ENTROPY GENERATION OF HYDRO-MAGNETIC STAGNATION POINT FLOW OF MICROPOLAR FLUID WITH ENERGY TRANSFER UNDER THE EFFECT OF UNIFORM SUCTION/ INJECTION

D. DEY[†] and M. HAZARIKA[2]

†Department of Mathematics, Dibrugarh University, Assam
debasish41092@gmail.com
‡Department of Mathematics, Dibrugarh University, Assam
madhuryahazarika1995@gmail.com

Abstract **–– The entropy generation of hydro-magnetic stagnation point flow of micro-polar fluid with energy transfer has been analyzed numerically. A uniform magnetic field is applied along the normal to plate. The partial differential equations are transformed into ordinary differential equations using similarity transformations. The effects of magnetic parameter, material parameter, Prandtl number, Grashof number on the flow and entropy generation are discussed and plotted graphically using the MATLAB built in bvp4c solver.**

Keywords **––Entropy generation, Stagnation point flow, micro-polar fluid, MHD heat generation, suction/injection.**

I. INTRODUCTION

Fluid consisting of randomly oriented particles suspended in a viscous medium and having non symmetric stress tensor is called micropolar fluid. Physically the fluid can be considered of very small rigid cylindrical elements. Micropolar fluid theory characterizes with certain microscopic effects arising from micro-rotation of the fluid. Attention on micropolar fluid model is given due to its many applications such as solidification of liquid crystals, exotic lubricants, animal blood, cooling of a metallic plate in a bath. Eringen (1966, 1972) have developed the concept of thermo micropolar fluid with the help of the theory of micropolar fluid. Ariman *et al.* (1973, 1974) have investigated the applications of micropolar fluid in various science and engineering purposes .The flow of heat convection in micropolar fluids past flat plate has been studied by Ahmadi (1976), Mathur and Subhadra (1980), Jena and Mathur (1981) and Gorla (1983) and regular surfaces. Perdikis and Raptis (1996) have studied the effect of heat transfer of a micropolar fluid under the effect of radiation. Nazar *et al.* (2004), Attia (2006) and Lok *et al.* (2007) have studied the stagnation point flow using micropolar fluid model. Dey (2017) has investigated the hydromagnetic Oldroyd fluid flow past a flat surface. Vaidya *et al.* (2019) have discussed the impact of variable liquid properties on peristaltic flow of Rabinowitsch fluid. Manjunatha *et al.* (2020a, 2020b) have discussed on the impact of variable transport properties and slip effect on MHD Jeffrey fluid flow with heat and mass transfer.

Factors responsible for the entropy generation are temperature gradient, energy decapitation, convective energy transfer etc. Various researchers, Bejan (1979, 1982a, 1996), Havzali *et al.* (2008), Komurgoz *et al.* (2010), Butt *et al*. (2012) have studied entropy generation using different flow configurations. Liu and Lo (2012) have analysed entropy generation within a mixed convective magneto hydrodynamic (MHD) flow through vertical channel. Makinde and Eegunjobi (2013) have carried out the entropy generation analysis in the flow of couple stress fluid. Das and Jana (2014) have studied the combined effects of Navier slips, suction/injection on magnetic fields on entropy generation in a porous channel by considering constant pressure gradient. Liu and Lo (2012) numerically examined the viscous dissipation effect on entropy generation. Rashidi *et al.* (2014) have investigated the entropy generation analysis for the stagnation point flow considering the porous medium over a stretching surface.

The phenomenon of heat and mass transfer problem is used in industrial and engineering works such as drying, wet cooling tower, humidifiers, dehumidifiers etc. in our daily life, heat and mass transfer mechanism is used in refrigeration, coffee making machine and in oven etc. Simultaneous heat and mass transfer is also seen in the evaporation of river water into the wind moving over the system. Choudhury and Dey (2012), Dey and Khound (2016, 2019) have studied simultaneous heat and mass transfer effects on fluid flow.

Our main objective is to investigate the entropy generation analysis of stagnation point flow of micropolar fluid under the influence of suction/injection with bouncy force**.** In the work of Jat and Saxena (2013), the flow is taken over the horizontal surface. On the other hand, we have considered the flow along the vertical surface. This geometry helps to create free convective heat and mass transfer phenomena due to the appearance of bouncy force for flow along a vertical surface. Further, the entropy generation analysis has been carried out in our study. We have obtained the graphs and the numerical values of skin friction co efficient, Nusselt number and Sherwood number by using MATLAB built in bvp4c solver technique.

II. MATHEMATICAL FORMULATION

We consider a steady two dimensional flow of electrically conducting incompressible micropolar fluid flow with heat generation/ absorption. The fluid is acted upon by magnetic field of strength B_0 assuming that magnetic

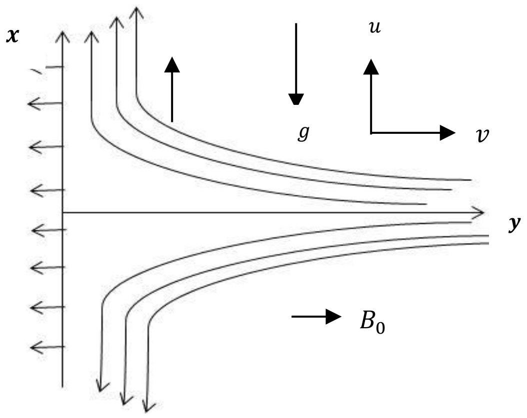

Fig. 1: Geometry of flow and co-ordinate system

Reynolds number is very small. Let u and v be the velocity component along x and y directions and N be the component of micro-rotation vector which is normal to the xy plane, T and C are the temperature and concentration respectively. A uniform injection /suction are applied to the plate. Figure 1 shows the geometry of the flow and coordinate system.

The governing equations (following Jat and Saxena, 2013; Choudhury and Dey, 2012, Mishra *et al.* 2018) under the usual boundary layer approximation and Boussinesq approximation are given by

Continuity Equation

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}=0, \qquad (1)$$

The momentum equation

$$u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}=U\frac{dU}{dx}+\frac{\mu+k}{\rho}\frac{\partial^2 u}{\partial y^2}+\frac{k}{\rho}\frac{\partial N}{\partial y}$$
$$-\frac{1}{\rho}g\beta^*(C-C_\infty)-\frac{1}{\rho}\,g\beta^*(T-T_\infty)+\,\sigma B_0^2 u\,, \qquad (2)$$

The angular momentum equation

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

The energy equation

$$c_p\left(u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}\right)\;=k^*\frac{\partial^2 T}{\partial y^2}+\;\;(\mu+k)\left(\frac{\partial u}{\partial y}\right)^2+$$
$$\rho+Q(T-T_\infty)+\frac{D_m k^*}{c_s c_p}\frac{\partial^2 C}{\partial y^2}-\frac{\sigma B_0^2 u}{\rho}, \qquad (4)$$

The concentration equation

$$u\frac{\partial C}{\partial x}+v\frac{\partial C}{\partial y}=D_m\frac{\partial^2 C}{\partial y^2}+\frac{D_m k^*}{c_s c_p}\frac{\partial^2 T}{\partial y^2}\;, \qquad (5)$$

The relevant boundary conditions for solving (1)-(5) in the neighborhood of stagnation point (following Jat and Saxena, 2013)

$$y=0:\;\; u=0, v=v_0, N=-m\frac{\partial u}{\partial y}, T=T_w,$$
$$\frac{\partial C}{\partial y}=-\frac{m}{D_m}, \qquad (6)$$

$$y\to\infty:\; u\to ax, v\to 0, N\to 0, T\to T_\infty, C\to C_\infty \quad (7)$$

where, σ is the electrical conductivity, μ the viscosity of the fluid, ρ the density of the fluid, j the gyration parameter, α the thermal diffusivity, D_m the coefficient of mass diffusivity, T_∞ the temperature of the fluid at infinity, C_∞ the concentration of the fluid at infinity, m the boundary parameter, c_s and c_p the concentration susceptibility and specific heat at constant pressure respectively, $k^*$and k the thermal conductivity and vortex viscosity parameter, Q termed as heat generation/ absorption coefficient, a is a constant with the dimension of time inverse.

III. METHOD OF SOLUTION

The equation of continuity satisfied by the stream function $\psi(x,y)$ is defined as

$$u=\frac{\partial\psi}{\partial y},\;\; v=-\frac{\partial\psi}{\partial x}. \qquad (7)$$

Now we consider the following similarity transformation

$$\psi(x,y)=x\sqrt{a\nu}f(\eta), N(x,y)=ax\sqrt{\frac{a}{\nu}}g(\eta), \frac{T-T_\infty}{T_w-T_\infty}$$
$$=\theta(\eta), \frac{C-C_\infty}{C_w-C_\infty}=\phi(\eta), \eta=y\sqrt{\frac{a}{\nu}}. \qquad (8)$$

Using theses transformations the Eqs. (1)-(5) are reduced to

$$(1+K)f'''+ff''-f'^2+Kg'-Mf'+$$
$$G_m\phi+Gr\theta+1=0\,, \qquad (9)$$
$$\left(1+\frac{K}{2}\right)g''+fg'-f'g-K(2g+f'')=0, \quad (10)$$
$$\theta''+Prf\theta'+PrB\theta+(1+K)PrEcf''^2+$$
$$MEcPrf'^2+PrD_f\phi''=0\,, \qquad (11)$$
$$\phi''+Scf\phi'-S_0\theta''=0\,, \qquad (12)$$

Corresponding boundary conditions for solving (9)-(10) are listed below

$$\text{At } \eta=0:\; f=S, f'=0, g=-mf'', \theta=1, \phi'=-1,$$
$$\text{At } \eta\to\infty:\; f'\to 1, g\to 0, \theta\to 0, \phi\to 0.$$

In the above equations, primes denote the differentiation with respect to η. $Re=xu/\nu$ is the Reynolds number, $M=\sigma B_0^2/(\rho a)$ is the magnetic field parameter, $K=k/\mu$ is the material parameter, Gr and Gm are the Grashof number for heat and mass transfer, D_m is the co-efficient of mass diffusivity, $S=-v_0/\sqrt{(a\nu)}$ is the Suction / Injection parameter, $Ec=\mu U^2/[c_p(T_w-T_\infty)]$ is the Eckert Number, $B=Q/(a\rho c_p)$ is the heat generation/absorption parameter, $Pr=\mu c_p/\kappa$ is the Prandtl number, Q is the heat generation/absorption rate, $S_0=D_m k^*/(mc_s c_p)\cdot Q/k$ is the Soret number β and β^* are the coefficient of thermal and volumetric expansion, D_f is the Dufour number and $Sc=\nu/D_m$ is the Schmidt number.

IV. ENTROPY GENERATION

According to Bejan (1982b) the volumetric local entropy generation rate per unit volume is given by

$$S_G=\frac{k^*}{T_\infty^2}\left(\left(\frac{\partial T}{\partial x}\right)^2+\left(\frac{\partial T}{\partial y}\right)^2\right)+\frac{\mu+k}{T_\infty}\left(\frac{\partial u}{\partial y}+\frac{\partial v}{\partial x}\right)^2$$
$$+\frac{2k}{T_\infty}\left(N^2+N\frac{\partial u}{\partial y}\right)+\frac{\sigma B_0^2 u^2}{T_\infty}+\frac{RD}{C_\infty}\left(\frac{\partial C}{\partial y}\right)^2$$
$$+\frac{RD}{T_\infty}\left(\frac{\partial C}{\partial y}\frac{\partial T}{\partial y}+\frac{\partial C}{\partial x}\frac{\partial T}{\partial x}\right). \qquad (13)$$

Now the entropy generation number is defined as

$$Ns=\;\frac{S_G}{S_{G\,0}},$$

where $S_{G_0}=k^*(T_w-T_\infty)^2/\left[T_\infty^2\left(\sqrt{\frac{\nu}{a}}\right)^2\right]$ is the characteristic entropy generation rate.

Applying the similarity transformation (7) and (8) entropy generation number for this flow problem can be derived as

$$Ns = \theta'^2 + \frac{(1+K)Br}{\Omega} f''^2 + \left(\frac{2KBr}{\Omega}\right)(g^2 + gf'') + \frac{MBr}{\Omega} f'^2 + \lambda_1 \left(\frac{\chi}{\Omega}\right)\left(\frac{\chi}{\Omega}\phi'^2 - \phi'\theta'\right), \quad (14)$$

Here, $Br = \mu U_w{}^2/[k_f(T_w - T_\infty)^2]$ is the Brinkman Number, Ω is the dimensionless temperature ratio $(\Delta T/T_\infty)$, χ is the dimensionless concentration ratio $(\Delta C/C_\infty)$ and $\lambda_1 = RDC_\infty/k$.

Skin friction coefficient

The physical quantities of interest are the local skin-friction coefficient C_f, the local Nusselt number Nu and local Sherwood number Sh which are defined, respectively, as

$$C_f = \frac{\tau_w}{\frac{\rho U^2}{2}}, Nu = \frac{xq_w}{K(T_w - T_\infty)}, Sh = \frac{xm_w}{D(C_w - C_\infty)}$$

where, $U_w = ax$, Characteristic velocity,

$\tau_w = \left\{\frac{(\mu+k)\partial u}{\partial y} + kN\right\}_{y=0}$ (Shear stress at the surface),

$q_w = -k\left\{\frac{\partial T}{\partial y}\right\}_{y=0}$ (Heat transfer from the plate).

$m_w = -D\left\{\frac{\partial C}{\partial y}\right\}_{y=0}$ (mass transfer from the plate)

Thus, $C_f = \frac{2\left(1+\frac{K}{2}\right)}{\sqrt{Re}} f''(0)$, $Nu = -\sqrt{(Re)}\theta'(0)$, $Sh = -\sqrt{(Re)}\phi'(0)$.

V. RESULTS AND DISCUSSIONS

The non-linear differential equations with the boundary conditions are solved numerically using MATLAB built in bvp4c solver technique. In the discussion part, we have compared our result with Jat and Saxena (2013). Since, we have considered the flow along vertical direction so by considering $Gr = Gm = 0$ (zero bouncy force for horizontal flow) and $D_f = 0$ (no diffusion thermo effect). The obtained results are in good agreement with the results of Jat and Saxena (2013) and these are depicted by Table 1. Table 2 and 3 portray the numerical values of Skin friction coefficient $f''(0)$ and Nusselt number, $-\theta'(0)$ at the surface for the different values of parameters K, Pr, B, M, Gr, Gm, Sc, Ec and S. In this problem, we have considered the stagnation point flow along vertical direction considering mass transfer effect and buoyancy force. From the tables, it is concluded that skin friction coefficient reduces with the increasing values of suction/injection parameter (S) and Magnetic parameter M. Physically, it interprets that enhancement of suction parameter reduces the speed of motion in the surface or its neighborhood, and as result, the velocity gradient across the fluid layers increases and this helps to increase the shearing stress at the surface. Similarly, the growth in magnetic parameter has a retarding impact on the fluid motion and it helps to enhance the shear stress at the surface. It is noticed that for the given values of parameters K, Ec, M, Pr and B the Nusselt number increases with the increasing values of parameter S and reduces for the values of M.

Figures 2-4 indicate the velocity component along along x-axis, micro-rotation, temperature and concentration profile for different values of magnetic parameter M.

Table 1: Comparisons results for the function $f''(0)$ and $-\theta'(0)$ for several values of $S$when $Pr = 0.71, Ec = 0.2, B = 0.2$, $Gr = Gm = 0, D_f = 0$

	Present Study ($M = 0$)	Jat and Saxena (2013)	Present study	Jat and Saxena (2013)
S	$f''(0)$	$f''(0)$	$-\theta'(0)$	$-\theta'(0)$
-1	0.6766	0.6766	-0.0056	-0.0058
-0.5	0.8278	0.8278	-0.1091	-0.1092
0	1.0064	1.0063	0.2546	0.2548
0.5	1.2100	1.2099	0.4611	0.4613

Table 2: Numerical values of $f''(0)$ for different values of M and $S$when $Pr = 0.71, B = 0.1, K = 1$, $Gr = Gm = 1, D_f = 0.2$, $Ec = 0.1$ and $Sc = 0.60$

M	$S = -1$	$S = -0.5$	$S = 0$	$S = 0.5$	$S = 1$
0	1.7706	1.6360	1.5665	1.5061	1.5944
0.1	1.7598	1.6201	1.5452	1.5291	1.5615
0.3	1.7493	1.6048	1.5248	1.5031	1.5299
0.5	1.7203	1.5623	1.4680	1.4313	1.4425
0.7	1.6943	1.5245	1.4175	1.3671	1.3651
1.0	1.6786	1.5014	1.3869	1.3294	1.3186

Table 3: Numerical values of $-\theta'(0)$ for different values of M and S when $Pr = 0.71, Ec = 0.2, B = 0.2, Gr = Gm = 1, D_f = 0.2$.

M	$S = -1$	$S = -0.5$	$S = 0$	$S = 0.5$	$S = 1$
0	-0.0361	0.0662	0.1894	0.3365	0.5055
0.1	-0.0490	0.0526	0.1749	0.3212	0.4895
0.2	-0.0613	0.0398	0.1614	0.3069	0.4745
0.5	-0.0.49	0.0054	0.1259	0.2690	0.4354
0.8	-0.1241	-0.0239	0.0952	0.2381	0.4038
1.0	-0.1415	-0.0409	0.0780	0.2207	0.3863

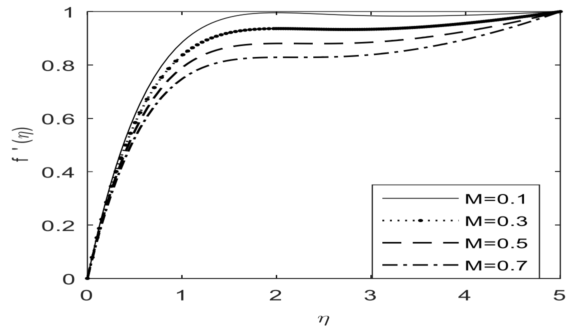

Fig. 2: Velocity component against η for different value of M when K =1 and $S = 1, B = 0.2, Ec = 0.1, Pr = 0.71, Gr = Gm = 1, Df = 0.2, Sc = 0.60$, $S_0 = 0.2$

It is observed that velocity component show the decreasing trend with increasing values of M. Physically, this is possible as the Lorentz force (exhibited through parameter M) opposes the fluid motion and consequently velocity component along the primary motion reduces.

Influence of magnetic parameter on the microrotation is portrayed by Fig. 3. The figure depicts that the angular velocity of fluid motion enhances with the magnetic parameter until it reaches to equilibirum position ($\eta \geq 1.5$).This is possible as we have seen that Lorentz force reduces the velocity and kinetic energy and to maintain the conservation of energy principle, rotational energy is increased. So, more angular velocity is experienced.

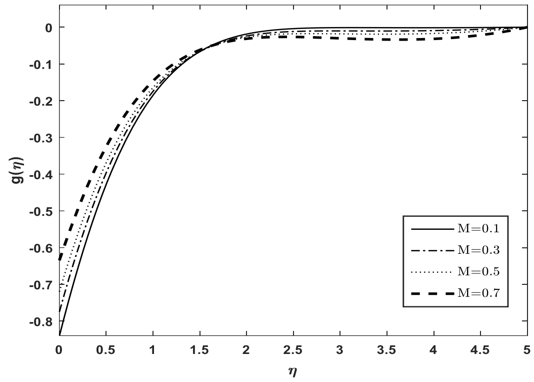

Fig. 3: Microrotation profile against η for different values of M when K =1 and $S = 1, B = 0.2, Ec = 0.1,\ Pr = 0.71, Gr = Gm = 1, Sc = 0.60,\ S_0 = 0.2$

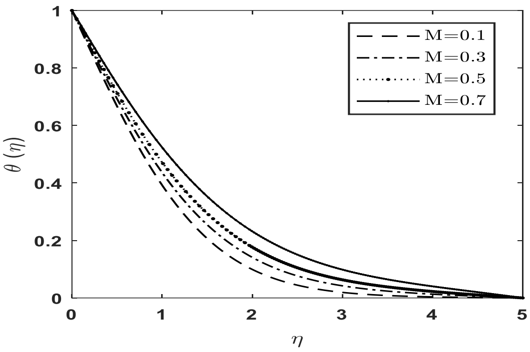

Fig. 4: Temperature profile against η for different values of M when K =1 and $S = 1,\ B = 0.2, Ec = 0.1, Pr = 0.71$

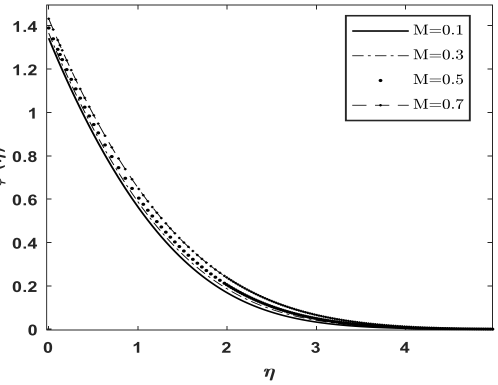

Fig. 5: Concentration profile against η for various values of parameter $M$when K =1 and $S = 1, B = 0.2,\ Ec = 0.1,\ Pr = 0.71, Gr = Gm = 1, Sc = 0.60, S_0 = 0.2$.

Temperature field against the displacement variable is shown by Fig. 4 and it is seen that the growth of magnetic parameter helps to raise the temperature through the energy dissipation (enhance of heat energy after the reduction in momentum due to Lorentz force).

Pattern of concentration field against the displacement variable is shown by Fig. 5 and it is seen that the deposition is high at the vicinity of the surface. Further, concentration of fluid will be higher with the increment in magnetic parameter. Higher concentration is experienced for slow motion due to Lorentz force.

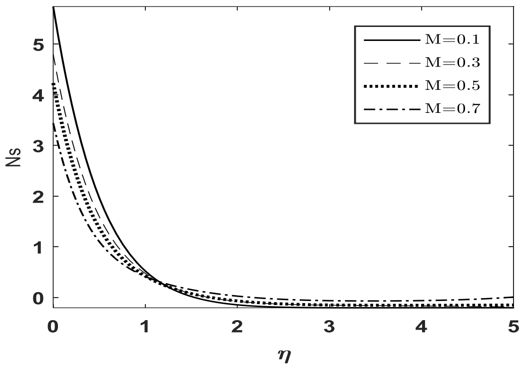

Fig. 6: Entropy generation profile against η for different values of M when K =1 and $S = 1, B = 0.2,, Pr = 0.71,\ Ec = 0.2, Gr = Gm = 1, Sc = 0.60, S_0 = 0.2$

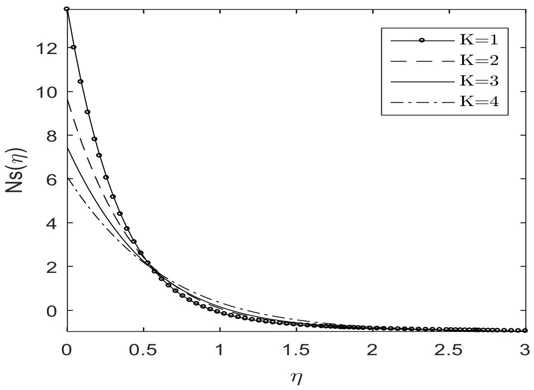

Fig. 7: Entropy generation profile against η for various values of parameter $K$when M =1,S = 1, $B = 0.2,\ Ec = 0.1,\ Pr = 0.71,\ Gr = Gm = 1, Sc = 0.60,\ S_0 = 0.2\ , Br = 1$

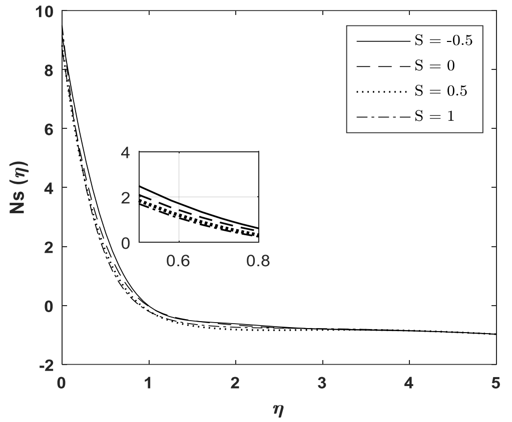

Fig. 8: Entropy generation profile against η for various values of parameter $S$when M =1, K= 1, $B = 0.2,\ Ec = 0.1,\ Pr = 0.71, Gr = Gm = 1, Sc = 0.60, S_0 = 0.2, Br = 1$

Figures 6-10 represent the effect of magnetic parameter (M), material parameter (K), Suction /injection parameter (S), Prandtl number (Pr) and the Grashof number (Gr) on entropy generation. From the Figs. 6 and 7, it is observed that entropy generation decreases before the point of inflection and beyond the point it shows reverse effect. Thus, the rate of entropy generation may be controlled by increasing magnetic and material parameters in the negihbouhood of the

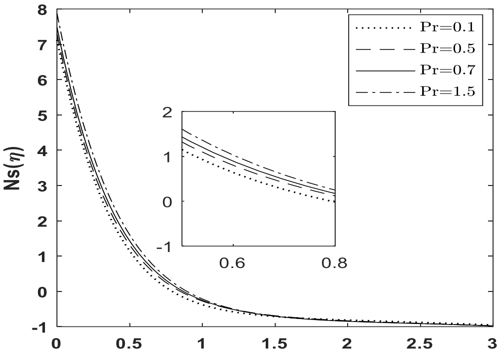

Fig. 9: Entropy generation profile against $\eta$for various values of parameter $Pr$when $M=1$,$Br=1$,$B=0.2$, $Ec=0.1$, $Gr=1$, $Gm=1$,$Sc=0.60$, $S_0=0.2$, $Br=1$.

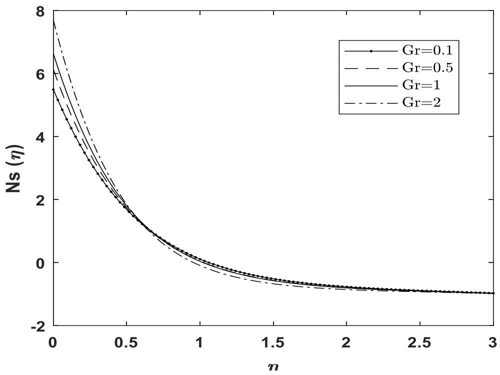

Figure.5.9:Entropy generation profile against $\eta$for various values of parameter Grwhen $M=1$,$B=0.2$, $Ec=0.1$, $K=0.71$and $Gm=1$.

surface. Figures 8 and 9 represent the effect of suction/injection parameter $\boldsymbol{S}$ and Prandtl number on entropy generation. During suction at the surface, rate of entropy generation is higher than injection. This is possible because, during flow injection, flow momentum is maintained and there is lower chance of energy dissipation. Prnadtl number enhances the entropy generation rate with the momentum diffusion as it is directly proportional to viscosity. Grashof number (Gr) is directly proportional to the bouyancy force and Fig. 10 reveals that there is a growth in entropy generation ratio with the rise in Grashof number. These figures also show that entropy generation rate is high at the viscosity dominant region. Reduction in viscosity may help to reduce the entropy generation rate.

VI. CONCLUSION

The entropy generation analysis of MHD boundary layer stagnation point flow of micro-polar fluid with heat and mass transfer under the effect of magnetic field and suction /injection has been studied. Some of the important findings of these investigations are given by

i. Velocity profile decreases with rise in magnetic parameter (M) .
ii. Microtation profile enhances with increasing values of magnetic parameter.
iii. Entropy generation profile enhances with increasing values of Prandtl number (Pr) and Material parameter$K$ and reduces for the values of M.
iv. Entropy generation profiles show reverse effect with the increasing values of suction/injection parameter.
v. Entropy generation profile enhances near the boundary layer with increasing values of Gr.

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