Chapter

Heat Transfer in a MHD Nanofluid Over a Stretching Sheet

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Abstract

The intention behind carrying out this research work is to analyze the heat transfer characteristics in a Magnetohydrodynamic (MHD) boundary layer nanofluid flow over a stretching sheet. Two phase representation of nanofluid studied the consequence of Brownian motion along with thermophoresis. The major purpose of study is to investigate the significant role of prominent fluid parameters thermophoresis, Brownian motion, Eckert number, Schmidt number and magnetic parameter on profile of velocity, temperature distribution and concentration. Runge–Kutta Fehlberg (RKF) method was adopted to numerically solve the non-linear governing equations and the linked boundary conditions by use of shooting technique. Over all the consequence of prominent fluid parameters are explained via graphs, whereas distinction of several valuable engineering quantities like skin friction coefficient, local Nusselt number and local Sherwood number are also tabulated. The finding of present study helps to control the rate of heat transportation as well as fluid velocity in any manufacturing processes and industrial applications to make desired quality of final product.

Keywords: heat transfer, nanofluid, stretching sheet, MHD flow

1. Introduction

In various fields of science and technology rapid progress has urged the researchers to extend their study towards the regime of boundary layer flow over a stretching sheet. The boundary layer flow behavior towards a linearly or non-linearly stretching sheet plays a significant role for solving engineering problems and possess vast applications in manufacturing and production processes including metal spinning, rubber sheet manufacturing, production of glass fibers, wire drawing, extrusion of polymer sheets, petroleum industries, polymer processing etc. In these cases, the final product of desired characteristics depends on the rate of cooling in the process and the process of stretching. The dynamics of the boundary layer fluid flow over a stretching surface originated from the pioneering work of Crane [1] and he examined the incompressible steady boundary layer fluid flow caused by stretching sheet which moves in its own plane with linear velocity due to the uniform stress applications. This problem is particularly interesting as Crane [1] obtained the exact solution of 2D Navier–Stokes equations. Afterthat, Gupta and Gupta [2] extend Crane [1] work over different mathematical geometries. Yoon et al. [3] studied the theoretical and experimental results using Coulomb friction model by considering punch-sheet interface. Also, Sarma and Rao [4] examined the viscoelastic fluid flow by considering stretched sheet. In view of this, Vajravelu [5] studied flow and heat transfer in a viscous fluid over a nonlinear stretching sheet without using the impact of viscous dissipation. Cortell [6] examined heat and fluid flow transportation over a nonlinear stretching sheet for two different types of thermal boundary conditions, prescribed surface temperature (PST) and constant surface temperature (CST). The influence of heat transfer on the stagnation point flow of a third-order fluid over a shrinking surface has been studied by Nadeem et al. [7]. Recently, Prasad et al. [8] examined the mixed convection heat transfer aspects with variable fluid flow properties over a non-linear stretching surface.

Fluid heating and cooling are important in many industries such as power, manufacturing and transportation. Effective cooling techniques are greatly needed for cooling any sort of high energy device. Common heat transfer fluids such as water, ethylene glycol, and engine oil have limited heat transfer capabilities due to their low heat transfer properties. In contrast, metals have thermal conductivities up to three times higher than these fluids, so it is naturally desirable to combine the two substances to produce a heat transfer medium that behaves like a fluid, but has the thermal of a metal. Since last two decades, study of nanofluid has urged the researcher's attention due to their heat transportation rate. Nanofluid comes in existence when we add a small quantity of nano-sized $10^{-9} - 10^{-7}$ particles to the base fluids. Low heat transportation fluids like fluorocarbons, glycol, deionized water, etc. have badly thermal conductivity and therefore deliberated necessary for heat transfer coefficient surrounded by heat transfer medium and surface. The nanoparticles are typically made up of metals (Al, Cu), nitrides (AlN, SiN), carbides (Sic), oxides (Al_2O_3), or nonmetals (carbon nanotubes, Graphite, etc.) and the base fluid (conductive fluid) is usually water or ethylene glycol. Also, it has been experimentally proved that rate of heat conduction of nanofluids is more than rate of heat conduction of the base fluids. The concept of nanofluid was initially proposed by Choi and Eastman [9] to indicate engineered colloids composed of nanoparticles dispersed in a base fluid. An MIT based comprehensive survey has been done by Buongiorno [10] for convective transportation in nanofluids by considering seven slip conditions that may produce a relative velocity within the base fluid and nanoparticles. Only two (Brownian motion and thermophoresis) out of these seven slip mechanisms were found to be important mechanisms. By adopting Buogiorno's model, Kuznetsov and Nield [11] explored the nanofluid boundary layer uniform convecting fluid flow.

In recent years, MHD fluid flow has gained researchers attention due to its controllable heat transfer rate. Magnetohydrodynamics (MHD) effect also play and influential role in controlling the rate of cooling as well as segregation of molten metal's from various non-metallic impurities. Magnetohydrodynamic (MHD) fluid flow has enormous utilization in manufacturing processes, even in the industrial areas as well. The terminology "Magnetohydrodynamic" is combination of three elementary terms magneto that stands for magnetic field, hydro that stands for fluid/liquid and dynamics that stands for evolution of particles. The existence of external magnetic field gives rise to Lorentz drag force which acts on the fluid, so potentially altering the characteristics of fluid flow especially velocity, temperature and concentration. Grouping of electromagnetism Maxwell's equation and fluid mechanics Navier's stokes equations therefore provides Magnetohydrodynamic (MHD) relation [12, 13]. Hayat et al. [14] studied the MHD fluid flow transportation over stretching surfaces. Later, the influence of viscous and Ohmic dissipation (i.e. joule heating) in nanofluid has been presented by Hussain et al. [15]. Vajravelu and Canon [16] studied the flow behavior of fluid towards a non-linear stretching sheet. Further, Matin et al. [17] analyzed the entropy effect in MHD nanofluid flow over stretching surface. Shawky et al. [18] studied the Williamson nanofluid flow in porous medium and he acknowledged that enhancement in non-Newtonian parameter escalates skin friction coefficient along with the rate of heat transfer. Basir et al. [19] examined the consequences of Peclet and Schmidt number in existence of partial slip towards a stretching surface. After that, rate of heat transfer along with partial slip condition was generalized by Pandey and Kumar [20]. Recently, Vinita and Poply [21] discussed MHD slip fluid flow of nanofluid in the existence of free stream velocity or outer velocity towards a stretching surface. Vinita et al. [22] studied MHD fluid flow with variable slip conditions over non-linear stretching surface. Furthermore, non-linearity effect towards the stretching surface under different physical circumstances has been examined by researchers in [6, 23–25].

The outcomes of current study reveal that the results obtained is very significant in the formation of quality object in various manufacturing processes like polymer engineering, paper technology, wire and plastic industries. This study holds important industrial application, particularly in the field of extrusion where the fluid dispersed with particles is used to augment the strength and durability of the material.

2. Materials and methods

In present analysis, 2-D incompressible fluid flow in MHD nanofluid over linear stretching sheet has been considered. Linear behavior generates flow and sheet is stretched in both direction of x axis with stretching velocity $u_w = ax$, where a and x denotes a constant and stretching surface coordinate respectively. $T_w = T_\infty + T_0 x^m$ at $y = 0$, where T_0 refers to the positive constant, T_∞ refers to the ambient temperature attained and m refers to the physical parameter known as surface temperature parameter. Also, by introducing $m = 0$, we have a special case of constant surface temperature (CST). **Figure 1** represents the physical model of the current study. The continuity, momentum, energy and concentration equations of the incompressible nanofluid boundary layer flow are as follows [10]

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

$$u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} = \nu\frac{\partial^2 u}{\partial y^2} - \frac{\sigma B^2}{\rho}u \tag{2}$$

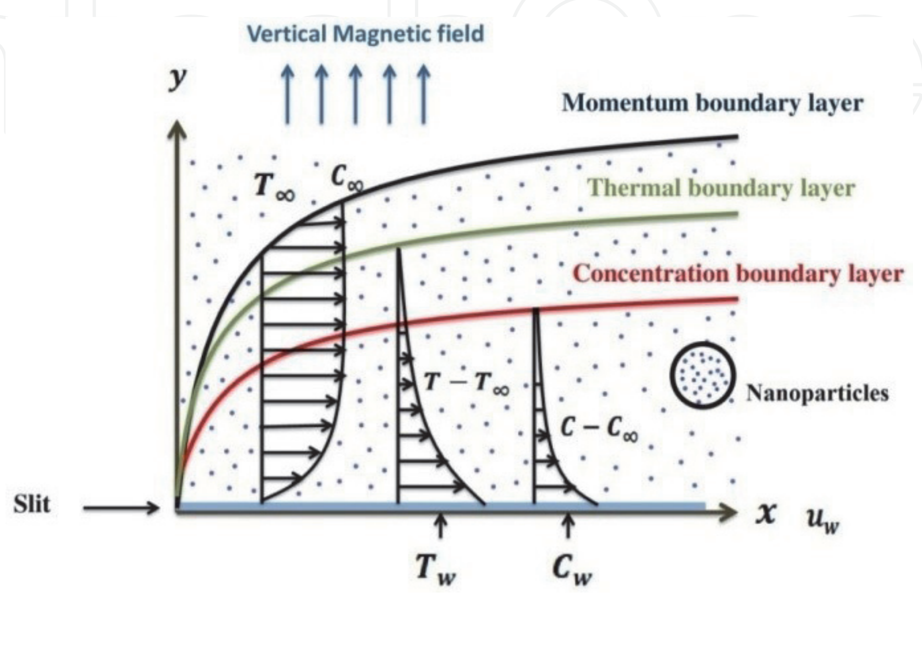

Figure 1.
Physical model and coordinate system.

$$u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}=\tau\left[D_B\frac{\partial C}{\partial y}\frac{\partial T}{\partial y}+(D_T/T_\infty)\left(\frac{\partial T}{\partial y}\right)^2\right] \tag{3}$$

$$u\frac{\partial C}{\partial x}+v\frac{\partial C}{\partial y}=D_B\frac{\partial^2 C}{\partial y^2}+\frac{D_T}{T_\infty}\frac{\partial^2 T}{\partial y^2} \tag{4}$$

Boundary conditions are given as:

$$u=u_w, v=0, T=T_w, C=C_w \; at \; y=0 \tag{5}$$

$$u\to 0, T\to T_\infty, C\to C_\infty \; as \; y\to\infty \tag{6}$$

Here horizontal and vertical velocities are represented by u and v, respectively. Also ν denotes kinematic viscosity, ρ is the density of fluid, $\tau=\frac{(\rho c)_p}{(\rho c)_f}$ defines a proportion of heat capacities, D_T reflects thermophoretic diffusion coefficient, B is the magnetic field intensity, D_B denotes Brownian diffusion coefficient, σ represents electrical conductivity

The fundamental Eqs. (1)-(4) with boundary conditions (5) and (6) are transformed using similarity variables

$$\begin{gathered} u=axf'_\delta(\xi), v=-\sqrt{a\nu}f_\delta(\xi) \\ \phi_\delta(\xi)=\frac{C-C_\infty}{C_w-C_\infty}, \theta_\delta(\xi)=\frac{T-T_\infty}{T_w-T_\infty}, \xi=y\sqrt{\frac{a}{\nu}} \end{gathered} \tag{7}$$

Inserting Eq. (7) into Eqs. (2)–(4), the governing Eqs. (1)–(4) takes the form

$$f'''_\delta+f_\delta f''_\delta-Mf'_\delta-{f'_\delta}^2=0 \tag{8}$$

$$\frac{1}{Pr}\theta''_\delta+f_\delta\theta'_\delta-f'_\delta\theta_\delta+Nb\theta'_\delta\phi'_\delta+Nt{\theta'_\delta}^2+Ec\,{f''_\delta}^2+MSc\,{f'_\delta}^2=0 \tag{9}$$

$$\phi''_\delta+\frac{1}{2}Scf_\delta\phi'_\delta+\frac{Nt}{Nb}\theta''_\delta=0 \tag{10}$$

The relevant boundary conditions are reduced to

$$f_\delta(\xi)=0, f'_\delta(\xi)=1, \theta_\delta(\xi)=1 \; and \; \phi_\delta(\xi)=1 \; at \; \xi=0 \tag{11}$$

$$f'_\delta(\xi)\to 0, \phi_\delta(\xi)\to 0 \; and \; \theta_\delta(\xi)\to 0 \; as \; \xi\to\infty \tag{12}$$

where prime denotes derivative with respect to ξ and the key crucial parameters are defined by:

$$\begin{gathered} M=\frac{\sigma B^2}{a}, Nt=\frac{(\rho c)_p D_T(T_w-T_\infty)}{(\rho c)_f\nu T_\infty}, Sc=\frac{\nu}{D_B}, Pr=\frac{\nu}{\alpha}, \\ Ec=\frac{u_w^2}{C_p(T_w-T_\infty)} \; and \; Nb=\frac{(\rho c)_p D_B(C_w-C_\infty)}{(\rho c)_f\nu} \end{gathered} \tag{13}$$

Here M is the magnetic parameter, Nt is the thermophoresis parameter, Sc is the Schmidt number, Pr is Prandtl number, Ec is the Eckert number and Nb is the Brownian motion parameter. Also, the physical quantities of interest skin friction coefficient, local Nusselt number and local Sherwood number are respectively defined as:

$$Cf_x = \frac{\tau_w}{\rho u_w^2}, Nu_x = \frac{xq_w}{k(T_w - T_\infty)} \text{ and } Sh_x = \frac{xq_m}{D_B(C_w - C_\infty)} \tag{14}$$

where τ_w, q_w and q_m are wall shear stress, local heat flux and local mass flux at the stretching surface serially given as:

$$\tau_w = \mu a x^{\frac{1}{2}} \sqrt{\frac{a}{\nu}} f''_\delta(0), q_w = -k(T_w - T_\infty)\sqrt{\frac{a}{\nu}}\theta'_\delta(0) \text{ and } q_m = -D_B(C_w - C_\infty)\sqrt{\frac{a}{\nu}}\phi'_\delta(0) \tag{15}$$

3. Results and discussion

Present study finds numerical solution of differential Eqs. (8)–(10) subjected to the boundary conditions (11) and (12) that are computed using RKF method by applying shooting technique. The main reason behind to solve the present problem are to determine the impact of prominent fluid parameters namely Eckert number Ec, thermophoresis Nt, Brownian motion parameter Nb, Schmidt number Sc and magnetic parameter M on $f'_\delta(0), \theta_\delta(0)$ and $\phi_\delta(0)$. **Table 1** demonstrate the impact of fluid parameters $Nb, N t, Ec, Sc$ and M on skin friction coefficient $f''_\delta(0)$, local Nusselt number$-\theta'_\delta(0)$ and local Sherwood number$-\phi'_\delta(0)$ by taking fixed entries of fluid parameters Prandtl number, Pr as 5.0 and surface temperature parameter m as 1.0.

Figure 2 manifests variation in fluid velocity against magnetic parameter M (0.8, 1.0, 1.2). This figure shows that existence of magnetic parameter M resists the fluid particle to move freely and main reason behind the resistance is that magnetic parameter M produces Lorentz force and this magnetism behavior can be adopted for controlling the fluid movement. Thus, enhancement in the value of magnetic parameter M causes the declination of velocity distribution

Nb	Nt	Ec	Sc	M	$f''_\delta(0)$	$-\theta'_\delta(0)$	$-\phi'_\delta(0)$
0.1	0.2	0.4	1.5	1.0	−0.62674	0.72369	−0.41288
					−0.69140	0.78127	−0.55822
					−0.74178	0.82246	−0.66610
0.05	0.2	0.4	1.5	1.0	−0.69140	0.82355	−1.77998
0.10					−0.69140	0.78127	−0.55822
0.15					−0.69140	0.74045	−0.15292
0.1	0.2	0.4	1.5	1.0	−0.69140	0.78127	−0.55822
	0.3				−0.69140	0.73298	−0.95811
	0.4				−0.69140	0.68790	−1.28267
0.1	0.2	0.0	1.5	1.0	−0.69140	2.18627	−3.19235
		0.1			−0.69140	1.83840	−2.54049
		0.2			−0.69140	1.48829	−1.88419
0.1	0.2	0.4	1.1	1.0	−0.69140	0.81074	−0.78101
			1.4		−0.69140	0.78800	−0.60993
			1.7		−0.69140	0.76889	−0.46155
0.1	0.2	0.4	1.5	0.8	−0.65763	0.95086	−0.85564
				1.0	−0.69140	0.78127	−0.55882
				1.2	−0.72329	0.61783	−0.27004

Table 1.
Values of skin friction coefficient $f''_\delta(0)$, local Nusselt number $-\theta'_\delta(0)$ and local Sherwood number $-\phi'_\delta(0)$ for crucial fluid parameters Nb, Nt, Ec, Sc and M with fixed entries of $Pr = 5.0$ and $m = 1.0$.

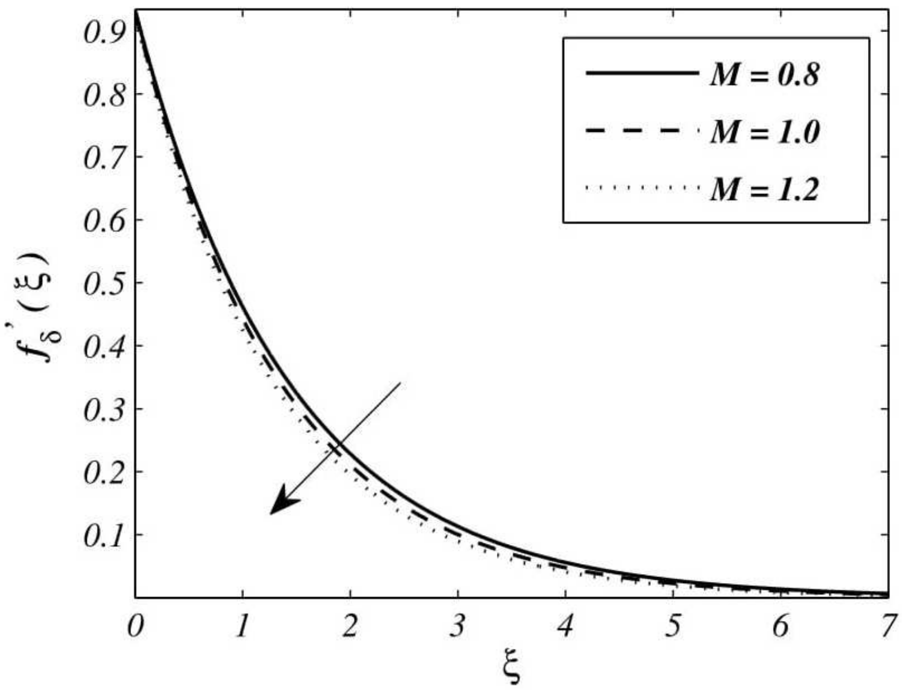

Figure 2.
Impact of magnetic parameter M on velocity profile $f'_\delta(\xi)$.

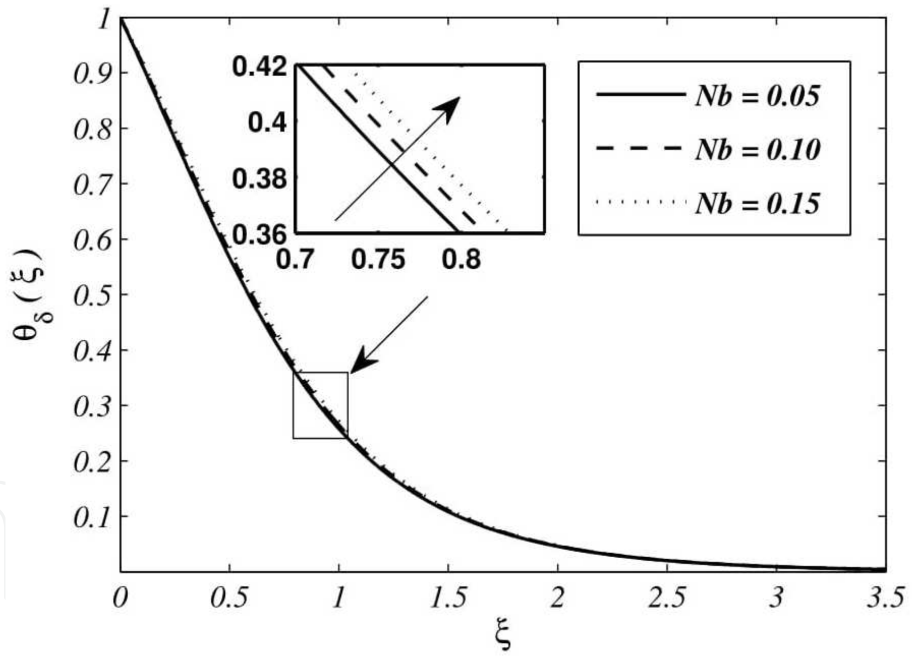

Figure 3.
Impact of Brownian motion parameter Nb on temperature profile $\theta_\delta(\xi)$.

Figure 3 examines temperature distribution variation against the fluid parameter Brownian motion parameter Nb $(0.05, 0.10, 0.15)$. The striking of atoms or molecules of the fluid particles with each other will create an arbitrary motion called Brownian motion of suspended (pendulous) particles and that will enhances width of boundary layer. Hence, fluid temperature increases for higher Brownian motion parameter *Nb* and in consequence local Nusselt number decreases.

Figure 4 deliberates the impact of fluid temperature under the consequence of thermophoresis parameter Nt $(0.2, 0.3, 0.4)$. Temperature gradient falls down for higher values of thermophoresis parameter Nt that result in reduction of

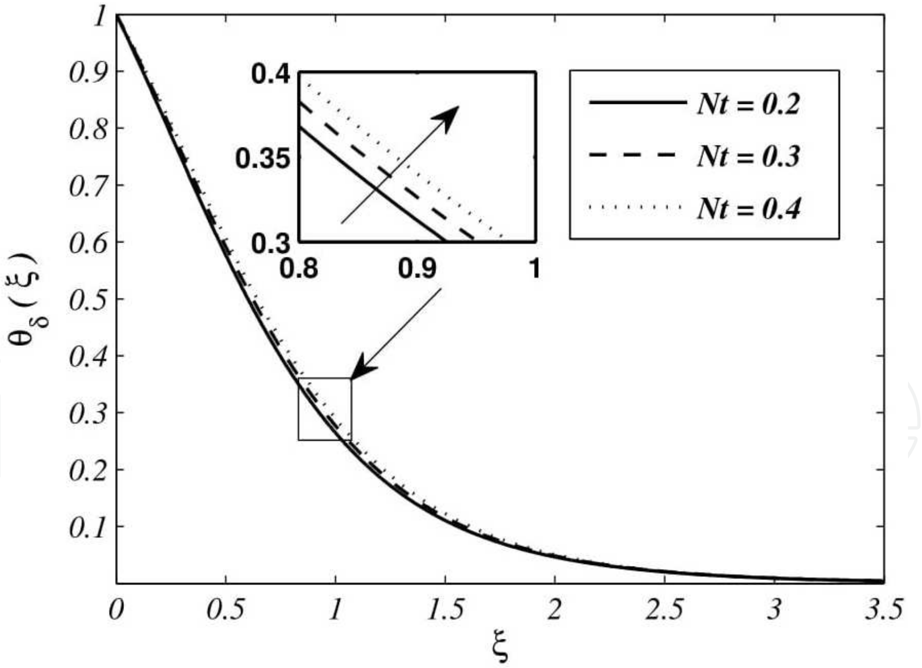

Figure 4.
Impact of thermophoresis parameter Nt on temperature profile $\theta_\delta(\xi)$.

conduction of nanoparticles. Thus, width of boundary layer enhances due to reallocation of ultrafine particles from hotter to colder part and hence, temperature enhances for higher thermophoresis parameter *Nt* that can be seen in **Figure 4**.

Figure 5 demonstrate fluid temperature variation against Eckert number Ec $(0.0, 0.1, 0.2)$. A dimensionless quantity Ec is the fraction of advective transportation and heat dissipation potential. As Eckert number Ec enhances, thermal buoyancy effect raises that results in increasing temperature and that is the main reason behind the conversion of kinetic energy into thermal energy. Hence, fluid temperature enhances because of this conversion effect. Consequently, declination in Nusselt number Nu_x is noticed that can be seen via **Table 1**.

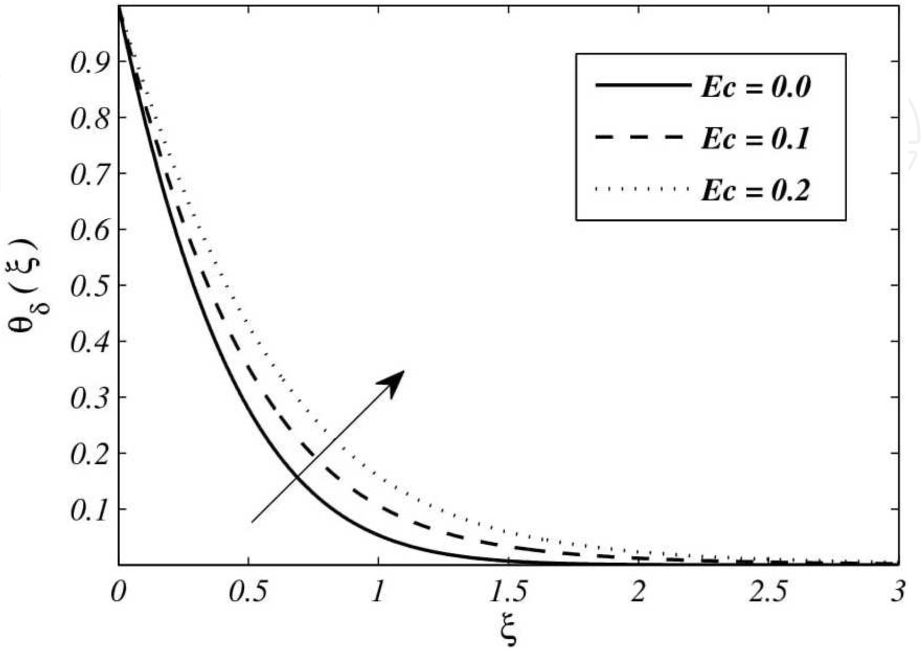

Figure 5.
Impact of Eckert number Ec on temperature profile $\theta_\delta(\xi)$.

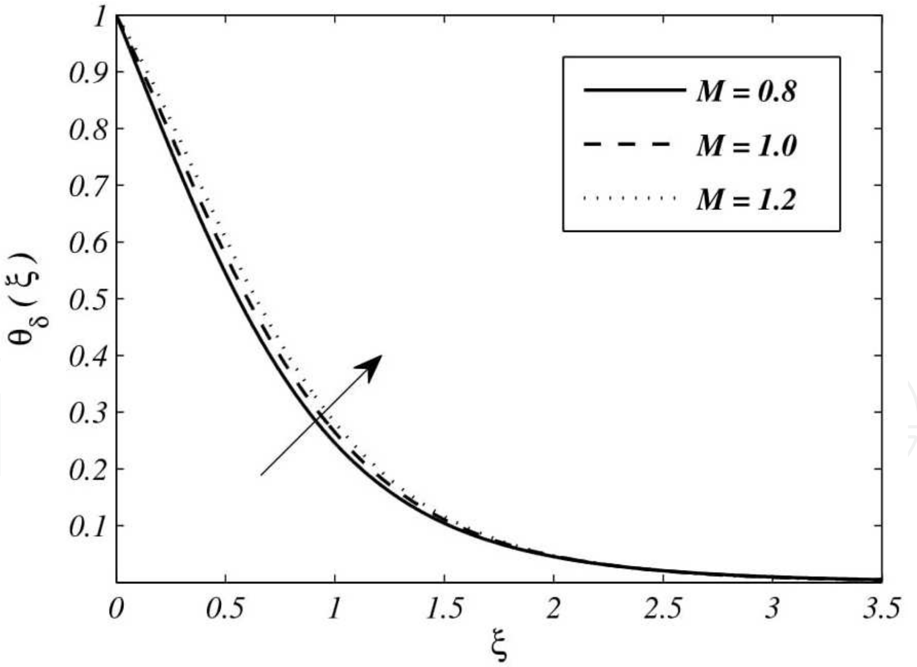

Figure 6.
Impact of magnetic parameter M on temperature profile $\theta_\delta(\xi)$.

Figure 6 reflects variation of temperature distribution against magnetic parameter M. With an increases in magnetic parameter M, velocity profile decreases because of generation of Lorentz force that consequently intensify the boundary thickness and rate of heat transportation and hence fluid temperature enhances as shown via **Figure 6**.

Figure 7 manifests the impact of Brownian motion parameter Nb $(0.05, 0.10, 0.15)$ on nanoparticle concentration $\phi_\delta(\xi)$. With an increase in the value of Brownian motion parameter Nb, fluid particles collides with each other with higher speed which results in increase in the nanoparticle concentration and consequently, local Sherwood number reduces as depicted in the **Table 1**.

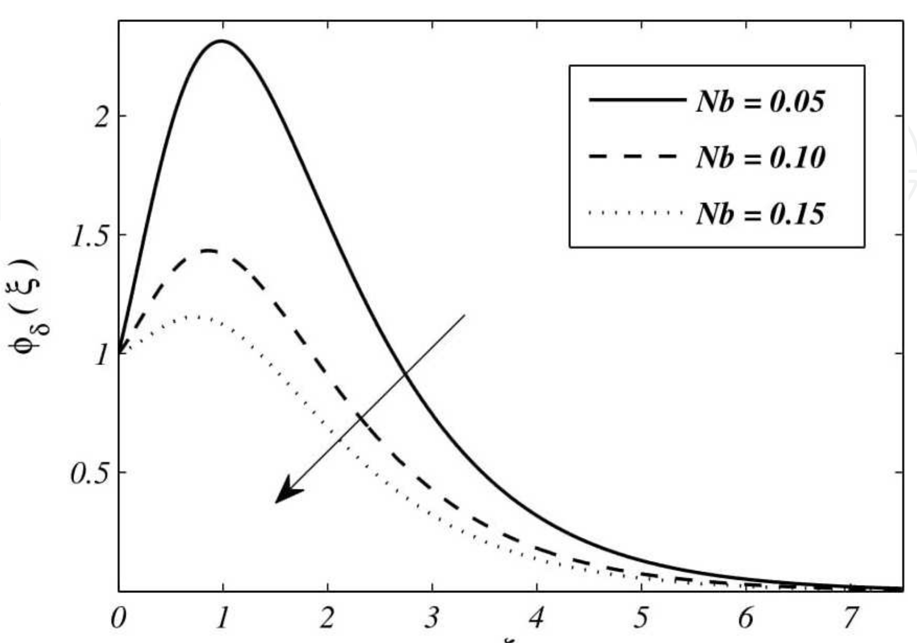

Figure 7.
Impact of Brownian motion parameter Nb on Concentration profile $\phi_\delta(\xi)$.

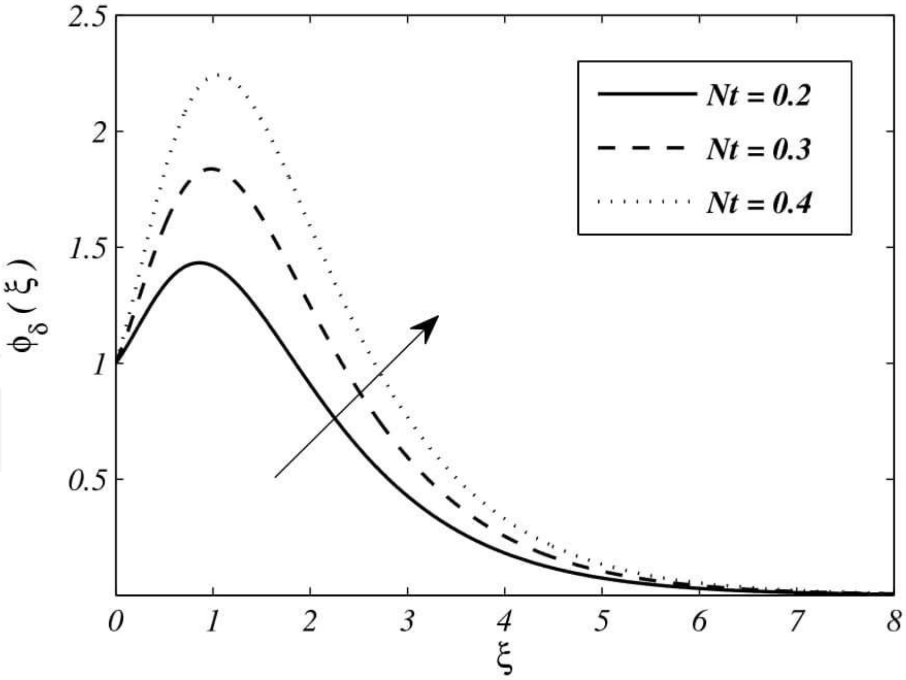

Figure 8.
Impact of thermophoresis parameter Nt on Concentration profile $\phi_\delta(\xi)$.

Figure 8 portraits variation for nanoparticle volume fraction $\phi_\delta(\xi)$ against thermophoresis parameter Nt $(0.2, 0.3, 0.4)$. This graph shows that with an increase in thermophoresis parameter, nanoparticle concentration increases. Basically, in case of thermophoresis force applied by a particle on the other particle will generates the movement of particles from hotter to colder part and hence fluid moves from hotter to colder region and hence intensification in the nanoparticle volume fraction is observed via **Figure 8**.

Figure 9 portraits the impact of Schmidt number Sc $(1.1, 1.4, 1.7)$ on profile of nanoparticle concentration. Intensification in the value of physical parameter Sc,

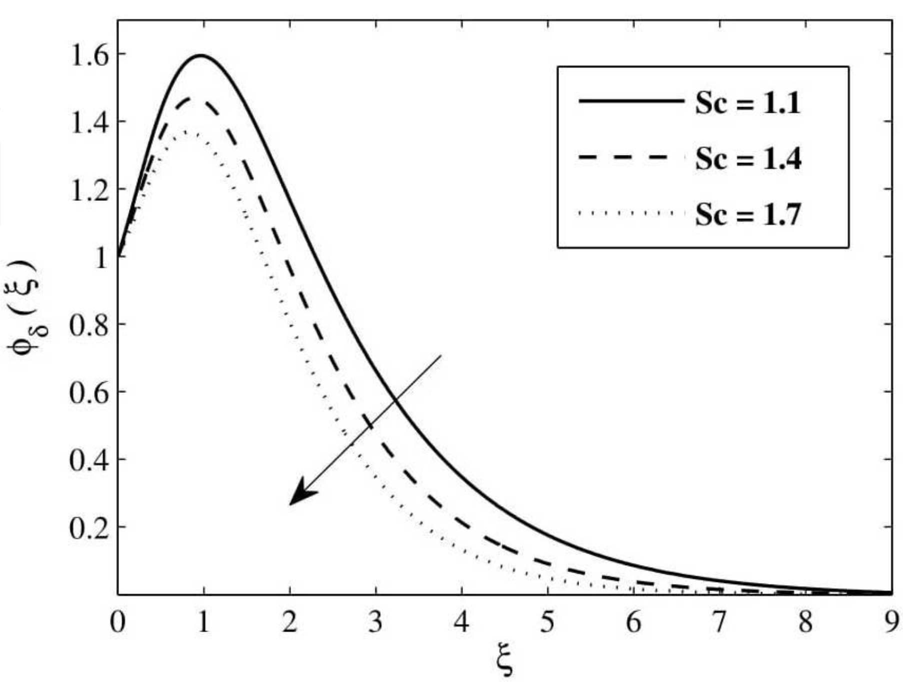

Figure 9.
Impact of Schmidt number Sc on Concentration profile $\phi_\delta(\xi)$.

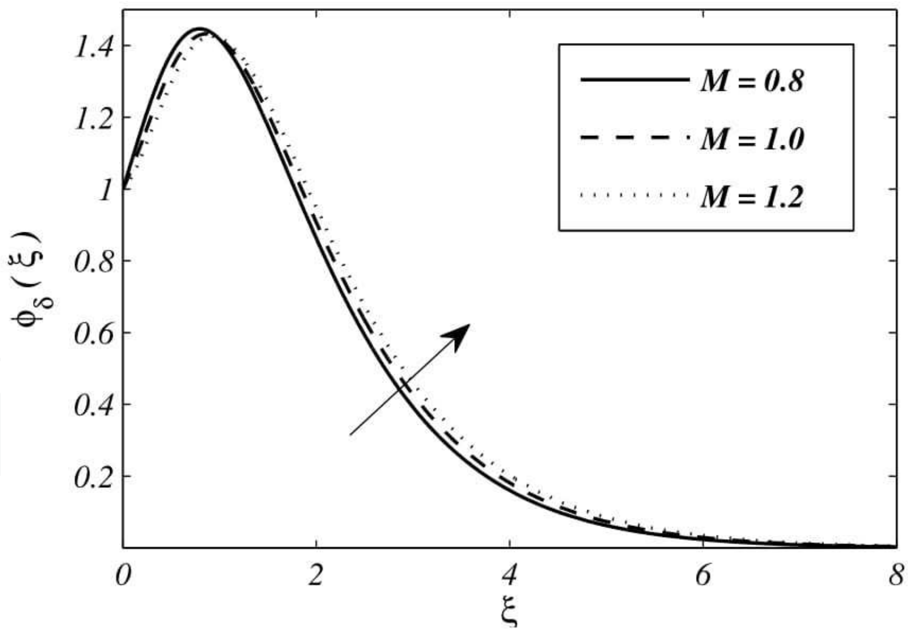

Figure 10.
Impact of magnetic parameter M on Concentration profile $\phi_\delta(\xi)$.

declination in mass diffusivity is observed. Due to this effect nanoparticle concentration decreases.

Figure 10 reflects the variation for nanoparticle concentration $\phi_\delta(\xi)$ against the magnetic parameter M $(0.8, 1.0, 1.2)$. With increase in magnetic parameter M, rate of mass transportation decreases that consequently increase nanoparticle concentration and hence reduction in the value of local Sherwood number is notice as seen in **Table 1**.

4. Conclusions

Present study reflects the heat, mass and flow transportation of Magnetohydrodynamic (MHD) nanofluid towards a sheet which is stretched linearly. Key findings of current analysis are summarized as:

1. Skin friction coefficient elevates with increment in magnetic parameter M due to produced Lorentz force that ultimately improves local Sherwood number along with Nusselt number for higher magnetic parameter M.

2. Fluid temperature enhances for greater values of physical parameters Eckert number Ec, Brownian motion parameter Nb and thermophoresis parameter Nt.

3. An enhancement in the profile of nanoparticle concentration is noticed for greater values of thermophoresis parameter Nt,. Whereas, it declines for Brownian motion parameter Nb and Schmidt number Sc.

Nomenclature

x, y	Cartesian coordinates
B	Magnetic field intensity
a	Positive constant

m	Surface temperature parameter
Sc	Schmidt number
C	Concentration
C_w	Nanoparticle volume fraction
q_m	Mass flux
Pr	Prandtl number
Nu_x	Nusselt number
Nt	Thermophoresis parameter
T_∞	Ambient temperature attained
Sh_x	Sheerwood number
v	Vertical velocity
D_B	Brownian diffusion coefficient
Nb	Brownian motion parameter
T	Temperature
u_w	Stretching velocity
D_T	Thermophoresis diffusion coefficient
T_w	Temperature at the sheet
q_w	Hass flux
C_∞	Ambient nanoparticle volume fraction
u	Horizontal velocity
M	Magnetic parameter

Greek symbols

ν	Kinematic viscosity
β	Casson fluid parameter
σ	Electrical conductivity
ξ	Similarity variable
α_m	Thermal diffusivity
τ	Ratio of heat capacities
θ_δ	Non-dimensional temperature
ϕ_δ	Non-dimensional nanoparticle concentration

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