Hall Current and Joule Heating Effects on Flow of Couple Stress Fluid with Entropy Generation

Abiodun A. Opanuga
Department of Mathematics
Covenant University
Ota, Nigeria
abiodun.opanuga@covenantuiversity.edu.ng

Hilary I. Okagbue
Department of Mathematics
Covenant University
Ota, Nigeria
hilary.okagbue@covenantuiversity.edu.ng

Sheila A. Bishop
Department of Mathematics
Covenant University
Ota, Nigeria
sheila.bishop@covenantuiversity.edu.ng

Olasunmbo O. Agboola
Department of Mathematics
Covenant University
Ota, Nigeria
ola.agboola@covenantuiversity.edu.ng

***Abstract*—In this work, an analytical study of the effects of Hall current and Joule heating on the entropy generation rate of couple stress fluid is performed. It is assumed that the applied pressure gradient induces fluid motion. At constant velocity, hot fluid is injected at the lower wall and sucked off at the upper wall. The obtained equations governing the flow are transformed to dimensionless form and the resulting nonlinear coupled boundary value problems for velocity and temperature profiles are solved by Adomian decomposition method. Analytical expressions for fluid velocity and temperature are used to obtain the entropy generation and the irreversibility ratio. The effects of Hall current, Joule heating, suction/injection and magnetic field parameters are presented and discussed through graphs. It is found that Hall current enhances both primary and secondary velocities and entropy generation. It is also interesting that Joule heating raises fluid temperature and encourages entropy production. On the other hand Hartman number inhibits fluid motion while increase in suction/injection parameter leads to a shift in flow symmetry.**

Keywords-Hall current; Joule heating; entropy generation; couple stress fluid; Adomian decomposition method

I. INTRODUCTION

The study of hydromagnetic flow has been extensively investigated in the past years due to its applications in MHD generators, flow control, shock damping in car absorbers, nuclear reactors, plasma studies, purifications of metal from non-metal enclosures, geothermal energy extractions, polymer technology and metallurgy. Relevant investigation was pioneered in the first half of the twentieth century. Thereafter several studies have been conducted. Author in [1] investigated the spontaneous magnetic field in a conducting liquid in turbulent motion. In [2], magnetohydrodynamics at high Hartmann numbers were investigated. Author in [3] considered the effect of a uniform magnetic field on the Eckman layer over an infinite horizontal plate at rest relative to an electrically conducting liquid rotating with uniform angular velocity about a vertical axis while authors in [4] analyzed the combined effect of free and forced convection on MHD flow in a rotating porous channel, authors in [5] investigated the radiation effect of magnetohydrodynamics flow of gas between concentric spheres. In [6], authors considered the radiative effect on velocity, magnetic and temperature fields of a magnetohydrodynamic oscillatory flow past a limiting surface with variable suction In [7], author considered the hydromagnetic natural convection flow between vertical parallel plates with time-periodic boundary conditions, Authors in [8] studied convection heat and mass transfer in a hydromagnetic flow of second grade fluid in the presence of thermal radiation and thermal diffusion. In the studies above where the effect of magnetic field is reported, small and moderate values of the magnetic field are assumed. However, the current trend of research is geared toward a strong magnetic field and a low density gas due to its numerous applications such as in space flight, nuclear fusion research, magnetohydrodynamic generators, refrigeration coils, electric transformers, Hall accelerators and biomedical engineering (e.g. cardiac MRI and ECG). Hall current occurs when the applied magnetic field is very strong or gas is ionized with low density leading to a reduction in conductivity normal to the magnetic field, as a result of the free spiraling of electrons and ions around the magnetic lines of force before collisions. This then induces a current in the direction of both electric and magnetic fields. This is referred to as Hall effect, the induced current is called Hall current [9-15].

In this study, the Hall current and Joule heating effects on the flow of couple stress fluid with entropy generation is considered. The study is essential due to the fact that entropy generation occurs in moving fluid with high temperature which can lead to loss of resources and effort if the inherent irreversibility in the fluid flow is not well addressed. Authors in

[16] submitted that all processes that produce, convert and consume energy must be re-examined very carefully and all available-work destruction mechanisms must be removed. To the best of our knowledge similar study has not yet been reported in literature, although various factors responsible for the entropy production have been studied, for instance in [17] authors considered effects of velocity slip and temperature jump on the entropy generation in MHD flow over a porous rotating disk. Also, authors in [18] presented entropy generation on MHD nanofluid blood flow due to peristaltic waves. Recently, authors in [19] studied the thermodynamic analysis of hydromagnetic third grade fluid flow through a channel filled with porous medium. In [20], the effect of thermal radiation on the entropy generation of hydromagnetic flow through porous channel was investigated. More studies on the factors responsible for entropy production are reported in [21-26]. Several techniques such as Homotopy perturbation [27], differential transform method [28-29], variational iteration technique [30], finite difference technique [31] etc. are available in literature. However, the Adomian decomposition method is applied in this work due to its simplicity in application and rapid convergence, (see Tables I and II). Furthermore, the method has been used to analyze various linear and nonlinear problems such as the fractional-order differential equations [32], the time dependent Edem–Fowler type equation [33], the Navier–Stokes equations [34], the evolution model [35], the Flierl–Petviashivili equation [36], the fourth-order wave equation [37], the peristaltic transport model [38], the Fokker–Planck equation [39] and the Bratu's problem [40].

II. PROBLEM FORMULATION

Fully developed, steady, incompressible and electrically conducting couple stress fluid between two parallel plates of distance *h* apart has been investigated. The coordinate system is taken such that the x-axis is along the lower plate in the flow direction, the y-axis is normal to the xy-plane while z-axis is made perpendicular to the plates. A constant pressure gradient is induced along the x-direction. Hot fluid is injected into the channel wall at the lower plate and sucked off at the upper plate with the same velocity. Following [41], the generalized Ohm's law with Hall current is

$$J+\frac{\omega_e\tau_e}{B_0}(J\times B)=\sigma(E\times q\times B) \quad (1)$$

It is further assumed that if (j_x, j_y, j_z) are the components of the current density J, the equations of conservation of electric charge $\nabla\cdot J=0$ shows that j_z is constant which is assumed to be zero because $j_z=0$ at the plates which are electrically non-conducting. It then implies that $j_z=0$, everywhere in the flow. Furthermore, the electrical field $E=0$ [42]. Following the given assumptions, (1) becomes:

$$j_x+mj_y=\sigma wB_0 \quad (2)$$

$$j_y-mj_x=-\sigma uB_0 \quad (3)$$

Note that $m=\omega_e\tau_e$ represents the Hall parameter. Solving (2) and (3) for j_x and j_y gives:

$$j_x=\frac{\sigma B_0}{1+m^2}\left(w+mu\right) \quad (4)$$

$$j_y=\frac{\sigma B_0}{1+m^2}\left(mw-u\right) \quad (5)$$

The governing equations for the flow following [43-44] are:

Momentum equation along axis x:

$$\rho v_\circ\frac{du^*}{dy^*}=-\frac{dp}{dx}+\mu\frac{d^2u^*}{dy^{*2}}-\eta\frac{d^4u^*}{dy^{*4}}-\frac{M^2}{1+m^2}\left(u^*-mw^*\right);$$
$$u^*(0)=\frac{d^2u^*}{dy^{*2}}(0)=0=u^*(h)=\frac{d^2u^*}{dy^{*2}}(h), \quad (6)$$

Momentum equation along axis y:

$$\rho v_\circ\frac{dw^*}{dy^*}=\mu\frac{d^2w^*}{dy^{*2}}-\eta\frac{d^4w^*}{dy^{*4}}-\frac{M^2}{1+m^2}\left(w^*+mu^*\right);$$
$$w^*(0)=\frac{d^2w^*}{dy^2}(0)=0=w^*(h)=\frac{d^2w^*}{dy^2}(h), \quad (7)$$

Energy equation**:**

$$\rho c_pv_0\frac{dT^*}{dy^*}=k\frac{d^2T^*}{dy^{*2}}+\mu\left[\left(\frac{du^*}{dy^*}\right)^2+\left(\frac{dw^*}{dy^*}\right)^2\right]+$$
$$\eta\left[\left(\frac{d^2u^*}{dy^{*2}}\right)^2+\left(\frac{d^2w^*}{dy^{*2}}\right)^2\right]+\lambda\sigma B_0^2\left(w^{*2}+u^{*2}\right); \quad (8)$$
$$T^*(0)=T^*(h)=0.$$

Introducing the following dimensionless variables,

$$y=\frac{y^*}{h},u=\frac{u^*}{v_0},w=\frac{w^*}{v_0},\theta=\frac{T^*-T_0}{T_h-T_0},G=-\frac{h^2}{\mu v_0}\frac{dP}{dx}$$
$$a=\mu\frac{h^2}{\eta},v=\frac{\mu}{\rho},\Omega=\frac{T_h-T_0}{T_0},s=\frac{v_0h}{v}, \quad (9)$$

Equations (6), (7) yield the following dimensionless form;

$$s\frac{du}{dy}=G+\frac{d^2u}{dy^2}-\frac{1}{a^2}\frac{d^4u}{dy^4}-\frac{M^2}{1+m^2}\left(u-mw\right),$$
$$u(0)=\frac{d^2u}{dy^2}(0)=0=u(1)=\frac{d^2u}{dy^2}(1), \quad (10)$$

$$s\frac{dw}{dy}=\frac{d^2w}{dy^2}-\frac{1}{a^2}\frac{d^4w}{dy^4}-\frac{M^2}{1+m^2}\left(w+mu\right), \quad (11)$$
$$w(0)=\frac{d^2w}{dy^2}(0)=0=w(1)=\frac{d^2w}{dy^2}(1),$$

$$\frac{d^2\theta}{dy^2}=sp_r\frac{d\theta}{dy}-Br\left[\left(\frac{du}{dy}\right)^2+\left(\frac{dw}{dy}\right)^2\right]+$$
$$\frac{Br}{a^2}\left(\left(\frac{d^2u}{dy^2}\right)^2+\left(\frac{d^2w}{dy^2}\right)^2\right)+\lambda Jh\left(u^2+w^2\right); \quad (12)$$
$$\theta(0)=0,\theta(1)=1.$$

where

$$\Pr = \frac{\nu \rho c_p}{k}, Br = \frac{\mu v_0^2}{k(T_h - T_\circ)}, Ns = \frac{T_\circ^2 h^2 E_G}{k(T_h - T_\circ)^2}, \quad (13)$$
$$Jh = BrM^2, M^2 = \frac{\sigma B_0^2 h^2}{\mu}.$$

III. ADOMIAN DECOMPOSITION

The Adomian decomposition method is applied by writing (10), (11) and (12) in integral form as:

$$u(y) = b_1 y + \frac{b_2}{3!} y^3 - \int_0^y\int_0^y\int_0^y\int_0^y \left\{ s\frac{du}{dY} - G - \frac{d^2u}{dY^2} + \frac{M^2}{1+m^2}\left(u - mw\right) \right\} dYdYdYdY, \quad (14)$$

$$w(y) = f_1 y + \frac{f_2}{3!} y^3 - \int_0^y\int_0^y\int_0^y\int_0^y \left\{ s\frac{dw}{dY} - \frac{d^2w}{dY^2} + \frac{M^2}{1+m^2}\left(w + mu\right) \right\} dYdYdYdY, \quad (15)$$

and

$$\theta(y) = b_3 + b_4 y - \int_0^y\int_0^y \left\{ \begin{array}{l} s\Pr\dfrac{d\theta}{dy} - Br\left(\dfrac{du}{dy}\right)^2 + \left(\dfrac{dw}{dy}\right)^2 + \\ \dfrac{Br}{a^2}\left(\left(\dfrac{d^2u}{dy^2}\right)^2 + \left(\dfrac{d^2w}{dy^2}\right)^2\right) + \\ \lambda Jh\left(u^2 + w^2\right) \end{array} \right\} dYdY. \quad (16)$$

Using the partial sum in (17) and the Adomian polynomials for the non-linear terms in (18), (14)-(16) yield (19)-(21). The final stage for the implementation of ADM is the coding of equations (19)-(21) in symbolic Mathematica software, which yields a very large symbolic solution.

$$u(y) = \sum_{n=0}^{\infty} u_n(y), \quad w(y) = \sum_{n=0}^{\infty} w_n(y),$$
$$\theta(y) = \sum_{n=0}^{\infty} \theta_n(y), \quad (17)$$

$$\left.\begin{array}{l} A_n = u^2 : A_0 = u_0^2, A_1 = 2u_0u_1, A_2 = u_1^2 + 2u_0u_2 \\ B_n = w^2 : B_0 = w_0^2, B_1 = 2w_0w_1, B_2 = w_1^2 + 2w_0w_2 \end{array}\right\}. \quad (18)$$

$$\sum_{n=0}^{r} u_n(y) = b_1 y + \frac{b_2}{3!} y^3 - \int_0^y\int_0^y\int_0^y\int_0^y \left\{ s\frac{du}{dY} - G - \frac{d^2u}{dY^2} + \frac{M^2}{1+m^2}\left(u - mw\right) \right\} dYdYdYdY, \quad (19)$$

$$\sum_{n=0}^{r} w_n(y) = f_1 y + \frac{f_2}{3!} y^3 - \int_0^y\int_0^y\int_0^y\int_0^y \left\{ s\frac{dw}{dY} - \frac{d^2w}{dY^2} + \frac{M^2}{1+m^2}\left(w + mu\right) \right\} dYdYdYdY, \quad (20)$$

$$\sum_{n=0}^{r} \theta_n(y) = b_3 + b_4 y - \int_0^y\int_0^y \left\{ \begin{array}{l} s\Pr\dfrac{d\theta}{dy} - Br\left(\dfrac{du}{dy}\right)^2 + \left(\dfrac{dw}{dy}\right)^2 + \\ \dfrac{Br}{a^2}\left(\left(\dfrac{d^2u}{dy^2}\right)^2 + \left(\dfrac{d^2w}{dy^2}\right)^2\right) + \\ \lambda J\left(A_n + B_n\right) \end{array} \right\} dYdY. \quad (21)$$

A. Results Verification

The approximate solution obtained by ADM can be verified by comparing our result and the one in [44] as displayed in Table I.

B. Entropy Generation Analysis

The local entropy generation expression [35] for the flow is given as

$$E_G = \frac{k}{T_0^2}\left(\frac{dT^*}{dy^*}\right)^2 + \frac{\mu}{T_0}\left(\left(\frac{du^*}{dy^*}\right)^2 + \left(\frac{dw^*}{dy^*}\right)^2\right) + \frac{\eta}{T_0}\left(\left(\frac{d^2u^*}{dy^{*2}}\right)^2 + \left(\frac{d^2w^*}{dy^{*2}}\right)^2\right) + \lambda\frac{\sigma B_0^2}{T_0 \rho v}\left(w^{*2} + u^{*2}\right) \quad (22)$$

Using (9) in (22) yields

$$Ns = \left(\frac{d\theta}{dy}\right)^2 + \frac{Br}{\Omega}\left(\left(\frac{du}{dy}\right)^2 + \left(\frac{dw}{dy}\right)^2\right) + \frac{Br}{\Omega a^2}\left(\left(\frac{d^2u}{dy^2}\right)^2 + \left(\frac{d^2w}{dy^2}\right)^2\right) + \frac{\lambda Jh}{\Omega}\left(w^2 + u^2\right) \quad (23)$$

Entropy generation within the flow can be analysed by letting

$$N_1 = \left(\frac{d\theta}{dy}\right)^2, N_2 = \frac{Br}{\Omega}\left(\left(\frac{du}{dy}\right)^2 + \left(\frac{dw}{dy}\right)^2\right) + \frac{Br}{\Omega a^2}\left(\left(\frac{d^2u}{dy^2}\right)^2 + \left(\frac{d^2w}{dy^2}\right)^2\right) + \frac{\lambda Jh}{\Omega}\left(w^2 + u^2\right) \quad (24)$$

If Bejan number (*Be*) is less than one-half, irreversibility due to viscous dissipation dominates entropy generation and when (*Be*) is greater than one-half irreversibility due to heat transfer dominates the fluid flow. Bejan number (*Be*) equal to one-half indicates that both contribute equally to entropy generation. The Bejan number can be written as

$$Be = \frac{N_1}{N_s} = \frac{1}{1+\Phi}, \quad \Phi = \frac{N_2}{N_1}. \qquad (25)$$

TABLE I. RESULTS FOR VELOCITY PROFILES

G=1, s=0.1,α=1, M=0		[44]	
S/N	U_{ADM}	U_{EXACT}	U_{ADM}
0	0	-3.91321×10^{-14}	0
0.1	0.003714182	0.00371418	0.00371418
0.2	0.007024039	0.00702404	0.00702404
0.3	0.009612623	0.00961262	0.00961262
0.4	0.011255559	0.0112556	0.0112556
0.5	0.011818879	0.0118189	0.0118189
0.6	0.011257781	0.0112578	0.0112578
0.7	0.009616293	0.00961629	0.00961629
0.8	0.007027825	0.00702782	0.00702783
0.9	0.003716603	0.0037166	0.0037166
1	2.202672×10^{-11}	-3.91321×10^{-14}	-7.66586×10^{-18}

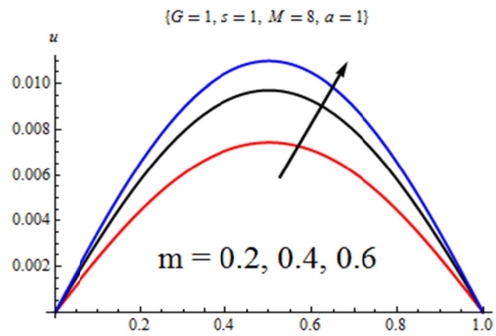
TABLE II. RESULTS (EXACT SOLUTION) FOR VELOCITY PROFILES $G=1, s=0.1, \alpha=1, M=0$

S/N	U_{EXACT}	U_{ADM}	
0	6.94E-15	0	6.94E-15
0.1	0.003714182	0.00371418	1.20E-12
0.2	0.007024039	0.00702404	2.22E-12
0.3	0.009612623	0.00961262	2.91E-12
0.4	0.011255559	0.01125556	3.05E-12
0.5	0.011818879	0.01181888	2.44E-12
0.6	0.011257781	0.01125778	8.78E-13
0.7	0.009616293	0.00961629	1.87E-12
0.8	0.007027825	0.00702782	6.13E-12
0.9	0.003716603	0.0037166	1.22E-11
1	9.98E-15	2.0267E-11	2.03E-11

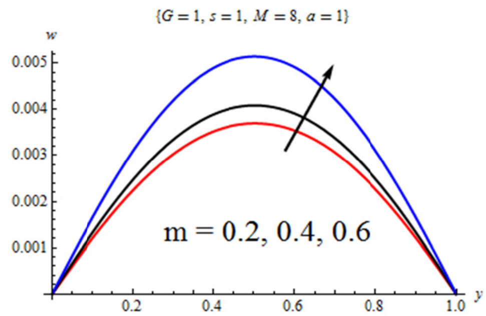
IV. RESULTS AND DISCUSSION

This section presents results of the analysis as plots in Figures 1-13 by fixing parameters Pr=0.71, m=0.5, Jh=2, G=1, Br=0.5. To explain the effect of Hall current (m), Joule heating (J), suction/injection (s) and magnetic (M) parameters on velocity profile, the non-dimensional velocity u and w against y is presented in Figures 1 to 3. Figures 1(a) and 1(b) illustrate the influence of Hall current on fluid velocity. It is apparent from these figures that fluid motion is enhanced as hall current increases. This is due to the fact that Hall current reduces the effect of the Lorentz resistive force imposed by the applied magnetic field on fluid motion. Figures 2(a) and 2(b) demonstrate that fluid motion accelerates at the lower wall, the trend is reversed at the upper wall with injection as suction/injection parameter ($s>0$) increases, this indicates a shift in flow symmetry.

In Figures 3(a) and 3(b), magnetic effect on fluid velocity is displayed. We can see that fluid motion is inhibited, this is due to the fact that application of transverse magnetic field usually generates a resistive type of force called Lorentz force that retards fluid flow. The response of temperature profile to the variation in Hall parameter, Joule heating and magnetic parameter is depicted in Figures 4-6. In Figure 4, fluid temperature is reduced for different values of Hall parameter, however Hall current does not have much significant effect on fluid temperature.

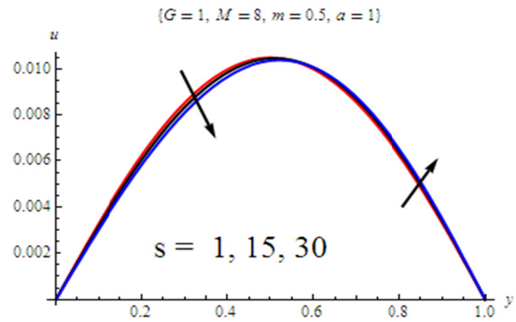


(a)

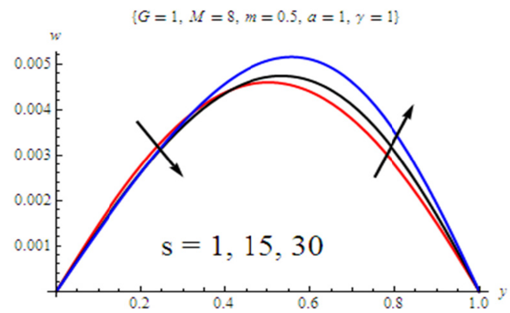


(b)

Fig. 1. (a) Primary velocity profile and (b) Secondary velocity profile, for different m

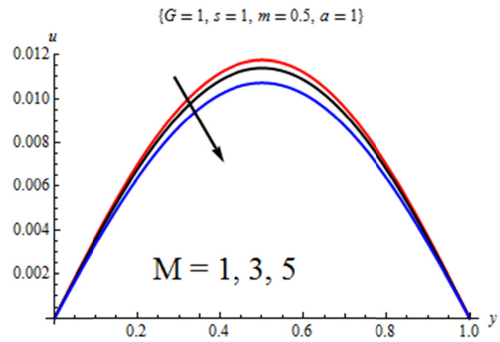


(a)

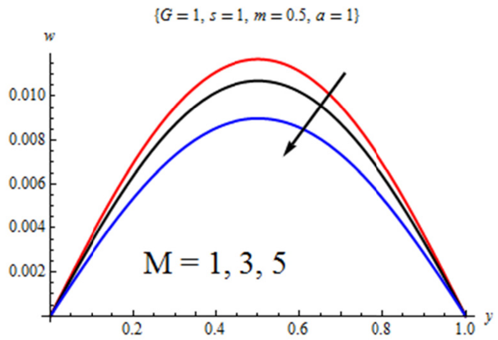


(b)

Fig. 2. (a): Primary velocity profile and (b) Secondary velocity profiles for for different s



(a)



(b)

Fig. 3. (a) Primary velocity profile and (b) Secondary velocity profile for different M

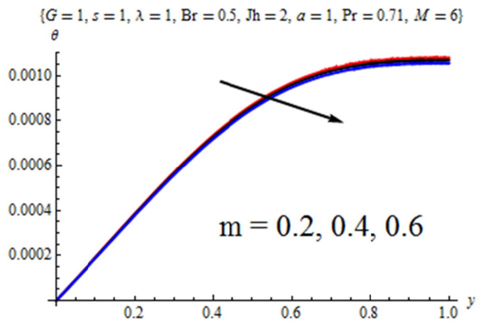


Fig. 4. Temperature profile for different m

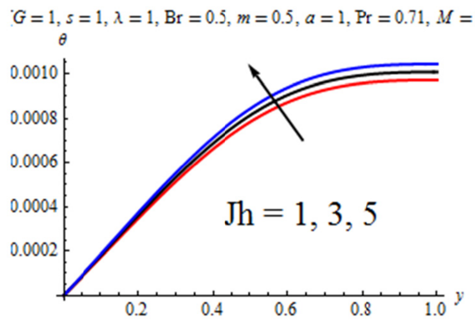


Fig. 5. Temperature profile for different J

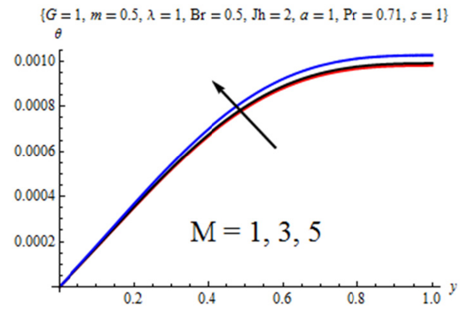


Fig. 6. Temperature profile for different M

Figure 5 demonstrates that fluid temperature rises with increase in the Joule heating parameter. Figure 6 depicts the effect of varying values of magnetic field parameter on fluid temperature. It is observed that temperature is enhanced as magnetic field increases, due to the increase in fluid viscous heating which enhances transfer of heat to the boundaries. Figures 7-9 represent the influence of Hall current, Joule heating and suction/injection parameters on the entropy generation. Entropy generation is enhanced with the increase in Hall current and Joule heating parameters as depicted in Figures 7-8. Joule heating is the product of Brinkman number and Hartman number, increase in the parameters result in the corresponding rise in entropy generation. In Figure 9, increase in suction/injection parameter retards fluid flow at plate y = 0 while opposite trend is observed at plate y = 1. This phenomenon is attributed to the change in flow symmetry reported in Figures 2a and 2b.

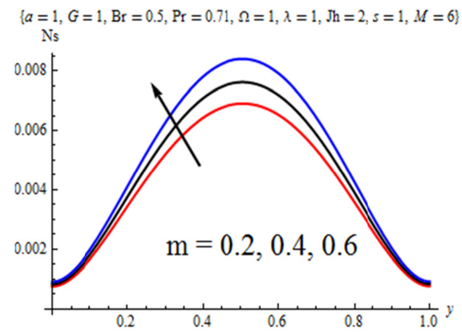


Fig. 7. Entropy generation for different m

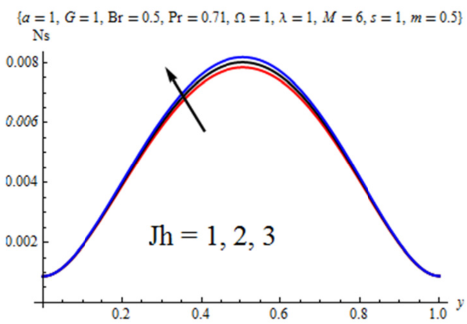


Fig. 8. Entropy generation for different J

Finally, the influence of Hall current, Joule heating, suction/injection and magnetic parameters on Bejan number are displayed in Figures 10–13. Figures 10 and 13 reveal that Bejan number reduces as the values of Hall current and suction/injection parameters vary while the trend is reversed as Joule heating and magnetic parameters increase. It is concluded that both viscous dissipation and heat transfer contribute to entropy generation.

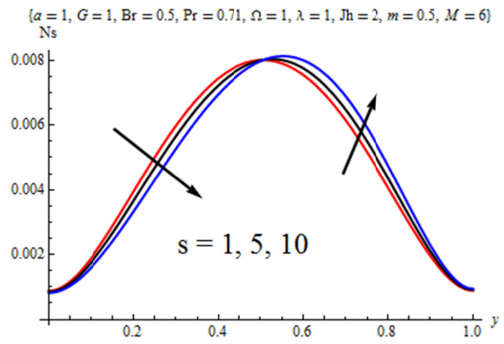


Fig. 9. Entropy generation profile for different s

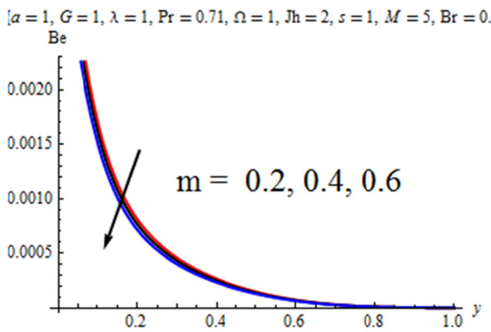


Fig. 10. Bejan number for different m

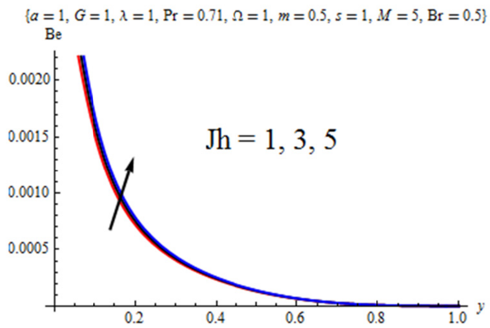


Fig. 11. Bejan number for different J

V. Conclusion

An analytical investigation of the effects of hall current and Joule heating on entropy generation of a couple stress fluid has been conducted. The governing equations were obtained, nondimensionalised and solved using Adomian decomposition technique. The solution obtained is used to compute entropy generation and irreversibility ratio. Plots are presented to explain the physics of the flow.

From the results it is concluded that:

- Hall current increases fluid velocity and entropy generation while the temperature and Bejan number are reduced.
- Increase in Joule heating parameter enhances fluid temperature, entropy generation and Bejan number.
- Hartman number retards fluid flow, increases fluid temperature and Bejan number.
- Both viscous dissipation and heat transfer contributes to entropy generation.

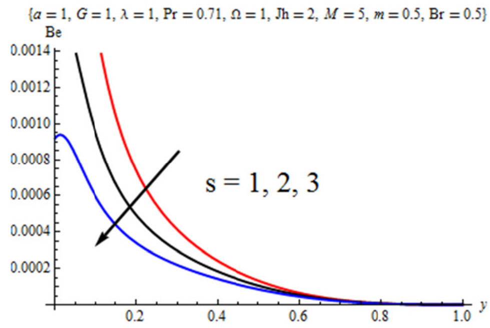


Fig. 12. Bejan number for different s

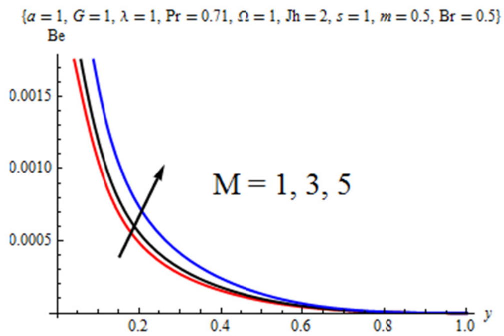


Fig. 13. Bejan number for different M

Nomenclature

u'	velocity component along x-axis
w'	velocity component along y-axis
μ	dynamic viscosity
p	fluid pressure
T'	fluid temperature
T_0	initial fluid temperature
k	thermal conductivity of the fluid
Br	Brinkman number
G	dimensionless pressure gradient
θ	dimensionless temperature
u, w	the dimensionless velocities
v_0	constant velocity of fluid suction/injection
s	suction/injection parameter

	(s>0 is suction and s<0 is injection)
v	kinematic viscosity
N_S	dimensionless entropy generation rate
Be	Bejan number
E_G	entropy generation parameter
Ω	temperature difference parameter
C_p	specific heat at constant pressure
η	fluid particle size effect due to couple stresses
h	channel width
ρ	fluid density
B_0	uniform transverse magnetic field
M	magnetic field parameter
Jh	Joule heating parameter
a	couple stress parameter
Pr	Prandtl number
m	Hall current parameter

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