid. Also, the irreversibility ratios of this study are enhanced with the material parameter. This fluid model has multifarious physical applications in engineering sciences and industrial processes such as polymer extrusion, annealing and thickening of Copper wire etc.**

Keywords**––Micropolar fluid, Heat transfer, Mass transfer, Exponentially stretching/shrinking sheet, Entropy generation.**

I. INTRODUCTION

In the modern time, researchers have been dealing with non-Newtonian fluids than the Newtonian fluid due to their various applications in different industries and medical sciences. Non-Newtonian fluids have important characteristics such as it does not satisfy the Newton law of viscosity and specific constitutive equations. Micropolar fluid model is a special kind of non-Newtonian fluid that have multifarious applications in different physical fields. The micropolar fluid display microrotational properties and can bear couple stresses and body couples only. Crystal liquid, lubricating oil and naturally arising fluids such as animal blood etc are some important examples of micropolar fluid. Theory of micropolar fluid flow is applied in micro-devices, defectoscopy (diagnostic method for identification of defects), living organism, etc. Eringen (1966) was the first author who has brought in micropolar fluid into different important applications in engineering and industrial processes. This micropolar fluid display micro rotational properties and can bear couple stresses and body couples only. Crystal liquid, lubricating oil and naturally arising fluids such as animal blood etc. are some important examples of micropolar fluid. Based on the physical applications of micropolar fluid flow caused due to different geometries, the researchers Turkyilmazoglu (2016), Koriko and Animasaun (2017), Chandra and Pandey (2018) and Lund *et al.* (2020a, 2020b) have studied the flow behaviours along with the effects of heat and mass transfers of micropolar fluid flow by adopting different techniques. Again, magnetized flow of fluid over different geometries is captured numerous important applications in different fields e.g., applied sciences, industrial processes, engineering sciences and so on. After introduced the model of flow of fluid due to shrinking /stretching geometry by Crane (1970), many researchers have been contributing their ideas to these field. During the last five years, the fluid flow together with thermal and mass transmissions caused due to this present geometry has achieved a great success because of its large number of applications in engineering and industrial processes. Some of these applications are polymer extrusions, drawing of copper wires, artificial fibres, glass fibres, etc. Recently, the researchers Hayat *et al*. (2016), Salah and Elhafian (2019), Turkyilmazoglu (2016) and Dey and Borah (2020) have investigated the non-Newtonian fluid flow by taking shrinking/stretching surfaces. Also, the recent applications of MHD boundary layer flow in different fields with this geometry are investigated by numerous researchers such as Dey (2017), Dey (2016) and Lund *et al*. (2020). The applications in science and engineering the MHD fluid flow over a stretching surface have attracted many researchers. Stretching sheets have been widely used in the process of the boundary layers through liquid firm, concentration process, aerodynamics extractions of plastic sheets etc. Turkyilmazoglu (2012, 2015) have discussed the exact multiple solutions for the slip flow over a stretching surface.

The estimation of entropy generation and irreversibilties are very essential than the first one because it condenses the misuse of energy and the effectiveness of thermally stratified system. However, from the several decades, the analysis of second law and its applications have attracted many researchers since it has various useful applications in engineering sciences. Analysis of entropy generation gives idea about the irreversibilities and the energy losses in the system. The optimal performance of a thermodynamic system can be achieved by minimizing the entropy generation. This topic has great importance in many engineering fields such as MHD power generators, heat exchanger, geophysical fluid dynamics energy system, cooling of electronics devices etc. There is always a reduction in the amount of available energy. By minimizing this entropy generation or wastage production in a thermal system, optimal performance can be enhanced which will lead to increase the efficiency of the system. Entropy generation analysis was introduced by Bejan (1982). Srinivasacharya and Bindu (2016), Komurgoz *et al.* (2010) and Abdelhameed (2021) have carried out the details of entropy generation through an inclined channel, concentric cylinder annulus and accelerated plate. Nazim Tufali and Ali (2015), Rashidi and Abbas (2017), Dey and Hazarika (2020), Vyas *et al.* (2020) and Fatunmbi and Adiniyan (2020) have investigated the generation of entropy of this present fluid model through stretching sheet and drawn the importance of their works in different physical areas.

The main intention of this work is to carry out the entropy production rate and irreversibilities arise in the magnetized micro-polar fluid stream over an extending surface.In the literature, enough evidence is found of the influences of various flow parameters on Bejan number (thermal diffusion irreversibility ratio) but in our work, we have made an attempt to study the irreversibility ratios due to microrotation (Be_1) and momentum diffusion (Be_2), combined effect of heat and mass transfer (Be_3) along with Bejan number. Subsequent to conversion of the basic equations into the solvable systems using similarity variables, the MATLAB routine bvp4c solver technique is executed to solve the problems. Entropy analysis and nature of flow characteristics are discussed graphically with their novel values of flow parameters. To validate our results, a comparison has been made with the pioneer work of Kumar (2015).

II. FORMULATION OF THE PROBLEM

The 2D, time independent, incompressible flow of micropolar fluid with the influence of both thermal and mass diffusions is considered. The flow is induced by an exponentially stretching sheet. An exponential form of variable magnetic field $\vec{B} = (0, B_y, 0) = B_0 e^{x/L}$ is concerned along the opposite of tangential direction of the flow. The flow diagram and coordinate system of this problem is exposed by Fig. (1). The surface velocity is considered as $U_w(x) = be^{e^{x/L}}$ where b is the constant such that its positive value recognizes stretch at the surface of the sheet and its negative value represent shrinking sheet. The variable wall temperature and concentration are taken as $T_w(x) - T_\infty = T_0 e^{x/(2L)}$ and $C_w(x) - C_\infty = C_0 e^{x/(2L)}$, respectively.

Conversions of physical laws into their mathematical forms are (Kumar, 2015)

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

$$u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} = \left(\frac{\mu+k}{\rho}\right)\frac{\partial^2 u}{\partial y^2} + \frac{k}{\rho}\frac{\partial N}{\partial y} - \frac{\sigma}{\rho}B_y^2 u \tag{2}$$

$$u\frac{\partial N}{\partial x} + v\frac{\partial N}{\partial y} = \frac{\gamma}{\rho j}\frac{\partial^2 N}{\partial y^2} - \frac{k}{\rho j}\left(2N + \frac{\partial u}{\partial y}\right) \tag{3}$$

$$u\frac{\partial T}{\partial x} + v\frac{\partial T}{\partial y} = \frac{k_T}{\rho C_p}\frac{\partial^2 T}{\partial y^2} \tag{4}$$

$$u\frac{\partial C}{\partial x} + v\frac{\partial C}{\partial y} = D_m\frac{\partial^2 C}{\partial y^2} \tag{5}$$

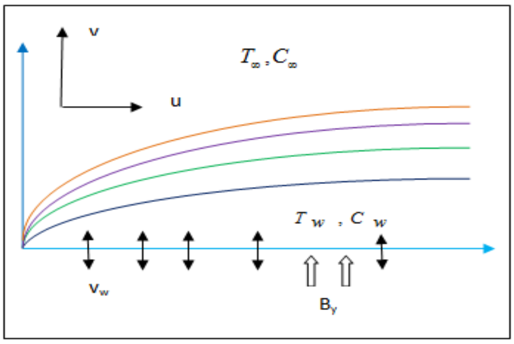

Figure 1. Stream configuration.

Restrictions imposed on the boundary are:

$$y = 0: \;\; u = ce^{\frac{x}{L}}, v = v_w, N = -n\frac{\partial u}{\partial y}, T = T_w, C = C_w$$

$$y \to \infty: \;\; u \to 0, N \to 0, T \to 0, C \to 0 \tag{6}$$

where, $0 \leq n \leq 1$is the constant such that the case $n = 0$ corresponds to no-slip boundary condition, following Ahmadi (1976), $n = 0.5$ leads to zero anti-symmetricity of stress and turbulent boundary layer formulated in the case of $n = 1$. Following Ahmadi (1976) and Ishak *et al.* (2008), we have introduced a relationship among spin gradient γ, vortex viscosity k, dynamic viscosity μ and spin inertia density j as $\gamma = \left(\mu + \frac{k}{2}\right)j = \mu\left(1 + \frac{K}{2}\right)j$, $K = \frac{k}{\mu}$, is the material parameter such that its non -zero values represent non-Newtonian (micropolar) fluid and the case $K = 0$ characterizes Newtonian fluid.

The following dimensionless similarity variables are used to alter the above system (Eqs. 1-5) into a new system:

$$\psi = \sqrt{2\nu Lb}\, f(\eta)e^{\frac{x}{2L}}, \eta = \left(\frac{b}{2\nu L}\right)^{1/2} y\, e^{\frac{x}{2L}},$$

$$N = \left(\frac{b}{2\nu L}\right)\sqrt{2\nu Lb}\, h(\eta)e^{\frac{3x}{2L}}$$

$$\theta(\eta)(T_w - T_\infty) = T - T_\infty, \phi(\eta)(C_w - C_\infty) = C - C_\infty \tag{7}$$

where, the velocity components are characterized as $u = \frac{\partial\psi}{\partial y}$, $v = -\frac{\partial\psi}{\partial x}$. Using the Eq. (7) into the system (Eqs. 1-5) (Eq. (1) clearly holds), then we have obtained the following new set of system:

$$f''' + \frac{Kh' - 2Mf' - 2f'^2 + ff''}{(1+K)} = 0 \tag{8}$$

$$h'' + \frac{2\left(fh' - 3f'h - K(2h + f'')\right)}{2+K} = 0 \tag{9}$$

$$\theta'' + Pr\theta' f - Pr\theta f' = 0 \tag{10}$$

$$\phi'' + Sc\phi' f - Sc\phi f' = 0 \tag{11}$$

The primes appear in the above equations characterize derivative with respect to dimensionless variableη.

$$Pr = \frac{\mu C_p}{k_T}, M = \frac{\sigma B_0^2 L}{\rho c}, l = \frac{c}{b}, Sc = \frac{\nu}{D_m}, K = \frac{k}{\mu}.$$

Restrictions on the surface in terms of similarity variables are:

$$f(0) = s, f'(0) = l. h(0) = -n\, f''(0), \theta(0) = 1, \phi(0) = 1,$$

$$f'(\infty) \to 0, h(\infty) \to 0, \theta(\infty) \to 0, \phi(\infty) \to 0 \tag{12}$$

where, s symbolizes mass suction/injection constant such that its positive value recognizes injection and negative value represents suction.

III. NUMERICAL PROCEDURE

The MATLAB routine bvp4c solver scheme is adopted to solve the Eqs. (8)-(11) along with Eq. (12). It works out the results numerically by taking finite difference code and resolving the error indirectly up to 10^{-6}. The users have to give two main functions to implement this technique for solving boundary value problem (following Dey and Borah, 2021; Dey and Chutia, 2020). These are:

(i) Set of first order differential equations:
The set of coupled non-linear ordinary differential Eqs. (8)-(11) are reduced to a set of first order differential equations. This can be happened by launching new variables as given below

$$f = d_1, f' = d_2, f'' = d_3, h = d_4, h' = d_5,$$
$$\theta = d_6, \theta' = d_7, \phi = d_8 \& \phi' = d_9$$

Then, the Eqs. (8)-(11) are transformed in the following set of equations:

$$d_1' = d_2, d_2' = d_3,$$
$$d_3' = \frac{2Md_2 + 2d_2^2 - d_1 d_3 - Kd_5}{(1+K)};$$
$$d_4' = d_5, d_5' = \frac{2(3d_2 d_4 + K(2h + d_3) - d_1 d_5)}{(2+K)};$$
$$d_6' = d_7; d_7' = \Pr(d_6 d_2 - d_7 d_1);$$
$$d_8' = d_9, d_9' = Sc(d_8 d_2 - d_9 d_1).$$

(ii) Residual function (boundary conditions): The boundary conditions (12) of the solvable equations can be written in the following form:

$$d0(1), d0(2) - l, d0(4) + nd0(3), d0(6) - 1,$$
$$d0(8) - 1; d1(2), d1(4), d1(6), d1(8).$$

IV. ENTROPY GENERATION

Entropy is the most significant thermodynamic characteristics that represent the measure of thermodynamic irreversibilities. In thermodynamics, the entropy generation is the amount of entropy generated during irreversible processes such as heat flow through a thermal resistance, fluid flow through a flow resistance, diffusion, Joule heating, friction between solid surfaces, fluid viscosity within a system etc. In order to get better efficiency and performance in most engineering and industrial applications, the key concern of the researchers is to lessen the entropy generation. The volumetric entropy generation per unit volume can be delineated as (Bejan, 1982; Dey and Hazarika, 2020)

$$S_G = \frac{k_f}{T_\infty^2}\left(\frac{\partial T}{\partial y}\right)^2 + \frac{\mu+k}{T_\infty}\left(\frac{\partial u}{\partial y}\right)^2 + \frac{\sigma B_0^2 u^2}{T_\infty} + \frac{2k}{T_\infty}\left(N^2 + N\frac{\partial u}{\partial y}\right) + \frac{R_d}{C_\infty}\left(\frac{\partial C}{\partial y}\right)^2 + \frac{R_D}{T_\infty}\left(\frac{\partial C}{\partial x}\frac{\partial T}{\partial x} + \frac{\partial C}{\partial y}\frac{\partial T}{\partial y}\right) \quad (13)$$

Here the first, second and third terms in the Eq. (13) represent the irreversibilities due to heat transfer, fluid friction and microrotation. Last two terms signify the irreversibilities due to combined effect of heat and mass transfer.

Now, using the similarity transformation we have

$$Ns = \frac{S_G}{S_{G_0}} = \theta'^2 + 2K\frac{Br}{\Omega}\{h(\eta)^2 + h(\eta)f''(\eta)\} + \lambda_1\left(\frac{\chi}{\Omega}\right)\left\{\left(\frac{\chi}{\Omega}\right)\phi'(\eta)^2 + \phi'(\eta)\theta'(\eta)\right\} + \frac{(1+K)Br}{\Omega}f''(\eta)^2 + \frac{MBr}{\Omega}f'(\eta)^2 \quad (14)$$

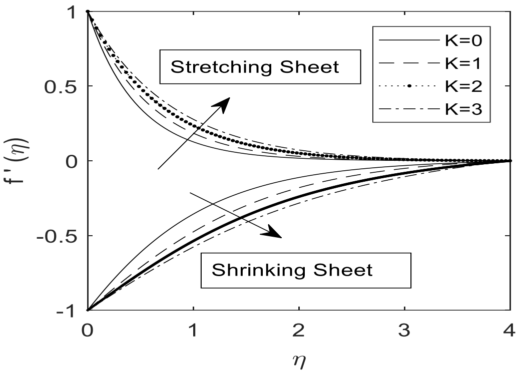

Figure 2. Sketch of the velocity field against η when $M = 0.5$, $n = 0.5$, $\Pr = 0.71$

where $S_{G_0} = \frac{k_f(T_w - T_\infty)^2}{l^2 T_\infty^2}$ is the characteristic entropy generation rate and l typical length, $Br = \frac{\mu U_w^2}{k_f(T_w - T_\infty)}$ Brinkmann number, $\Omega = \frac{T_w - T_\infty}{T_\infty}$ and $\chi = \frac{C_w - C_\infty}{C_\infty}$ dimensionless temperature and concentration ratios, respectively, and $\lambda_1 = \frac{R_D C_\infty}{k_f}$.

In this investigation, we have considered the inrreversibilities due to heat transfer (Bejan Number, Be), microrotation (Be_1), momentum diffusivity (Be_2) and simultaneous heat and mass transfers (Be_3) and their mathematical definitions are:

$$Be = \frac{\theta'(\eta)^2}{Ns} \text{ (Bejan Number)},$$
$$Be_1 = \frac{2K\frac{Br}{\Omega}\{h(\eta)^2 + h(\eta)f''(\eta)\}}{Ns},$$
$$Be_2 = \frac{\frac{(1+K)Br}{\Omega}f''(\eta)^2 + \frac{MBr}{\Omega}f'(\eta)^2}{Ns},$$
$$Be_3 = \frac{\lambda_1\left(\frac{\chi}{\Omega}\right)\left\{\left(\frac{\chi}{\Omega}\right)\phi'(\eta)^2 + \phi'(\eta)\theta'(\eta)\right\}}{Ns} \quad (15)$$

V. RESULTS AND DISCUSSIONS

In methodology, we have used bvp4c solver scheme from MATLAB software to carry out the numerical solutions of Eqs. (8-11) along with the suitable restrictions (12). Velocity of magnetized micro-polar fluid stream for material parameter K is illustrated by Fig. 2. It is perceived that the micro-polar fluid experiences acceleration over Newtonian fluid ($K = 0$) for stretching sheet. That is vortex viscosity helps to enhance the speed of the fluid. But, an opposite case is noticed for shrinking sheet.

Appliance of crossways magnetic field in the stream creates a resistive type force named "Lorentz Force" which rules the stream by reducing the speed. This is seen during the stream over stretching surface. But, a reverse case is observed for shrinking sheet (Fig. 3).

The entropy generation is exhibited through the parameter Ns. Figures (4)-(7) indicate the entropy generation rate profile for increasing values of M, K, Pr and s. The effects of Lorentz force (exhibited through M) on the entropy generation have been shown by Fig. 4. Lorentz force is a resistive force and it helps to increase the power

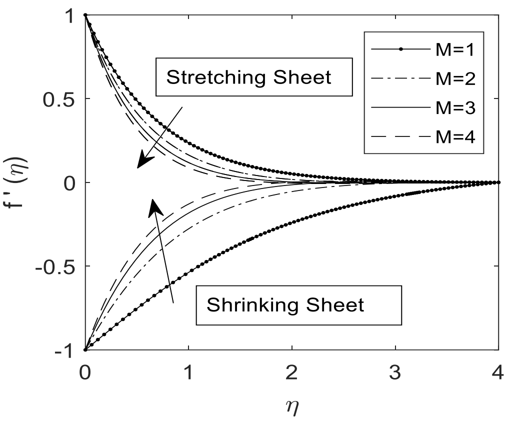

Fig. 3: Sketch of the velocity field $f'(\eta)$against η when $s = 1.5, K = 2, n = 0.5, \mathrm{Pr} = 0.71$

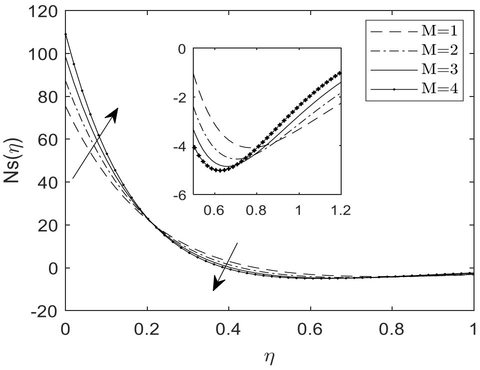

Fig. 4: Entropy generation profile against η when $K = 1, Sc = 0.60, \mathrm{Pr} = 0.71, s = 0.5, Br = 5, \lambda_1 = 0.2$

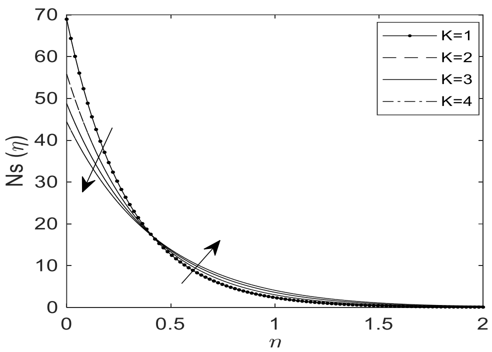

Fig. 5: Entropy generation profile against η when $M = 2, Sc = 0.60, Pr = 0.71, s = 0.5, Br = 5, \lambda_1 = 0.2$

of viscosity, the entropy generation is directly proportional to viscosity. Similarly, from the definition of Prandtl number (Pr), we have seen that, Pr is also directly proportional to viscosity. So, the enhancement of M and Pr (Figs. 4 and 6, respectively) enhance the entropy generation. In all the figures of entropy generation, we have seen a critical point (Critical point indicates the point where there is no variation with respect to variable parameter) in the boundary layer region. Material parameter or vortex viscosity parameter (K) helps to diminish the generation of entropy near the stretching sheet (Fig. 5) and increases beyond the critical point. All these figures reveal the fact that there is a clear increment in entropy generation in the vicinity of stretching sheet. Prandtl number (Pr) helps to enhance the entropy of the

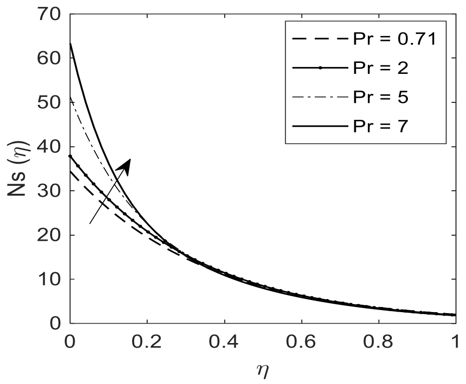

Fig. 6: Entropy generation profile against η when $K = 1, Sc = 0.60, M = 2, s = 0.5, Br = 5, \lambda_1 = 0.2$

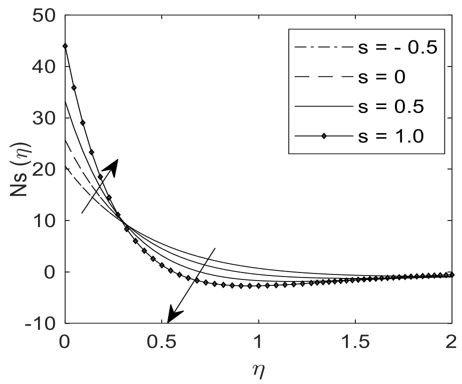

Fig. 7: Entropy generation profile against η when $K = 1, Sc = 0.60, \mathrm{Pr} = 0.71, M = 2, Br = 5, \lambda_1 = 0.2$

fluid in the close domain of the surface of the stretching sheet (Fig. 6). The suction (negative value s) at the surface helps to reduce the entropy generation in the vicinity of the surface but the fluid injection will enhance entropy generation rate (Fig. 7). Thus, porous surface having good quality of suction may help in the need of entropy reduction cases.

Table 1 specifies the irreversibilitiess due to heat transfer (Be), microrotation (Be_1), Momentum diffusivity (Be_2) and simultaneous thermal and concentration distribution (Be_3) at the stretching plane. The irreversibility due to heat transfer breeds more wastage than the others. Further, vortex viscosity parameter (K) and the suction/injection parameter (s) enhance Be and Be_3. Magnetic parameter (M) helps to reduce all the irreversibilities due to heat transfer, angular momentum and combined effect of thermal and mass diffusion except irreversibility due to momentum diffusion. Thus, it may be concluded that the parameters may be chosen in such a fashion that irreversibilities should be reduced.

A. Validation:

In the Present study, we have compared the velocity and temperature profiles (Figs. 8) of Newtonian fluid ($K = 0$) for exponentially shrinking sheet with Figs. 1 and 8 of formerly published paper of Kumar (2015) which demonstrate a perfect conformity. From this figure, it is observed that the suction parameter accelerates the velocity of the Newtonian fluid, but a reverse case is noticed during temperature field

Table 1: Numerical values of irreversibility ratios due heat transfer (Bejan number), angular momentum (Be_1), Momentum diffusion (Be_2) and Combined effect of heat and mass transfer (Be_3).

M	K	s	Be	Be_1	Be_2	Be_3
1			0.0697	-0.2692	1.0618	0.1298
2			0.0595	-0.2944	1.1241	0.1109
3			0.0517	-0.3201	1.1721	0.0964
	1		0.0703	-0.3952	1.1940	0.1309
	1.5		0.0752	-0.3811	1.1658	0.1401
	2		0.0792	-0.3699	1.1432	0.1475
		-0.5	0.0630	-0.2941	1.1067	0.1244
		0	0.0720	-0.2996	1.0898	0.1379
		0.5	0.0809	-0.3034	1.0717	0.1507

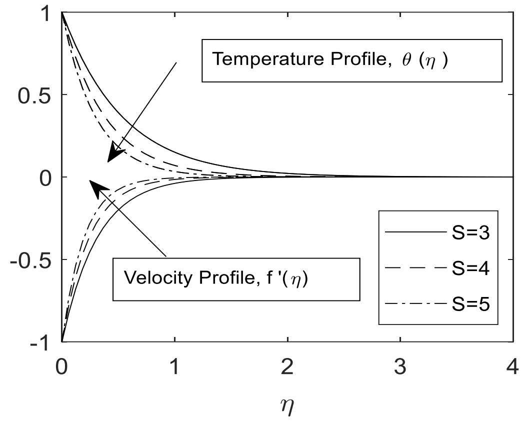

Fig. 8: Velocity $f'(\eta)$and temperature $\theta(\eta)$profiles against η for various values of suction parameter s when $\Pr = 0.71, Sc = 0, n = 0$ and $l = -1$(shrinking sheet).

VI. CONCLUSIONS

The following results are found to this discussion.

- The material parameter K (responsible for micropolar fluid) helps to enhance the speed of the fluid.
- Due to the effects of Hartmann number M (responsible for imposed magnetic field), the speed of the fluid grow down.
- Magnetic field parameter (M), Prandtl number Pr and suction /injection parameter (s) help to enhance the entropy generation at $0 < \eta < 0.5$. But it reduces for the growing values of K (material parameter).
- Irreversibility due to momentum diffusion contributes more wastage production than others.

NOMENCLATURE

(T_∞, C_∞) −free stream (temperature, concentration), $(T_0\ , C_0)$ characteristic (temperature and concentration) L- the characteristic length, (u, v) −velocity components along (x, y) −directions v_w- the velocity suction ($v_w >$ 0)/injection ($v_w < 0$) − parameter,(N, T, C)- the angular velocity, temperature and concentration of the fluid respectively, σ −electric conductivity, ρ− density for the general fluid, k_T −thermal conductivity, C_p −specific heat at constant pressure , D_m – mass diffusivity,$M = \frac{\sigma {B_0}^2 L}{\rho c}$ −the Hartmann number, $Pr = \frac{\mu C_p}{k_T}$ −the Prandtl number, $Sc = \frac{v}{D_m}$ −the Schmidt number and $l = \frac{c}{b}$ −stretching ($l > 0$)/shrinking ($l < 0$) parameter, ψ − stream function, (μ, v) −dynamic and kinematic viscosity, s −suction parameter, η −dimensionless similarity variable.

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