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Magnetohydrodynamics Micropolar Boundary Layer Flow Past a Stretching Sheet with Microstructural Slip Heat Generation with Convective Boundary Condition

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ABSTRACT

The formulation depicting the magnetohydrodynamics MHD boundary layer of a micropolar fluid on a moving sheet with heat generation and convective boundary conditions in its rectangular form is presented. The PDEs formulated are transformed into nonlinear ODEs via the stream functions and appropriate similarity variables. The solution to the nonlinear coupled equations were presented in decomposed form. The comparison of skin friction values with literatures for validation were carried out and an agreement depicted. The implications of dimensionless physical parameters that appear in this work are graphically studied in the presence of microstructural slip. Physical parameters such as Biot number and heat generation parameters are found to enhance the fluid temperature profile.

Keywords: Micropolar fluid, Heat generation parameter, Microstructural slip, Magnetohydrodynamics (MHD), Adomian Decomposition method (ADM), Boundary layer.

Introduction

Fluids such as Micropolar are in the class of fluids that has the habit of some specific microscopic effects as a result of the micro element motion. These particular fluids are mostly non-Newtonian because they consist of some micro-constituents that are able to rotate in other to interfere with the hydrodynamics. Thermomicropolar fluids were considered so as to extend the theory of micropolar fluid by Eringen (1972). The similarity solution of boundary layer flow close to stagnation point of a micropolar fluid was presented by Ebert (1973). Karwe and Jaluria (1988), the study of mixed convective micropolar fluid over a flat curvy surface has received a significant attention by various researches due to it wide applicability in heat transfer of a micro polar fluids. Aiyesimi *et al.* (2013) presented boundary layer flow of MHD micro polar fluids over a flat moving surface in a non-Dacian medium with variable permeability and magnetic parameter was found to reduce the fluid velocity. He and Choi (2017) depicted the influence of temperature jump and velocity slip on

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boundary layer flow over a flat surface. They observe that slip velocity and temperature jump can lead to turbulent flow from earlier laminar flow. Xinnui *et al.* (2017) show the influence of slip-velocity on MHD non-Newtonian fluid on stretched surface. Hosseini *et al*. (2017) iteratively presented unsteady heat transfer boundary layer flow with velocity slip over a porous moving surface. Daniel *et al.* (2017) theoretically gave the analysis of velocity slip over MHD nanofluid on a stretching/shrinking sheet. In the first results presented the fluid velocity, temperature and nano solutal boundary thickness is less than the second result and it was found to be more robust relative to the second result. It was also reported that heat and mass convective boundary conditions are enhanced by the fluid temperature and nanoparticle distribution profiles. Oudina *et al.* found that heat is magnetized Newtonian nanoliquids between vertical cylinders. They reported that increase in porosity, nanoparticle, concentration, Rayleigh number, Darcy number and length enhances the natural convection. Theoretical works in transfer of heat with mixed convective micropolar and slip condition was presented by Mahmoud and Waheed (2010).

Several Researchers such as Suleiman and Yusuf (2020), Yusuf *et al.* (2021a), Yusuf *et al.* (2021b), Bolarin *et al.* (2019), Yusuf *et al.* (2019) have all affirmed the usefulness of a domain decomposition method in obtaining the solution of problems governed by boundary layers.

The adoption of Adomian decomposition method to solve the problem formulated in this work is a new advancement in the literature.

Problem Formulation

The laminar flow of a micropolar fluid boundary layer at steady state is considered over a stretching surface with microstructural slip second order condition. The micropolar fluid flow stretches with a velocity of $u_s = ax$ with a being a stretching velocity. Extending Dawar *et al*. (2021) by adding heat generation effect with convective boundary condition, the models are:

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

$$u\frac{\partial u}{\partial x} + v\frac{\partial v}{\partial y} = \frac{\kappa}{\rho}\frac{\partial N}{\partial y} + \frac{(\mu+\kappa)}{\rho}\frac{\partial^2 u}{\partial y^2} - \frac{\sigma B_0^2}{\rho}u + g\beta_T(T-T_\infty) + g\beta_c(C-C_\infty), \tag{2}$$

$$u\frac{\partial N}{\partial x} + v\frac{\partial N}{\partial y} = \frac{\Omega}{\rho j}\left(2N + \frac{\partial u}{\partial y}\right), \tag{3}$$

$$u\frac{\partial T}{\partial x} + v\frac{\partial T}{\partial y} = \frac{k}{\rho c_p}\left(1+\frac{16}{3}\frac{\sigma^* T_\infty^3}{kk^*}\right)\frac{\partial^2 T}{\partial y^2} + \frac{\sigma B_0^2}{\rho c_p}u^2 + \tau\left[D_B\frac{\partial T}{\partial y}\frac{\partial C}{\partial y} + \frac{D_T}{T_\infty}\left(\frac{\partial T}{\partial y}\right)^2\right] + \frac{Q}{\rho c_p}(T-T_\infty), \tag{4}$$

$$u\frac{\partial C}{\partial x} + v\frac{\partial C}{\partial y} = D_B\frac{\partial^2 C}{\partial y^2} + k_1(C_\infty - C) + \frac{D_T}{T_\infty}\left(\frac{\partial^2 T}{\partial y^2}\right), \tag{5}$$

The corresponding boundary conditions are:

$$\left.\begin{array}{l} u=u_s+u_{slip},\ v=0,\ -k^*\dfrac{\partial T}{\partial y}=h\left(T_s-T_\infty\right),\ N=-n_0\dfrac{\partial u}{\partial y},\ C=C_s \text{ at } y=0 \\ u\rightarrow 0,\ N\rightarrow 0,\ T\rightarrow\infty, \text{as } y\rightarrow 0 \end{array}\right\} \quad (6)$$

Where,

$$\left.\begin{array}{l} u_{slip}=\dfrac{\partial u}{\partial y}\lambda\left(\dfrac{3-\beta l^2}{\beta}-\dfrac{3}{2}\dfrac{1-l^2}{k_n}\right)\dfrac{2}{3}-\dfrac{1}{4}\left[l^4+\dfrac{2\left(1-l^2\right)}{k_n^2}\right]\lambda^2\dfrac{\partial}{\partial y}\left(\dfrac{\partial u}{\partial y}-R_0N\right) \\ u_{slip}=A\dfrac{\partial u}{\partial y}+B\dfrac{\partial}{\partial y}\left(\dfrac{\partial u}{\partial y}-R_0N\right) \end{array}\right\} \quad (7)$$

Where x and y are coordinate along velocity u and v respectively, a stretching constant, A B Slip constant, B_0 magnetic field, C fluid concentration, C_∞ concentration at free stream, C_s concentration near surface, c_p specific heat, D_1 *and* D_2 constants, D_B Brownian diffusion, D_T thermopheric diffusion, Ec Eckert number, j micro inertia density, k thermal conductivity, kr chemical reaction, $k_1$reaction, T temperature, T_∞ temperature at free stream, T_s temperature near the surface, Q heat generation, R_0microstructural slip, μ dynamic viscosity, τ heat capacity ratio, κ votex viscosity, σ electrical conductivity, σ^* Stefan Boltzmann constant, υ kinematic viscousity, ρ density.

Equation (1) to (7) are reduced to ODEs by introducing the similarity transformation:

$$\left.\begin{array}{l} \psi=\sqrt{a\upsilon}xf\left(\eta\right), u=\dfrac{\partial\psi}{\partial y}, v=-\dfrac{\partial\psi}{\partial x}, N=ax\sqrt{\dfrac{a}{\upsilon}}g\left(\eta\right), \eta=\sqrt{\dfrac{a}{\upsilon}}y \\ T-T_\infty=\left(T_s-T_\infty\right)\theta\left(\eta\right), \mathrm{C}-C_\infty=\left(C_s-C_\infty\right)\varphi\left(\eta\right), D_1=\dfrac{T_s-T_\infty}{x}, D_2=\dfrac{C_s-C_\infty}{x} \\ \Omega=\mu\left(1+\dfrac{\alpha}{2}\right)j \\ u_{slip}=A\sqrt{\dfrac{a}{\upsilon}}axf^{//}+B\dfrac{a^2}{\upsilon}xf^{///}-R\dfrac{a^2x}{\upsilon}g^{/} \\ u=ax+A\sqrt{\dfrac{a}{\upsilon}}axf^{//}+B\dfrac{a^2}{\upsilon}xf^{///}-R\dfrac{a^2x}{\upsilon}g^{/} \\ N=-n\dfrac{\partial u}{\partial y}=-n_0\sqrt{\dfrac{a}{\upsilon}}axf^{//} \end{array}\right\} \quad (8)$$

Where $\eta, f, g, \theta, \varphi$ are the dimensionless fluid distance, velocity, micro-rotation, temperature, and concentration. The continuity equation in (1) is satisfied on introducing the transformation in (8) while equation (2) to (7) becomes:

$$\left.\begin{array}{l}
(1+\alpha) f^{///} + ff^{//} - f^{/2} + \alpha g^{/} - Mf^{/} + \gamma_1\theta + \gamma_2\varphi = 0 \\
\left(1+\frac{\alpha}{2}\right) g^{//} - f^{/} g + fg^{/} - \alpha\left(2g + f^{//}\right) = 0 \\
(1+Ra)\theta^{//} + \Pr f\theta^{/} - \Pr \theta f^{/} + \Pr MEcf^{/} + Nb\Pr \theta^{/}\varphi^{/} + Nt\theta^{/2} + \Pr Q_0\theta = 0 \\
\varphi^{//} + Scf\varphi^{/} - Scf^{/}\varphi - ScKr\varphi + \frac{Nt}{Nb}\theta^{//} = 0 \\
\textit{with the corresponding boundary conditions}: \\
f = 0, f^{/} = 1 + \gamma f^{//} + \delta f^{///} + R_0 g^{/}, g = -nf^{//}, \theta^{/} = -\mathrm{Bt}(1-\theta), \varphi = 1, \quad \eta = 0 \\
f^{/} \to 0, \mathrm{g} \to 0, \theta \to 0, \varphi \to 0,
\end{array}\right\} \quad (9)$$

Where

$$\alpha = \frac{k}{\rho\upsilon}, \gamma = A\sqrt{\frac{a}{\upsilon}}, \delta = B\frac{a}{\upsilon}, R_0 = R\frac{a}{\upsilon}, M = \frac{\sigma B_0^2}{a\rho}, \gamma_1 = \frac{g\beta_T D_1}{a^2}, \gamma_2 = \frac{g\beta_c D_2}{a^2}$$

$$Ra = \frac{16\sigma^* T_\infty^3}{2kk^*}, Ec = \frac{a^2x^2}{c_p\left(T_s - T_\infty\right)}, \Pr = \frac{\upsilon\rho c_p}{k}, \mathrm{Q}_0 = \frac{Q}{a\rho c_p}, Nt = \frac{\tau D_T\left(T_s - T_\infty\right)}{\upsilon T_\infty}$$

$$Nb = \frac{\tau D_B\left(C_s - C_\infty\right)}{\upsilon}, Kr = \frac{K_1}{a}, Sc = \frac{\upsilon}{D_B}, Bt = \frac{h}{k^*}\sqrt{\frac{a}{\upsilon}}, n = n_0\sqrt{\frac{a}{\upsilon}}ax$$

Corresponding to:

Micro polar parameter, first order slip parameter, second order slip parameter, micro structural parameter, magnetic field, thermal Grashof number, mass Grashof number, radiation parameter, Eckert number, Prandtl number, Heat generation parameter, thermophoresis parameter, Brownian motion, chemical reaction parameter, Schmidt number, Biot number, and micro rotation parameter respectively.

Materials and Methods

In other to solve the problem in equation (9), the method of Decomposition is introduced by setting

$$\left.\begin{aligned}
&(1+\alpha)f^{///} = -ff^{//} + f^{/2} - \alpha g^{/} + Mf^{/} - \gamma_1\theta - \gamma_2\varphi \\
&\left(1+\frac{\alpha}{2}\right)g^{//} = f^{/}g - fg^{/} + \alpha\left(2g + f^{//}\right) \\
&(1+Ra)\theta^{//} = -\Pr f\theta^{/} + \Pr\theta f^{/} - \Pr MEcf^{/} - Nb\Pr\theta^{/}\varphi^{/} - Nt\theta^{/2} - \Pr Q_0\theta \\
&\varphi^{//} = -Scf\varphi^{/} + Scf^{/}\varphi + ScKr\varphi - \frac{Nt}{Nb}\theta^{//}
\end{aligned}\right\} \tag{10}$$

Letting $L_1 = \dfrac{d^3}{d\eta^3}$ and $L_2 = \dfrac{d^2}{d\eta^2}$

Then equation (10) becomes

$$\left.\begin{aligned}
&(1+\alpha)L_1[f] = -ff^{//} + f^{/2} - \alpha g^{/} + Mf^{/} - \gamma_1\theta - \gamma_2\varphi \\
&\left(1+\frac{\alpha}{2}\right)L_2[g] = f^{/}g - fg^{/} + \alpha\left(2g + f^{//}\right) \\
&(1+Ra)L_2[\theta] = -\Pr f\theta^{/} + \Pr\theta f^{/} - \Pr MEcf^{/} - Nb\Pr\theta^{/}\varphi^{/} - Nt\theta^{/2} - \Pr Q_0\theta \\
&L_2[\varphi] = -Scf\varphi^{/} + Scf^{/}\varphi + ScKr\varphi - \frac{Nt}{Nb}\theta^{//}
\end{aligned}\right\} \tag{11}$$

Introducing Adomian polynomials into the equation,

$$\left.\begin{aligned}
&\sum_{n=0}^{\infty} f_n(\eta) = \frac{1}{(1+\alpha)}L_1^{-1}\left[-\sum_{n=0}^{\infty}A_n + \sum_{n=0}^{\infty}B_n - \alpha g_n^{/} + Mf_n^{/} - \gamma_1\theta_n - \gamma_2\varphi_n\right] \\
&\sum_{n=0}^{\infty} g_n(\eta) = \frac{1}{\left(1+\frac{\alpha}{2}\right)}L_2^{-1}\left[\sum_{n=0}^{\infty}C_n - \sum_{n=0}^{\infty}D_n + \alpha\left(2g_n + f_n^{//}\right)\right] \\
&\sum_{n=0}^{\infty} \theta_n(\eta) = \frac{\Pr}{(1+Ra)}L_2^{-1}\left[-\sum_{n=0}^{\infty}E_n + \sum_{n=0}^{\infty}F_n - MEcf_n^{/} - Nb\sum_{n=0}^{\infty}G_n - Nt\sum_{n=0}^{\infty}H_n - \Pr Q_0\theta_n\right] \\
&\sum_{n=0}^{\infty} \varphi_n(\eta) = L_2^{-1}\left[-Sc\sum_{n=0}^{\infty}I_n + Sc\sum_{n=0}^{\infty}K_n + ScKr\varphi_n - \frac{Nt}{Nb}\theta_n^{//}\right]
\end{aligned}\right\} \tag{12}$$

Where

$$\left.\begin{aligned}
&A_n = \sum_{k=0}^{n} f_{n-k}f_k^{//}, B_n = \sum_{k=0}^{n} f_{n-k}^{/}f_k^{/}, C_n = \sum_{k=0}^{n} f_{n-k}^{/}g_k, D_n = \sum_{k=0}^{n} g_{n-k}^{/}f_k, E_n = \sum_{k=0}^{n} f_{n-k}^{/}\theta_k, F_n = \sum_{k=0}^{n} \theta_{n-k}^{/}f_k, \\
&G_n = \sum_{k=0}^{n} \theta_{n-k}^{/}\varphi_k^{/}, \mathrm{H}_n = \sum_{k=0}^{n} \theta_{n-k}^{/}\theta_k^{/}, \mathrm{I}_n = \sum_{k=0}^{n} f_{n-k}^{/}\varphi_k, K_n = \sum_{k=0}^{n} \varphi_{n-k}^{/}f_k
\end{aligned}\right\} \tag{13}$$

are the polynomials.

Decomposing equation (13),

$$\left.\begin{aligned}
f_n &= \frac{1}{(1+\alpha)} L_1^{-1}\left[-\sum_{k=0}^{n} f_{n-k} f_k^{//} + \sum_{k=0}^{n} f_{n-k}^{/} f_k^{/}, -\alpha g_n^{/} + M f_n^{/} - \gamma_1 \theta_n - \gamma_2 \varphi_n\right] \\
g_n &= \frac{1}{\left(1+\frac{\alpha}{2}\right)} L_2^{-1}\left[\sum_{k=0}^{n} f_{n-k}^{/} g_k - \sum_{k=0}^{n} g_{n-k}^{/} f_k + \alpha\left(2 g_n + f_n^{//}\right)\right] \\
\theta_n &= \frac{\Pr}{(1+Ra)} L_2^{-1}\left[-\sum_{k=0}^{n} f_{n-k}^{/} \theta_k + \sum_{k=0}^{n} \theta_{n-k}^{/} f_k - MEc f_n^{/} - Nb \sum_{k=0}^{n} \theta_{n-k}^{/} \varphi_k^{/} - Nt \sum_{k=0}^{n} \theta_{n-k}^{/} \theta_k^{/} - \Pr Q_0 \theta_n\right] \\
\varphi_n &= L_2^{-1}\left[-Sc \sum_{k=0}^{n} f_{n-k}^{/} \varphi_k + Sc \sum_{k=0}^{n} \varphi_{n-k}^{/} f_k + Sc Kr \varphi_n - \frac{Nt}{Nb} \theta_n^{//}\right]
\end{aligned}\right\} \tag{14}$$

Maple 17 software is used to carry out the integrals in equation (14) and the initial guesses are assumed to be

$$\left.\begin{aligned}
f_0(\eta) &= \frac{1+R_0}{1-\delta+\gamma}\left(-a_1 e^{-\eta}\right) \\
g_0(\eta) &= \frac{n\left(1+R_0\right)}{1-\delta+\gamma} a_2 e^{-\eta} \\
\theta_0(\eta) &= \frac{a_3 e^{-\eta}}{Bt} \\
\varphi_0(\eta) &= a_4 e^{-\eta}
\end{aligned}\right\} \tag{15}$$

The final solutions are given as

$$\left.\begin{aligned}
f(\eta) &= \sum_{n=0}^{3} f_n \\
g(\eta) &= \sum_{n=0}^{3} g_n \\
\theta(\eta) &= \sum_{n=0}^{3} \theta_n \\
\varphi(\eta) &= \sum_{n=0}^{3} \varphi_n
\end{aligned}\right\} \tag{16}$$

Results and Discussion

The nonlinear coupled ODEs with corresponding boundary conditions in equation (10) are solved using the Adomian Decomposition method to obtain the solution in (16). The results obtained are compare with the existing literature and a good agreement are observed as seen in Table 1.

Table 1: Comparison of $f^{//}(0)$ with γ when $M=\gamma_1=\gamma_2=\delta=R_0=0$

γ	**Wabshet (2017)**	**Khan *et al.*(2020)**	**Dawar *et al.*(2021)**	**Present result**
0	1	1	1	1
0.1	0.872082	0.8719	0.87209	0.8735
0.2	0.776377	0.7762	0.77638	0.7973
0.3	0.701548	0.7014	0.70155	0.7309
0.5	0.591196	0.5922	0.5912	0.5981
1	0.43016	0.4301	0.43017	0.4994
2	0.28398	0.284	0.28399	0.2613
3	0.214055	0.214	0.21406	0.2706
5	0.144841	0.1448	0.14485	0.1378
10	0.081243	0.0812	0.08124	0.0788
20	0.04379	0.0438	0.04379	0.0431

Figures 1 to 3 and Figure 4 to 6 depict the variations of thermal and mass Grashof number on velocity, micro rotation, and temperature profile of the fluid respectively. Grashof number is the ratio of buoyancy to viscous force. Increase in the value of these Grashof numbers enhances the fluid velocity profile, decrease the micro rotation and increase the fluid temperature profile in the presence of micro structural parameter Ro. Dawar et al. (2021), increase in temperature which causes the fluid viscosity to drop leads to increase in velocity. The thermal Grashof number has more effect on micro rotation than mass Grashof number as depicted in Figure 2 and 5.

Figures 7 to 9 show the distribution of micro polar parameter on fluid velocity, micro rotation and temperature profiles. the fluid velocity and temperature here act as increasing agent of the parameter while the micro rotation is a reducing agent of the parameter. Dawar et al. (2021), the material parameter causes the boost in the linear velocity which shows that the momentum transfer thickens meaningfully well due to the intensification of the viscosity produced by the micro rotations of the particles.

Figures 10 to 12 is the distribution of the magnetic parameter on the fluid velocity, micro rotation and temperature. The heightening in the magnetic parameter produces a drag like force (Lorentz force) which results to a drop in the fluid velocity but enhances the micro rotation and the fluid temperature which complies with Aiyesimi *et al.*(2013).

Figure 13 and 14 present the variation of Prandtl number on micro rotation and temperature distributions. Prandtl number is the ratio of momentum diffusion to heat diffusion in the fluid. For higher values of Prandtl number, the fluid temperature drops while the micro rotation is enhanced. These results also correspond to the findings of Suleiman and Yusuf (2020).

Figure 15 displays the distribution of heat generation parameter on temperature profile and is seen that as the parameter increases from negative to positive, the fluid temperature is boosted. According to Yusuf *et al.*(2019a), the negativity shows absorption while the positivity signifies generation.

Figures 16 to 17 present the Radiation parameter on micro rotation and temperature profile respectively. Both micro rotation and the fluid temperature are increasing agent of the radiation parameter. As radiation parameter increases, the fluid temperature increases also (Aiyesimi *et al.* 2013).

Figures 18 to 19 depict the variation of Biot number on micro rotation and fluid temperature. As Biot number increases, the micro rotation reduces while the fluid temperature rises. Biot number are physical quantities that occur due to convective boundary conditions (Yusuf *et al,* 2021).

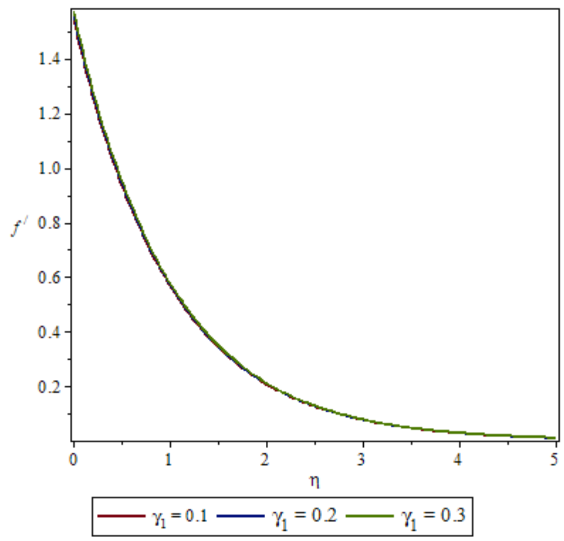

Figure 1: Variation of γ_1 on f'

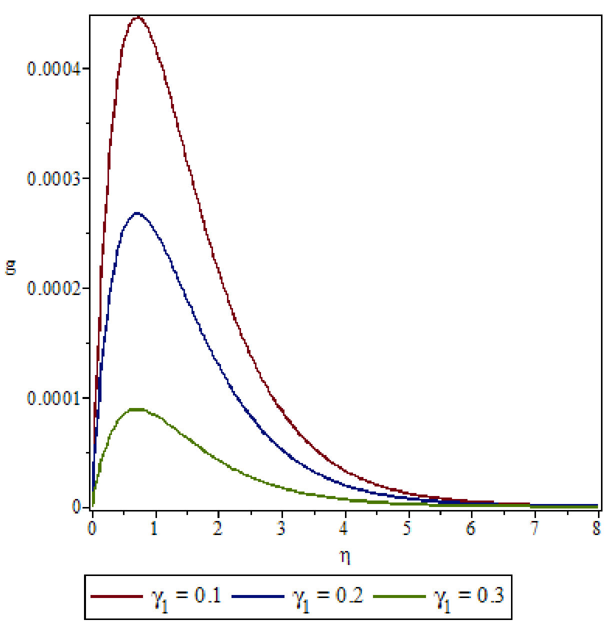

Figure 2: Variation of γ_1 on g

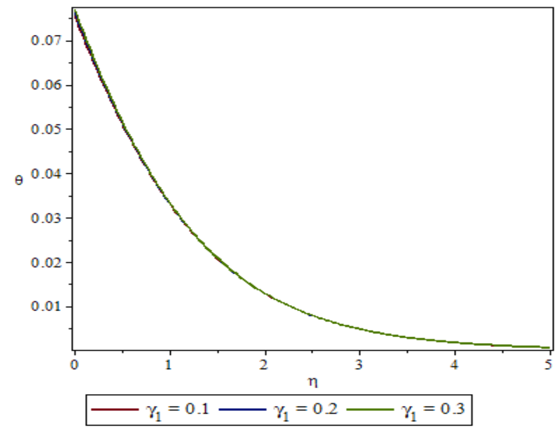

Figure 3: Variation of γ_1 on θ

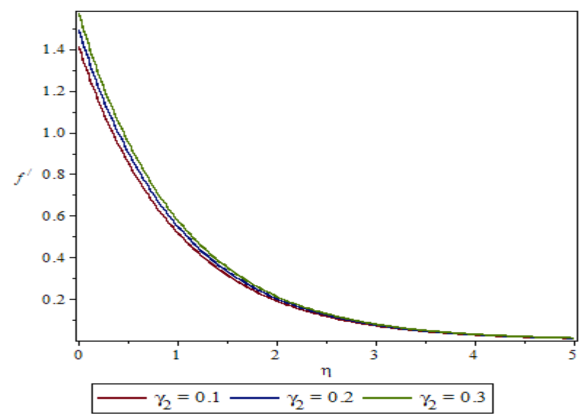

Figure 4: Variation of γ_2 on f'

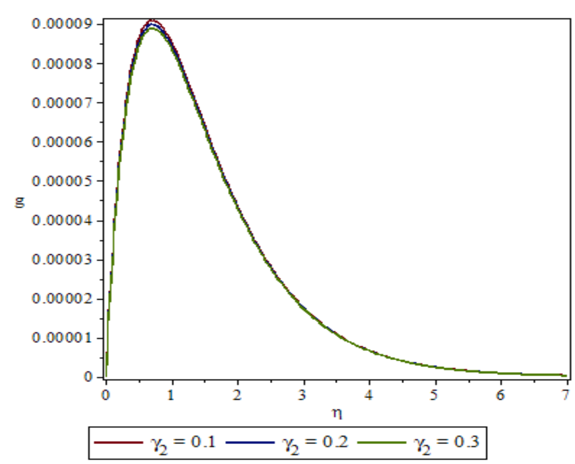

Figure 5: Variation of γ_2 on g

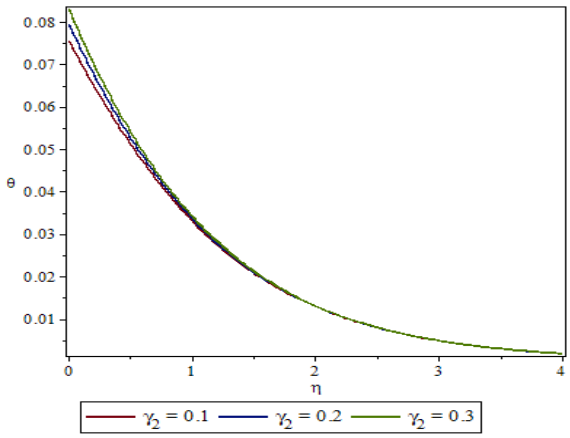

Figure 6: Variation of γ_2 on θ

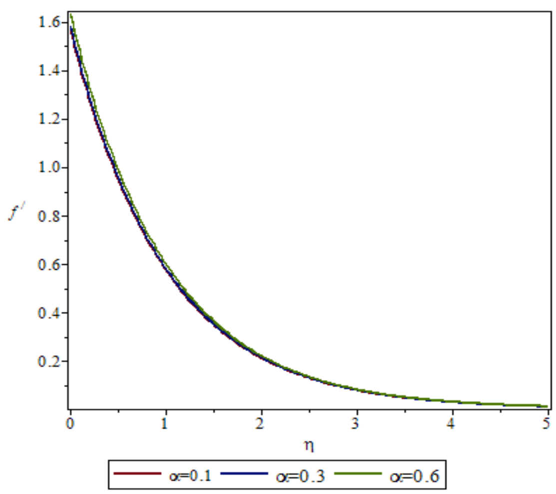

Figure 7: Variation of α on f'

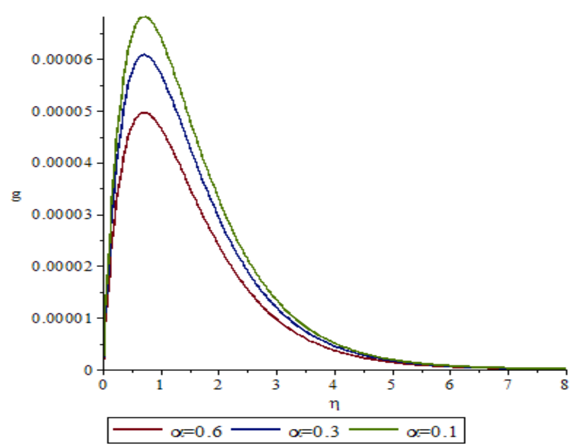

Figure 8: Variation of α on g

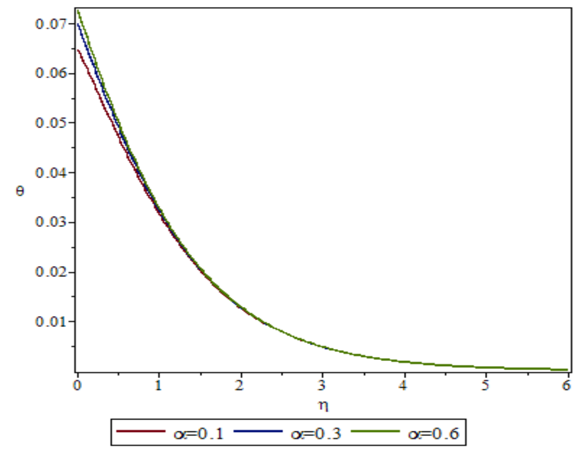

Figure 9: Variation of α on θ

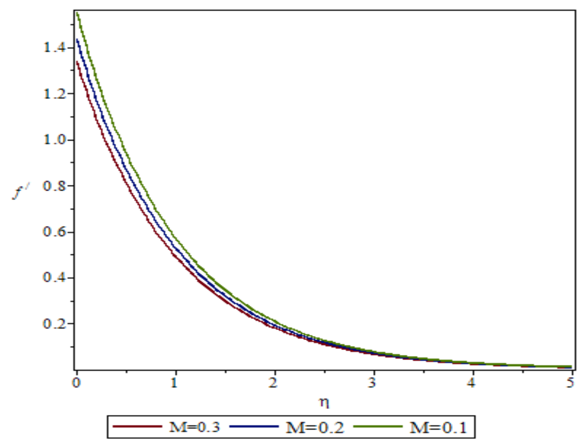

Figure 10: Variation of M on f'

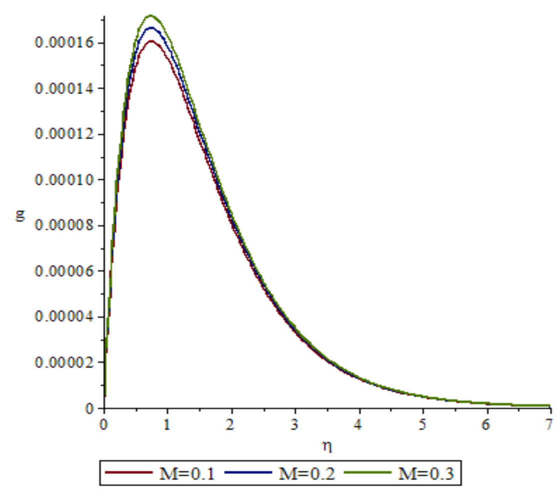

Figure 11: Variation of M on g

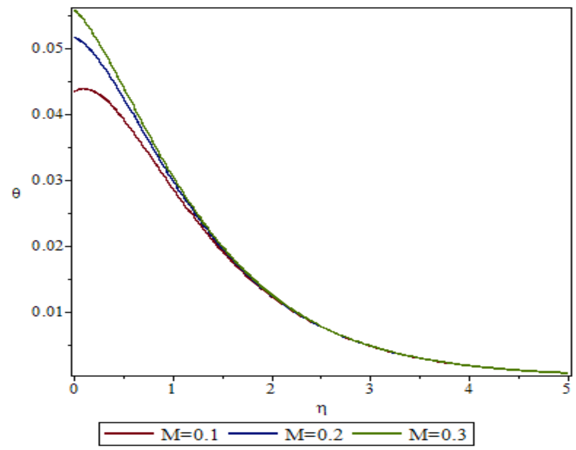

Figure 12: Variation of M on θ

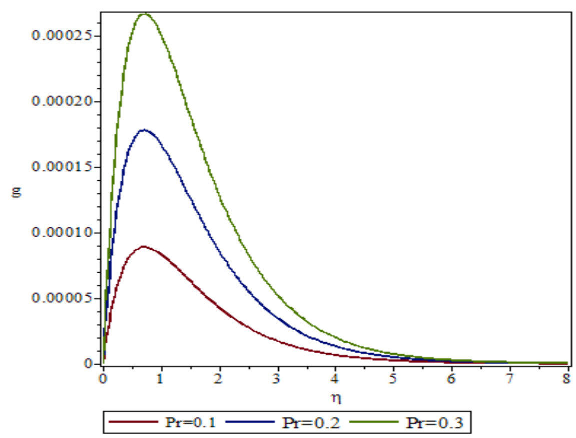

Figure 13: Variation of Pr on g

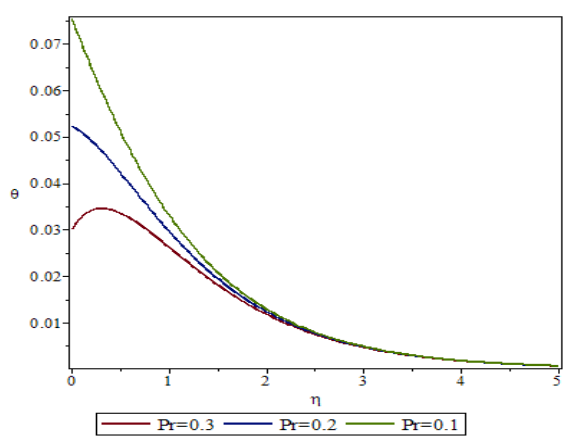

Figure 14: Variation of Pr on θ

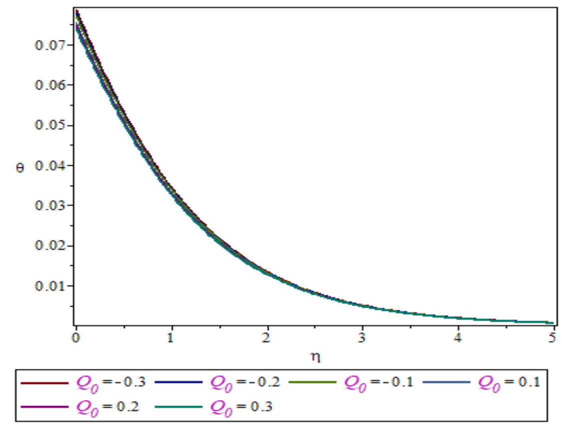

Figure 15: Variation of Q_0 on θ

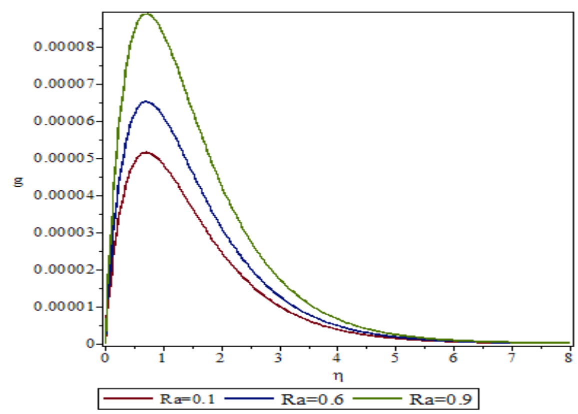

Figure 16: Variation of Ra on g

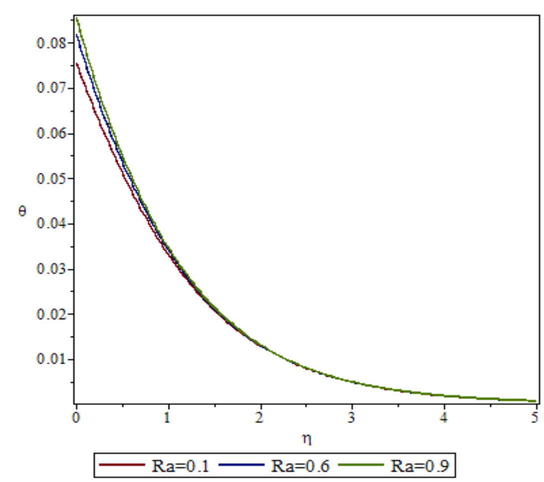

Figure 17: Variation of Ra on θ

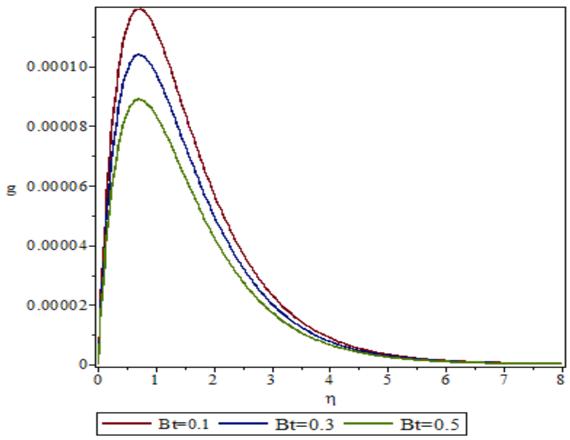

Figure 18: Variation of Bt on g

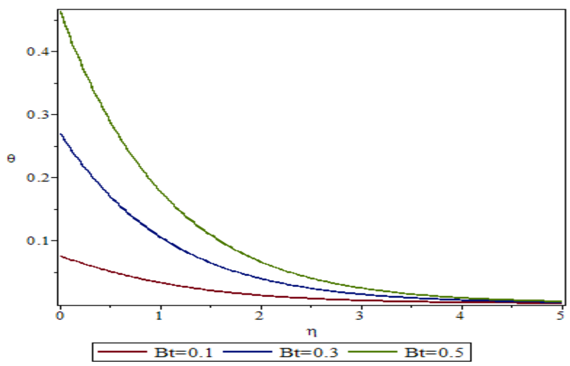

Figure 19: Variation of Bt on θ

Conclusion

This present work extended the work of Dawar *et al.* (2021) by introducing the heat generation parameter and convective boundary condition. The formulated problems were solved using decomposition method and the results obtained were compared with literature as presented in Table 1. These results show an agreement between the present work and the literature. In conclusion, the maximum velocity on the sheet surface varies as the parameter varied due to the effect of the slip parameters, the micro rotation is zero on the sheet surface irrespective of the parameter vary, the temperature on the sheet is not constant due to the convective boundary, all parameters are varied in the presence of micro structural parameter Ro, and the fluid velocity, micro rotation, temperature, and mass concentration all decayed to zero at free stream.

Competing Interest

There is no conflict of interest

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