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Entropy generation in bioconvection hydromagnetic flow with gyrotactic motile microorganisms

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Here, the magnetohydrodynamic bioconvective flow of a non-Newtonian nanomaterial over a stretched sheet is scrutinized. The characteristics of convective conditions are analyzed. Irreversibility analysis in the presence of gyrotactic micro-organisms is discussed. Energy expression is assisted with thermal radiation, heat generation and ohmic heating. Buongiorno's model is employed to discuss the characteristics of the nanoliquid through thermophoresis and random diffusions. Nonlinear expressions of the given model are transformed through adequate transformations. The obtained expressions have been computed by the Newton built in-shooting technique. Results of influential variables for velocity, concentration, microorganism field, temperature and entropy rate are graphically studied. Clearly, velocity reduction is witnessed for the bioconvection Rayleigh number and magnetic variable. A higher heat generation variable leads to augmentation of temperature. An increase in the magnetic variable results in entropy and temperature enhancement. A higher Peclet number results in microorganism field reduction. Temperature distribution rises for radiation and the thermal Biot number. A higher solutal Biot number intensifies the concentration. The entropy rate for radiation and diffusion variables is enhanced.

1 Introduction

Recently, nanotechnology has gained much consideration amongst researchers and investigators. It is due to its involvement in chemical processes, microelectronics, engineering, hybrid powered engines and biological processes. Nanomaterials are basically homogeneous colloidal suspensions of nano-size (1–10 nm) particles in an ordinary liquid which enhances the thermal conductivity of conventional liquids.[1,2] Nanofluids have specific characteristics that make them more applicable materials. Nanomaterials have innovative characteristics about heat transfer enhancement. Buongiorno[3] gave a theoretical model for heat transport rate enhancement of conventional liquids. He highlighted that only random and thermophoresis diffusions are main mechanisms for thermal transportation enhancement. Nanomaterials are very significant in improving the thermal productivity of hybrid power engines, electronic devices, nuclear system chillers, domestic refrigerators and many others. Shahzad *et al.*[4] analyzed the bioconvection convectively heated micropolar nanomaterial flow between two rotating disks. The mixed convective magnetohydrodynamic flow of a viscoelastic nanomaterial with heat generation was discussed by Waqas *et al.*[5] Anjum *et al.*[6] explored activation energy in the bioconvective MHD flow of a modified Eyring–Powell nanomaterial. Mabood *et al.*[7] reported chemically reactive micropolar nanoliquid flow considering thermal radiation. Numerical analysis of hydromagnetic unsteady nanomaterial flow towards an irregular stretched sheet was reported by Kalpana *et al.*[8] Thermal analysis for the hydromagnetic flow of a nanomaterial subject to entropy was addressed in Riaz *et al.*[9] Further investigations about nanomaterial flow are highlighted through ref. 10–17.

In recent years the bioconvection phenomenon in nanomaterials along motile microorganisms has attracted much attention from researchers. It is because of its significance in tremendous engineering, pharmaceutical and biological processes in fields such as biofuel, biomedicine, fertilizer, biotechnology, bio-microsystem and enzyme biosensor. Bioconvection occurs due to up swimming of microorganisms. Commonly the density of microorganisms is heavier than the base fluid and therefore it raises unsteady upper surface density stratification.[18,19] Bio convection is extensively used in environmental science, conversion in engineering, bio-microsystems, biological processes with microbial-upgraded oil recovery systems, enzyme biosensors, mass transport and bioengineering in biotechnology and the ecosystem. Prime utilization of this mechanism is to enhance the capacity of appropriate fraternization and mass transfer. Bio convection refers to macroscopic movement of liquid induced by a density gradient organized by an alternating floating system based on motile microbes. Thermal radiation impact in a bioconvective

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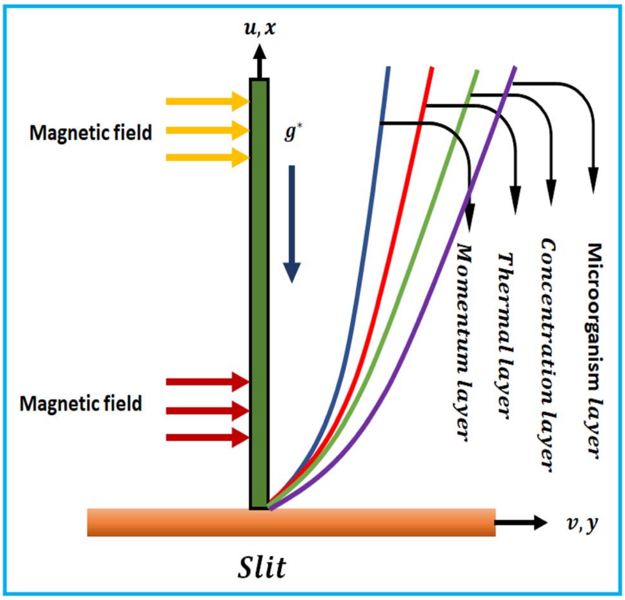

Fig. 1 Flow configuration.

numerical solutions of the considered model. Graphical analysis illustrating the influence of liquid flow, concentration, microorganism field, temperature and entropy rate is organized. Main results are listed in conclusion.

2 Formulation

Here the flow of the bioconvection Reiner–Rivlin nanomaterial past a stretched boundary is examined. Convective conditions along with chemical reaction are analyzed. Thermophoresis, random diffusion and involvement of motile microorganisms are considered. Influences of radiation, magnetic field and heat generation are considered. Physical impact for the entropy rate is explored. A uniform magnetic field of strength (B_0) is applied. The surface is stretched with velocity $(u_w = ax)$ subject to rate constant $(a > 0)$. Fig. 1 consists of flow configuration.[33]

Under the above assumptions, the related equations are:[34–38]

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

$$\left.\begin{aligned}&u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}=\nu_f\frac{\partial^2 u}{\partial y^2}+2\frac{\mu_c}{\rho_f}\left(\frac{\partial u}{\partial y}\frac{\partial^2 u}{\partial x\partial y}+\frac{\partial u}{\partial x}\frac{\partial^2 u}{\partial y^2}\right)-\frac{\sigma_f {B_0}^2}{\rho_f}u\\&+\frac{1}{\rho_f}\left(\rho_f(1-C_\infty)g^*\beta^*(T-T_\infty)-g^*(\rho_p-\rho_f)(C-C_\infty)-g^*\gamma^*(\rho_m-\rho_f)(N-N_\infty)\right)\end{aligned}\right\}, \tag{2}$$

$$\left.\begin{aligned}&u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}=\frac{k_f}{(\rho c_p)_f}\frac{\partial^2 T}{\partial y^2}+\frac{16\sigma^* {T_\infty}^3}{3k^*(\rho c_p)_f}\frac{\partial^2 T}{\partial y^2}+\frac{\sigma_f {B_0}^2}{(\rho c_p)_f}u^2+\tau\left(\frac{D_B}{\Delta C}\frac{\partial T}{\partial y}\frac{\partial C}{\partial y}+\frac{D_T}{T_\infty}\left(\frac{\partial T}{\partial y}\right)^2\right)\\&+\frac{Q_0}{(\rho c_p)_f}(T-T_\infty)\end{aligned}\right\}, \tag{3}$$

ferromagnetic Williamson material subject to dissipation was studied by Kada *et al.*[20] Majeed *et al.*[21] highlighted the features of gyrotactic microorganisms in magnetized time-dependent nanoliquid flow. Waqas *et al.*[22] scrutinized thermo and solutal stratification impacts in Casson nanomaterial flow with convective boundary conditions. Azam *et al.*[23] examined activation in the bioconvection flow of a cross nanoliquid subject to gyrotactic microorganisms. Some interesting explorations of bioconvective flow can be seen in Ref. 24–32.

Motivation of current analysis is to address the bioconvective flow of the Reiner–Rivlin nanoliquid. Gyrotactic microorganisms in the presence of convective conditions are discussed. The characteristics of thermophoresis and random diffusions are analyzed. Energy expression consists of radiation, heat generation and ohmic heating. Irreversibility analysis along with chemical reaction is analyzed. The Newton built in-shooting technique (ND-solve) is employed to develop

$$u\frac{\partial C}{\partial x}+v\frac{\partial C}{\partial y}=D_B\frac{\partial^2 C}{\partial y^2}+\frac{\Delta C D_T}{T_\infty}\frac{\partial^2 T}{\partial y^2}-k_r(C-C_\infty), \tag{4}$$

$$u\frac{\partial N}{\partial x}+v\frac{\partial N}{\partial y}+\frac{bW_c}{(C_w-C_\infty)}\left(\frac{\partial}{\partial y}\left(N\frac{\partial C}{\partial y}\right)\right)=D_m\frac{\partial^2 N}{\partial y^2}, \tag{5}$$

with the boundary condition:[36–38]

$$\left.\begin{aligned}&u=u_w(x)=ax,\ \ v=0,\ \ -k_f\frac{\partial T}{\partial y}=h_f(T_w-T),\\&-D_B\frac{\partial C}{\partial y}=h_w(C_w-C),\ \ -D_m\frac{\partial N}{\partial y}=h_n(N_w-N)\text{ at }y=0\\&u\to 0,\ \ T\to T_\infty, C\to C_\infty,\ \ N\to N_\infty\text{ as }y\to\infty\end{aligned}\right\}. \tag{6}$$

In the above expressions (u,v) denote the velocity components, ν_f the kinematic viscosity, μ_c the cross viscosity, g^* the gravity, (x,y) characterize Cartesian coordinates, β^* the thermal expansion coefficient, ρ_p the particle density, ρ_m the microorganism density, γ^* the average volume of microorganisms, h_f the heat transfer rate, B_0 the magnetic field strength, μ_f the dynamic viscosity, ρ_f the liquid density, b the chemotaxis constant, σ_f the electrical conductivity, h_w the mass transfer rate, T the temperature, D_B the Brownian diffusion coefficient, W_c the cell swimming speed, $Q_0 > 0$ the heat generation coefficient, T_w the wall temperature, τ the ratio of heat capacitance, $\alpha_f = \left(\dfrac{k_f}{(\rho c_p)_f}\right)$ the thermal diffusivity, $(c_p)_f$ the specific heat, T_∞ the ambient temperature, σ^* the Stefan–Boltzmann constant, D_T the thermophoresis coefficient, k_f the thermal conductivity, h_n the microorganism transfer rate, k^* the mean absorption coefficient, C the concentration, ΔC the concentration difference, C_w the wall concentration, k_r the reaction rate, C_∞ the ambient concentration, N the motile microorganisms, N_w the wall motile microorganisms, D_m the microorganism diffusion coefficient and N_∞ the wall motile microorganisms.

Letting l as the reference length and transformations:[38] one has

$$\left.\begin{aligned} u = ax\frac{\partial f(\xi,\eta)}{\partial \eta},\ \ v = -\sqrt{a\nu_f}\left(f(\xi,\eta) + \xi\frac{\partial f(\xi,\ \eta)}{\partial \xi}\right),\ \ \eta = \sqrt{\frac{a}{\nu_f}}y \\ \theta(\xi,\eta) = \frac{T - T_\infty}{T_w - T_\infty},\ \ \phi(\xi,\ \eta) = \frac{C - C_\infty}{C_w - C_\infty},\ \ \chi(\xi,\eta) = \frac{N - N_\infty}{N_w - N_\infty},\ \ \xi = \frac{x}{l} \end{aligned}\right\}, \tag{7}$$

$$\left.\begin{aligned} \frac{\partial^3 f}{\partial \eta^3} + f\frac{\partial^2 f}{\partial \eta^2} + \xi\frac{\partial f}{\partial \xi}\frac{\partial^2 f}{\partial \eta^2} - \left(\frac{\partial f}{\partial \eta}\right)^2 - \xi\frac{\partial^2 f}{\partial \xi \partial \eta}\frac{\partial f}{\partial \eta} + 2K\left(\begin{aligned} \left(\frac{\partial^2 f}{\partial \eta^2}\right)^2 + \xi\frac{\partial^2 f}{\partial \eta^2}\frac{\partial^3 f}{\partial \xi \partial \eta^2} \\ + \frac{\partial f}{\partial \eta}\frac{\partial^3 f}{\partial \eta^3} + \xi\frac{\partial^2 f}{\partial \xi \partial \eta}\frac{\partial^3 f}{\partial \eta^3} \end{aligned}\right) \\ -M\frac{\partial f}{\partial \eta} + \frac{\lambda}{\xi}(\theta - \beta_1^*\phi - \beta_2^*\chi) = 0 \end{aligned}\right\} \tag{8}$$

$$\left.\begin{aligned} (1+\mathrm{Rd})\frac{\partial^2 \theta}{\partial \eta^2} + \Pr\xi\frac{\partial f}{\partial \eta}\frac{\partial \theta}{\partial \eta} + \Pr f\frac{\partial \theta}{\partial \eta} - \Pr\xi\frac{\partial f}{\partial \eta}\frac{\partial \theta}{\partial \xi} + \Pr Q\theta \\ + \Pr\mathrm{Nb}\frac{\partial \theta}{\partial \eta}\frac{\partial \phi}{\partial \eta} + \Pr\mathrm{Nt}\left(\frac{\partial \theta}{\partial \eta}\right)^2 + MEc\Pr\xi^2\left(\frac{\partial f}{\partial \eta}\right)^2 = 0 \end{aligned}\right\}, \tag{9}$$

$$\left.\frac{\partial^2 \phi}{\partial \eta^2} + \mathrm{Sc}f\frac{\partial \phi}{\partial \eta} - \mathrm{Sc}\xi\frac{\partial f}{\partial \eta}\frac{\partial \phi}{\partial \xi} + \mathrm{Sc}\xi\frac{\partial f}{\partial \xi}\frac{\partial \phi}{\partial \eta} + \frac{Nt}{Nb}\frac{\partial^2 \theta}{\partial \eta^2} - \mathrm{Sc}\gamma\phi = 0\right\}, \tag{10}$$

$$\left.\begin{aligned} \frac{\partial^2 \chi}{\partial \eta^2} + \mathrm{Lb}f\frac{\partial \chi}{\partial \eta} - \mathrm{Lb}\xi\frac{\partial f}{\partial \eta}\frac{\partial \chi}{\partial \xi} + \mathrm{Lb}\xi\frac{\partial f}{\partial \xi}\frac{\partial \chi}{\partial \eta} \\ -\mathrm{Pe}\left(\Omega\frac{\partial^2 \phi}{\partial \eta^2} + \frac{\partial \chi}{\partial \eta}\frac{\partial \phi}{\partial \eta} + \chi\frac{\partial^2 \phi}{\partial \eta^2}\right) = 0 \end{aligned}\right\}, \tag{11}$$

$$\left.\begin{aligned} \frac{\partial f(\xi,\ 0)}{\partial \eta} = 1,\ \ f(\xi,\ 0) = -\xi\frac{\partial f(\xi,\ 0)}{\partial \xi},\ \frac{\partial \theta}{\partial \eta}(\xi,\ 0) = -\beta_1(1 - \theta(\xi,\ 0)) \\ \frac{\partial \varphi}{\partial \eta}(\xi,\ 0) = -\beta_2(1 - \phi(\xi,\ 0)),\ \frac{\partial \chi}{\partial \eta}(\xi,\ 0) = -\beta_3(1 - \chi(\xi,\ 0)) \\ \frac{\partial f}{\partial \eta}(\xi,\ \infty) = 0,\ \theta(\xi,\infty) = 0,\ \phi(\xi,\infty) = 0,\ \chi(\xi,\infty) = 0 \end{aligned}\right\}. \tag{12}$$

In the above equations $M\left(=\frac{\sigma_f B_0{}^2}{a\rho_f}\right)$ represents the magnetic variable, $\beta_1^*\left(=\frac{(\rho_p-\rho_f)(C_w-C_\infty)}{\rho_f(1-C_\infty)(T_w-T_\infty)\beta^*}\right)$ the buoyancy ratio variable, $\lambda\left(=\frac{g\beta^*(1-C_\infty)(T_w-T_\infty)}{a^2 l}\right)$ the mixed convection variable, $K\left(=\frac{\mu_c a}{\nu_f\rho_f}\right)$ the material variable, $\beta_2^*\left(=\frac{(\rho_m-\rho_f)(N_w-N_\infty)\gamma^*}{\rho_f(1-C_\infty)(T_w-T_\infty)\beta^*}\right)$ the bioconvection Rayleigh number, $\mathrm{Nb}\left(=\frac{\tau D_B(C_w-C_\infty)}{\Delta C\nu_f}\right)$ the Brownian motion variable, $\beta_1\left(=\frac{h_f}{k_f\sqrt{\frac{a}{\nu_f}}}\right)$ the thermal Biot number, $\Pr\left(=\frac{\nu_f}{\alpha_f}\right)$ the Prandtl number, $\mathrm{Sc}\left(=\frac{\nu_f}{D_B}\right)$ the Schmidt number, $\mathrm{Rd}\left(=\frac{16\sigma^* T_\infty{}^3}{3k^* k_f}\right)$ the radiation variable, $\beta_2\left(=\frac{h_w}{D_B\sqrt{\frac{a}{\nu_f}}}\right)$ the solutal

Biot number, $Q\left(=\frac{Q_0}{a(\rho c_p)}\right)$ the heat generation parameter, $\mathrm{Nt}\left(=\frac{\tau D_{\mathrm{T}}(T_{\mathrm{w}}-T_\infty)}{T_\infty \nu_{\mathrm{f}}}\right)$ the thermophoresis variable, $\beta_3\left(=\frac{h_{\mathrm{n}}}{D_{\mathrm{n}}\sqrt{\frac{a}{\nu_{\mathrm{f}}}}}\right)$ the microorganism Biot number, $\mathrm{Lb}\left(=\frac{\nu_{\mathrm{f}}}{D_{\mathrm{m}}}\right)$ the bioconvective Lewis number, $\gamma\left(=\frac{k_{\mathrm{r}}}{a}\right)$ the reaction variable, $\Omega\left(=\frac{N_\infty}{(N_{\mathrm{w}}-N_\infty)}\right)$ the microorganisms concentration difference factor and $\mathrm{Pe}\left(=\frac{bW_{\mathrm{c}}}{D_{\mathrm{m}}}\right)$ the Peclet number.

3 Entropy generation

In mathematical form one can express that:[39–45]

$$N_{\mathrm{G}}=\frac{k_{\mathrm{f}}}{{T_\infty}^2}\left(1+\frac{16\sigma^* {T_\infty}^3}{3k^* k_{\mathrm{f}}}\right)\left(\frac{\partial T}{\partial y}\right)^2+\frac{\sigma_f {B_0}^2}{T_\infty}u^2+\frac{RD_{\mathrm{B}}}{T_\infty}\left(\frac{\partial T}{\partial y}\frac{\partial C}{\partial y}\right)+\frac{RD_{\mathrm{B}}}{C_\infty}\left(\frac{\partial C}{\partial y}\right)^2. \tag{13}$$

Non-dimensional form is

$$S_{\mathrm{G}}=\alpha_1(1+\mathrm{Rd})\theta'^2+M\mathrm{Br}\xi^2 f'^2+L\theta'\phi'+L\frac{\alpha_2}{\alpha_1}\phi'^2, \tag{14}$$

in which R indicates the real gas constant, $S_{\mathrm{G}}\left(=\frac{N_{\mathrm{G}}\nu_{\mathrm{f}}T_\infty}{k_{\mathrm{f}}a(T_{\mathrm{w}}-T_\infty)}\right)$ the entropy rate, $\alpha_1\left(=\frac{(T_{\mathrm{w}}-T_\infty)}{T_\infty}\right)$ the temperature difference variable, $\mathrm{Br}\left(=\frac{\mu_{\mathrm{f}}(al)^2}{k_{\mathrm{f}}(T_{\mathrm{w}}-T_\infty)}\right)$ the Brinkman number, $\alpha_2\left(=\frac{(C_{\mathrm{w}}-C_\infty)}{C_\infty}\right)$ the concentration difference variable and $L\left(=\frac{RD_{\mathrm{B}}(C_{\mathrm{w}}-C_\infty)}{k_{\mathrm{f}}}\right)$ the diffusion variable.

4 Solution methodology

We consider $\frac{\partial(\cdot)}{\partial \xi}=0$ and denoting $\frac{\partial(\cdot)}{\partial \eta}$ by prime in eqn (8)–(12). We can express that

$$f'''+ff''-f'^2+2K\left(f''^2+f'f'''\right)-Mf'+\frac{\lambda}{\xi}\left(\theta-\beta_1^*\phi-\beta_2^*\chi\right)=0, \tag{15}$$

$$(1+\mathrm{Rd})\theta''+\mathrm{Pr}f\theta'+M\mathrm{Pr}Ec\xi^2 f'^2+\mathrm{PrNb}\theta'\phi'+\mathrm{PrNt}\theta'^2+\mathrm{Pr}Q\theta=0, \tag{16}$$

$$\phi''+\mathrm{Sc}f\phi'+\frac{\mathrm{Nt}}{\mathrm{Nb}}\theta''-\mathrm{Sc}\gamma\phi=0, \tag{17}$$

$$\chi''+\mathrm{Lb}f\chi'-\mathrm{Pe}\left(\Omega\phi''+\chi\phi''+\chi'\phi'\right)=0, \tag{18}$$

$$\left.\begin{array}{c} f'(0)=1,\ f(0)=0,\ \theta'(0)=-\beta_1(1-\theta(0)),\\ \phi'(0)=-\beta_2(1-\phi(0)),\ \chi'(0)=-\beta_3(1-\chi(0))\\ f'(\infty)=0,\ \theta(\infty)=0,\ \phi(\infty)=0,\ \chi(\infty)=0 \end{array}\right\}. \tag{19}$$

4.1 Numerical scheme

The ND-solve technique computes the analysis. The Mathematica software is employed to get the numerical solution. For this we set

$$\left.\begin{array}{c} f=y_1^*,\ f'=y_2^*,\quad f''=y_3^*,\quad f'''=y_3'^*\\ \theta=y_4^*,\ \theta'=y_5^*,\ \theta''=y_5'^*\\ \phi=y_6^*,\ \phi'=y_7^*,\ \phi''=y_7'^*\\ \chi=y_8^*,\ \chi'=y_9^*,\ \chi''=y_9'^* \end{array}\right\}, \tag{20}$$

$$\left.\begin{array}{c} y_3'^*=y_2^*-y_1^*y_2^*-2K\left({y_3}^{*2}-y_2^*y_3'^*\right)-My_2^*\\ -\frac{\lambda}{\xi}\left(y_4^*-\beta_1^*y_6^*-\beta_2^*y_8^*\right) \end{array}\right\}, \tag{21}$$

$$y_5'^*=\frac{-\mathrm{Pr}}{(1+\mathrm{Rd})}\left[y_1^*y_5^*+MEc\xi^2{y_2}^{*2}+\mathrm{Nb}y_5^*y_5^*+\mathrm{Nt}{y_5}^{*2}+Qy_4^*\right]\Bigg\}, \tag{22}$$

$$y_7'^*=-\mathrm{Sc}y_1^*y_7^*-\frac{\mathrm{Nt}}{\mathrm{Nb}}y_5'^*+\mathrm{Sc}\gamma y_6^*, \tag{23}$$

$$y_9'^*=-\mathrm{Lb}y_1^*y_9^*-\mathrm{Pe}\left(\Omega y_7'^*+y_8^*y_7'^*+y_7^*y_9^*\right) \tag{24}$$

with

$$\left.\begin{array}{c} y_1^*(0)=0,\ y_2^*(0)=1,\ y_5^*(0)=-\beta_1\left(1-y_4^*(0)\right)\\ y_7^*(0)=-\beta_2\left(1-y_6^*(0)\right),\ y_9^*(0)=-\beta_3\left(1-y_8^*(0)\right)\\ y_2^*(\infty)=0,\ y_4^*(\infty)=0,\ y_6^*(\infty)=0,\ y_8^*(\infty)=0 \end{array}\right\}. \tag{25}$$

5 Results validation

A comparative study of the present investigation with Kaswan *et al.*[46] is constructed in Table 1 in a limiting sense. From Table

Table 1 Thermal transport rate comparison with Kaswan *et al.*[46]

Pr	Kaswan *et al.*[46]	Present results
0.07	0.065539	0.065536
0.7	0.164035	0.164039
1.0	0.418237	0.418235
2.0	0.826737	0.826738
7.0	1.804291	1.804295
20.0	3.256791	3.256797
70.0	6.346675	6.346679

1 it is clearly detected that results here are in excellent agreement.

6 Graphical analysis

In this section, the physical description of emerging variables is organized.

6.1 Velocity

Fig. 2 displays the behavior of the magnetic variable for velocity. Physically the magnetic field enhances the Lorentz force which induces a resistance in the liquid flow region and the velocity declines. Fig. 3 shows the impact of the material variable on ($f'(\eta)$). Increasing values of the material variable lead to viscous force reduction which intensifies the velocity. Fig. 4 displays the outcomes of the buoyancy ratio variable for velocity. Here reduction in velocity occurs for the buoyancy ratio variable. Fig. 5 elucidates the impact of the bioconvection Rayleigh number. A larger approximation of the bioconvection Rayleigh number (β_2^*) corresponds to a decline in liquid flow ($f'(\eta)$).

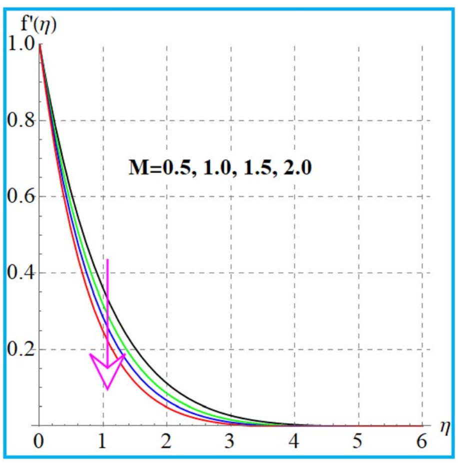

Fig. 2 $f'(\eta)$ variation *versus* M.

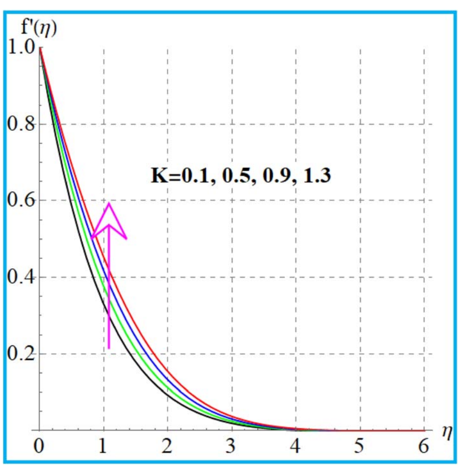

Fig. 3 $f'(\eta)$ variation *versus* K.

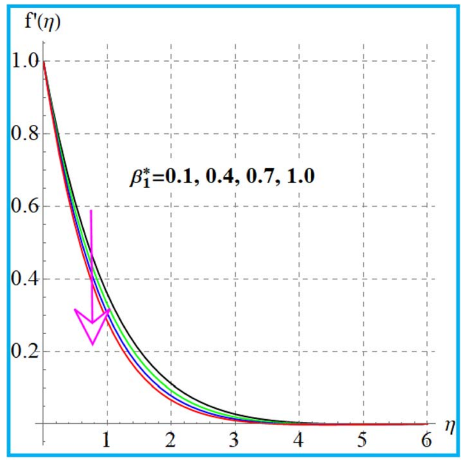

Fig. 4 $f'(\eta)$ variation *versus* β_1^*.

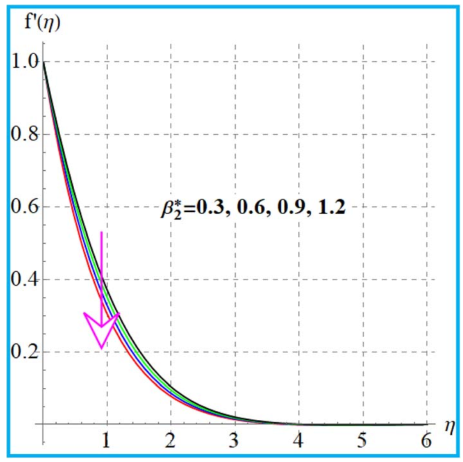

Fig. 5 $f'(\eta)$ variation *versus* β_2^*.

6.2 Temperature

The feature of temperature distribution for the magnetic field is illustrated in Fig. 6. A higher magnetic field increases the

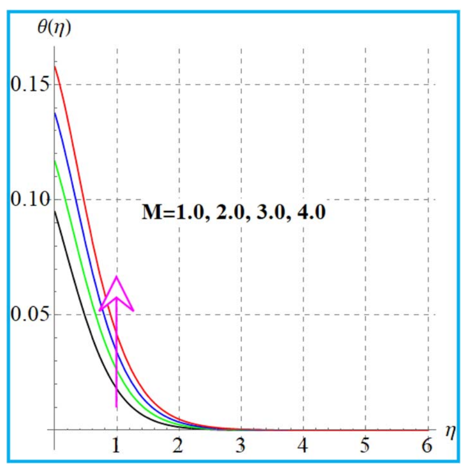

Fig. 6 $\theta(\eta)$ variation *versus* M.

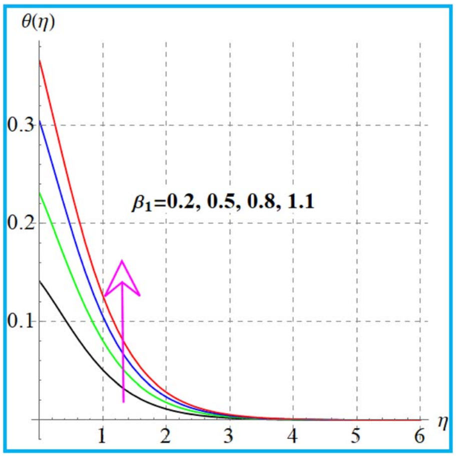

Fig. 7 $\theta(\eta)$ *versus* β_1.

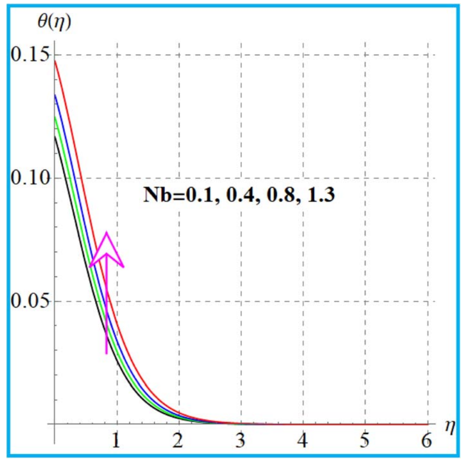

Fig. 10 $\theta(\eta)$ *versus* Nb.

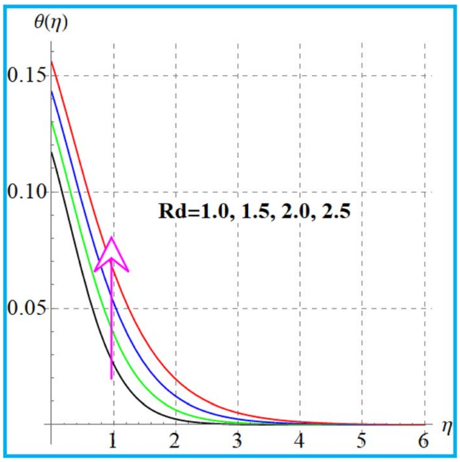

Fig. 8 $\theta(\eta)$ *versus* Rd.

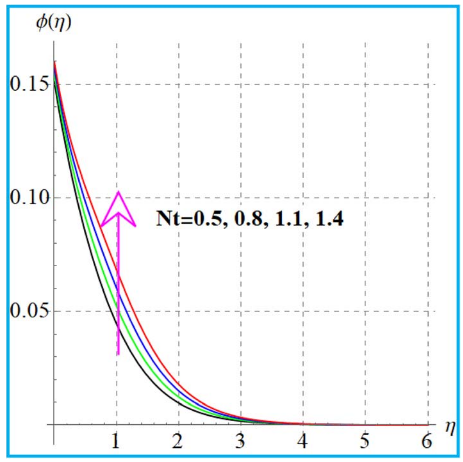

Fig. 11 $\phi(\eta)$ *versus* Nt.

Lorentz force which produces disturbance in the flow region and consequently the kinetic energy of the system is increased. Therefore thermal distribution is intensified. Fig. 7 shows the outcomes of (β_1) on temperature. An enhancement in thermal distribution occurs for a higher thermal Biot number. Results of radiation for temperature are portrayed in Fig. 8. As anticipated,

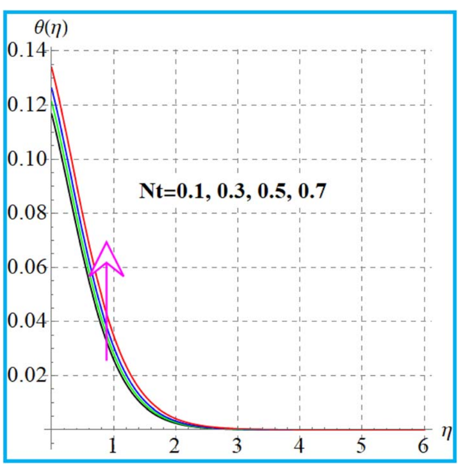

Fig. 9 $\theta(\eta)$ *versus* Nt.

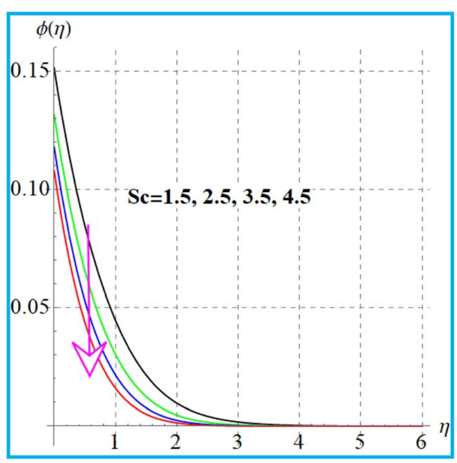

Fig. 12 $\phi(\eta)$ *versus* Sc.

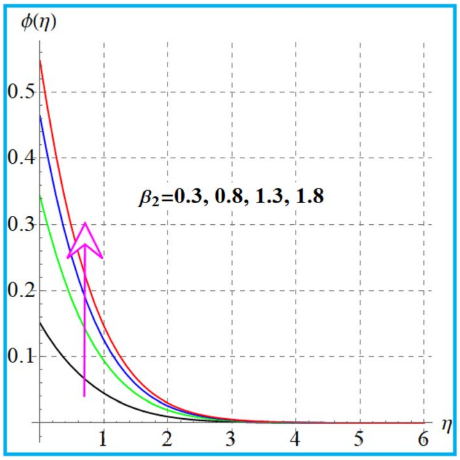

Fig. 13 $\phi(\eta)$ *versus* β_2.

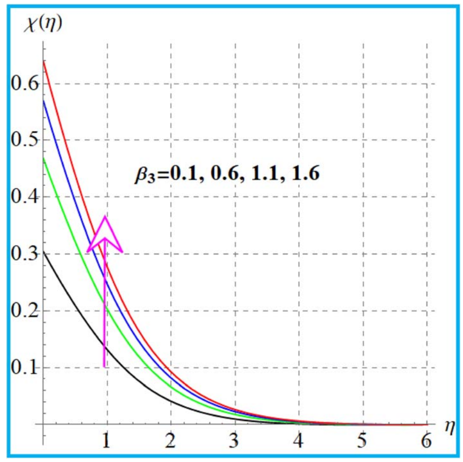

Fig. 16 $\chi(\eta)$ *versus* β_3.

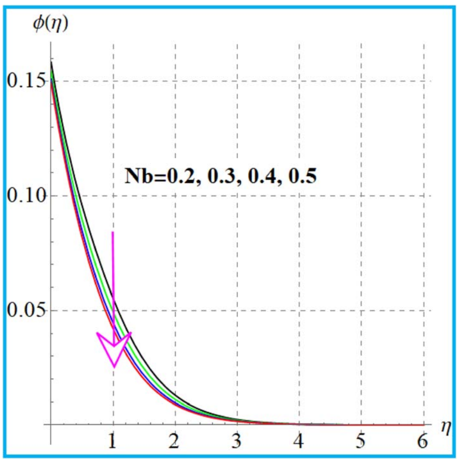

Fig. 14 $\phi(\eta)$ *versus* Nb.

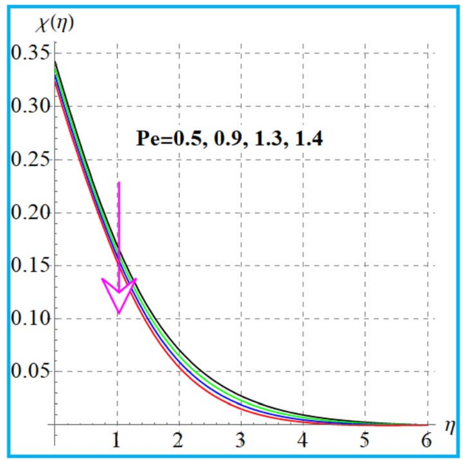

Fig. 17 $\chi(\eta)$ *versus* Pe.

higher radiation impact intensified the thermal field. Fig. 9 and 10 display (Nt) and (Nb) variations for temperature. A larger approximation of (Nt) corresponds to augmentation of the temperature. Additionally, it is seen through Fig. 10 that temperature improves with a higher random motion (Nb) variable.

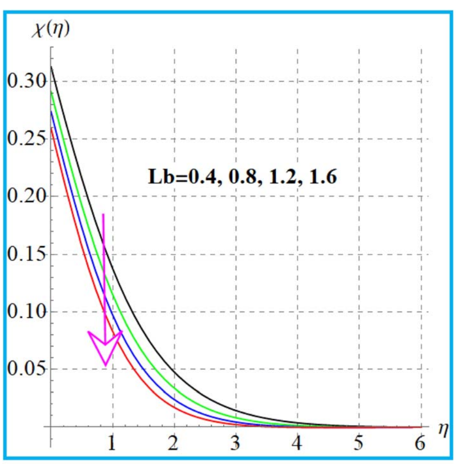

Fig. 15 $\chi(\eta)$ *versus* Lb.

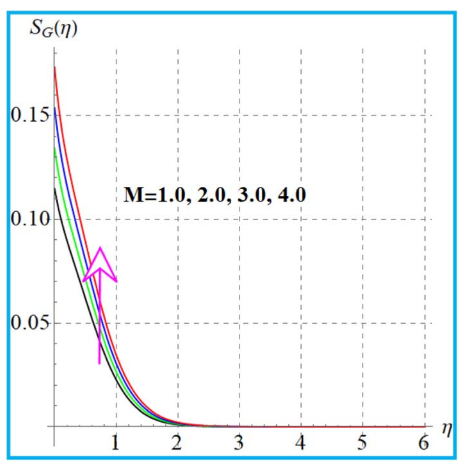

Fig. 18 $S_G(\eta)$ *versus* M.

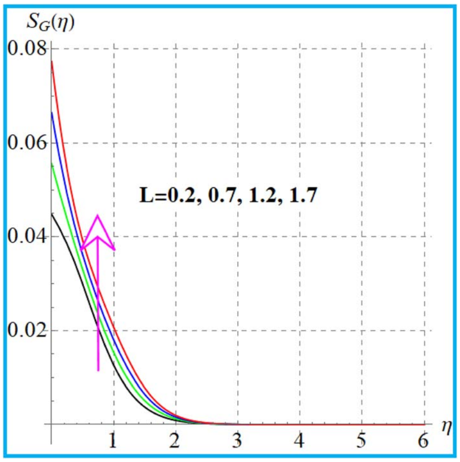

Fig. 19 $S_G(\eta)$ *versus* L.

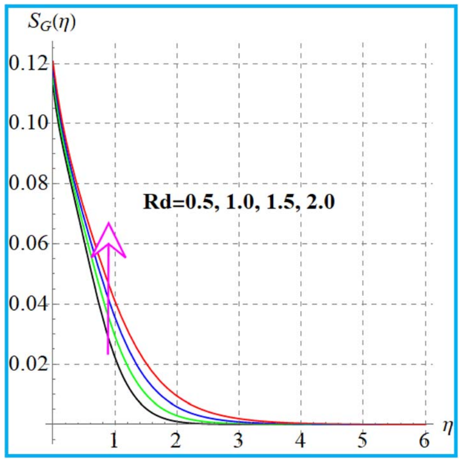

Fig. 21 $S_G(\eta)$ *versus* Rd.

6.3 Concentration

Fig. 11 illustrates the impact of (Nt) on concentration. An increment in concentration occurs through a higher thermophoresis variable. The feature of concentration ($\phi(\eta)$) for (Sc) is depicted in Fig. 12. Here due to an increase in (Sc), the concentration decays due to reduction in mass diffusivity. Fig. 13 displays the variation of (β_2) for concentration. Clearly, the concentration boosts up for a higher solutal Biot number. Additionally, it is evident through Fig. 14 that concentration decays with a random motion variable.

6.4 Microorganism field

Fig. 15 exhibits the result of the bioconvection Lewis number on ($\chi(\eta)$). Clearly, microorganism field degradation is detected against a higher bioconvection Lewis number (Lb). The influence of (β_3) on the microorganism field ($\chi(\eta)$) is shown in Fig. 16. A higher estimation of (β_3) leads to augmentation of the microorganism ($\chi(\eta)$) field. The graphical feature of ($\chi(\eta)$) *versus* the Peclet number is portrayed in Fig. 17. A clearly decreasing trend of microorganisms ($\chi(\eta)$) is witnessed for a higher Peclet (Pe) number.

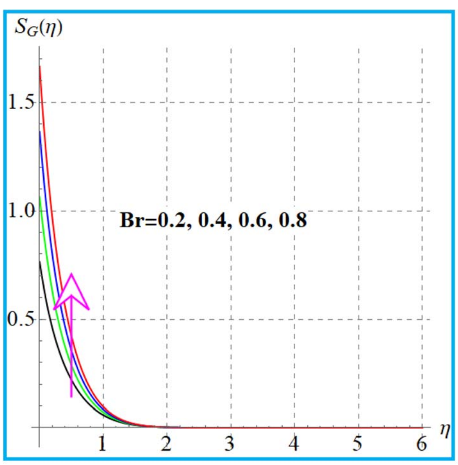

Fig. 20 $S_G(\eta)$ *versus* Br.

6.5 Entropy production

Fig. 18 shows the entropy variation against the magnetic variable. With an increase in the magnetic field the Lorentz force causes more resistance in the flow region. As a result, the internal energy of the system increases and consequently the entropy rate is augmented. Fig. 19 displays the impact of the diffusion parameter (L) on ($S_G(\eta)$). Here entropy rises against the diffusion variable. Effects of (Br) on the entropy rate are given in Fig. 20. An increment in entropy generation is found for a larger Brinkman number due to a larger kinetic energy. Fig. 21 elucidates the outcomes of the radiation parameter (Rd) for ($S_G(\eta)$). The entropy rate against radiation is enhanced.

7 Closing remarks

Here the magnetized bioconvective flow of the Reiner–Rivlin nanomaterial by convective conditions is examined. Entropy analysis in the presence of chemical reaction is addressed. Gyrotactic micro-organisms are taken into account. Key points of recent analysis are given below.

• Reduction occurs in liquid flow for the magnetic field and bioconvection Rayleigh number.

• Velocity improves for higher values of the material variable while the reverse impact holds for the buoyancy ratio variable.

• Temperature enhancement is noted for thermophoresis and radiation variables.

• An increase in temperature distribution and entropy rate is witnessed for the magnetic field.

• Higher random motion leads to temperature enhancement.

• A larger approximation of the thermal Biot number intensifies the temperature distribution.

• The reverse trend holds for concentration against random motion and thermophoresis variables.

• A decline in concentration occurs for a higher Schmidt number.

• Concentration increases for a higher solutal Biot number.

• Reduction in microorganisms occurs *versus* the Peclet number.

• Microorganism field decays against a higher bioconvection Lewis number.

• Entropy rate has similar behavior against radiation and diffusion variables.

• Entropy rate increases *versus* a larger Brinkman number.

Conflicts of interest

There are no conflicts to declare.

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