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Dissipative Effects on MHD Stagnation Point Flow of a Heat Absorbing Nano-Fluid past a Stretchable Surface with Melting

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ABSTRACT: In this paper we studied, numerically, the dissipative effects on MHD stagnation point flow of a heat absorbing nano-fluid past a stretchable surface with melting. To validate accuracy of results, we have compared results obtained in the present paper with the existing literature and found to be in an excellent agreement. Numerical results of velocity $f'(\eta)$, temperature $\theta(\eta)$, and species concentration $\phi(\eta)$ are depicted graphically for various values of pertinent flow parameters whereas these of skin friction coefficient, Nusselt number, and Sherwood number are presented in tabular form. Such nano-fluid flows find applications in heat transfer processes, heat exchanger, engine cooling, vehicle thermal management etc.

Keywords: Nano-fluid, Melting heat transfer, Viscous and Joule Dissipations, Heat Absorption.

I. INTRODUCTION

Heat transfer has a vital role in many industrial processes (e.g. heat transfer in gas turbines, heat exchangers, propulsion of aircrafts, missiles, and space vehicles etc.). Plenty of research studies have been conducted by researchers so far to understand and analyze the heat transfer characteristics in the fluid flow problem. Some of these studies are due to [1-4]. In MHD heat transfer problems, the Reynolds analogy between skin friction and heat transfer is not valid because in addition to the viscous dissipation, there is also a Joule dissipation of heat which is caused by flow of electric current in the fluid [5]. A significant change has been encountered in the heat transfer characteristics within the boundary layer region due to the cooling/heating effect on the surface which is caused by the energy dissipated due to the fluid motion and retardation due to external magnetic field applied into the system.

In recent days, due to the limitation of conventional energy sources, emphasize is given more towards the development sustainable energy sources and hence rapid advancement is observed in the field of science and technology. To fulfil the high energy demand, renewable energy can only be the source of energy. Solar energy is the easiest and most available source of renewable energy in the universe. Conventional fluids are used as a heat transfer medium in solar thermal collectors which are designed to capture solar radiations. But the performance of most of these fluids is not so good due to their limited capacity to heat-up and low thermal conductivity. To overcome the issues of limited thermal conductivity, researchers have been forced to focus their study in this direction. Choi and Eastman [6], who were the first in this direction, coined the term “nano-fluid”. Nano-fluids are fluids with suspended nanoparticles and have unique thermos-physical properties. Later, Choi *et al*., [7] encountered the unexpected enhancement in thermal conductivity of fluid by mixing a small amount (<1% volume fraction) of nanoparticles in the base fluid. Motivated by this pioneer work, researchers jumped into this direction and carried out their studies [8-10] to understand the enhancement of heat transfer property in different geometrical configurations and conditions.

Fluid flow and heat transfer caused by a stretching surface is of great importance in many industrial processes such as drawing, annealing and tinning of coper wires, artificial fibers, rolling and manufacturing of plastic films etc. The credit goes to Crane [11] who studied first the “fluid flow over a linearly stretching sheet”. He obtained an exact solution of the two-dimensional Navier-Stokes equations. After his work, the problems of fluid flow through stretchable surface have been studied by many researchers [12-14]. Recently Mahatha *et al*., [15] studied “two dimensional MHD boundary layer nano-fluid flow over a stretchable surface”. In their study, they have also considered convective heating, viscous and Joule dissipations into account.

In several fluid engineering devices, temperature difference between the boundary layer surface and fluid plays an important role. Due to the significant implications in heat transfers characteristics, heat sources/sinks become key point of attraction of researchers. “Effect of heat generation/absorption on the hydromagnetic flow and heat transfer along a semi-infinite flat plate in a saturated porous medium” is studied by Chamkha and Khaled [16]. They have considered two different cases viz. uniform heat flux and uniform wall temperature at the plate. Kamel [17] studied, analytically, the “MHD transient convective heat and mass transfer flow towards a vertical surface considering heat generation/absorption into account”. Many researchers [18-21] have their contributions in the study of fluid flow problems taking heat generation/absorption into account. In 2018, Nandkeolyar *et al*., [22] analyzed “MHD nano-liquid flow through a stretchable wall”. Effects of transverse magnetic field and heat absorption on the flow field are presented in their study.

Melting heat transfer has its own significance in many real life applications (i.e. cooling and heating process, thermal energy storage, melting of permafrost, unfreezing of frozen grounds, setting up of semiconductor-material, casting and welding of manufacturing processes etc). Keeping in view the importance of melting heat transfer, Epstein and Cho [23] investigated "melting heat transfer in laminar flow over flat surface". Hayat *et al.*, [24] studied "Numerical simulation for melting heat transfer and radiation effects in stagnation point flow of carbon–water nanofluid". Gireesha *et al.*, [25] investigated "Melting heat transfer in boundary layer stagnation-point flow of nanofluid toward a stretching sheet with induced magnetic field". Hayat *et al.*, [26] studied "Homogeneous-heterogeneous reactions and melting heat transfer effects in the MHD flow by a stretching surface with variable thickness". Kameswaran *et al.*, [27] performed study on "Melting effect on convective heat transfer from a vertical plate embedded in a non-Darcy porous medium with variable permeability". Adegbie *et al.*, [28] did a research study on "Melting heat transfer effects on stagnation point flow of micropolar fluid with variable dynamic viscosity and thermal conductivity at constant vortex viscosity". Singh and Kumar [29] investigated "Melting and heat absorption effects in boundary layer stagnation-point flow towards a stretching sheet in a micropolar fluid". A study on "Magneto hydrodynamic (MHD) boundary layer stagnation point flow and heat transfer of a nanofluid past a stretching sheet with melting" has been carried out by Ibrahim [30]. Very recently (i.e. in 2019), Sarkar and Endalew [31] investigated the influence of melting process and permeability of the medium on the hydromagnetic wedge flow of a Casson nano-fluid.

Upto the knowledge of the authors, there is a lack of research studies on boundary layer MHD stagnation point nano-fluid flow through a stretchable surface, under the conditions of the present problem, considering the combined effects of heat absorption, melting of the surface, viscous and Joule dissipations into account. As absorption, melting, viscous and Joule dissipations plays a vital role in the process of heat transfer, authors were motivated to study the melting and dissipative effects on steady MHD boundary layer stagnation point flow of a viscous, incompressible, electrically conducting and heat absorbing nano-fluid past a stretchable surface.

II. MATHEMATICAL MODEL OF THE PROBLEM

Consider a two-dimensional steady boundary layer flow of a viscous, incompressible, electrically conducting, and heat absorbing nano-fluid over a stretchable surface. The surface is melting steadily at a constant property. In the geometry (see Fig. 1), x-axis is considered along the surface and y-axis normal to it. A magnetic field, of uniform strength B_0, is applied parallel to y-axis (i.e. normal to the fluid flow). Temperature of the melting surface is T_m, and concentration *C* assumes the constant value C_w at the surface. In the far-field (i.e. when $y \longrightarrow \infty$), the values of T and C are assumed to be uniform i.e. T_∞ and C_∞. Here $T_\infty > T_m$. Free stream velocity takes the form $U_\infty = bx$ and velocity of the surface is $u_w = ax$, where *a* and *b* are positive constants. It is further assumed that there is no applied or polarized voltages exist so the effect of polarization of fluid is negligible [32]. The effect induced magnetic field is neglected. This assumption is justified because magnetic Reynolds number is very small for liquid metal and partially ionized fluids [33]. Nanoparticles and base fluid are both in a state of thermal equilibrium and there is no slip between them.

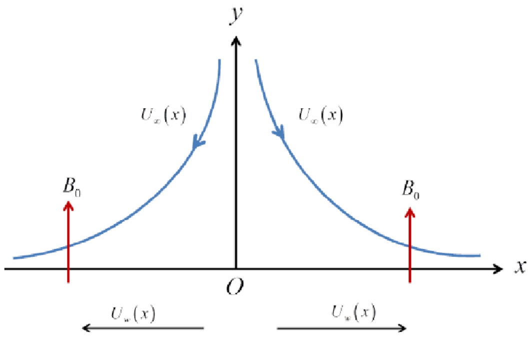

Fig. 1. Geometrical model of the flow.

Based on the assumptions made above, the equations for conservation of mass, momentum, energy and nano-particle volume fraction may be written as

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

$$u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}=\upsilon\frac{\partial^2 u}{\partial y^2}+U_\infty\frac{\partial U_\infty}{\partial x}+\frac{\sigma {B_0}^2}{\rho_f}\left(U_\infty-u\right) \tag{2}$$

$$u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}=\alpha\frac{\partial^2 T}{\partial y^2}+\tau\left\{D_B\frac{\partial C}{\partial y}\frac{\partial T}{\partial y}+\frac{D_T}{T_\infty}\left(\frac{\partial T}{\partial y}\right)^2\right\}+\frac{\mu}{\rho c_p}\left(\frac{\partial u}{\partial y}\right)^2$$
$$+\frac{\sigma {B_0}^2}{\rho c_p}\left(U_\infty-u\right)^2+\frac{Q_0}{\rho c_p}\left(T-T_m\right) \tag{3}$$

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

Boundary conditions:

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

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

Introducing the following transformation:

$$\psi = \sqrt{a\upsilon}\,x f(\eta),\ \theta(\eta) = \frac{T - T_m}{T_\infty - T_m},\ \ \phi(\eta) = \frac{C - C_w}{C_\infty - C_w},\ \eta = y\sqrt{\frac{a}{\upsilon}} \qquad (6)$$

where η is the dimensionless stream function.

Here the above transformation is chosen such a way that $u = \frac{\partial \psi}{\partial y},\ v = -\frac{\partial \psi}{\partial x}$.

The continuity Eqn. (1) is satisfied, identically, on using (6). Also, Eqns. (2), (3) and (4) take the following forms

$$f''' + ff'' - f'^2 + A^2 + M\left(A - f'\right) = 0 \qquad (7)$$

$$\theta'' + \Pr\Big[f\theta' + Nb\,\phi'\theta' + Nt\,\theta'^2 + Ec\, f''^2 + M\,Ec\left(A - f'\right)^2 + Q\,\theta\Big] = 0 \qquad (8)$$

$$\phi'' + Le\, f\phi' + \frac{Nt}{Nb}\theta'' = 0 \qquad (9)$$

where

$$M = \frac{\sigma {B_0}^2}{\rho_f a},\ Le = \frac{\upsilon}{D_B},\ \Pr = \frac{\upsilon}{\alpha},\ A = \frac{b}{a},\ Q = \frac{Q_0}{a\rho c_p},$$

$$Nb = \frac{(\rho c)_p D_B \left(C_\infty - C_w\right)}{(\rho c)_f\, \upsilon},\ Nt = \frac{(\rho c)_p D_T \left(T_\infty - T_m\right)}{(\rho c)_f\, \upsilon T_\infty},$$

$$B = \frac{C_f\left(T_\infty - T_m\right)}{\lambda + C_s\left(T_m - T_0\right)},\ Ec = \frac{a^2 x^2}{C_p\left(T_\infty - T_m\right)} = \frac{{u_w}^2}{C_p \Delta T}.$$

Non-dimensional variables defined above, i.e. $M,\ Le,\ \Pr,\ A,\ Nb,\ Nt,\ Q$ and Ec, are the magnetic parameter, Lewis number, Prandtl number, velocity ratio parameter, Brownian motion parameter, thermophoresis parameter, heat absorption parameter and Eckert number respectively.

Non-dimensional boundary conditions are

$$\left.\begin{array}{l} f'(0) = 1,\ B\theta'(0) + \Pr f(0) = 0,\ \theta(0) = 0,\ \phi(0) = 0, \\ f'(\infty) \to A,\ \theta(\infty) \to 1,\ \phi(\infty) \to 1. \end{array}\right\} \qquad (10)$$

where B (dimensionless melting parameter) is the combination of Stefan numbers $\frac{C_f\left(T_\infty - T_m\right)}{\lambda}$ (for liquid phase) and $\frac{C_s\left(T - T_0\right)}{\lambda}$ (for solid phase).

The other physical quantities, which are of much interest from the point of their engineering applications, are local skin friction coefficient C_f, the local Nusselt number Nu_x, and the local Sherwood number Sh_x which are defined as:

$$C_f = \frac{\tau_w}{\rho u_w^2},\ Nu_x = \frac{x q_w}{k\left(T_\infty - T_m\right)},\ Sh_x = \frac{x h_m}{D_B\left(C_w - C_\infty\right)} \qquad (11)$$

where

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

are, respectively, the wall shear stress, the wall heat flux, and wall mass flux.

Using similarity variables, we obtain from Eqn. (11) as

$$C_f\sqrt{\mathrm{Re}_x} = -f''(0),\ \frac{Nu_x}{\sqrt{\mathrm{Re}_x}} = -\theta'(0),\ \frac{Sh_x}{\sqrt{\mathrm{Re}_x}} = -\phi'(0) \qquad (12)$$

where Re_x is local Reynolds number.

III. NUMERICAL SOLUTION AND VALIDATION

A numerical approach, bvp4c routine of MATLAB, is applied to solve the non-linear ordinary differential Eqns. (7), (9) together with boundary conditions (10), which have been transformed from the governing non-linear partial differential Eqns. (1)-(4) along with the boundary conditions (5). For justification of the correctness of our computations, we have run the same numerical code in the absence of absorption parameter and Eckert number and computed the numerical values of skin friction coefficient $-f''(0)$. A comparison is made with the values of $-f''(0)$ obtained by Ibrahim [29] and found to be in excellent agreement. This comparison is presented in Table 1. This justifies the accuracy and robustness of our numerical computations.

Table 1: Comparison Table.

$Nb = Nt = 0.5,\ \Pr = 1,$ $Le = 2,\ Q = 0,\ Ec = 0$			**Ibrahim [29]**	**Present paper**
A	M	B	$-f''(0)$	$-f''(0)$
0	1	0.5	–1.2876	-1.287573
0.1			–1.1923	-1.192303
0.2			–1.0914	-1.091395
0.3			–0.9825	-0.982504
0.6			–0.6070	-0.606969
1.5			0.91	0.910045
2			1.9687	1.968685
2.5			3.1604	3.160361
0.5	1		–0.7401	-0.740129
0.5	2		–0.8798	-0.879843
0.5	3		–1.0019	-1.001949
0.5	4		–1.1117	-1.11174
0.5	0.5	0.1	–0.7279	-0.727904
0.5		0.5	–0.6608	-0.660771
0.5		1	–0.6142	-0.614155
0.5		10	–0.4596	-0.459576

IV. RESULTS AND DISCUSSION

To have better physical insight into the flow pattern and to analyze the influences of various physical parameters on nano-fluid velocity $f'(\eta)$, nano-fluid temperature $\theta(\eta)$, nano-particle concentration $\phi(\eta)$, skin friction $-f''(0)$, rate of heat and mass transfers, we have computed the numerical values of $f'(\eta)$, $\theta(\eta)$, $\phi(\eta)$, $-f''(0)$, $-\theta'(0)$, and $-\phi'(0)$ with respect to flow parameters and presented in the form of graphs and table.

The effects of magnetic field, Brownian motion, thermophoresis parameter, heat absorption, melting parameter, viscous dissipation, thermal diffusion and velocity ratio parameter on the nano-fluid velocity are presented in Figs. 2-9. It is evident from Figs. 2-9 that magnetic field and velocity ratio parameter have the tendency to enhance the nano-fluid velocity while rest of the physical entities (i.e. Brownian motion, thermophoresis parameter, heat absorption, melting parameter, viscous dissipation, and thermal diffusion) have reverse effect on it.

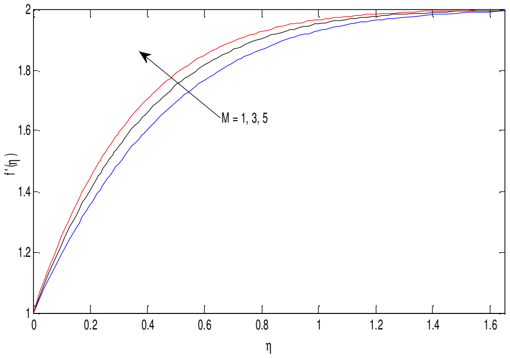

Fig. 2. Velocity profiles for M.

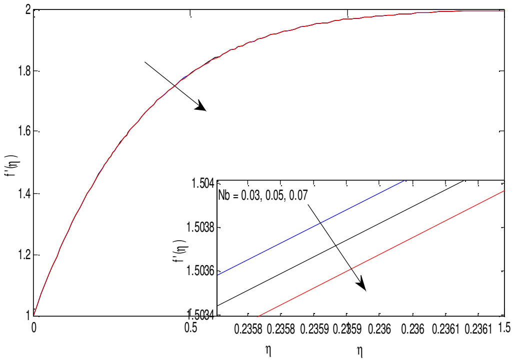

Fig. 3. Velocity profiles for Nb.

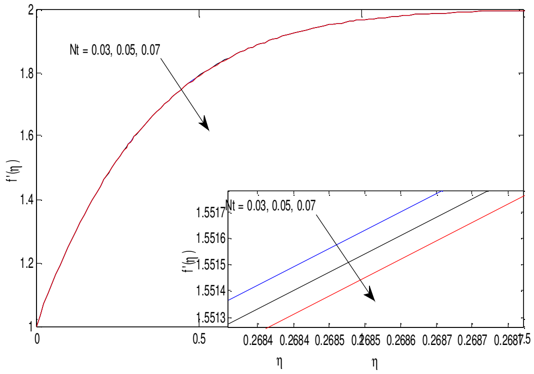

Fig. 4. Velocity profiles for Nt.

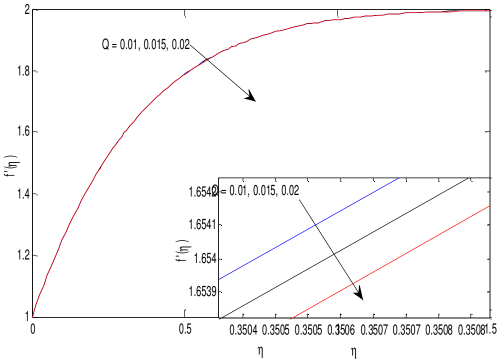

Fig. 5. Velocity profiles for *Q*.

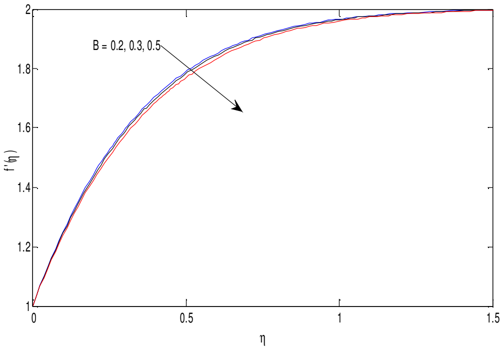

Fig. 6. Velocity profiles for B.

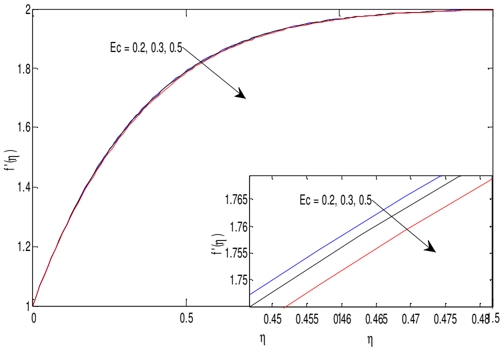

Fig. 7. Velocity profiles for Ec.

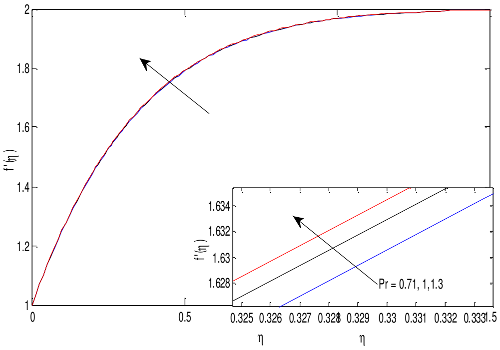

Fig. 8. Velocity profiles for Pr.

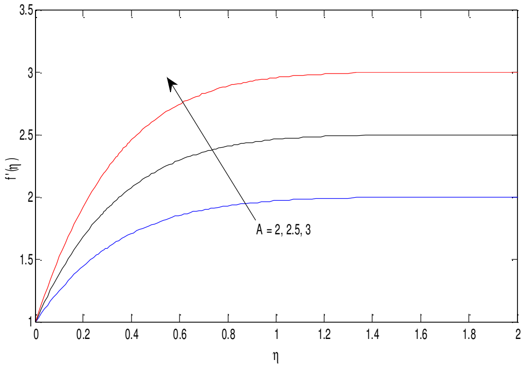

Fig. 9. Velocity profiles for A.

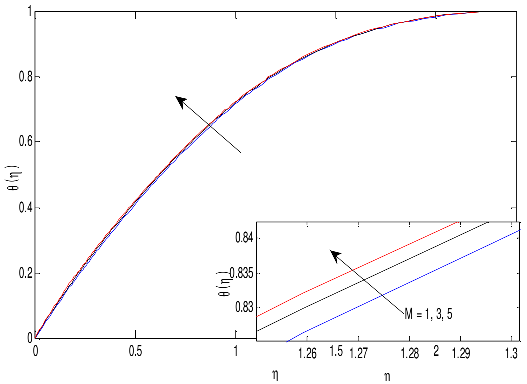

Fig. 10. Temperature profiles for M.

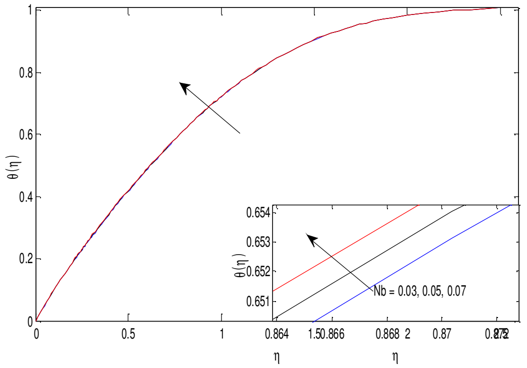

Fig. 11. Temperature profiles for Nb.

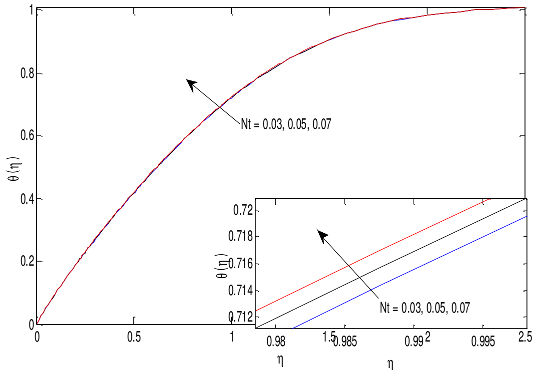

Fig. 12. Temperature profiles for Nt.

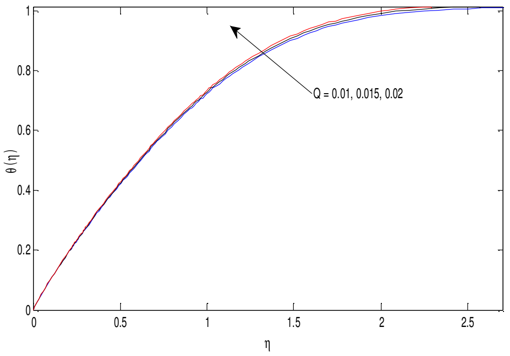

Fig. 13. Temperature profiles for Q.

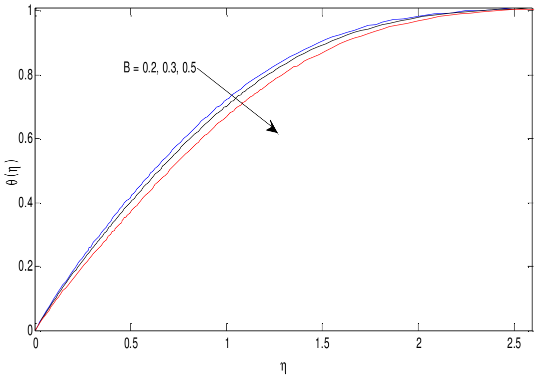

Fig. 14. Temperature profiles for B.

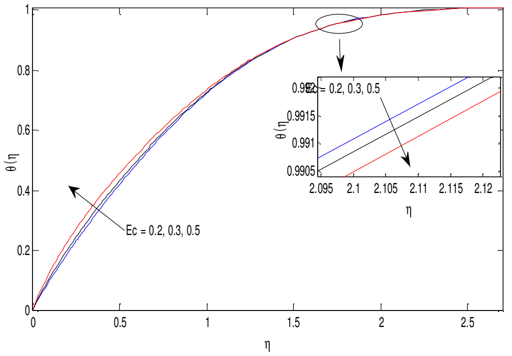

Fig. 15. Temperature profiles for Ec.

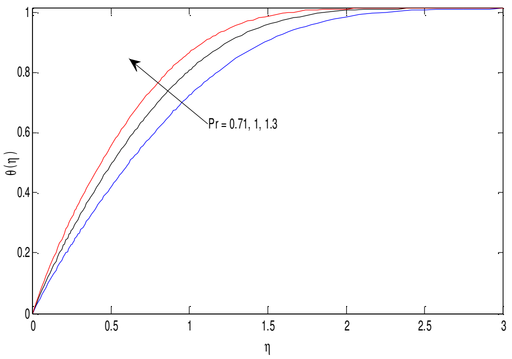

Fig. 16. Temperature profiles for Pr.

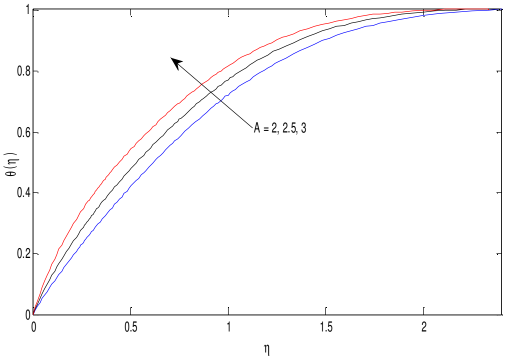

Fig. 17. Temperature profiles for A.

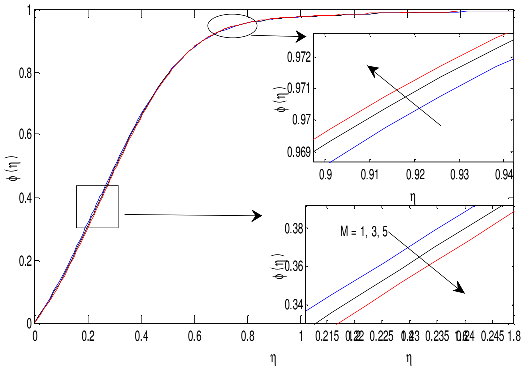

Fig. 18. Concentration profiles for M.

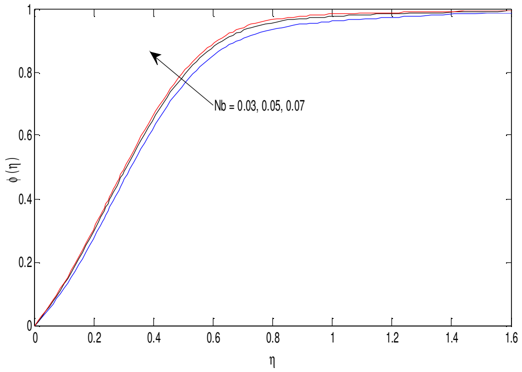

Fig. 19. Concentration profiles for Nb.

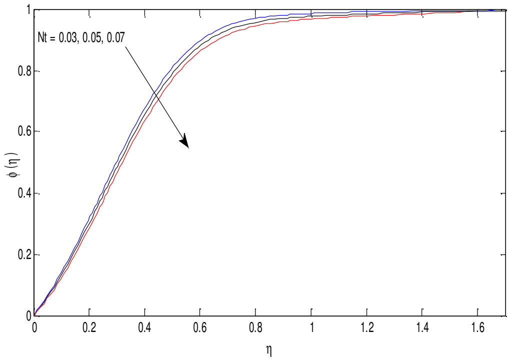

Fig. 20. Concentration profiles for Nt.

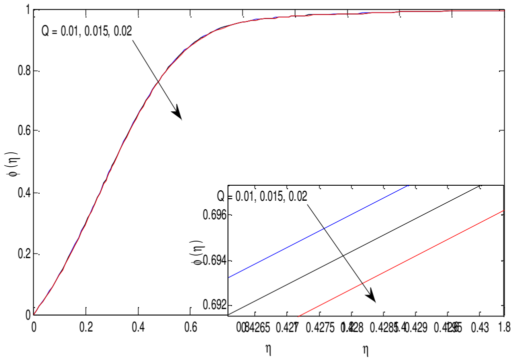

Fig. 21. Concentration profiles for Q.

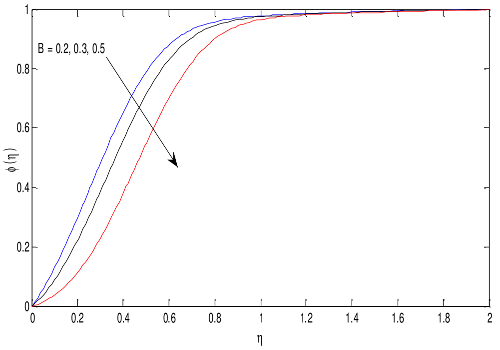

Fig. 22. Concentration profiles for B.

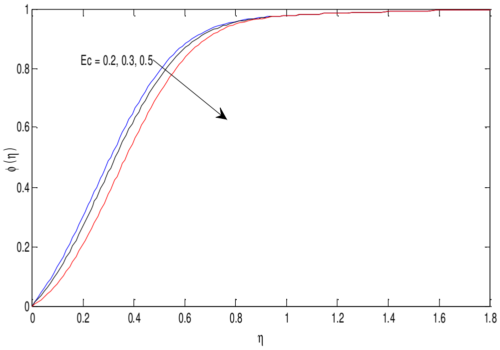

Fig. 23. Concentration profiles for Ec.

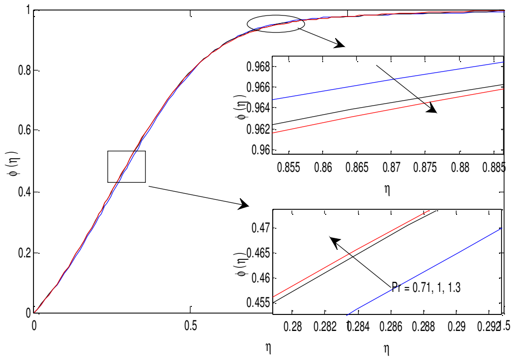

Fig. 24. Concentration profiles for Pr.

Figs. 10-17 demonstrate the impact of flow parameters on nano-fluid temperature. It is observed from Figs. 10 - 17 that the melting parameter and thermal diffusion are the cause for the decrease in nano-fluid temperature while magnetic field, Brownian diffusion, thermophoretic diffusion, heat absorption, and velocity ratio parameter are reversely responsible. In the boundary layer region, viscous dissipation enhances the nano-fluid temperature whereas it has reverse effect on it, outside the boundary layer region.

Figs. 18-25 describe the influences of various parameters on species concentration. We can conclude from these figures that Brownian motion induces the species concentration and thermophoresis parameter, heat absorption, melting parameter, and viscous dissipation reduce the concentration throughout the region. Magnetic field, thermal diffusion and velocity ratio parameter behave as decreasing agents in the boundary layer region whereas the same quantities act reversely in the region outside the boundary layer.

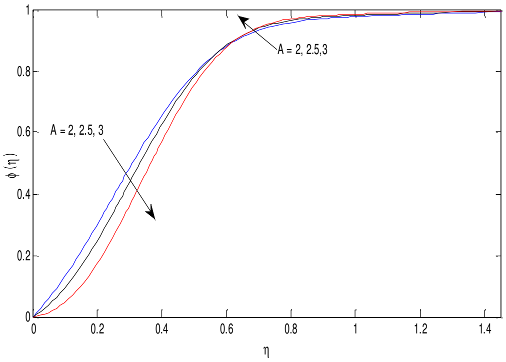

Fig. 25. Concentration profiles for A.

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

A	M	Pr	Nb	Nt	Q	Le	B	Ec	$-C_f\sqrt{\mathrm{Re}_x}$	$-\frac{Nu_x}{\sqrt{\mathrm{Re}_x}}$	$-\frac{Sh_x}{\sqrt{\mathrm{Re}_x}}$
2	5	0.71	0.05	0.05	0.01	10	0.2	0.5	2.8512	1.066	1.0712
2.5									4.3777	1.4554	0.6172
3									5.9293	1.9636	0.0822
	1								2.1082	0.9393	1.2466
	3								2.5059	1.0085	1.1516
	5								2.8512	1.066	1.0712
		0.71							2.8512	1.066	1.0712
		1							2.8696	1.3193	1.1027
		1.3							2.8816	1.5606	1.0795
			0.03						2.8524	1.0579	0.9146
			0.05						2.8512	1.066	1.0712
			0.07						2.8501	1.0741	1.133
				0.03					2.852	1.0609	1.1815
				0.05					2.8512	1.066	1.0712
				0.07					2.8505	1.0711	0.9594
					0.01				2.8505	1.0711	0.9594
					0.015				2.8503	1.0725	1.0636
					0.02				2.8494	1.0791	1.056
						5			2.8515	1.064	0.9375
						7			2.8514	1.065	1.0243
						10			2.8512	1.066	1.0712
							0.2		2.8512	1.066	1.071
							0.3		2.7891	1.0065	0.6708
							0.5		2.6852	0.9092	0.2279
								0.2	2.8512	1.066	1.0712
								0.3	2.8333	1.1933	0.8497
								0.5	2.798	1.4452	0.4513

The influences 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 the magnetic field and velocity ratio parameter are the reason for enhancement in skin friction while the other parameters (viz. Brownian diffusion, thermophoretic diffusion, heat absorption, melting of the surface, viscous dissipation, thermal diffusion, and Levis number) are the cause for the decrease in skin friction. Heat transfer rate at the surface is getting enhanced by magnetic field, Brownian diffusion, thermophoretic diffusion, heat absorption, viscous dissipation, velocity ratio parameter, and Levis number while it is getting reduced by melting parameter, and thermal diffusion. An increment is observed in the rate of mass transfer with the increase in Brownian diffusion and Levis number while a reduction can be seen with the increase in magnetic field, thermophoretic diffusion, melting of the sheet, viscous dissipation, and velocity ratio parameter. The heat absorption and thermal diffusion shows an oscillatory impact on mass transfer rate.

V. CONCLUSIONS

Melting and dissipative effects on steady MHD boundary layer stagnation point flow of a viscous, incompressible, electrically conducting and heat absorbing nano-fluid past a stretchable surface is studied. Following conclusions are drawn from the of the problem studied:

- Magnetic field works as an enhancing agent for the nanofluid velocity whereas heat absorption, viscous dissipation, thermal diffusion and melting of the sheet looks like reducing agent.

- Heat absorption and magnetic field has the tendency to induce the nanofluid temperature while melting of the sheet has reverse effect on it.
- Heat absorption, melting of the sheet and viscous dissipations are the cause for a decrease in nanofluid concentration
- Magnetic field and velocity ratio parameter are the reason for enhancement in skin friction while the other parameters 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, viscous dissipation, velocity ratio parameter, and Levis number while it is getting reduced by melting parameter, and thermal diffusion.
- An increment is observed in the rate of mass transfer with the increase in Brownian diffusion and Levis number while a reduction can be seen with the increase in magnetic field, thermophoretic diffusion, melting of the sheet, viscous dissipation, and velocity ratio parameter.
- The heat absorption and thermal diffusion shows an oscillatory impact on mass transfer rate.

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CONFLICT OF INTEREST

Authors have no any conflict of interest.

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