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Effects of Natural Convection and Heat Absorption on MHD Nano-Fluid Flow Past a Stretching Sheet With Melting

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Abstract

An attempt is made to provide a boundary layer solution and observe the effect of various flow parameters, viz. buoyancy, heat absorption, melting, Brownian and thermophoretic diffusions on stagnation point nano-fluid flow through a stretchable surface, in the presence of an applied transverse magnetic field. The bvp4c routine of Matlab is employed to solve the governing equations of the flow problem. To validate accuracy of results, the numerical results obtained in the present paper have been compared with the existing literature and found to be in an excellent agreement.

Key words: Nano-fluid, MHD Stagnation point flow, Melting surface, Free Convection, Absorption.

Introduction

In the present century (i.e. the age of technology invention), there is a high demand of fluids with high thermal conductivity. To overcome the problems of low conductivity, researchers are forced to develop fluids with enhanced thermal conductivities. Choi and Eastman [1] initiated research in this direction and coined the term "nano-fluid" to refer fluids with suspended nanoparticles. These fluids have peculiar and improved thermo-physical properties. Choi et al. [2] encountered that thermal conductivity of the base fluids (conventional fluids) could be enhanced (around 40% to 150%) significantly by mixing a small amount (<1% volume fraction) of nanometre-sized-particles in the base fluid. After this encouraging work, many researchers [3–5] carried out their research studies on the flow of nano-fluids to examine different aspects of the problem.

It was Crane [6] who first investigated the flow of fluid over a linearly stretching sheet. This problem is of particular interest since an exact solution of the two-dimensional Navier-Stokes equations has been obtained by him. After his work, the fluid flow past a stretching surface has attracted researchers and sufficient amount of work has been carried out [7–9]. Heat transfer over stretching/shrinking surface has its own significance due to its wide applications in industrial and manufacturing processes. Many researchers [10-12] studied fluid flow problems on heat transfer over stretching/shrinking surfaces.

Temperature difference between the boundary layer surface and fluid plays an important role in several fluid engineering devices. Due to temperature-differences heat generation/absorption effects produced and have significant implications on heat transfer characteristics, such as, in processes where the working fluid undergoes exothermic/endothermic chemical reactions [13], and in preparation of metal waste obtained as a by-product from used nuclear fuel [14]. Thus, the heat sources / sinks studies have become a key point of attraction for researchers involved in fluid flow with heat transfer problems. Chamkha and Khaled [15] investigated "Similarity solutions for hydromagnetic simultaneous heat and mass transfer by natural convection from an inclined plate with heat generation or absorption". They have considered two different cases viz. "uniform heat flux" and "uniform wall temperature" at the plate. Kamel [16] studied, analytically, "Unsteady MHD convection through porous medium with combined heat and mass transfer with heat source/sink". Many researchers [17-20] have their contributions in the study of fluid flow problems taking heat generation/absorption into account.

Transient free convection flows under the influence of a magnetic field have drawn attention of many researchers in view of their applications in modern material processing where magnetic fields are known to achieve excellent manipulation and control of electrically conductive materials (Ibrahim and Shanker [21]). There are significant applications of MHD flow with convection in renewable energy devices including MHD power generators (Chen et al. [22], Yamaguchi et al. [23]) as well as nuclear reactor transport processes (Mukhopadhyay [24]) where magnetic fields are used to control the rate of heat transfer. Several authors [25-29] concentrated their studies on MHD natural convection boundary layer flow of an electrically-conducting fluid to get clear understanding about the impact of free convection in various heat transfer processes.

Melting (or solidification) characteristics in heat transfer has varied and wide industrial applications, such as welding and magma solidification, thawing of frozen ground, casting, melting of permafrost, and in the process of silicon wafer etc.) [30]. In recent years, researchers attracted in this area and doing their research studies on melting heat transfer. In this direction, Tien and Yen [31] investigated the melting effect on convective heat transfer between a melting body and fluid surrounded. They found that melting retards the rate of heat transfer. Epstein and Cho [32] discussed the usefulness of melting phenomenon in the laminar flow over flat surface. Stretched flow of viscous nano-liquid with stagnation point, considering melting heat transfer and inclined magnetic field into the problem has been investigated by Gireesha et al. [33]. Hayat et al. [34] studied the effect of melting parameter in the flow of a chemically reacting fluid. A comprehensive study of heat transfer phenomenon in nano-fluid flow was made by many researchers [35-41]. Recently, Mahatha et al [42] investigated "Radiation and Dissipative Effects on MHD Stagnation Point Nano-Fluid Flow past a Stretchable Melting Surface".

Though the researchers are doing their research studies on melting heat transfer and considerable amount of work has been done in the nano-fluid flow over a stretching surface, still more attention is needed to study the effects of natural convection, heat absorption etc on melting heat transfer of a nano-fluid flow past a stretching sheet. Objective of the present study is to provide a boundary layer solution and observe the effect of various flow parameters, viz. buoyancy, heat absorption, melting, Brownian and thermophoretic diffusions on stagnation point flow of a viscous, incompressible, and electrically conducting nano-fluid over a stretching sheet, in the presence of an applied transverse magnetic field.

2. Mathematical Model of the Problem

Consider a 2-dimensional steady state natural convection MHD stagnation point boundary layer flow and heat transfer of a viscous, incompressible, electrically conducting, and heat absorbing nano-fluid past a stretching sheet which is melting steadily. The x-axis is considered along the stretching surface and y- axis normal to it. Schematic diagram of the physical configuration is displayed in Fig. 1. A uniform magnetic field of strength $B = B_0$ is imposed along the y-axis. Temperature of the sheet is T_m, concentration C take constant value C_w. It is further assumed that

- "The ambient value of T and C are denoted by T_∞ and C_∞, respectively, where $T_\infty > T_m$ ".

- Free stream velocity assumes the form $U_\infty = bx$ and velocity of the sheet is $u_w = ax$, where a and b are positive constants.

- "There is no applied or polarized voltages exist so the effect of polarization of fluid is negligible".

- "Magnetic Reynolds number of the fluid is very small therefore induced magnetic field effects are neglected in comparison to the applied one".

- "Both (nanoparticles and base fluid) are in a state of thermal equilibrium and there is no slip between them".

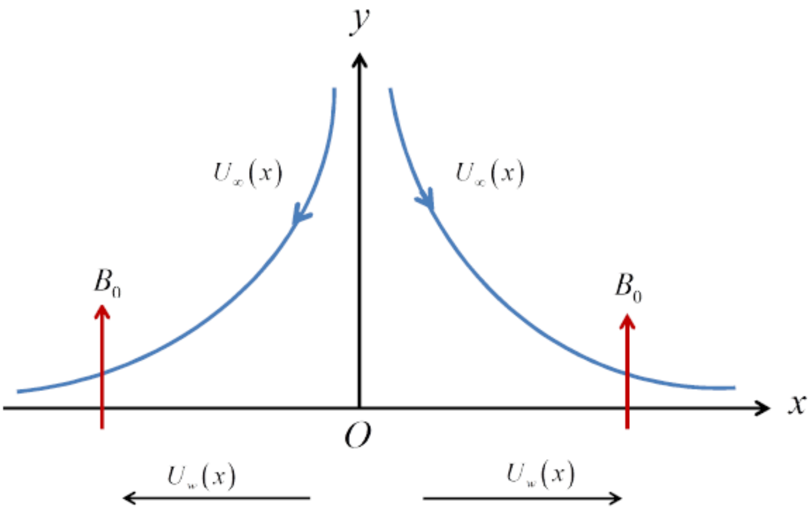


Fig. 1: Geometry of the flow

Under the assumptions made above equations governing the conservation of mass, momentum, energy, and species concentrations, are given by

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

$$\begin{aligned} u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y} &= \upsilon\frac{\partial^2 u}{\partial y^2}+U_\infty\frac{\partial U_\infty}{\partial x}+\frac{\sigma B_0^2}{\rho_f}(U_\infty-u) \\ &+\frac{1}{\rho_f}\left[(1-C_\infty)\rho_{f\infty}\beta g(T-T_\infty)-(\rho_p-\rho_{f\infty})g(C-C_\infty)\right] \end{aligned} \tag{2}$$

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

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

where $\alpha=\dfrac{k}{(\rho c)_f}$ $,\tau=\dfrac{(\rho c)_p}{(\rho c)_f}$

The boundary conditions are:

$$\left.\begin{array}{ll} u = U_w = ax,\ v = 0,\ T = T_m,\ C = C_w & \text{at } \ y = 0 \\ u \to U_\infty = bx,\ v = 0,\ T \to T_\infty,\ C \to C_\infty & \text{at } \ y \to \infty \\ \alpha \left(\dfrac{\partial T}{\partial y} \right)_{y=0} = \rho \left[\lambda + C_s \left(T_m - T_0 \right) \right] v\left(x, 0\right) & \end{array} \right\} \qquad (5)$$

where u and v are the components of velocity along x and y axes, respectively. Furthermore, $\upsilon, \sigma, \rho_f, \rho_p, \alpha, k, (\rho c)_f, (\rho c)_p, Q_0, \lambda$ and C_s are respectively the kinematic viscosity coefficient, electric conductivity, density of base fluid, density of nanoparticle, thermal diffusivity, thermal conductivity, heat capacity of the base fluid, heat capacity of the nanoparticle material, heat absorption, latent heat of the fluid, and heat capacity of the solid surface.

The similarity and dimensionless variables are introduced as follow:

$$\left.\begin{array}{l} \eta = y\sqrt{\dfrac{a}{\upsilon}}, \psi = \sqrt{a\upsilon}\ x\ f\left(\eta\right) \\ \theta\left(\eta\right) = \dfrac{T - T_m}{T_\infty - T_m}, \phi\left(\eta\right) = \dfrac{C - C_w}{C_\infty - C_w} \end{array}\right\} \qquad (6)$$

The equation of continuity is satisfied if we choose a stream function $\psi(x, y)$ such that

$$u = \frac{\partial \psi}{\partial y}, v = -\frac{\partial \psi}{\partial x} \qquad (7)$$

With the help of above transformations, equation (1) is identically satisfied, and equations (2), (3) and (4) along with boundary conditions (5) take the following forms:

$$f''' + ff'' - f'^2 + A^2 + M\left(A - f'\right) + Gr\,\theta - Nr\,\phi = 0 \qquad (8)$$

$$\theta'' + \Pr\left(f\theta' + Nb\phi'\theta' + Nt\theta'^2 + Q\theta \right) = 0 \qquad (9)$$

$$\phi'' + Lef\phi' + \frac{Nt}{Nb}\theta'' = 0 \qquad (10)$$

The corresponding boundary conditions are:

$$\left.\begin{array}{l} f'\left(0\right) = 1,\ B\theta'\left(0\right) + \Pr\, f\left(0\right) = 0,\ \theta\left(0\right) = 0,\ \phi\left(0\right) = 0, \\ f'\left(\infty\right) \to A,\ \theta\left(\infty\right) \to 1,\ \phi\left(\infty\right) \to 1. \end{array}\right\} \qquad (11)$$

Here the governing parameters are defined by:

$$\left.\begin{array}{l} M=\dfrac{\sigma B_o^2}{\rho_f a},\ Le=\dfrac{\upsilon}{D_B},\ \Pr=\dfrac{\upsilon}{\alpha},\ A=\dfrac{b}{a},\ B=\dfrac{C_f\left(T_\infty-T_m\right)}{\lambda+C_s\left(T_m-T_0\right)}, \\ Nb=\dfrac{\left(\rho c\right)_p D_B\left(C_\infty-C_w\right)}{\left(\rho c\right)_f \upsilon}, Nt=\dfrac{\left(\rho c\right)_p D_T\left(T_\infty-T_m\right)}{\left(\rho c\right)_f \upsilon T_\infty},\ Q=\dfrac{Q_0}{a\rho c_p}, \\ Gr=\dfrac{(1-C_\infty)\beta\rho_{f\infty}\, g(T_\infty-T_m)}{\rho_f U_w\, a}, Nr=\dfrac{(\rho_p-\rho_{f\infty})g(C_\infty-C_w)}{\rho_f U_w\, a}. \end{array}\right\} \quad (12)$$

where f', θ and ϕ are the non-dimensionless velocity, temperature and concentration respectively. M, Le, Pr, A, Nb, Nt, Q, B, Gr, and Nr are respectively, the magnetic parameter, Lewis number, Prandtl number, velocity ratio parameter, Brownian diffusion coefficient, thermophoretic diffusion coefficient, heat absorption parameter, melting parameter, Grashof number and the buoyancy-ratio parameter. Dimensionless melting parameter (B) is the combination of Stefan numbers $\dfrac{C_f\left(T_\infty-T_m\right)}{\lambda}$ (for liquid phase) and $\dfrac{C_s\left(T-T_0\right)}{\lambda}$ (for solid phase).

Based on the above quantities, the skin friction coefficient C_f the local Nusselt number Nu_x and the local Sherwood number Sh_x are defined as:

$$C_f=\frac{\tau_w}{\rho u_w^2},\ Nu_x=\frac{xq_w}{k\left(T_\infty-T_m\right)},\ Sh_x=\frac{xh_m}{D_B\left(C_\infty-C_w\right)} \quad (13)$$

where the wall shear stress τ_w, the wall heat flux q_w and wall mass flux h_m are given by

$$\tau_w=\mu\frac{\partial u}{\partial y},\ q_w=-k\left(\frac{\partial T}{\partial y}\right)_{y=0},\ h_m=-D_B\left(\frac{\partial C}{\partial y}\right)_{y=0} \quad (14)$$

By using the above equations, we get

$$C_f\sqrt{\mathrm{Re}_x}=-f''(0),\ \frac{Nu_x}{\sqrt{\mathrm{Re}_x}}=-\theta'(0),\ \frac{Sh_x}{\sqrt{\mathrm{Re}_x}}=-\phi'(0) \quad (15)$$

where Re_x, Nu_x, Sh_x are local Reynolds number, local Nusselt number and local Sherwood number, respectively.

3. Numerical Procedure and Validation

The non-linear PDEs (governing to the present problem) (1) - (4) are transferred into non-linear ODEs. These ODEs (8) - (10) are solved, numerically, by using bvp4c routine of MATLAB, together with BCs (11). To ensure the accuracy and robustness of our computations, we have computed the numerical values of skin friction coefficient by using the same code by considering the values of Nr, Gr, and Q as zero and computed the numerical values of skin friction coefficient $-f''(0)$, rate of heat transfer $-\theta'(0)$ and rate of mass transfer $-\phi'(0)$. A comparison is made with the values of $-f''(0), -\theta'(0), -\phi'(0)$ obtained by Ibrahim [38] and found to be in excellent agreement (see Table 1). This authenticates the accuracy and robustness of our numerical computations.

Table 1: Computations showing comparison with Ibrahim [38] for
$Nb = Nt = 0.5,\ \Pr = 1,\ Le = 2,\ Nr = 0,\ Gr = 0,\ Q = 0$

			Present Paper			Ibrahim [38]		
A	M	B	$-f''(0)$	$-\theta'(0)$	$-\phi'(0)$	$-f''(0)$	$-\theta'(0)$	$-\phi'(0)$
0	1	0.5	-1.2876	0.5315	0.184	-1.2876	0.5315	0.184
0.1	1	0.5	-1.1923	0.5954	0.206	-1.1923	0.5954	0.206
0.2	1	0.5	-1.0914	0.6405	0.2228	-1.0914	0.6405	0.2228
0.3	1	0.5	-0.9825	0.6786	0.2372	-0.9825	0.6786	0.2372
0.5	1	0.5	-0.7401	0.7437	0.262	-0.7401	0.7437	0.262
0.5	2	0.5	-0.8798	0.7321	0.2574	-0.8798	0.7321	0.2574
0.5	3	0.5	-1.0019	0.7234	0.254	-1.0019	0.7234	0.254
0.5	0.5	0.1	-0.7279	1.0063	0.3145	-0.7279	1.0063	0.3145
0.5	0.5	0.5	-0.6608	0.7513	0.265	-0.6608	0.7513	0.265
0.5	0.5	1	-0.6142	0.5834	0.2307	-0.6142	0.5834	0.2307

4. Results and Discussion

The non-linear ordinary differential equations (8) - (10) with boundary conditions (11) have been solved using by the bvp4c routine of Matlab. In order to investigate the effects of various parameters viz. velocity ratio parameter *A*, magnetic parameter *M*, Thermal diffusion parameter *Pr*, Brownian motion parameter *Nb*, thermophoresis parameter *Nt*, heat absorption parameter *Q*, Levis number *Le*, melting parameter *B*, Grashof number *Gr* and the buoyancy-ratio parameter *Nr*, the profiles of nano-fluid velocity, nano-fluid temperature and nano-particle concentration are depicted graphically in Fig. 2 - Fig. 31 while the values of coefficient of skin-friction, Nusselt number, and Sherwood number are tabulated in Table 2.

Figures 2 to 11 shows the effects of the flow parameters on nano-fluid velocity. It may be concluded from the figures 2 to 11 that the nano-fluid velocity is being enhanced by the velocity ratio parameter, magnetic field, thermophoresis diffusion, heat absorption and Grashof number *Gr* while it is being reduced by thermal diffusion, Brownian diffusion, Levis number *Le*, melting parameter, buoyancy-ratio parameter *Nr*.

Figures 12 to 21 cater the effects of the flow parameters on nano-fluid temperature in the flow field. It is clearly observed that from these figures that the nano-fluid temperature is induced by the velocity ratio parameter, magnetic field, thermophoresis diffusion, Brownian diffusion (near the plate), heat absorption and Grashof number *Gr* while it is reduced by thermal diffusion, Levis number *Le*, melting parameter, buoyancy-ratio parameter *Nr*.

Figures 22 to 31 display the effects of the flow parameters on nano-fluid concentration in the flow field. It is revealed from these figures that the nano-fluid concentration is induced by the velocity ratio parameter, magnetic field, Brownian diffusion, Levis number *Le*, and Grashof number *Gr*. On the other hand, it is reduced by thermal diffusion (near the plate), thermophoresis diffusion, heat absorption, melting parameter, buoyancy-ratio parameter *Nr*.

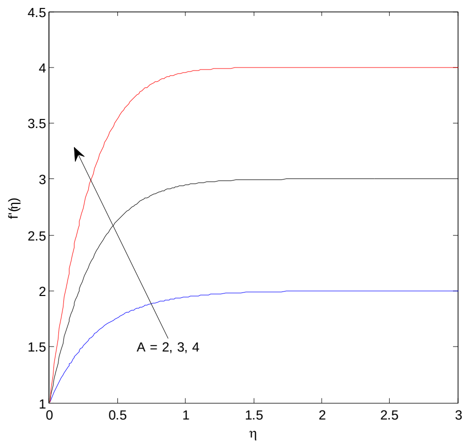


Fig. 2 Velocity profiles for *A*.

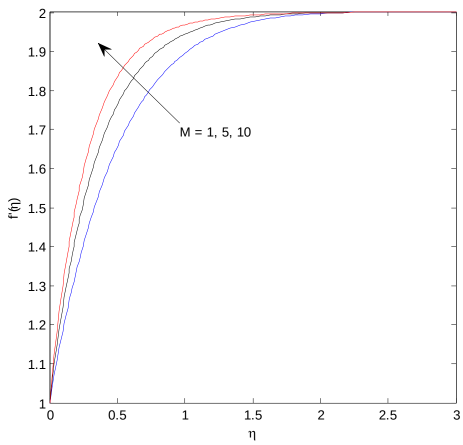


Fig. 3 Velocity profiles for *M*.

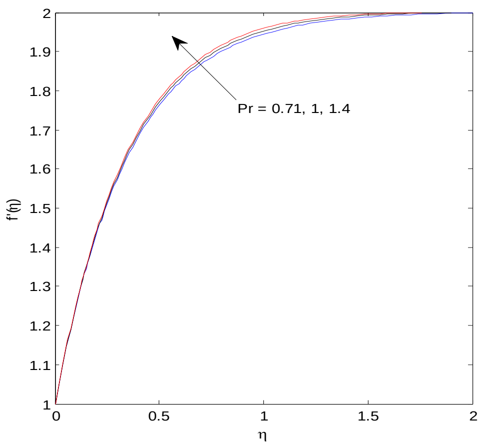


Fig. 4 Velocity profiles for *Pr*.

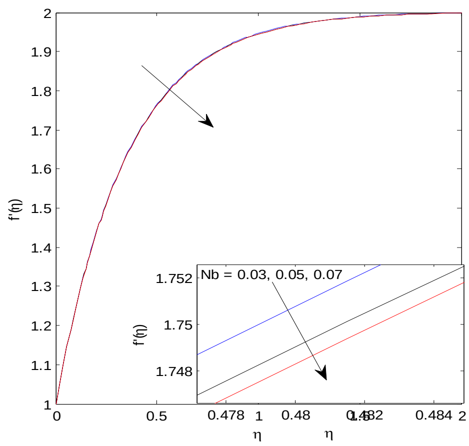
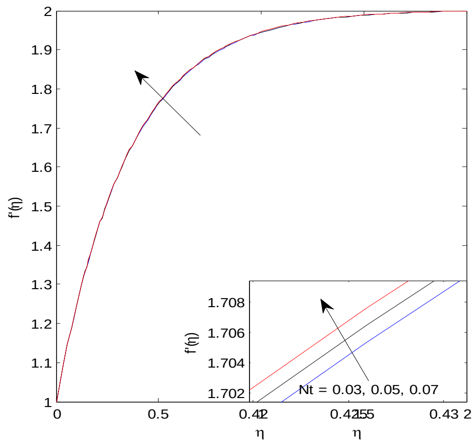


Fig. 5 Velocity profiles for *Nb*.



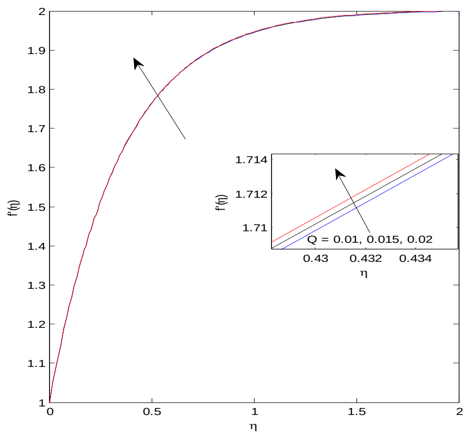
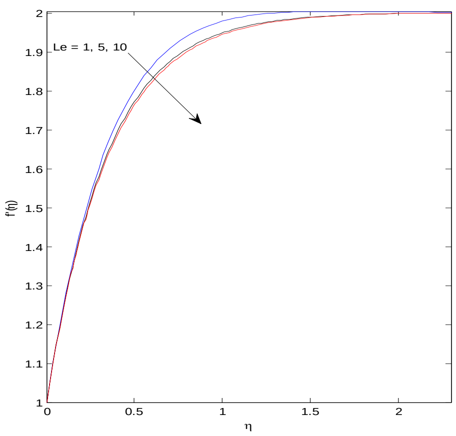


Fig. 6 Velocity profiles for *Nt*.

Fig. 7 Velocity profiles for *Q*.



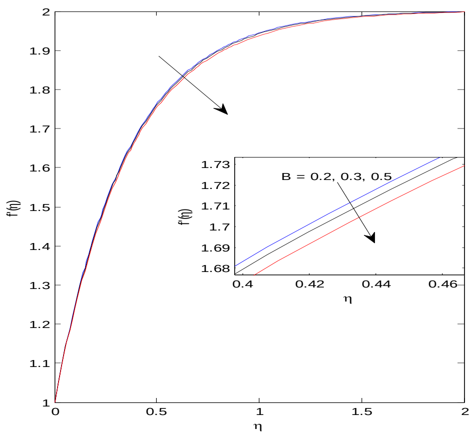
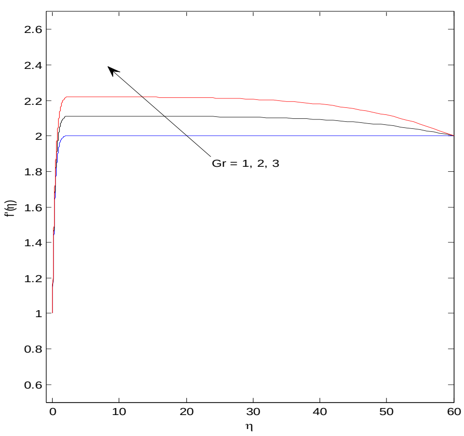


Fig. 8 Velocity profiles for *Le*.

Fig. 9 Velocity profiles for *B*.



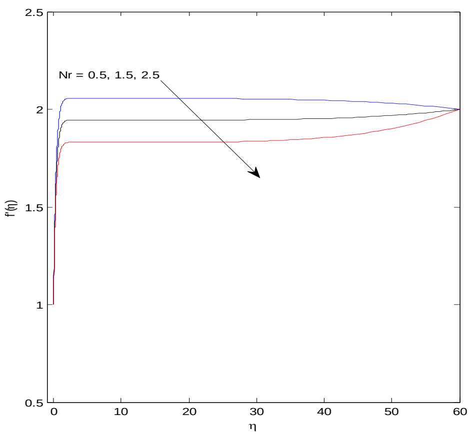


Fig. 10 Velocity profiles for *Gr*.

Fig. 11 Velocity profiles for *Nr*.

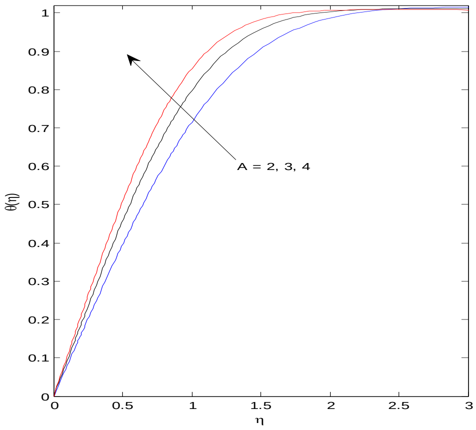


Fig. 12 Temperature profiles for *A*.

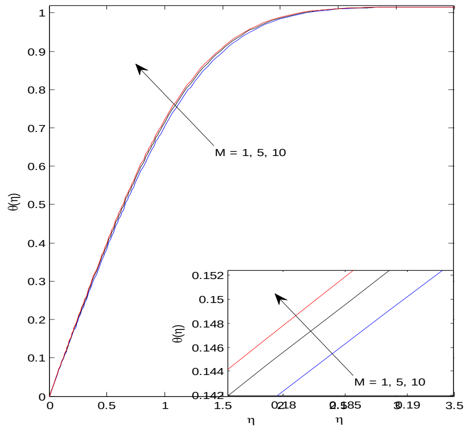


Fig. 13 Temperature profiles for *M*.

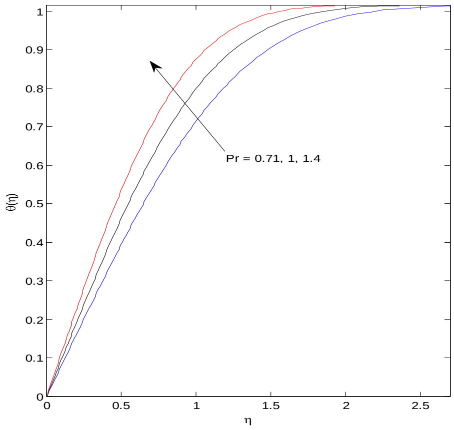


Fig. 14 Temperature profiles for *Pr*.

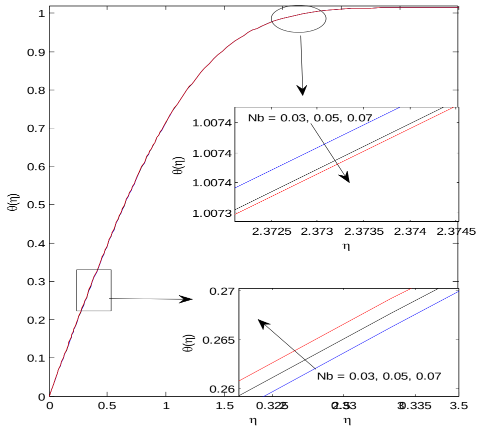


Fig. 15 Temperature profiles for *Nb*.

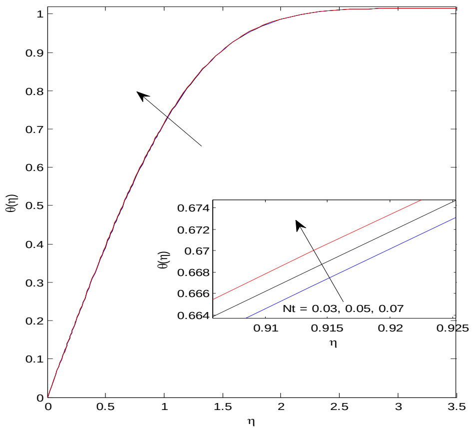


Fig. 16 Temperature profiles for *Nt*.

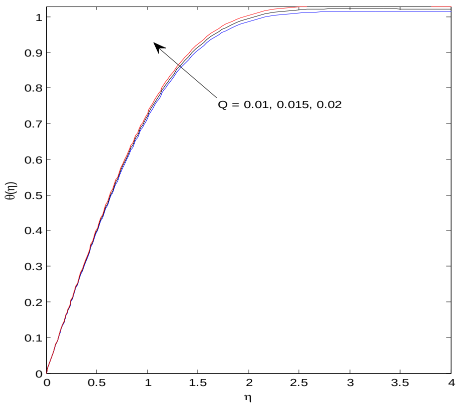


Fig. 17 Temperature profiles for *Q*.

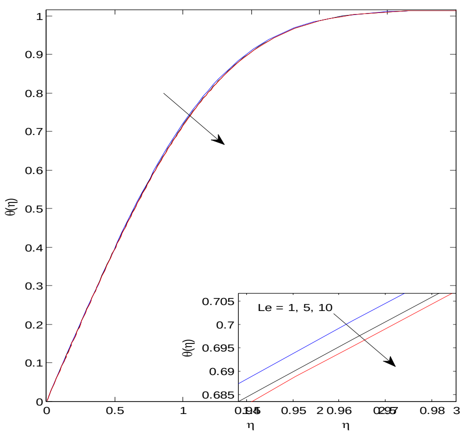


Fig. 18 Temperature profiles for *Le*.

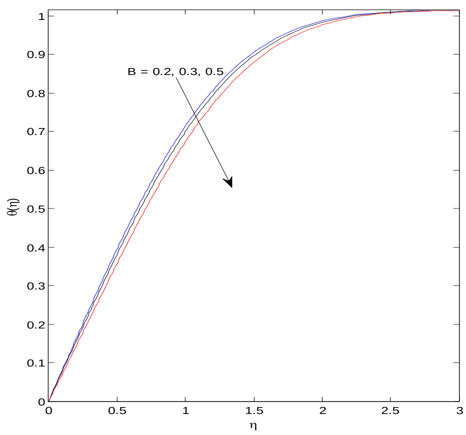


Fig. 19 Temperature profiles for *B*.

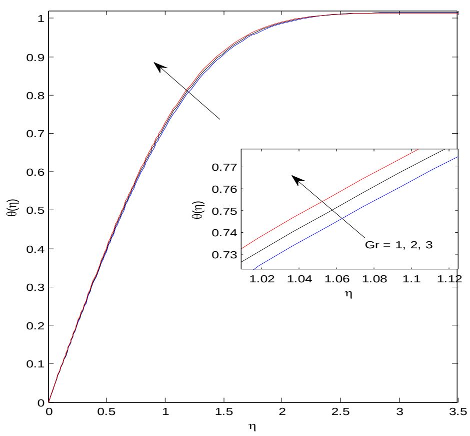


Fig. 20 Temperature profiles for *Gr*.

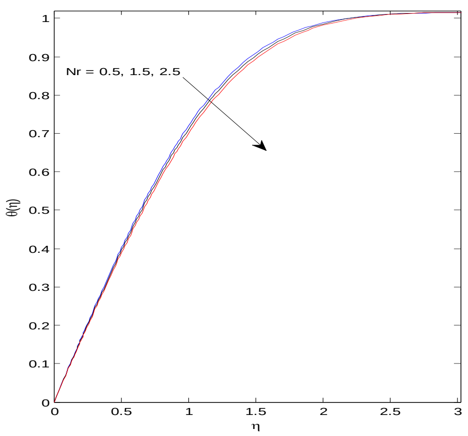


Fig. 21 Temperature profiles for *Nr*.

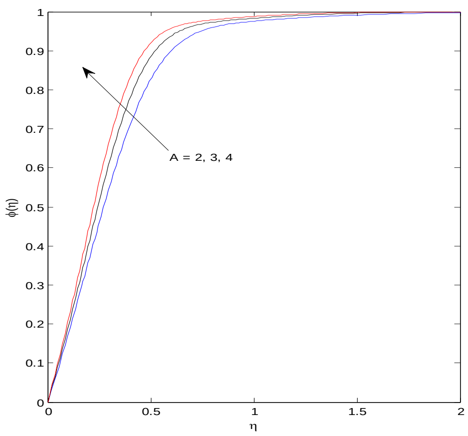


Fig. 22 Concentration profiles for *A*.

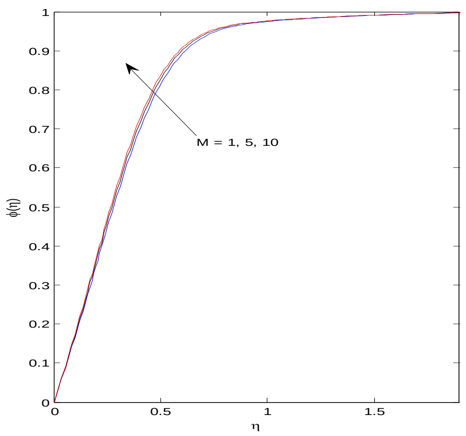


Fig. 23 Concentration profiles for *M*.

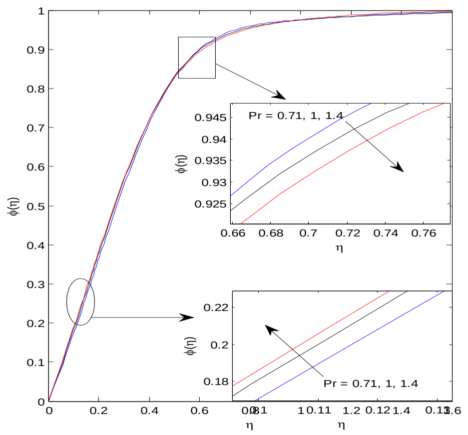


Fig. 24 Concentration profiles for *Pr*.

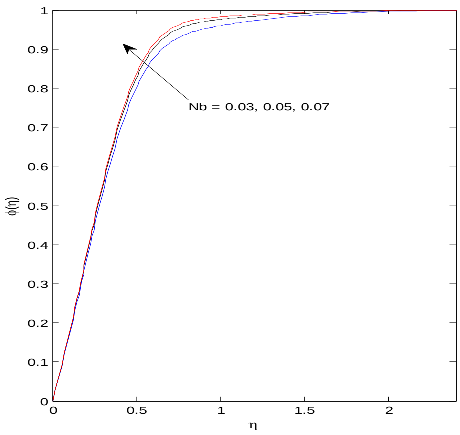


Fig. 25 Concentration profiles for *Nb*.

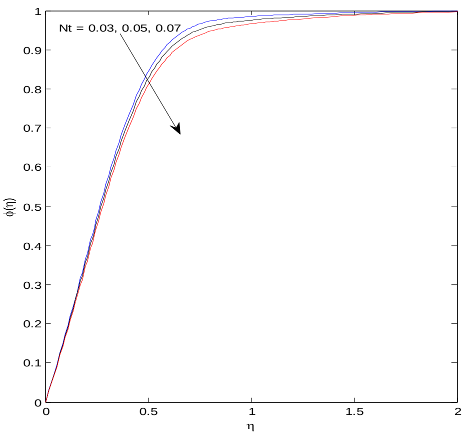


Fig. 26 Concentration profiles for *Nt*.

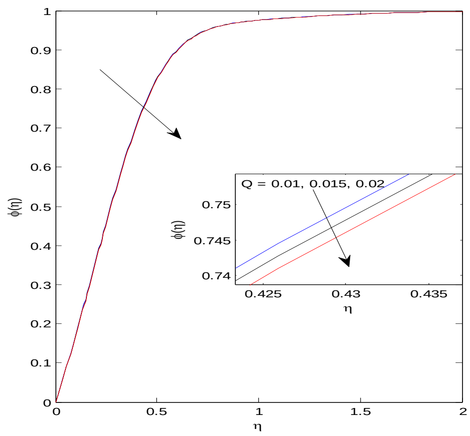


Fig. 27 Concentration profiles for Q.

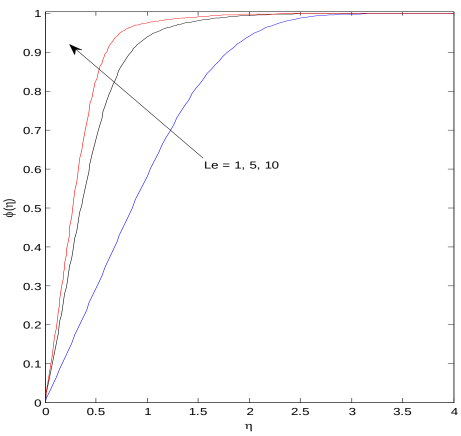


Fig. 28 Concentration profiles for *Le*.

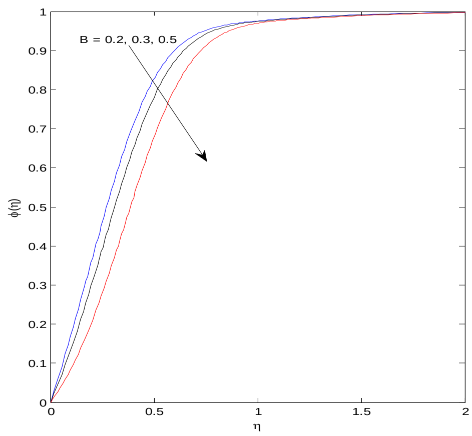
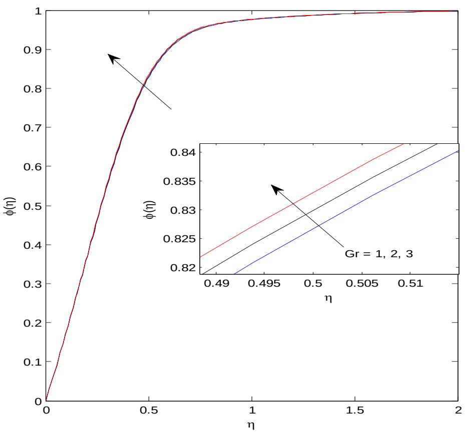


Fig. 29 Concentration profiles for *B*



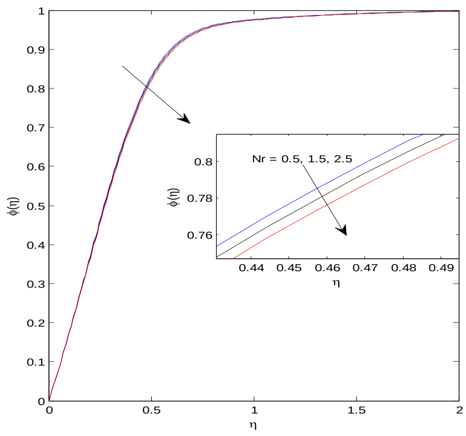


Fig. 30 Concentration profiles for *Gr*

Fig. 31 Concentration profiles for *Nr*

Table 2 Effects of various parameters on coefficient of skin-friction, Nusselt number and Sherwood numbers

A	*M*	*Pr*	*Nb*	*Nt*	*Q*	*Le*	*B*	*Gr*	Nr	$-C_f\sqrt{\mathrm{Re}_x}$	$-\frac{Nu_x}{\sqrt{\mathrm{Re}_x}}$	$-\frac{Sh_x}{\sqrt{\mathrm{Re}_x}}$
2										2.8125	0.8067	1.5518
3										6.1521	0.9385	1.6911
4										9.8913	1.0508	1.8186
	1									2.0211	0.789	1.5119
	5									2.8125	0.8067	1.5518
	10									3.5713	0.8193	1.5848
		0.71								2.8125	0.8067	1.5518
		1								2.8411	0.9618	1.6704
		1.4								2.8693	1.1481	1.7424
			0.03							2.8176	0.799	1.511

			0.05							2.8125	0.8067	1.5518
			0.07							2.81	0.8146	1.5633
				0.03						2.8097	0.8015	1.5944
				0.05						2.8125	0.8067	1.5518
				0.07						2.8153	0.8119	1.5076
					0.01					2.8125	0.8067	1.5518
					0.015					2.8127	0.8148	1.5409
					0.02					2.8129	0.8231	1.5299
						1				2.91	0.8039	0.576
						5				2.8382	0.8061	1.3102
						10				2.8125	0.8067	1.5518
							0.2			2.8125	0.8067	1.5518
							0.3			2.7757	0.7638	1.1747
							0.5			2.7141	0.6924	0.6749
								1		2.8125	0.8067	1.5518
								2		2.9077	0.8155	1.5551
								3		3.0037	0.8241	1.5585
									0.5	2.8974	0.8132	1.5558
									1.5	2.7274	0.8	1.5478
									2.5	2.5572	0.7861	1.5398

The influence of various physical entities on skin friction, rate of heat transfer and rate of mass transfer at the plate are presented in table 2. It is clearly visible from table 2 that velocity ratio parameter, magnetic field, thermophoresis diffusion, heat absorption and Grashof number Gr have the tendency to enhance skin friction but the skin friction is being reduced by thermal diffusion, Brownian diffusion, Levis number Le, melting parameter, and buoyancy-ratio parameter Nr. There is a significant increase in rate of heat transfer with the increase in velocity ratio parameter, magnetic field, Brownian diffusion, thermophoresis diffusion, heat absorption, Levis number *Le*, and Grashof number *Gr* whereas there is a significant decrease in rate of heat transfer with the increase in thermal diffusion, melting parameter, and buoyancy-ratio parameter *Nr*. Velocity ratio parameter, magnetic field, Brownian diffusion, Levis number *Le*, and Grashof number *Gr* have the tendency to enhance the rate of mass transfer while it is being reduced by thermal diffusion, thermophoresis diffusion, heat absorption, melting parameter, and buoyancy-ratio parameter *Nr*.

5. Conclusions

Effects of free convection, heat absorption on MHD stagnation point flow of a viscous, incompressible, and electrically conducting nano-fluid past a stretchable surface with melting is studied. Following conclusions are drawn from the problem studied:

- Magnetic field, heat absorption, and Grashof number work as enhancing agent for the nanofluid velocity whereas thermal diffusion, melting of the sheet and buoyancy-ratio parameter *Nr* looks like reducing agent.

- Heat absorption and magnetic field and Grashof number have the tendency to induce the nanofluid temperature while melting of the sheet and buoyancy-ratio parameter *Nr* have reverse effect on it.

- Heat absorption, melting of the sheet and buoyancy-ratio parameter *Nr* are the cause for an decrease in nano-fluid concentration.

- Magnetic field, heat absorption and Grashof number are the reason for enhancement in skin friction while melting of the sheet and buoyancy-ratio parameter *Nr* are the cause for the decrease in skin friction.

- Rate of heat transfer at the surface is getting enhanced by magnetic field, Brownian diffusion, thermophoretic diffusion, heat absorption, Grashof number, velocity ratio parameter, and Levis number while it is getting reduced by melting parameter, thermal diffusion and buoyancy-ratio parameter *Nr*.

- An increment is observed in the rate of mass transfer with the increase in magnetic field, Brownian diffusion, Levis number and Grashof number while a reduction can be seen with the increase in melting of the sheet, heat absorption and buoyancy-ratio parameter *Nr*.

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