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Hall Current and Thermal Radiation Effects on MHD Nanofluid in the Presence of Heat Source/Sink, Brownian Motion and Thermophoresis with Inclined Plates

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ABSTRACT

The purpose of present study is to analyse the influence of Hall current and thermal radiation MHD electrically conducting nanofluid flow past a continuously stretching surface with heat absorption/generation in the presence of Brownian motion and Thermophoresis has been explored. Transverse magnetic field with the assumption of small Reynolds number is implemented vertically. Appropriate similarity transformations are utilized to transform the governing partial differential equations into the non-linear ordinary differential equations. Numerical solutions for the dimensionless velocity, temperature and nanoparticle concentration are computed with the help of the shooting method. The impact of each of the Hall current parameter, thermal radiation parameter, Heat source/sink parameter, Brownian motion parameter, thermophoresis parameter and magnetic parameter on velocity, concentration and temperature, is discussed through graphs. The skin friction coefficient, the local Nusselt number and the Sherwood number are calculated numerically to look into the inside behaviour of the emerging parameters. It is witnessed that the flow velocity is a diminishing function of the linear and non-linear thermal radiation parameter. Moreover, mounting values of Brownian motion parameter reduce the nanoparticle concentration profile.

1. Introduction

The study of nanofluids have fascinated because of its remarkable applications in industry such as solar cells, electronics, solar stills, communication, solar cooling systems, computing technologies, solar collectors, optical devices, water heaters, lasers, absorption refrigeration systems, and medicine, synthesis of various solar devices because of their higher properties over the conventional fluids. A nanofluid, consisting of a base fluid and nanoparticles, is a modern division of heat transfer fluids. The utilization of supplement is an approach to intensify the performance of heat transfer in base fluids. The heat conductance of conventional heat transfer fluids does not encounter the demands of modern cooling rate. Nanofluids are suspensions of ultrafine-grained solid particles

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(nanoparticles) and it improves the convective heat transfer and heat conductivity in common fluids. Choi and Eastman [1] analysed the increased thermal conductivity of nanoparticle fluids. Das *et al.,* [2] investigated the Heat Transfer in Nanofluids. Natural convective heat and mass transfer nanofluid boundary layer flow through a vertical plate with convective boundary condition was studied by Aziz and Khan [3]. Srinivasacharya and Surender [4] examined the non-similar solution by considering double stratification on natural convection heat transfer of a nanofluid in a porous saturated medium over a vertical plate. Mebarek-Oudina *et al.,* [5] have studied Hydromagnetic flow of magnetite–water nanofluid utilizing adapted Buongiorno model. Umair Khan *et al.,* [6] have discussed an exact solution of a Casson fluid flow induced by dust particles with hybrid nanofluid over a stretching sheet subject to Lorentz forces. Shafiq *et al.,* [7] have analysed Sensitivity analysis for Walters-B nano liquid flow over a radiative Riga surface by RSM. Mebarek-Oudina *et al.,* [8] have possessed a review on Nano-Fluids Applications and Heat Transfer Enhancement Techniques in Different Enclosures. Raza *et al.,* [9] have expressed the flow of magnetised convective Casson liquid via a porous channel with shrinking and stationary walls. A very recently Dharmaiah *et al.,* [10] have reviewed nuclear reactor application on Jeffrey fluid flow with Falkner-skan factor, Brownian and thermophoresis, non-linear thermal radiation impacts past a wedge. Chabani *et al.,* [11] have studied Ismail, Numerical analysis of magnetic hybrid Nano-fluid natural convective flow in an adjusted porous trapezoidal enclosure. Mebarek-Oudina [12] has expressed Convective heat transfer of Titania nanofluids of different base fluids in cylindrical annulus with discrete heat source.

The analysis of non-Newtonian fluid flows is a widespread topic of modern research. Non-Newtonian fluids cover many products which we come across regularly such as mud, juices, lubricant oils and cosmetics. It is salient to understand the thermal transfer attributes of these fluids on account of their merits in bio, nuclear, polymer and material processes. Nazir *et al.,* [13] have studied Finite element simulations of hybrid nano-Carreau Yasuda fluid with hall and ion slip forces over rotating heated porous cone. Rabeeah Raza *et al.,* [14] have discussed exploration of temperature-dependent thermal conductivity and diffusion coefficient for thermal and mass transportation in sutterby nanofluid model over a stretching cylinder. Sohail *et al.,* [15] have analyzed Computational exploration for radiative flow of Sutterby nanofluid with variable temperature-dependent thermal conductivity and diffusion coefficient. Naseem *et al.,* [16] have reviewed Contribution of Dufour and Soret effects on hydromagnetized material comprising temperature-dependent thermal conductivity. Wang *et al.,* [17] have expressed Galerkin strategy for tri-hybridized mixture in ethylene glycol comprising variable diffusion and thermal conductivity using non-Fourier's theory. Algehyne *et al.,* [18] have possessed Investigation of thermal performance of Maxwell hybrid nanofluid boundary value problem in vertical porous surface via finite element approach. Sohail *et al.,* [19] have investigated Theoretical and numerical investigation of entropy for the variable thermophysical characteristics of couple stress material, applications to optimization. Zubair *et al.*, [20] have discussed computational analysis of radiative Williamson hybrid nanofluid comprising variable thermal conductivity. A recent researcher, Sahar *et al.,* [21], explored drug release using nanoparticles in cancer cells on 2-D materials to target drug delivery: A numerical simulation via the molecular dynamic's method, Engineering Analysis with Boundary Elements. Amjad [22] reviewed the bioconvection flow of Cross nanofluid due to the cylinder with activation energy and second-order slip features. Iskander and Thamer [23] have reviewed an investigation into the effect of changing the air quality and stream size on the Trombe wall for two different arrangements of rectangular blocks of phase change material in this wall. Sumera *et al.,* [24] have expressed the contribution of the suction phenomenon and thermal slip effects for radiated hybrid nanoparticles (Al2O3-Cu/H2O) with a stability framework. Banawas *et al.,* [25] have discussed reinforced calcium phosphate types of cement with zinc by changes in initial properties: A molecular dynamics simulation. Amjad *et al.,* [26] have proposed an investigation of phase change and heat transfer in water/copper oxide nanofluid enclosed in a cylindrical tank with a porous medium. Abisek *et al.,* [27] have analysed, Prediction of strength and analysis in self-compacting concrete using machine learning based regression techniques. Huhemandula *et al.,* [28] have discussed Numerical analysis and two-phase modelling of water Graphene Oxide nanofluid flow in the riser condensing tubes of the solar collector heat exchanger. Barhoumi *et al.,* [29] have possessed Optimal sizing of photovoltaic systems based green hydrogen refuelling stations case study Oman.

Hall current is most prominent on the absolute value and orientation of the current density and thereby on the magnetic force term. Under the effects of Hall currents the convective flow problem with magnetic field is significant in view of engineering uses in electric transformers, transmission lines, refrigeration coils, power generators, MHD accelerators, nanotechnological processing, nuclear energy systems exploiting fluid metals, blood flow control and heating elements. In case of magnetic field of high strength and less density of the gas, the investigation of magnetohydrodynamic flows with Hall current have the best utilizations in the study of Hall accelerators and flight magnetohydrodynamic. Peristaltic flows have vast applications under the effects of applied magnetic field in the magnetohydrodynamic feature of blood, process of dialysis, oxygenation and hypothermia. Exploration of non-Newtonian fluid flows has been the focus of many scientists due to its vast applications in industries and engineering. Important applications are existed in food engineering, petroleum production, power engineering, in polymer solutions and in melt in the plastic processing industries. Hall effect plays an important role when the Hall parameter is high. Hall parameter is the ratio of electron cyclotron frequency to atom-electron collision frequency. Maatoug *et al.,* [30] have studied Variable chemical species and thermo-diffusion Darcy–Forchheimer squeezed flow of Jeffrey nanofluid in horizontal channel with viscous dissipation effects. Omar *et al.*, [31] have analysed Hall Current and Soret Effects on Unsteady MHD Rotating Flow of Second-Grade Fluid through Porous Media under the Influences of Thermal Radiation and Chemical Reactions. Deepthi *et al.,* [32] have discussed Recent Development of Heat and Mass Transport in the Presence of Hall, Ion Slip and Thermo Diffusion in Radiative Second Grade Material: Application of Micromachines. Aruna *et al.,* [33] have possessed an unsteady MHD flow of a second-grade fluid passing through a porous medium in the presence of radiation absorption exhibits Hall and ion slip effects. Influence of MHD mixed convection flow for maxwell nanofluid through a vertical cone with porous material in the existence of variable heat conductivity and diffusion was analysed by Raghunath *et al.,* [34]. The chemically reactive second grade via porous saturated space was investigated by Raghunath *et al.,* [35] using a perturbation technique. Raghunath *et al.,* [36] have investigated the effects of Soret, Rotation, Hall, and Ion Slip on the unsteady flow of a Jeffrey fluid through a porous medium. Raghunath and Mohanaramana [37] have researched Hall, Soret, and rotational effects on unsteady MHD rotating flow of a second-grade fluid through a porous media in the presence of chemical reaction and aligned magnetic field.

Thermal radiation plays an important role in dissipating heat from the surface. It has applications in manufacturing industries such as chopper, space vehicles, reliable equipment design, satellites, atomic furnaces, missiles, space technology and procedures related to high temperature. Dharmendar *et al.,* [38] analysed thermal radiation and suction effects on MHD Nanofluid boundary layer flow on a non-linear stretching sheet. Li *et al.,* [39] have expressed Effects of activation energy and chemical reaction on unsteady MHD dissipative Darcy–Forchheimer squeezed flow of Casson fluid over horizontal channel. Suresh Kumar *et al.,* [40] have discussed Numerical analysis of magnetohydrodynamics Casson nanofluid flow with activation energy, Hall current and thermal radiation. Obulesu *et al.,* [41] have possessed unsteady MHD on convective flow of a Newtonian fluid past an inclined plate in presence of chemical reaction with radiation absorption and Dufour effects.

Raghunath and Mohana Ramana [42] have studied Soret and chemical reaction effects on heat and mass transfer in MHD flow of a Kuvshinski fluid through porous medium with aligned magnetic field and radiation. Raghunath *et al.,* [43] have analyzed Chemical reaction with aligned magnetic field effects on unsteady MHD Kuvshinski fluid flow past an inclined porous plate in the presence of radiation and Soret effects. Obulesu *et al.,* [44] have discussed MHD Heat and Mass Transfer Steady Flow of a Convective Fluid through a Porous Plate in The Presence of Diffusion Thermo and Aligned Magnetic field.

The study of heat generation/absorption parameter on the moving fluid is influential in sight of diverse physical problems. Uneven heat generation plays crucial part in heat dissipation problems. With the accelerated development of electronic technology, efficient cooling of electronic equipment has evolved to cool a variety of electronic equipment and is provided by separate transistors for mainframes and power supplies for telephone switches. The influence of the heat generation/absorption plays a crucial role in the heat efficiency of base fluids. Its pertinence is seen in the heat discharge of nuclear fuel residues, food storage, the production of plastic and rubber sheets, motion of fluids in fixed bed reactors and much more. Recently, Raghunath *et al.,* [45–47] studied the Heat absorption effects on dissimilar flow geometries. Kumar and Singh [48] investigated impact of heat source/sink on MHD steady laminar boundary layer natural convective flow through a concentric annulus region directed vertically. Bataller [49] has analysed effects of heat source/sink, radiation and work done by deformation on flow and heat transfer of a viscoelastic fluid over a stretching sheet. Heat source and chemical reaction impact on MHD flow past a moving vertical plate with convective surface conditions are analysed by Dharmendar and Shankar [50].

Motivated by the above studies and applications, the present work examines the effect of Hall Current and thermal radiation on MHD heat and mass transfer Nanofluid flow with inclined plates in the presence of Brownian motion and Thermophoresis. The effects of flow regulating parameters on the distributions of flow are presented in tabular and graphical form. This consideration has an important value in engineering and biological research. Analytical and numerical approaches are applied to examine the modelled problem and also compared each other, and good results were obtained.

2. Formulation of the Problem

Here, steady heat and mass transfer of an incompressible hydromagnetic nanofluid flow along a vertical stretching sheet coinciding with the plane y = 0, has been considered in the presence of the Hall current effects. By keeping the origin fixed, two opposite and equal forces are assumed to employ along the x-axis so that the sheet stretches linearly in both positive and negative direction (see Figure 1).

i. With the assumption that the Newtonian nanofluid be electrically conducting and heat generating/absorbing, a strong magnetic field has been imposed normal to the direction of flow.
ii. Moreover, no electric field has been assumed to apply and the frequency of atom-electron collision has also been considered high for the generation of Hall current effect [55].
iii. Due to the strong magnetic flux density B_0, the Hall current effect is taken into consideration, however the small magnetic Reynolds number is employed and the induced magnetic field is ignored.
iv. Hall current effect is strong enough to give rise to a force in the z−direction and a cross flow is induced in the same direction which causes a three-dimensional flow.

v. It is further assumed that there are no variations in the flow, heat and mass transfer in the z-direction.
vi. This assumption can be achieved by taking the sheet of infinite width. Non-conducting plate is considered so that the generalized Ohm's law [52] gives $J_y=0$ in the flow field.
vii. Brownian motion and thermophoresis effects are considered using the Buongiorno model [53] for the nanofluid.
viii. Further, the effects of viscous dissipation and Joule heating are ignored.

The governing equations and its corresponding boundary conditions followed by Ibrahim and Anbessa [51].

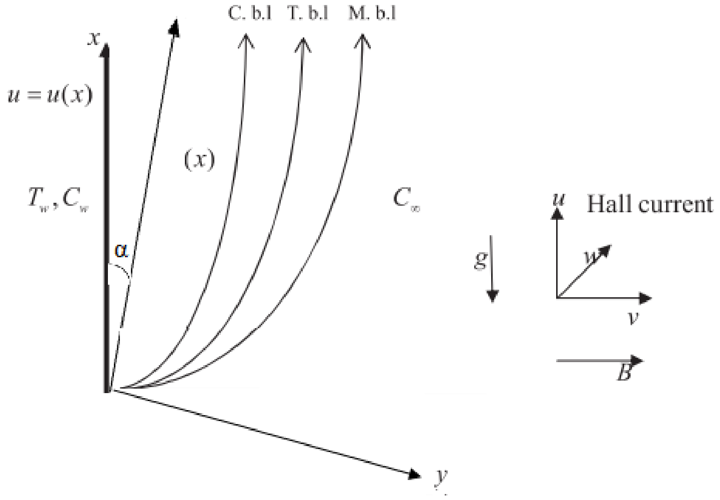

Fig. 1. Physical configuration of the problem

By the above-mentioned assumptions and Boussinesq approximation, the mathematical form of the problem is

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

$$u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}=\nu\frac{\partial^2 u}{\partial y^2}-\frac{\sigma B_0^2}{\rho\left(1+m^2\right)}\left(mw+u\right)+g_C\beta_T(T-T_\infty)Cos\alpha+g_C\beta_C(C-C_\infty)Cos\alpha \tag{2}$$

$$u\frac{\partial w}{\partial x}+v\frac{\partial w}{\partial y}=\nu\frac{\partial^2 w}{\partial y^2}+\frac{\sigma B_0^2}{\rho\left(1+m^2\right)}\left(mu-w\right) \tag{3}$$

$$u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}=\frac{k}{\rho C_p}\frac{\partial^2 T}{\partial y^2}+\frac{Q_0}{\rho C_p}(T-T_\infty)+\tau\left(D_B\frac{\partial C}{\partial y}\frac{\partial T}{\partial y}+\frac{D_T}{T_\infty}\left(\frac{\partial T}{\partial y}\right)^2\right)-\frac{1}{\rho C_p}\frac{\partial q_r}{\partial y} \tag{4}$$

$$u\frac{\partial C}{\partial x}+v\frac{\partial C}{\partial y}=D_B\frac{\partial^2 C}{\partial y^2}+\frac{D_T}{T_\infty}\frac{\partial^2 T}{\partial y^2} \tag{5}$$

The corresponding boundary conditions for the governing PDEs are

$$\begin{aligned} &u=ax,\quad v=0,\quad w=0,\quad T=T_w,\quad C=C_w \qquad \text{at } y=0\\ &u\to 0,\quad v\to 0,\quad w\to 0,\quad T\to T_\infty \quad C\to C_\infty \qquad \text{as } \ y\to\infty \end{aligned} \tag{6}$$

The similarity transformation used to transform the PDEs to dimensionless ODEs

$$\eta=\sqrt{\frac{a}{v}}y\text{, }\psi(x,y)=\sqrt{av}x\,f(\eta)\text{, }\ w=axg(\eta)\ \ \phi(\eta)=\frac{C-C_\infty}{C_w-C_\infty}\text{, }\ \theta(\eta)=\frac{T-T_\infty}{T_w-T_\infty}\ \theta=\frac{T}{T_w} \tag{7}$$

The Rosseland approximation can be used for the radiative heat flux vector qr because there is also self-absorption in addition to emission for an optically thick fluid. Since the absorption coefficient is typically wavelength dependent and significant, we can use the Rosseland approximation. Therefore, the definition of qr is [54].

$$q_r=\frac{-4\sigma^*}{3k^*}\frac{\partial^2 T^4}{\partial y} \tag{8}$$

In this equation, k^* denotes the Rosseland mean absorption co-efficient and σ_1 stands for the Stefan–Boltzmann constant.

We are working under the assumption that the temperature changes inside the flow are not very significant, allowing us to describe T^4 as a linear function. We extend T'^4 about the free stream temperature T using Taylor's series, ignoring higher order variables in the process. The following is an approximation that may be derived from this

$$T^4\approx 4T_\infty^3-3T_\infty^4 \tag{9}$$

The equation for energy may be obtained by combining Eq. (8) and Eq. (9), as shown in the following

$$u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}=\frac{k}{\rho C_p}\frac{\partial^2 T}{\partial y^2}+\frac{Q_0}{\rho C_p}(T-T_\infty)+\tau\left(D_B\frac{\partial C}{\partial y}\frac{\partial T}{\partial y}+\frac{D_T}{T_\infty}\left(\frac{\partial T}{\partial y}\right)^2\right)+\frac{16\sigma^* T_\infty^3}{3\rho C_p k^*}\frac{\partial^2 T}{\partial y^2} \tag{10}$$

Substitute Eq. (7) into Eq. (2), Eq. (3) Eq. (5) and Eq. (10) yields to obtain the subsequent non dimensional equations

$$f'''+ff''-f'^2+Gr\theta Cos\alpha+Gm\phi Cos\alpha-\frac{M}{1+m^2}\left(f'+mg\right)=0 \tag{11}$$

$$g'' + fg' - f'g + \frac{M}{1+m^2}\left(mf' - g\right) = 0 \tag{12}$$

$$\theta''\left(1 + R\Pr\right) + \Pr f\theta' + \Pr N_b\left(\theta'\phi' + \frac{N_T}{N_b}\theta'^2\right) + \Pr Q\theta = 0 \tag{13}$$

$$\phi'' + \Pr\ L_e\ f\ \phi' + \frac{N_t}{N_b}\theta'' = 0 \tag{14}$$

The correlated Dimensionless boundary conditions (BCs) are

$$\begin{aligned} &f(0) = 0, \quad f'(0) = 1, \quad g(0) = 0, \quad \theta(0) = 0, \quad \phi(0) = 1 \qquad at \quad \eta = 0 \\ &f'(\eta) \to 0, \quad g(\eta) \to 0, \quad \theta(\eta) \to 0, \quad \phi(\eta) \to 0 \qquad as \quad \eta \to \infty \end{aligned} \tag{15}$$

In the equations that do not include dimensions, the important parameters are defined as

$$\begin{aligned} &M = \frac{\sigma B_0^2}{\rho a},\ \Pr = \frac{\nu}{\alpha} = \frac{\nu\rho C_p}{k},\ L_e = \frac{\alpha}{D_B},\ Q = \frac{Q_0}{a\rho C_p},\ Gr = \frac{g_c\beta_T\left(T_w - T_\infty\right)}{a^2 x}, \\ &N_b = \frac{\tau D_B\left(C_w - C_\infty\right)}{\nu},\ \ N_t = \frac{\tau D_T\left(T_w - T_\infty\right)}{\nu},\ Gm = \frac{g_c\beta_C\left(C_w - C_\infty\right)}{a^2 x}, R = \frac{16\sigma^* T_\infty^3}{3\rho C_p k^*} \end{aligned} \tag{16}$$

3. Physical Quantities of Interests

The local skin friction coefficient in the direction of x Cf_x, and in the direction of z Cf_z, the local Nusselt number Nu_x, and the local Sherwood number Sh_x are the physical quantities of relevance that influence the flow. These numbers have the following definitions.

$$C\,f_x = \frac{2\tau_{wx}}{\rho(ax)^2},\ Cf_z = \frac{2\tau_{wz}}{\rho(ax)^2},\ Nu_x = \frac{xq_w}{k\left(T_w - T_\infty\right)},\ Sh_x = \frac{x\,j_w}{D_B\left(C_w - C_\infty\right)} \tag{17}$$

where τwx, τwy, qw and jw are the wall skin friction, wall heat flux and wall mass flux respectively given by

$$\tau_{wx} = \mu\left[\frac{\partial u}{\partial y}\right]_{y=0},\quad \tau_{wz} = \mu\left[\frac{\partial w}{\partial y}\right]_{y=0},\quad q_w = -k\left[\frac{\partial T}{\partial y}\right]_{y=0},\quad j_w = -D_B\left[\frac{\partial C}{\partial y}\right]_{y=0} \tag{18}$$

The coefficient of skin friction, the Nusselt number, and the Sherwood number are all expressed in their non-dimensional versions in terms of the similarity variable as follows.

$$\mathrm{Re}_x^{1/2}\,Cf_x = 2f''(0),\quad \mathrm{Re}_x^{1/2}\,Cf_z = 2g'(0),\quad \mathrm{Re}_x^{1/2}\,Nu_x = -\theta'(0),\quad \mathrm{Re}_x^{1/2}\,Sh_x = -\phi'(0) \tag{19}$$

4. Results and Discussion

To envision the effect of various physical parameters on tangential velocity f^{i}(η), transverse velocity g(η), nanoparticle concentration ϕ(η) and temperature θ(η) profiles, Figures 2-26 are plotted. In all these computations, unless mentioned, otherwise we have considered Nb= 0.3, Nt= 0.7, P r= 0.71, Le = 0.6, M= 0.5, m= 0.2, Gr= 0.5, Gm = 0.5, Q_0=0.5, R=1.

Figure 2 to 5 shows the effect of magnetic parameter M on the tangential velocity f ’(η), transverse velocity g(η), temperature θ(η), and concentration ϕ(η) profiles, respectively. The velocity profile f’(η) decreases with an increase in the values of M, the same behaviour has observed transverse velocity g(η), and temperature θ(η) and concentration ϕ(η) profiles increase as M increases. As M increases, a drag force, called Lorentz force increases. Since this force opposes the flow of nanofluid, velocity in the flow direction decreases. Moreover, since an electrically conducting nanofluid with the strong magnetic field in the direction orthogonal to the flow are considered, an increase in M increases the force in the z-direction which results in an diminishes in the transverse velocity profile g(η).

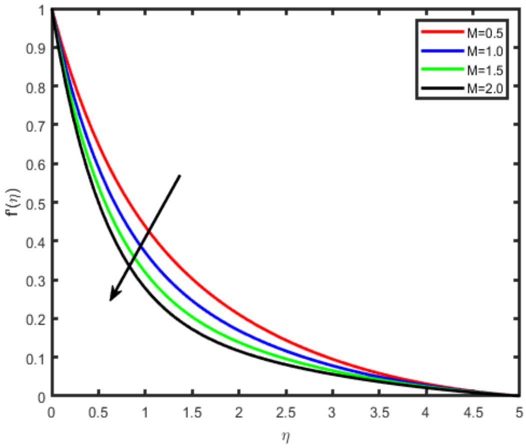

Fig. 2. Effect of M on f$'$(n)

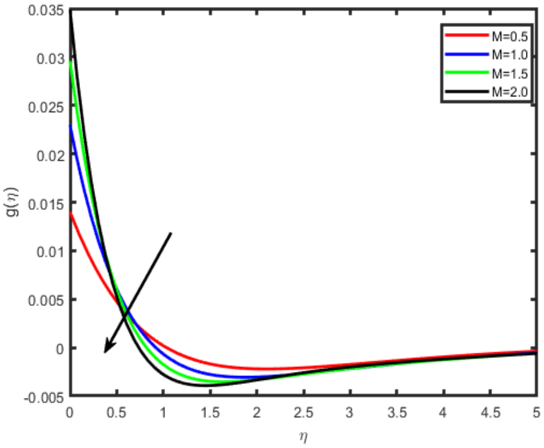

Fig. 3. Effect of M on g(n)

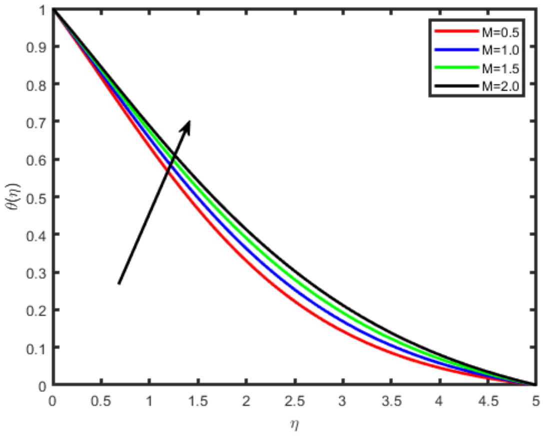

Fig. 4. Effect of M on θ(n)

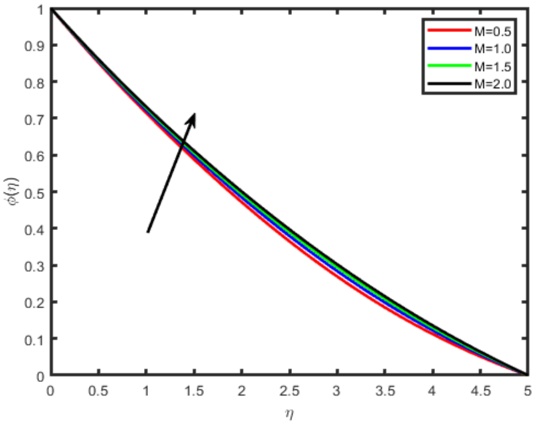

Fig. 5. Effect of M on φ (n)

Figure 6 to 9 illustrate the impacts of the Hall parameter m on tangential velocity $f^{I}(\eta)$, transverse velocity g(η), nanoparticle concentration ϕ(η) and temperature θ(η) profiles, respectively. It is observed Figure 6 and 7, the velocity f’(η) and g(η) profiles increase as m increases. But the temperature and concentration profiles decrease with an increase in m as shown in Figure 8 and 9. This is because the enclosure of Hall parameter decreases the resistive force caused by the magnetic field due to its effect of reducing the effective conductivity. Hence, the velocity component increases as the Hall parameter increases.

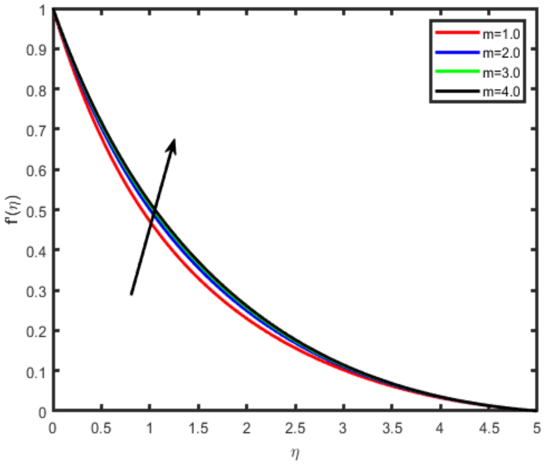

Fig. 6. Effect of m on $f'(n)$

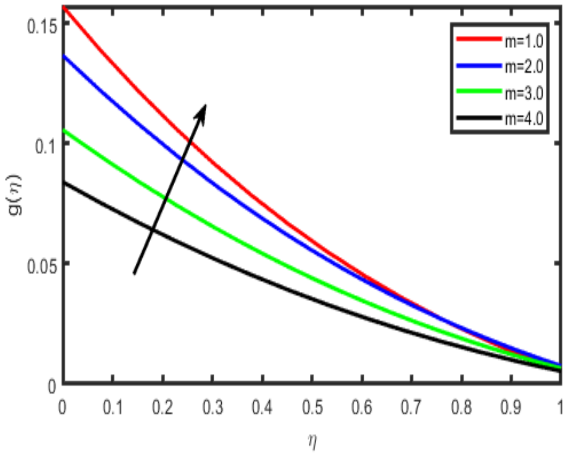

Fig. 7. Effect of m on g(n)

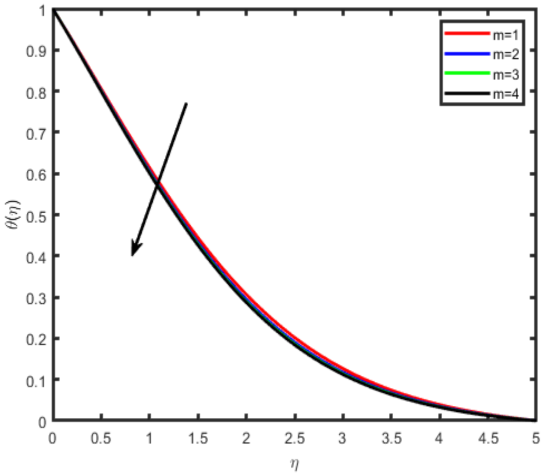

Fig. 8. Effect of m on θ(n)

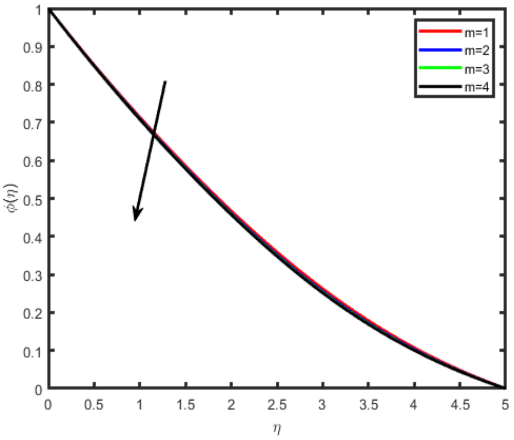

Fig. 9. Effect of m on φ (n)

In Figure 10 to 13 the effects of the thermal Grashof Gr and mass Grashof Gm numbers on the tangential velocity $f''(\eta)$, the transverse velocity g(η), are displayed respectively. As the Grashof number is a ratio of the buoyancy force to the viscous force and it appears due to the natural convection flow, so an increase in the tangential velocity as well as the transverse velocity of the fluid. It happens because of the fact that higher the Grashof number implies higher the buoyancy force which means higher the movement of the flow. Figure 8 and 9 depict the influence of the solutal Grashof number on the temperature and the concentration profile respectively. An increase in the solutal Grashof number means a decrease in the viscous force which reduces the temperature and the concentration of the fluid.

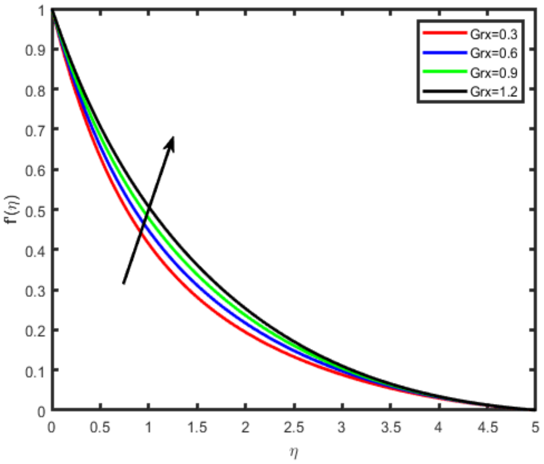

Fig. 10. Effect of Gr on f′(n)

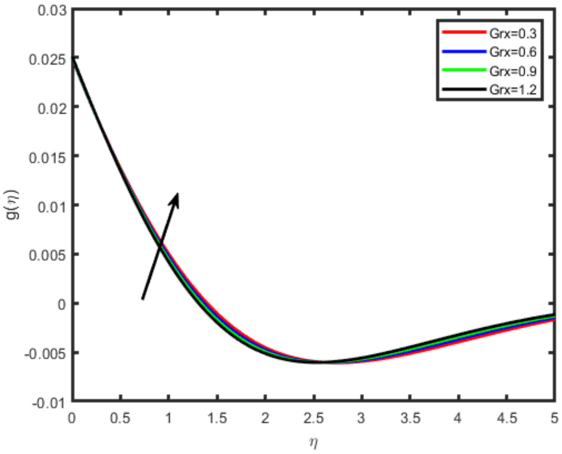

Fig. 11. Effect of Gr on g(n)

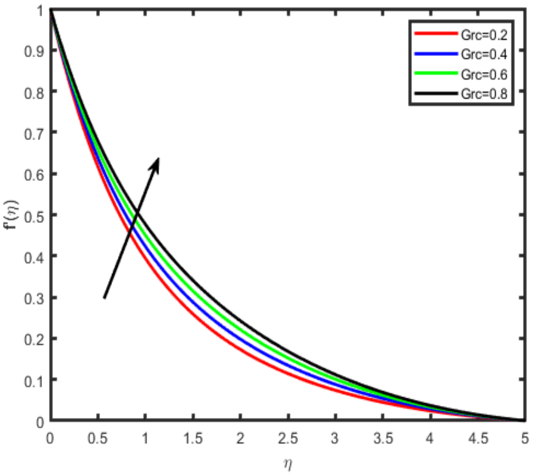

Fig. 12. Effect of Gm on f′(n)

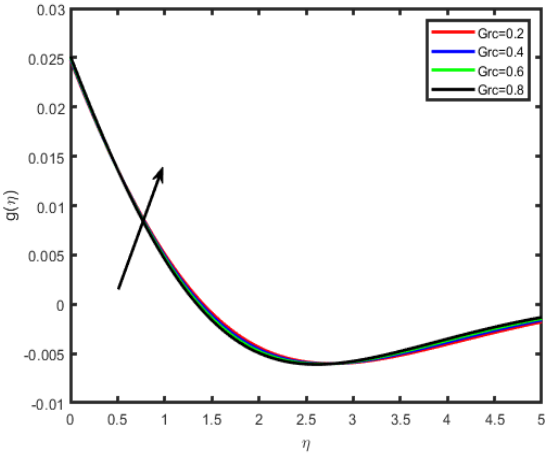

Fig. 13. Effect of Gm on g(n)

Figure 14 to 15 describes the behaviour of thermal radiation parameter (R) on both temperature and concentration fields. It interesting to observe that for higher value of R strengthen the temperature because radiation parameter produces thermal energy in the flow region, therefore enhancement have been seen in the temperature field whereas reverse behaviour is seen for concentration. Figure 16 shows that the temperature θ(η) increases with an increase in the resistance of the heat source / sink, due to an increase in the resistance of the heat generation, the temperature rises. The opposite behaviour is observed in the case of concentration as showed in Figure 17.

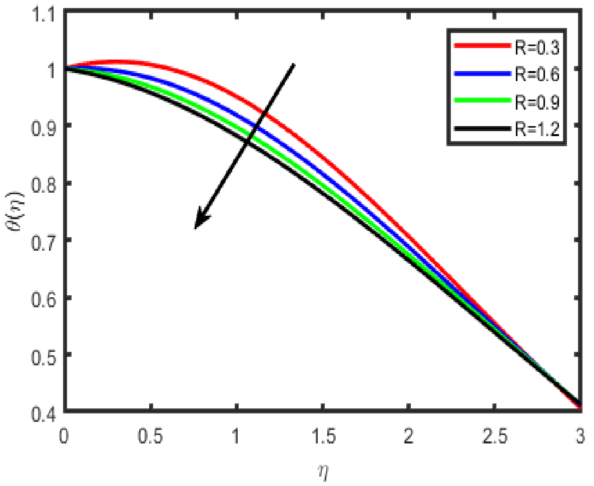

Fig. 14. Effect of R on θ(n)

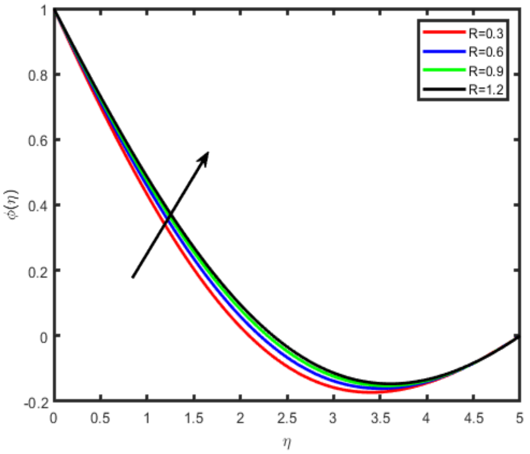

Fig. 15. Effect of R on φ(n)

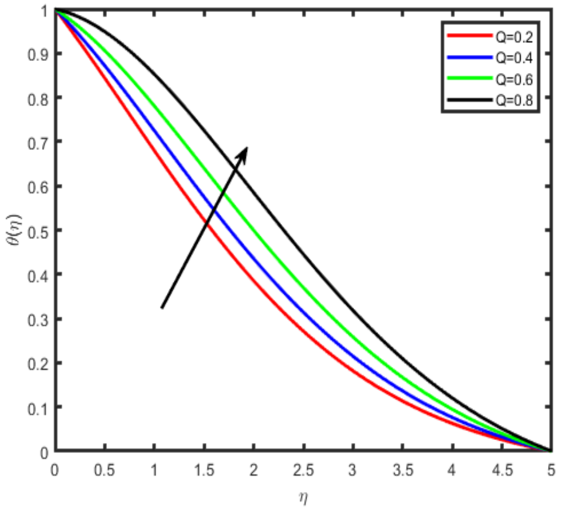

Fig. 16. Effect of Q on θ(n)

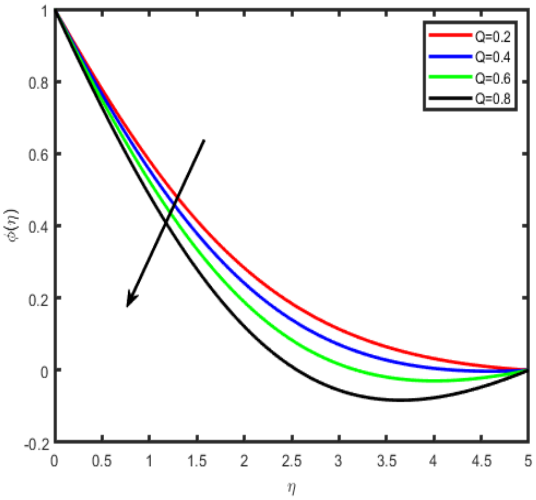

Fig. 17. Effect of Q on φ(n)

Influence of Brownian motion parameter Nb on the temperature and concentration profiles is studied in Figure 18 and 19. From these figures, we notice that an enhancement in the values of Nb gives rise to the temperature, while it causes a decrease in the nanoparticle concentration profile. Brownian motion is the random motion of nanoparticles suspended in the fluid, caused by the collision of nanoparticles with the fluid particles. An increment in the thermophoretic effect causes an increment in the Brownian motion effect which results in the rise of the temperature due to the increment in the kinetic energy. Figure 20 and 21 illustrate the effect of thermophoresis parameter Nt on the temperature and the nanoparticles concentration profile. One can observe that temperature and concentration fields increase with an enhancement in Nt. Thermophoresis parameter plays an important role in the heat transfer flow. Thermophoresis force enhances when Nt is increased which tends to move the nanoparticles from the hot region to the cold and as a result the temperature and the boundary layer thickness increase. Figure 22 and 23 shows the impact of the Lewis number (Le) on temperature and nanoparticle concentration profiles respectively. It is observed that the temperature increases by increasing Le while concentration decreases with an increase in the Lewis number.

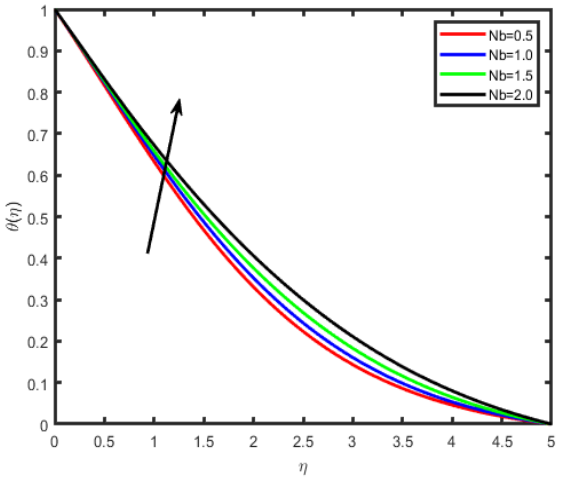

Fig. 18. Effect of Nb on θ(n)

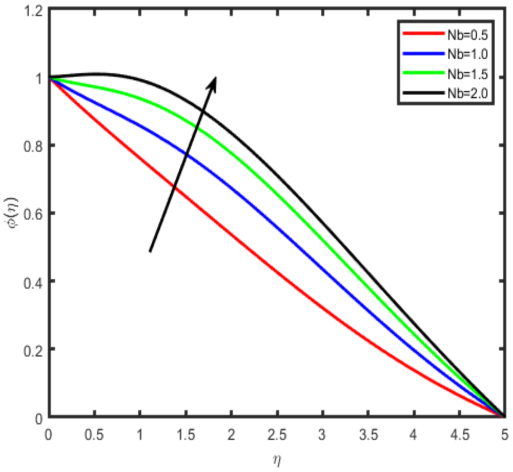

Fig. 19. Effect of Nb on φ(n)

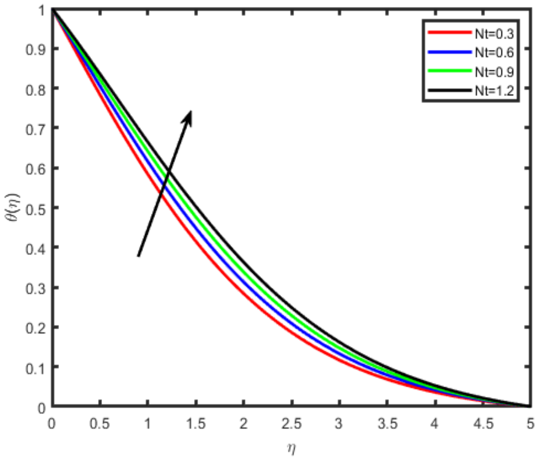

Fig. 20. Effect of Nt on θ(n)

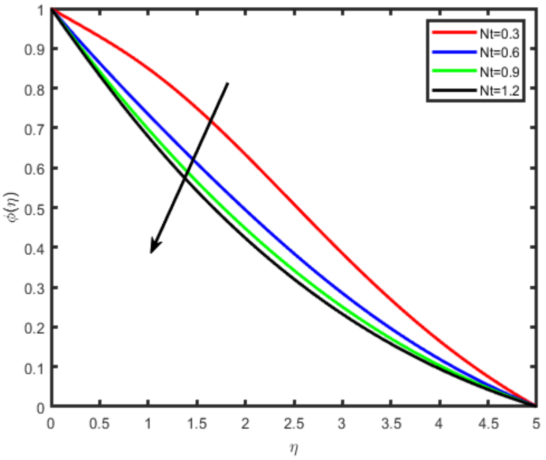

Fig. 21. Effect of Nt on φ(n)

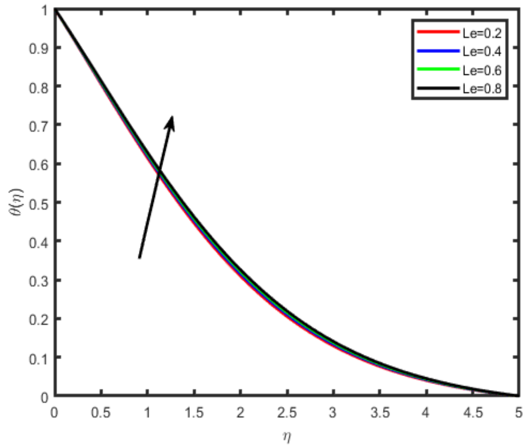

Fig. 22. Effect of Le on θ(n)

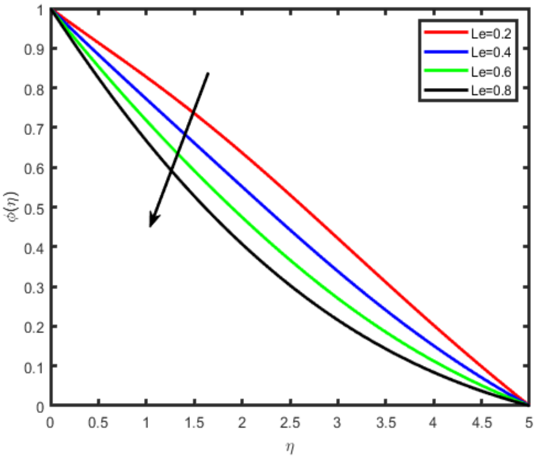

Fig. 23. Effect of Le on φ(n)

The impact of the various physical parameters on the local Sherwood number, skin friction coefficient and local Nusselt number, mathematical results are achieved for Nb= 0.3, Nt= 0.7, Pr= 0.71, Le = 0.6, M= 0.5, m= 0.2, Gr = 0.5, Gr = 0.5, Q=0.5, and R=1are enumerated as shown in Table 1. it is viewed that the skin-friction coefficient in x− direction decreases with an increase in the thermal Grashof number Gr, the mass Grashoff number Gm, Hall current parameter m, and Brownian motion parameter Nb, while it increases for the increasing value of magnetic parameter M, Heat source parameter, Radiation and Prandtl number Pr, and thermophoresis parameter Nt. A completely opposite behavior is recorded for the coefficient of the skin-friction in the z-direction. Nusselt number increases when the Hall current parameter m, thermal Grashof number, the mass Grashoff number, and Prandtl number, increase whereas it is reduced by increasing the value of Magnetic field parameter M, Heat source and radiation parameters. Sherwood number has increasing behavior for thermal Grashof number Gr, Magnetic field parameter M, Brownian motion parameter Nb, Heat source and radiation parameters and thermophoresis parameter Nt, while it has decreasing behavior for Grashoff number Gm and Prandtl number.

Table1
Numerical values of $\mathrm{Re}_x^{1/2}\,Cf_x$, $\mathrm{Re}_x^{1/2}\,Cf_z$, $\mathrm{Re}_x^{1/2}\,Nu_x$, $\mathrm{Re}_x^{1/2}\,Sh_x$

Gr	Gm	Q	m	Nb	R	M	Pr	Nt	-2f''(0)	-2g'(0)	-θ'(0)	-ϕ'(0)
0.5									1.254347	0.8521	0.521212	0.951412
1.0									0.997845	0.91252	0.532334	0.99123
1.5									0.735443	0.95424	0.54573	1.02452
	0.3								0.987567	0.85125	0.503223	0.12471
	0.6								0.847543	0.98526	0.51244	0.11082
	0.9								0.712545	1.25217	0.578556	0.917834
			1						1.521498	0.85213	0.314576	0.885232
			2						1.021409	0.95472	0.297878	0.795245
			3						0.8125534	0.99851	0.231276	0.945245
				0.2					0.951212	0.95212	0.845254	0.585278
				0.4					0.815246	0.96123	0.821543	0.612465
				0.6					0.712590	0.98524	0.803232	0.697812
						0.5			0.945286	1.02545	0.98752	0.785290
						1.0			1.245445	0.98524	0.912598	0.895275
						1.5			1.403523	0.85123	0.895265	0.945244
							0.68		0.978558	1.02142	0.125444	0.987832
							0.71		0.912078	0.98521	0.157833	0.945213
							0.76		0.845208	0.903223	0.198745	0.9231244
								0.3	1.545253	0.98525	0.854231	0.512065
								0.6	1.125478	0.91206	0.812558	0.5921112
								0.9	0.875290	0.89627	0.752176	0.612076
		0.2							0.712498	0.98758	0.954234	0.985267
		0.4							0.785290	0.94529	0912526	0.974534
		0.6							0.812509	0.91320	0.865716	0.964592
					0.5				0.875287	1.08756	0.745256	0.912417
					1.0				0.895265	0.94426	0.736589	0.912064
					1.5				0.912554	0.91144	0.715409	0.910213

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For the authentication of the numerical method used, the results were compared with the previously obtained results Ibrahim and Anbessa [51] for various values of parameters and it indicates an excellent accord as shown in Table 2.

Table 2
Comparison of −θ′ (0) for various value10s of Pr when Nb= 0.3, Nt= 0.7, P r= 0.71, Le = 0.6, M= 0.5, Gr = 0.5, Gm= 0.5, m=0, Q=0, R=0.06

Pr	Ibrahim and Anbessa [51]	Present values
0.01	0.019887	0.0198987
0.72	0.808635	0.8072345
1	1.000000	1.0001110
3	1.923687	1.9243677
10	3.720676	3.7321658

4. Conclusion

The influence of the Hall current and thermal radiation on the heat and mass transfer of nanofluid flowing across a linearly stretched sheet in the presence of Heat source/sink Thermophoresis and Brownian motion will be discussed in the present paper. The most significant accomplishments have been broken down into the following categories

i. The temperature increases as the Heat source/sink (Q) and Brownian motion parameter (Nb) values increase, but the concentration profile of nanoparticles decreases. The opposite behavior was observed for the case of radiation parameter (R). The temperature and concentration fields intensify with a rise in the Thermophoresis parameter (Nt). The temperature and concentration profiles tend to fall when the Prandtl number (Pr) is raised.
ii. The temperature increases by increasing Le while concentration decreases with an increase in the Lewis number. The velocity increases with enhance of hall parameter (m), whereas the reversal behavior has observed in the case of temperature and concentration.

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