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ORIGINAL ARTICLE

Thermodynamic second law analysis of magneto-micropolar fluid flow past nonlinear porous media with non-uniform heat source

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Abstract This study analyzes the second law of thermodynamic for entropy generation in an irreversible hydromagneto-micropolar flow system with non-homogenous heat generation. The non-symmetric microstructure fluid flow past a stretching sheet with saturated porous nonlinear media under magnetic field influence. Ignoring the fluid particle deformation, the microstructure is assumed rigid with the viscous suspended medium. The reduced dimensionless nonlinear formulated model is computationally coded and solved to obtain solutions for the entropy volumetric production, Bejan number and heat transfer magneto-micropolar fluid. The parameter dependent solutions for the flow characteristics and irreversibility processes are plotted and discussed. It is revealed from the study that minimization of entropy generation in a magneto-micropolar flow system is possible by improving the thermodynamic equilibrium with low material variables, viscosity and hysteresis magnetic. Also, it is seen that the terms that encourage internal heat generation reduces the micropolar fluid viscosity in the system.

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1. Introduction

The importance of non-Newtonian liquids as a raw material in chemical productions and other industrial processes can not be over emphasized, Kareem et al. [1]. Of the several kinds of non-Newtonian liquids,

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Nomenclature

x, y	cartesian coordinates (unit: m)
u, v	velocity component along x, y direction respectively (unit: $m \cdot s^{-1}$)
T	temperature inside the boundary layer (unit: K)
T_w	fluid temperature at wall (unit: K)
T_∞	free stream temperature (unit: K)
u_w	velocity at wall (unit: $m \cdot s^{-1}$)
K_p	permeability of the porous media (unit: m^2)
v_w	suction/injection velocity (unit: $m \cdot s^{-1}$)
k_*	thermal conductivity (unit: $W \cdot m^{-1} \cdot K^{-1}$)
B_0	magnetic field strength (unit: A/m)
j	micro-inertia per unit mass (unit: $kg \cdot m^{-3}$)
q_w	heat flux at the surface of the plate (unit: $W \cdot m^{-2}$)
Cp	specific heat at constant pressure (unit: $J \cdot kg^{-1} \cdot K^{-1}$)
f	dimensionless stream function
n	surface temperature parameter
D^*, C^*	space and heat source/sink
h	microrotation boundary parameter
ω	microrotation component (unit: s^{-1})

Greek symbols

ρ	density of the fluid (unit: $kg \cdot m^{-3}$)
σ	electric conductivity (unit: $S \cdot m^{-1}$)
μ	dynamic viscosity (unit: $kg \cdot m^{-1} \cdot s^{-1}$)
ν	kinematic viscosity (unit: $m^2 \cdot s^{-1}$)
γ	spin gradient viscosity (unit: $m^2 \cdot s^{-1}$)
μ_r	vortex viscosity
η	dimensionless transformation variable
$\theta(\eta)$	dimensionless temperature

micropolar fluid with stress tensor, non-symmetric microstructure particle gyration initiated by Eringen [2] is a well established one. It conveys significantly, the applications and theory of the classical generalized model of Navier-Stokes though with more phenomena, Kumar and Raju [3]. The polar fluid model is not complex but attractive to those who study its physicists and theory as well as engineering applications. Micropolar fluid is a micro fluids subclass with skew-symmetry assumption and three independent components [4—6]. The application of micropolar liquid accompanies with heat transfer is important in the study of a porous medium and lubricant theory as its has fascinating usage in the lubricants, oil exploration, combustion products, environmental pollution mitigation, drilling and so on.

In thermal science and renewable energy systems, flow of magneto-micropolar liquid is essential in enhancing systems and device performance. As a result, the study of micropolar flow fluid in nonlinear media and stretching sheet in the presence of dufour and soret was considered by Refs. [7,8]. The study reported on some important micropolar flow structures. Many machines and devices under different heat distribution operates with various kinds of lubricants, Waqas et al. [9]. The effect of heat transfer on the flow of micropolar hydromagnetic fluid viscosity was presented in the investigation. Lubricant viscosity is always affected by internal heat generation within the system [10,11]. The changes in the oil viscosity mostly impact the efficiency of the thermal technology engines and industrial machines, and this leads to the occurrence of irreversibility process in the system, Ogunseye et al. [12]. Monitoring and improving energy conservation in doing work has encouraged researchers to study the thermodynamic second law for entropy generation analysis in order to reduce energy resources degradation [13,14]. The second law analysis of energy transfer mechanism for the entropy generation helps in increasing industrial engine efficiency, energy system preservation, and reduces system solutions blowup.

In an adiabatic flow system, entropy remains uniform or rises to encourage irreversibility processes. Therefore, Srinivasacharya and Bindu [15,16] examined entropy generation in a convective concentric pipe by the flow of micropolar fluid. The Bejan number and irreversibility process of the flow are reported in the study. Thermal and electrical conductivities in an Eyring-Powell hydromagnetic fluid with entropy generation and system stability was examined by Refs. [17,18]. It was reported in the study that huge pitch ratio augments Bejan and entropy production field. Analysis of the second law of thermodynamic with heat convection transfer of magnetohydrodynamic fluid was considered in Refs. [19—21]. Akbar [22] studied entropy production in hydromagnetic peristaltic flow in a tube and energy conversion in the system. Abolbashari et al. [23] investigated entropy minimization of a magneto-nanofluid flow through the porous stretching sheet. Baag et al. [24] considered viscoelastic hydromagnetic flow with entropy generation in stretching permeable media. Kummer's function analytical solution was used for the study, and it is seen that the Darcy porosity term increases the entropy production, but the reversibility process is improved by liquid thermal diffusivity. Reports on the second law of couple stress hydromagnetic reactive viscous fluid with Navier slip conditions was presented in Refs. [25,26]. Analytical results for the problem were carried out, and it was found that low material terms and viscous dissipation enhances reversibility process.

Therefore, follow from previous works on micropolar fluid in the absence of species transfer and ohmic heating are done without considering entropy volumetric generation. The present study considered entropy generation in a flow of magneto-micropolar liquid past nonlinear porous stretching medium with internal non-homogenous heat generation and ohmic heating due to its usage in lubricant theory analysis and engineering applications. Computational analysis of the problem is carried out using shooting Runge-Kutta techniques, and the solution dependent parameters are illustrated graphically.

2. Development of the problem

Consider the flow of an incompressible magneto-micropolar laminar liquid over a non-linearly stretching impermeable plate in porous saturated non-Darcian media with internal non-homogenous heat generation as seen in Figure 1. The stretching sheet in the x direction is u which varies non-linearly as $u = u_w = cx^r$ with $c > 0$ being a constant and r is the power law index. A non-uniform magnetic field of strength $B(x) = B_0 x^{(r-1)/2}$ acts perpendicularly to the flow direction in which (x, y) defines the stretching co-ordinates corresponding to the momentum component (u, v).

In vector form, the governing continuity, momentum, microrotation and energy equations are respectively expressed as

$$\nabla \cdot \boldsymbol{V} = 0, \tag{1}$$

$$\rho(\boldsymbol{V} \cdot \nabla)\boldsymbol{V} = -\nabla p + (\mu + \mu_r)\nabla^2 \boldsymbol{V} + \mu_r \nabla \times \omega + \rho \boldsymbol{f} \tag{2}$$

$$\rho j(\boldsymbol{V} \cdot \nabla \omega) = \gamma \nabla^2 \omega - \mu_r (2\omega + \nabla \boldsymbol{V}) \tag{3}$$

$$\rho Cp(\boldsymbol{V} \cdot \nabla)T = k_* \nabla^2 T + (\mu + \mu_r)(\nabla \boldsymbol{V})^2 + q''' - \rho \boldsymbol{f} \tag{4}$$

where the external forces are expressed as $\boldsymbol{f}$ which are Lorentz force, Darcy and Forchheimer body forces respectively as given in equation below

$$\boldsymbol{f} = \boldsymbol{J} \times \boldsymbol{B} - \frac{\mu}{\rho K_P}\boldsymbol{V} - \frac{F}{K_p}|\boldsymbol{V}|\boldsymbol{V} \tag{5}$$

with $\boldsymbol{J}$ being the current density given as

$$\boldsymbol{J} = \sigma(\boldsymbol{E} + \boldsymbol{V} \times \boldsymbol{B} - \beta_* \boldsymbol{J} \times \boldsymbol{B}). \tag{6}$$

here, $\boldsymbol{B} = (0, B(x))$ is the magnetic field induction (strength) and $\boldsymbol{E}$, $\boldsymbol{V}$, σ, β_* are respectively the electric field intensity, velocity vector, medium, electric conductivity of micropolar fluid and Hall factor.

Follow from Refs. [6,15], the magneto-micropolar fluid and heat balance equations are present as:

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0, \tag{7}$$

$$u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} = \frac{(\mu + \mu_r)}{\rho}\frac{\partial^2 u}{\partial y^2} + \frac{\mu_r}{\rho}\frac{\partial \omega}{\partial y} - \frac{\sigma B^2(x)}{\rho}u - \frac{\mu}{\rho K_p}u - \frac{F}{K_p}u^2, \tag{8}$$

$$u\frac{\partial \omega}{\partial x} + v\frac{\partial \omega}{\partial y} = \frac{\gamma}{\rho j}\frac{\partial^2 \omega}{\partial y^2} - \frac{\mu_r}{\rho j}\left(2\omega + \frac{\partial u}{\partial y}\right), \tag{9}$$

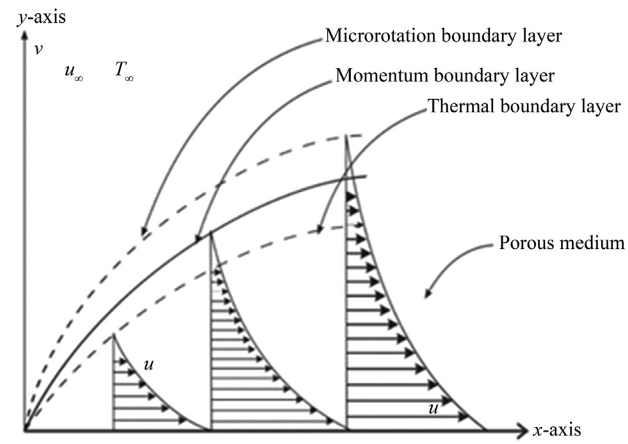

Figure 1 The flow geometry.

$$u\frac{\partial T}{\partial x} + v\frac{\partial T}{\partial y} = \frac{k_*}{\rho Cp}\frac{\partial^2 T}{\partial y^2} + \frac{(\mu + \mu_r)}{\rho Cp}\left(\frac{\partial u}{\partial y}\right)^2 + \frac{\sigma B^2(x)}{\rho Cp}u^2 + \frac{\mu}{\rho Cp K_p}u^2 + \frac{F}{Cp K_p}u^3 + \frac{q'''}{Cp}. \tag{10}$$

The incorporated boundary conditions are:

$$u = u_w,\ v = 0,\ \omega = -h\frac{\partial u}{\partial y}, \quad T = T_w = (T_\infty + Ax^n),\ \text{at } y = 0, \quad u \to 0,\ \omega \to 0,\ T \to T_\infty,\ \text{as } y \to \infty. \tag{11}$$

The surface boundary parameter has an interval $0 \le h \le 1$. The case when $h = 0$ implies that $\omega = 0$ and in such situation, the wall micro-particles is fixed, Jena and Mathur [27]. According to Ahmadi [28], $h = 1/2$ shows a weak wall micro-particles concentration and vanishing of stress tensor anti-symmetric term. Also, Peddieson [29] reported that $h = 1$ can be applied for the boundary layer turbulent flow modelling. By some previous researchers [30–32], assume that $F = F_0 x^{-r}$, $K_p = K_p^* x^{1-r}$, $C^* = \alpha x^{r-1}$ and $D^* = \beta x^{r-1}$ represent the Forchheimer constant, permeability of the porous medium, heat source space dependent and heat source temperature dependent where F_0, α, β are constants. The internal non-homogenous heat generation in the energy Eq. (10) is modeled as (see Tripathy et al. [33])

$$q''' = \frac{k_* u_w}{v x^r}[D^*(T - T_\infty) + C^*(T_w - T_\infty)f'], \tag{12}$$

where C^* and D^* denote heat generation space and temperature dependent respectively. For heat source, $C^* > 0$ and $D^* > 0$ while for heat sink, $C^* < 0$ and $D^* < 0$. Using the following defined terms (see Refs. [34,35]) and Eq. (12) on Eqs. (7)–(11), the conservation Eq. (1) is satisfied.

$$\psi = x^{(r-1)/2}\left(\frac{2c\nu}{r+1}\right)^{1/2} f(\eta), \quad u = cx^r f',$$
$$\eta = y\left(\frac{c(r+1)x^r}{2x\nu}\right)^{1/2}, \quad \theta(\eta) = \frac{T - T_\infty}{T_w - T_\infty}$$
$$v = -\left(\frac{c\nu(r+1)}{2}\right)^{1/2} x^{(r-1)/2}\left(f + \frac{(r-1)}{r+1}\eta f'\right), \tag{13}$$
$$\omega = x^{(3r-1)/2}\left(\frac{c^3(r+1)}{2\nu}\right)^{1/2} g(\eta),$$
$$\gamma = \left(\mu - \frac{\mu_r}{2}\right)j, \quad j = \left(\frac{\nu}{c}\right)x^{(1-r)}.$$

Then the resultant modeled equations becomes:

$$(1+K)f''' + ff'' + Kg' - 2\left(\frac{r+Fs}{r+1}\right)f'^2 - \left(\frac{2}{r+1}\right)(M+Da)f' = 0, \tag{14}$$

$$(1+K/2)g'' + fg' - \left(\frac{3r-1}{r+1}\right)f'g - K(2g+f'')\left(\frac{2}{r+1}\right) = 0, \tag{15}$$

$$\theta'' + Prf\theta' - \left(\frac{2n}{r+1}\right)Prf'\theta + (1+K)PrEcf''^2 + \left(\frac{2}{r+1}\right)MPrEcf'^2 + \left(\frac{2}{r+1}\right)PrDaEcf'^2 + \left(\frac{2}{r+1}\right)PrFsEcf'^3 + \left(\alpha f' + \beta\theta\right)\left(\frac{2}{r+1}\right) = 0, \tag{16}$$

While Eq. (11) transforms to:

$$\eta = 0: \ f' = 1, \ f = 0, \ g = -hf'', \ \theta = 1, \tag{17}$$

$$\eta \to \infty: \ f' = 0, \ g \to \infty, \ \theta \to \infty. \tag{18}$$

The differentiation is done with respect to η while the terms f, g and θ are respectively the dimensionless flow momentum, micropolar and temperature. The material (micropolar) term is $K = \frac{\mu_r}{\mu}$, the Darcy term is $Da = \frac{\nu}{cK_p^*}$, $Fs = \frac{F_0}{K_p^*}$ describes the Forchheimer term while $M = \frac{\sigma B_o^2}{\rho c}$ depicts the magnetic field term, $Pr = \frac{\mu Cp}{k_*}$ is the Prandtl number whereas α and β stands for the space dependent and heat source, $Ec = \frac{u_w^2}{Cp(T_w - T_\infty)}$ is the Eckert number.

3. Second thermodynamic law of entropy generation analysis

The entropy generation due to irreversibility in analysed using thermodynamic second law according to [26,36,37].

$$S_{Gen} = k_*\left(\frac{\nabla T}{T_\infty}\right)^2 + \frac{(\mu+\mu_r)}{T_\infty}\left(\frac{du}{dy}\right)^2 + \frac{\sigma B^2(x)}{T_\infty}u^2 + \frac{\mu}{K_p T_\infty}u^2 + \frac{F}{K_p T_\infty}u^3 \tag{19}$$

From Eq. (19), entropy production source includes entropy production due to heat transfer which is indicated by the first term on right of Eq. (19); the second is the entropy production due to viscous dissipation as a result of fluid friction while entropy generation due to Ohmic (Joule) heating is indicated by last terms. In the dimensionless form, Eq. (19) becomes

$$Ns = \frac{S_{Gen}}{S_0''} = \theta'^2 + \frac{Br}{\Omega}(1+K)f''^2 + \frac{Br}{\Omega}(M+Da)f'^2 + \frac{Br}{\Omega}Fsf'^3, \tag{20}$$

where Ns describes the overall entropy production in a system, $S_0'' = k_*\Omega^2 c/\nu$ describes the characteristic entropy production, $\Omega = \frac{T_w - T_\infty}{T_\infty}$ indicates the non-dimensional temperature difference and $Br = Pr \cdot Ec$ is the Brinkman number.

Similarly, it is quite essential to measure the significant contributions of the sources of entropy production in a system, in view of this, the Bejan number which measures the relative distribution of entropy production is described as

$$Be = \frac{N_H}{Ns} = \frac{N_H}{N_H + N_V + N_J}, \tag{21}$$

where Be is the Bejan number, N_H, N_V and N_J represent entropy production due to heat transfer, Joule heating and viscous dissipation in that order.

The Be number given in Eq. (21) lies in the interval $0 \le Be \le 1$. The dominance of the parameters $N_V + N_J$ over N_V is encountered when $Be = 0$, this implies that entropy production is due to heat transfer (N_H) is dominated by those of Joule heating and viscous dissipation $(N_V + N_J)$. On the other hand, $Be = 1$ signifies that generation of entropy due to thermal heat transport dominates that of viscous dissipation and Joule heating. In the situation when $Be = 0.5$, then entropy production due to heat transfer irreversibly and that of Joule heating and viscous dissipation are equal, that is $(N_H = N_V + N_J)$.

4. Results and discussion

The solution procedure for the heat transfer magneto-micropolar fluid and thermal irreversibility processes is numerically carried out using a stable, convergent shooting Runge-Kutta scheme with the help of Maple software for the analysis. Results comparison with other scholars results are presented in Tables 1 and 2, it shows a good degree of affinity with previous reports on the related studies. The

Table 1 Comparison of values of C_{fx} for variations in K, M, Da and Fs.

K	M	Da	Fs	Tripathy et al. [33]	Present
0.5	0.0	0.0	0.0	0.901878	0.901878
0.5	1.0	0.0	0.0	1.250358	1.250358
0.5	1.0	1.0	0.0	1.518062	1.518062
0.5	1.0	1.0	1.0	1.668701	1.668701
0.0	0.5	0.0	0.0	0.995088	0.995088
0.0	0.5	1.0	0.0	1.265126	1.265128
0.0	0.5	1.0	1.0	1.410952	1.410952
0.0	0.5	1.0	1.0	1.219616	1.219616

Table 2 Comparison of values of Nu_x for changes in Pr when $K = \lambda = M = Da = Fs = n = \alpha = \beta = 0$.

Ec	r	Hayat [34] $Pr = 1$	Present $Pr = 1$	Hayat [34] $Pr = 5$	Present $Pr = 5$
0.0	0.2	0.61020	0.61021	0.60792	1.60778
	0.5	0.59520	0.59522	0.58683	1.58678
	1.5	0.57473	0.57477	0.55767	1.55769
	3.0	0.56447	0.56471	0.54214	1.54318
	10.0	0.55496	0.55495	0.52886	1.52893

used solution techniques agreed well with an absolute error of order 10^{-7}.

4.1. Parameters dependent thermal micropolar fluid solutions

The impact of raising the values of magnetic term M with changes in the material term K is presented in Figure 2. At various values of M, the velocity of the fluid is encouraged as the material term varies. The fluid microstructure particles collided faster due to diminish in the micropolar fluid viscosity that in turn raises the overall magnitude of the flow momentum. Hence, the flow is enhanced with variation in the term K. Figure 3 denotes the response of a micropolar fluid to rising in the stretching terms r and Darcy term Da. Darcy porosity term resists the flow rate by tightening the medium pores and decreases the heat source terms while the term r enhances velocity field by opposing the microstructure bonding force that may slow down the flow rate.

Figures 4 and 5 show the reaction of micropolar liquid to respective rises in the Darcy term Da and material parameter K for different values of M. The fluid particle microstructure gyration is enhanced as the term Da rises but, dampen with a rise in the term K under various magnetic term M. Without particles micro stretch, respective rise and decrease in the inclusive polar liquid in noticed for variational augment in the Darcy and material terms. Hence, Darcy term boosted the micropolar distribution, but the liquid microstructure distribution is declining with increasing material term.

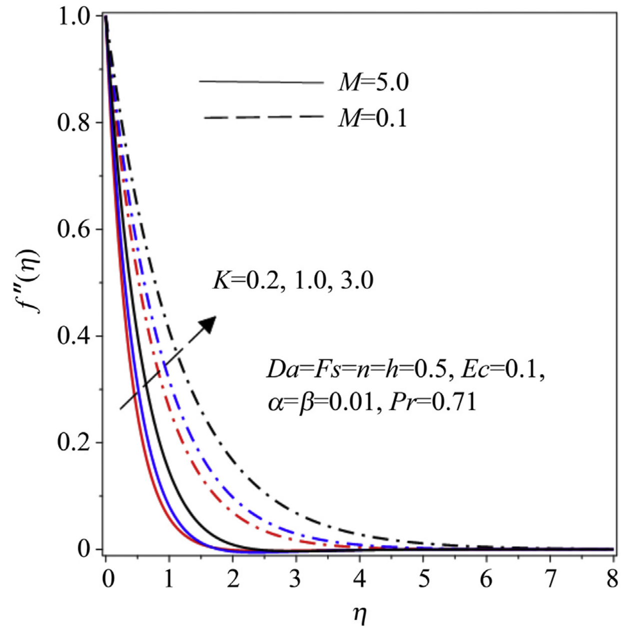

Figure 2 Effect of rise in M and K.

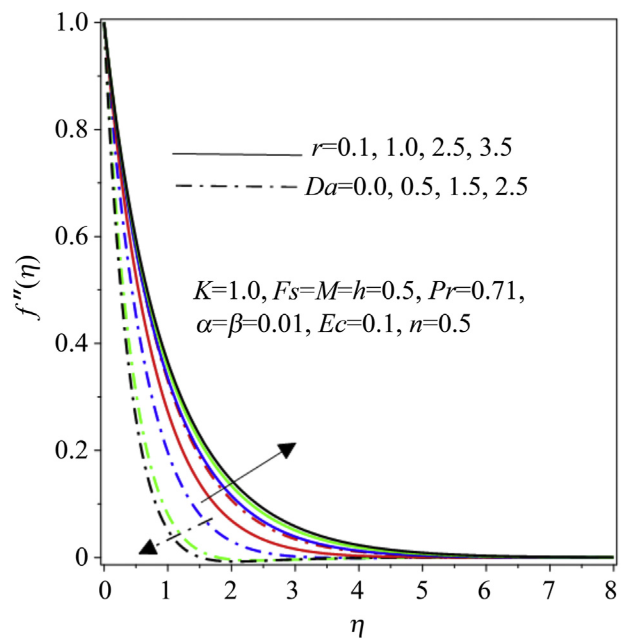

Figure 3 Velocity field for rising r and Da.

Figure 6 depicts the impact of space dependent α and heat power law n on the temperature field. The term α that denotes the microstructure space dependent improves heat transport profile while the boundary thermal power law n reduces heat distribution of gyrated fluid particles in a porous saturated medium. Heat distributions for different numbers of Eckert Ec and Prandtl Pr are illustrated in Figure 7. Variation in the heat dissipation term raises the magnitude of heat field in the system due to consistence increase in the heat boundary layer that reduces viscous dissipation process. The term Pr encourages loss of heat to the surroundings as a result of

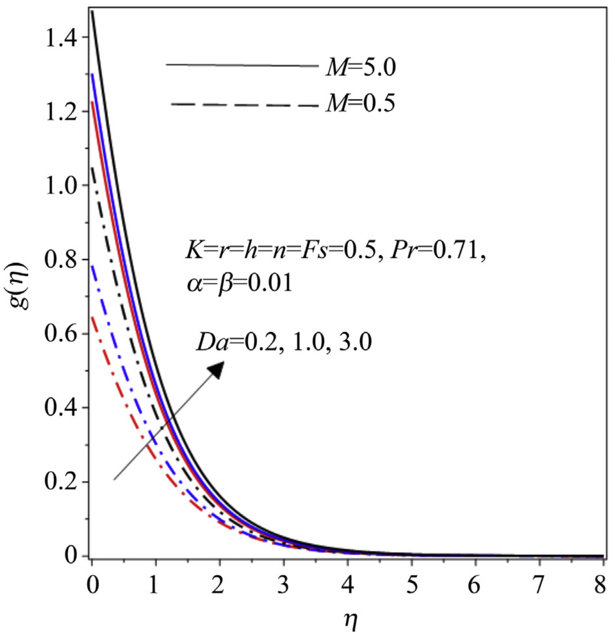

Figure 4 Rise in M and Da on micropolar.

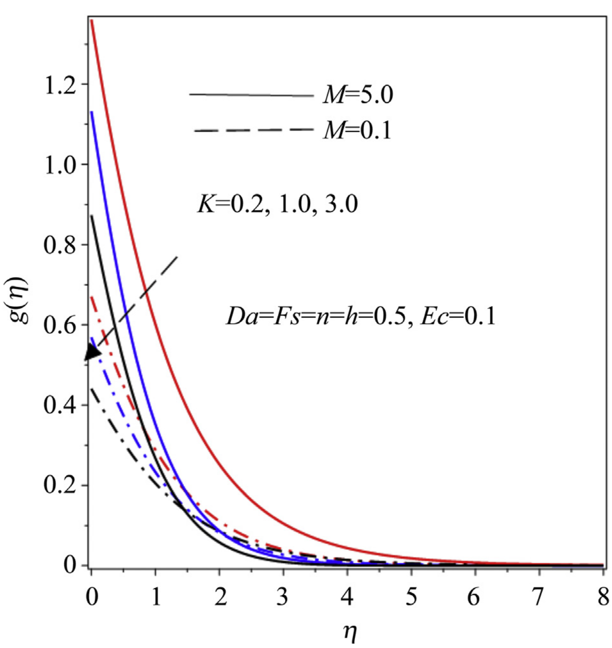

Figure 5 Effect of M and K on micropolar.

strictness and thinner in the temperature boundary layer that result to declination in the heat field.

4.2. Parameters dependent irreversibility analysis solutions

Irreversibility is a thermodynamics concept that occurs when there is an infinitesimal change of state without energy dissipation in thermodynamic systems and its environments.

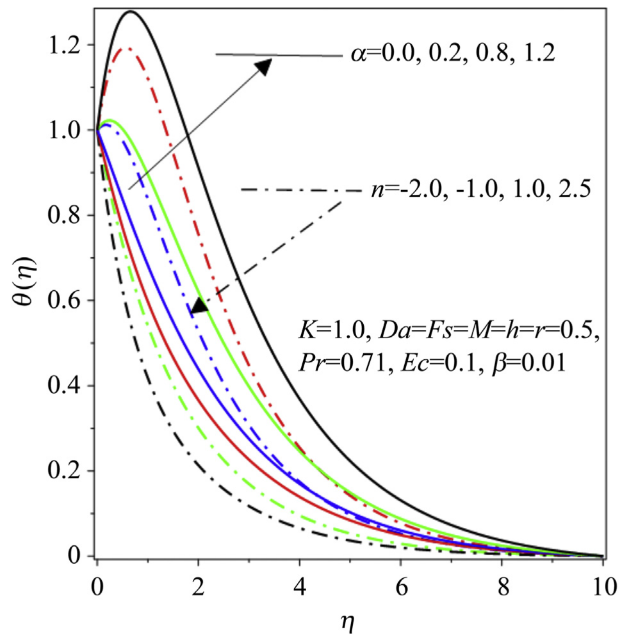

Figure 6 Heat field for rise in α and n.

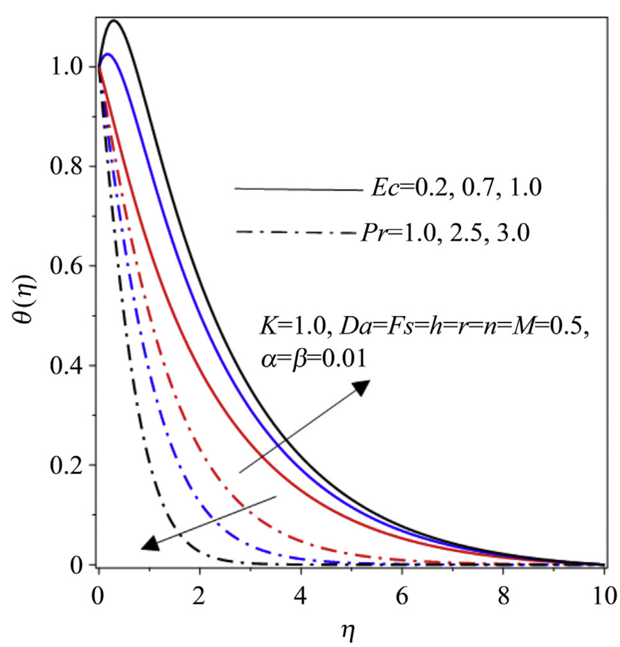

Figure 7 Effect of Ec and Pr on heat field.

Irreversibility process encourages the entropy generation in a thermal system and other devices. Figures 8 and 9 describe the entropy generation in a heat transfer magneto-micropolar fluid system. It is seen that the material term K and parameters ratio Br/Ω increases the fluid microscopic configurations entropy generation. Optimization of the fluid microstate entropy production is obtained at lower moving plate, it continues to rise until it gets to the peak of the plate. The entropy generation due

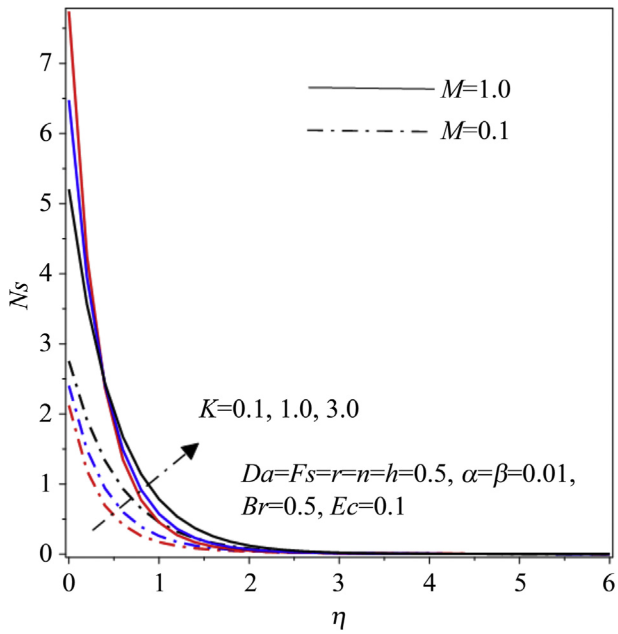

Figure 8 Entropy field for rise in M and K.

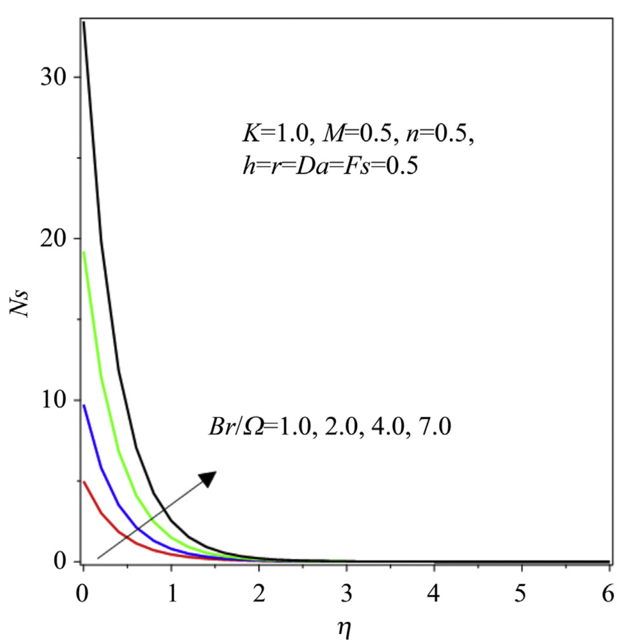

Figure 9 Entropy field for rising Br/Ω.

to ohmic and viscous heating then gradually reduces towards the free steady microstructure gyration stream state. In Figures 10 and 11, the influence of rising in the term K for various magnetic term and parameters ratio Br/Ω on the Bejan number is presented. Bejan number defined the ratio of heat transfer to the total heat transfer and liquid viscosity irreversibility in a thermodynamics system. Both terms enhance the irreversibility ratio in a magneto-micropolar saturated porous fluid medium.

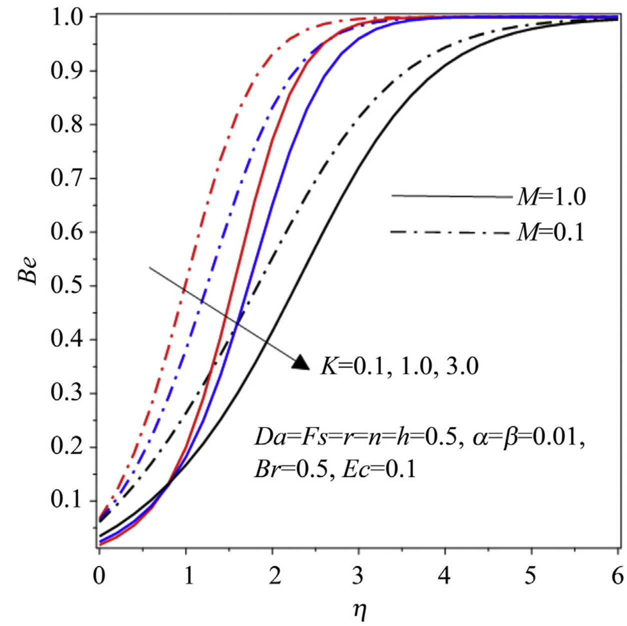

Figure 10 Bejan field for various M and K.

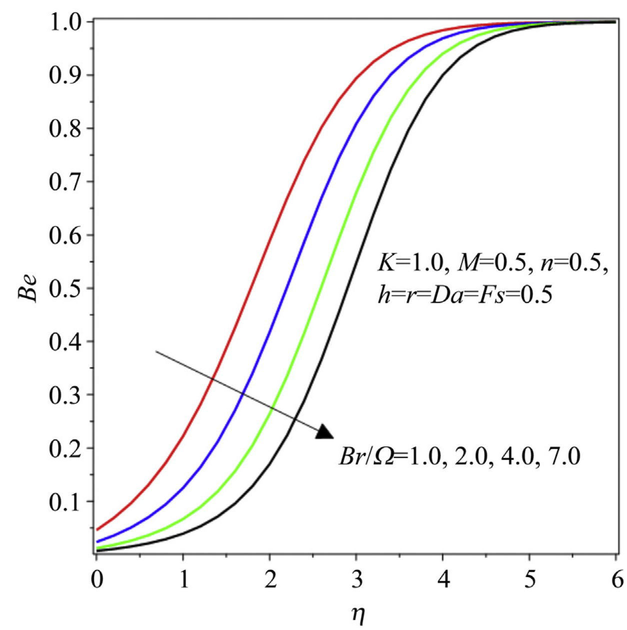

Figure 11 Bejan profile for rising Br/Ω.

5. Conclusion

Computational investigation into the thermodynamic second law analysis of magneto-micropolar fluid flow past nonlinear porous saturated media with non-homogenous internal heat source is considered. The heat dependent gyrating microscopic fluid particles with power law surface temperature is rigid and not deformed. It is obtained from study that the terms that encourage internal heat source reduces the micropolar fluid viscosity but incline the energy and microstructure distribution in the system. Also, entropy generation and irreversibility ratio are augmented by same parameters. Therefore, to enhance system efficiency, entropy generation needs to be minimized by improving the system thermodynamic equilibrium through viscosity, hysteresis magnetic and material term value reduction. Hence, this study results can help in the perceptive bond between energy conservation and machines efficiency. This work can be extended by considering the unsteady state and the industrial combustion process of micropolar fluid.

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