ELECTROMAGNETOCONVECTIVE STAGNATION POINT FLOW OF BIONANOFLUID WITH MELTING HEAT TRANSFER AND STEFAN BLOWING

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This study investigates the effect of induced magnetic field, melting heat transfer and Stefan blowing effects of mass transfer as well as mass convective boundary condition on the stagnation point flow of a bionanofluid over a vertical plate. The nonlinear boundary layer equations are transformed, by using suitable similarity transformations, into ordinary differential equations (ODEs) which are then solved numerically using the BVP4C technique. The solutions of the problem depends on parameters of magnetic M, blowing s, Brownian motion Nb, thermophoresis Nt, reciprocal of magnetic Prandtl number A, Lewis number Le, Bioconvection Schmidt number Sb and Péclet number Pe. The effects of these controlling parameters on the flow, heat, mass and microorganism transfer are studied. It is found that magnetic parameter leads to a decrease in the thickness of the momentum boundary layer. The temperature profile decreases with the increase of melting parameter. The blowing parameter enhances the concentration. The results of the present study are useful in many industrial applications such as heat exchangers, coolants, micro-channel heat sinks, lubricants and microbial fuel cell.

Keywords: *Magnetohydrodynamic; Stefan blowing; melting heat transfer.*

1. Introduction

Magnetohydrodynamics (MHD) has relevance to engineering, biomedical applications and process industries. Due to these and others applications, many authors have studied various aspects of nanofluids and MHD theoretically and experimentally. Michael [1]first established the interaction of hydrodynamics and electromagnetic effects. Davies [2]extended this work for MHD boundary layer past a semi-infinite flat plate. Ishak *et al.*[3] described the steady boundary layer flow with variable magnetic field along a moving wedge in a free stream. By considering the results of [3], Jafar *et al*. [4]studied boundary layer flows with induced magnetic field in a parallel free stream of an electrically conducting fluid. Khan *et al*. [5] introduced the combined effects of Navier slip and magnetic field on boundary layer bionanofluid flow over a vertical plate. Khan & Makinde [6]have investigated numerically magneto bioconvective laminar boundary layer flow with heat and mass transfer of an electrically conducting water-based nanofluid.

Stagnation point flows appear in many flow fields of engineering and scientific interest. In the stagnation area, fluid pressure and the rates of heat and mass transfer are highest [7].Stagnation point flow is considered to be fluid movement close to the stagnation area of a circular body and can exist for both a fixed or moving body in a fluid [8]. There has also been related work on induced magnetic field and stagnation point flow. For example, Ali *et al*. [9]have investigated the effect of induced magnetic field on stagnation point flow over a stretching sheet. Further, Ibrahim *et al.* [10] have examined the impactof magnetic field on stagnation point flow and heat transfer due to a nanofluid. Some applications that related the study of stagnation point flow include cooling of electronic devices, cooling of nuclear reactors, solar central receivers, drag reduction, thermal oil recovery and many hydrodynamic processes. Hiemenz [11] first studied stagnation flows by reducing the Navier Stokes equations to a nonlinear system of ODEs using similarity transformation. Some recent studies include Wang [12]described stagnation point flows as a basic fluid flows past a surface in maximum pressure and Nandy and Mahapatra[13] studied the MHD stagnation-point flow together with convective boundary condition and nanoparticle volume fractions.

The concept of nanofluid was first introduced by [14]. Nanofluids are the liquid suspension containing nano-sized particles of various materials, such as oxides, carbides, metals or carbon nanotubes. The use of nanoparticles is a process which enhances the heat transfer performance of base fluids like water, ethylene glycol, and engine oil [15]. Nanofluids are able to enhance the thermophysical characteristics of the base fluids. With improved heat transfer characteristics, the efficiency of many processes can be improved. Nanofluids have many applications in various fields such as nanofluid coolant, industrial and biomedical process [16]. Researches on nanofluids indicate that there are many potential applications of nanofluids. Shokoohi and Shekarian [17]have investigated the applications of nanofluid in machining operations. Machining is one of the largest and most widely used methods of producing segments in industries. Devendiran & Amirtham [18] have discussed in detail the application of nanofluids in automobiles, solar power, reactor-heat exchanger and optical.

Epstein and Cho[19]and Kazmierczak *et al.*[20] have considered the melting heat transfer in over a flat plate. Heat transfer with melting (or solidification) effects are important in the study of magma solidification, melting of permafrost and silicon wafer processing [21].These studieshas recently received increased attention due to various of applications, including latent heat storage, material processing, crystal growth, castings of metals, glass industry, purification of materials, magma solidification, etc.[22]. Recently, Gireesha *et al.* [23] analyzed influence of MHD effects on melting heat transfer in boundary layer stagnation point flow with heat source/sink and induced magnetic field.

The concept of bioconvection in nanofluid are defined as the spontaneous pattern formation and density stratification due to the simultaneous interaction of the denser self-propelled microorganisms, nanoparticles, and buoyancy forces [24]. Bioconvection occurs when these self-propelled motile microorganisms swimming in a particular direction which cause increase in density of the base fluid [6]. Examples of microorganisms in bioconvection are gyrotaxis, gravitaxis or oxytaxis organisms. The advantages of adding motile microorganisms to the suspension is to improve nanofluid stability, enhance the mass tranfer, microscale mixing, especially in microvolumes [25]. The smaller the concentration of nanoparticles will increase the viscosity of the base fluid which tend nanofluid bioconvection to occurs[26]. Aziz *et al*. [27] investigated free convection boundary layer flow with nanofluid and microorganisms embedded in a porous medium. Bioconvection can be applied in bio-microsystems. In biotechnology, bioconvection will increase the mass transport and mixing which are importance in many micro-systems[22]. Ravi & Vinod [16]have highlighted uses of bioconvection in the biomedicine industry such as nanodrug delivery and cancer therapeutics. The study of nanofluid with bioconvection are also important in microbial fuel cell technologies ([28], [29]). The investigate of the effect of velocity slip, thermal slip and zero mass flux boundary conditions on time-dependent bioconvection nanofluid boundary layer flow from a horizontal cylinder has contributed to nano-biopolymer manufacturing processes [30].

The blowing effect arises from the Stefan problem for species transfer. As an example, in real applications, paper drying process involves species transfer by evaporation[31].A bulk motion of fluid is produced from the diffusion of the species and give extra movement of the fluid. Blowing factor is used to find out the blowing effects for large mass transfer flux problem as the blowing factor can provide a correction factor when using traditional results without including blowing effects([31], [32]).Acrivos [33]analyzed blowing effects in boundary layer flow with stream-wise pressure gradient and this results shows that the blowing velocity was proportional to the mass transfer flux. Fang and Jing[34]investigated the flow, mass transfer, and heat transfer with blowing effects from mass transfer over a strecthing impermeable plate. Stefan blowing with multiple slip effects on bioconvection boundary layer flow of a nanofluid have also been studied by Uddin *et al.* [35]. Uddin *et al.*[29]have studied the influence of multiple slip boundary conditions on nanofluid bioconvection.

In our present study, the effect of the induced magnetic field, melting heat transfer and blowing effects of mass transfer as well as mass convective boundary condition on MHD stagnation point flow of nanofluids with microorganism over a vertical plate are investigated. The model is formulated, analysed and solved numerically. The obtained results are discussed and rendered graphically.

2. Mathematical formulations of the problem

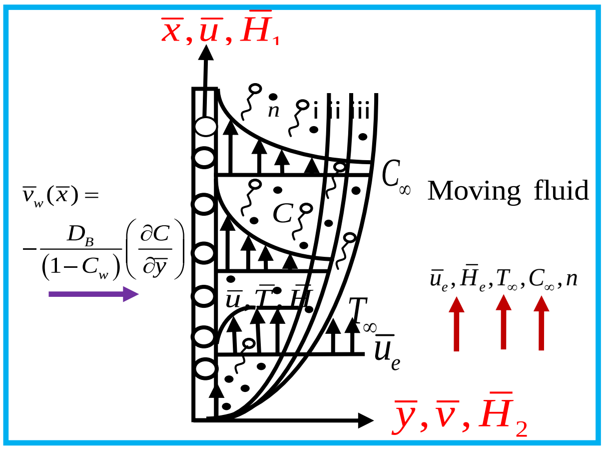


Figure 1. Physical model of the problem [29].

A steady two dimensional stagnation point flow of nanofluidbioconvectivewith induced magnetic field and melting heat transfer as well as blowing parameter in boundary layer is considered. The velocity of the external flow is $\bar{u}_e(\bar{x}) = a\,\bar{x}$. C_w isthe value of nanoparticle volume fraction at the surface. T_m is melting surface temperature while ambient values of temperature and nanoparticle volume fraction are T_∞ and C_∞ respectively, where $T_\infty > T_m$ .Using standard boundary layer approximation, the governing equations are as follow [29, 36]:

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

$$\frac{\partial \bar{H}_1}{\partial \bar{x}} + \frac{\partial \bar{H}_2}{\partial \bar{y}} = 0, \tag{2}$$

$$\bar{u}\frac{\partial \bar{u}}{\partial \bar{x}} + \bar{v}\frac{\partial \bar{u}}{\partial \bar{y}} = \bar{u}_e\frac{d\bar{u}_e}{d\bar{x}} + \upsilon\frac{\partial^2 \bar{u}}{\partial \bar{y}^2} + \frac{\mu_0}{\rho}\left(\bar{H}_1\frac{\partial \bar{H}_1}{\partial \bar{x}} + \bar{H}_2\frac{\partial \bar{H}_1}{\partial \bar{y}}\right) - \frac{\mu_0}{\rho}\left(\bar{H}_e\frac{\partial \bar{H}_e}{\partial \bar{x}}\right), \tag{3}$$

$$\bar{u}\frac{\partial \bar{H}_1}{\partial \bar{x}} + \bar{v}\frac{\partial \bar{H}_1}{\partial \bar{y}} - \bar{H}_1\frac{\partial \bar{u}}{\partial \bar{x}} - \bar{H}_2\frac{\partial \bar{u}}{\partial \bar{y}} = \alpha_1\frac{\partial^2 \bar{H}_1}{\partial \bar{y}^2}, \tag{4}$$

$$\bar{u}\frac{\partial T}{\partial \bar{x}} + \bar{v}\frac{\partial T}{\partial \bar{y}} = \alpha\frac{\partial^2 T}{\partial \bar{y}^2} + \tau D_B\frac{\partial T}{\partial \bar{y}}\frac{\partial C}{\partial \bar{y}} + \tau\frac{D_T}{T_\infty}\left(\frac{\partial T}{\partial \bar{y}}\right)^2, \tag{5}$$

$$\bar{u}\,\frac{\partial C}{\partial \bar{x}}+\bar{v}\,\frac{\partial C}{\partial \bar{y}}=D_B\,\frac{\partial^2 C}{\partial \bar{y}^2}+\frac{D_T}{T_\infty}\frac{\partial^2 T}{\partial \bar{y}^2}, \tag{6}$$

$$\bar{u}\,\frac{\partial \bar{n}}{\partial \bar{x}}+\bar{v}\,\frac{\partial \bar{n}}{\partial \bar{y}}+\frac{\tilde{b}W_c}{C_w-C_\infty}\left[\frac{\partial}{\partial \bar{y}}\left(\bar{n}\,\frac{\partial C}{\partial \bar{y}}\right)\right]=D_m\left(\frac{\partial^2 \bar{n}}{\partial \bar{y}^2}\right). \tag{7}$$

The relevant boundary conditions are [29, 34]:

$$\begin{aligned}
&\bar{u}=N_1(\bar{x})\upsilon\left(\frac{\partial \bar{u}}{\partial \bar{y}}\right),\quad \bar{v}=-\frac{D_B}{(1-C_w)}\left(\frac{\partial C}{\partial \bar{y}}\right),\quad \frac{\partial \bar{H}_1}{\partial \bar{y}}=\bar{H}_2=0,\\
&k\left(\frac{\partial T}{\partial \bar{y}}\right)_{y=0}=\rho_f\left[\lambda+c_s\left(T_m-T_o\right)\right]v(x,0),\quad -D_B\,\frac{\partial C}{\partial \bar{y}}=h_m\left(C_f-C\right),\quad \bar{n}=n_w \quad \text{at } \bar{y}=0, \quad (8)\\
&\bar{u}=\bar{u}_e(x)=a\,\bar{x},\quad \bar{H}_1\to\bar{H}_e(x)=H_0\,\bar{x},\quad T\to T_\infty,\quad C\to C_\infty,\quad \bar{n}\to 0 \qquad \text{as } \bar{y}\to\infty,
\end{aligned}$$

where $\bar{u}_e$ is the external fluid velocity, ρ is the constant fluid density, ρ_f is the density of the base fluid, c_p is the specific heat at constant pressure, c_s is the heat capacity of the solid surface, $\tilde{b}$ is the chemotaxis constant, W_c is the maximum cell swimming speed, k is the thermal conductivity of nanofluid, D_B is the Brownian diffusion coefficient, D_m is the microorganisms diffusion coefficient, D_T is the thermophoretic diffusion coefficient, μ_0 is the magnetic permeability, α is the thermal diffusivity, α_1 is the magnetic diffusivity, a is positive constant and λ is the latent heat transfer of the fluid.

3. Similarity Transformations

Introducing the following similarity transformations:

$$\begin{aligned}
&\eta=\bar{y}\sqrt{\frac{a}{\upsilon}},\quad \psi=\sqrt{a\upsilon}\bar{x}f(\eta),\quad \bar{H}_1=H_0\bar{x}\,h'(\eta),\quad \bar{H}_2=-H_0\sqrt{\frac{\upsilon}{a}}h(\eta),\\
&\theta(\eta)=\frac{T-T_m}{T_\infty-T_m},\quad \phi(\eta)=\frac{C-C_\infty}{C_w-C_\infty},\quad \chi(\eta)=\frac{n}{n_w}.
\end{aligned} \tag{9}$$

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

$$\bar{u}=\frac{\partial \psi}{\partial y},\ \bar{v}=-\frac{\partial \psi}{\partial x}. \tag{10}$$

Using the similarity transformations in Eq. (10), the governing Eqs. (1) - (8) are transformed intoa system ODEs:

$$f'''+ff''-f'^2+M\left(h'^2-hh''-1\right)+1=0, \tag{11}$$

$$Ah'''+fh''-hf''=0, \tag{12}$$

$$\theta''+\Pr f\theta'+Nb\theta'\phi'+Nt\theta'^2=0, \tag{13}$$

$$\phi''+\Pr Lef\phi'+\frac{Nt}{Nb}\theta''=0, \tag{14}$$

$$\chi'' + Sbf\chi' - Pe\left[\chi\phi'' + \phi'\chi'\right] = 0, \tag{15}$$

with boundary conditions

$$f'(0) = bf''(0), \quad f(0) = \frac{s}{\Pr Le}\phi'(0), \quad h''(0) = h(0) = 0,$$

$$\phi'(0) = -Nd\left[1-\phi(0)\right], \quad \chi(0) = 1, \quad \Pr f(0) + m\theta'(0) = 0 \qquad \text{at} \quad y = 0,$$

$$f'(\infty)\to 1,\ h'(\infty)\to 1,\ \theta(\infty)\to 1,\ \phi(\infty)\to 0,\ \chi(\infty)\to 0 \qquad \text{as} \ \ y\to\infty. \tag{16}$$

where $\Pr = \frac{\upsilon}{\alpha}$ is Prandtl number, $Nb = \frac{\tau D_B\left(C_f - C_\infty\right)}{\alpha}$ is Brownian motion parameter, $Nt = \frac{\tau D_T\left(T_\infty - T_m\right)}{\alpha T_\infty}$ is thermophoresis parameter, $Le = \frac{\alpha}{D_B}$ is Lewis number, $M = \frac{\mu_0}{\rho}\left(\frac{H_0}{a}\right)^2$ is magnetic parameter, $A = \frac{\alpha_1}{\upsilon}$ is reciprocal magnetic Prandtl number, $m = \frac{c_f\left(T_\infty - T_m\right)}{\lambda + c_s\left(T_m - T_0\right)}$ is dimensionless melting parameter, $Sb = \frac{\upsilon}{D_m}$ is bioconvection Schmidt number, $Pe = \frac{\tilde{b}W_c}{D_m}$ is Pécletnumber, $Nd = \frac{\left(h_m\right)_0}{D_B}$ is convective mass parameter, $b = \left(N_1\right)_0\sqrt{a\upsilon}$ is velocity slip parameter, $s = \frac{C_w - C_\infty}{(1-\mathrm{C}_\infty)}$ is blowing parameter.

4. Physical quantities

The local skin friction $C_{f_{\bar{x}}}$, Nusselt number $Nu_{\bar{x}}$, Sherwood number $Sh_{\bar{x}}$ and the density number of motile microorganisms $Nn_{\bar{x}}$ are defined as:

$$C_f = \frac{\mu}{\rho\bar{u}_e^2}\left(\frac{\partial\bar{u}}{\partial\bar{y}}\right)_{\bar{y}=0}, \ Nu_{\bar{x}} = -\frac{\bar{x}}{(T_\infty - T_m)}\left(\frac{\partial T}{\partial\bar{y}}\right)_{\bar{y}=0}, \ Sh_{\bar{x}} = -\frac{\bar{x}}{(\mathrm{C}_w - C_\infty)}\left(\frac{\partial C}{\partial\bar{y}}\right)_{\bar{y}=0},$$
$$Nn_{\bar{x}} = -\frac{\bar{x}_n}{(n_w - n_\infty)}\left(\frac{\partial n}{\partial\bar{y}}\right)_{\bar{y}=0}. \tag{17}$$

Substituting Eq. (9) into (17), yields

$$\mathrm{Re}_{\bar{x}}^{1/2} C_f = f''(0),\ \ \mathrm{Re}_{\bar{x}}^{1/2} Nu_{\bar{x}} = -\theta'(0),\ \ \mathrm{Re}_{\bar{x}}^{1/2} Sh_{\bar{x}} = -\phi'(0),\ \ \mathrm{Re}_{\bar{x}}^{1/2} Nn_{\bar{x}} = -\chi'(0), \tag{18}$$

where $\mathrm{Re}_{\bar{x}} = \frac{u_e\bar{x}}{\nu}$ is the local Reynolds number.

5. Numerical solutions and validation

Eqs. (11) - (15) subjected to the boundary conditions (16) were solved numerically by theBVP4C procedure, as discussed in ref.[37]. Many researchers have used this procedure in order to solve their problems ([38], [39], and [40]). The velocity, induced magnetic field, temperature, concentration as well as microorganisms profiles for different values of the governing parameters has been obtained. The value of parameter used range between $-1 \le s \le 1$, $0 < M \le 1$, $0 < Nt \le 5$, $0 \le A, b, m, Nb, Nd \le 10$, and $0 < Pe, Sb, Le \le 5$. In this study, we consider water-based nanofluids $(\Pr = 6.8)$. The results are displayed in figures 2-12. Moreover, figures 13-16 display the graphs of skin friction coefficient, local Nusselt number, local Sherwood number, and local microorganism transfer rate number respectively.

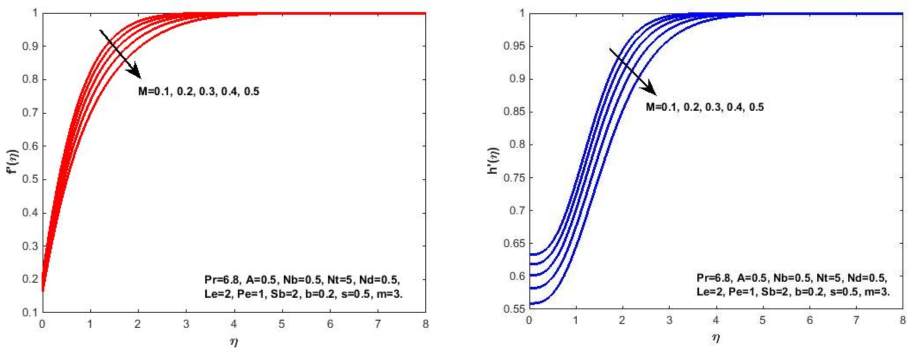
Table 1 Values of $f''(0)$ for $M = b = 0$,

β	Rajagopal *et al.* [41] [Quasilinearization method]	Jafar *et al.* [4] [Keller Box method]	Present [bvp4c method]
1.0	1.232585	1.2326	1.232587618

In this problem, our $\beta = 1$.Wenoticed that the result obtained for the present study are found to be in good agreement with those obtained by others.

6. Results and discussions

Figures 2(a) and (b) describe the impact of magnetic parameter *M* on velocity and induced magnetic field graphs respectively. As the value of *M* increases, both profiles are decreased. As *M* increases, so does the retarding force and thus the velocity decreases. Also, the presence of magnetic parameter leads to a decrease in the thickness of the momentum boundary layer and tends asymptotically to zero as the distance increases from boundary.



2(a) **2(b)**

Figure 2. Effect of M on (a) velocity and (b) magneticfield.

Figure 3 represents the effect of reciprocal magnetic Prandtl number, A on induced magnetic field. The induced magnetic field is found to increase with increasing in A .

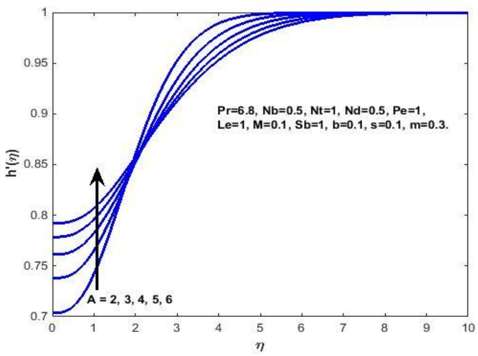


Figure 3. Effect of A oninduced magnetic

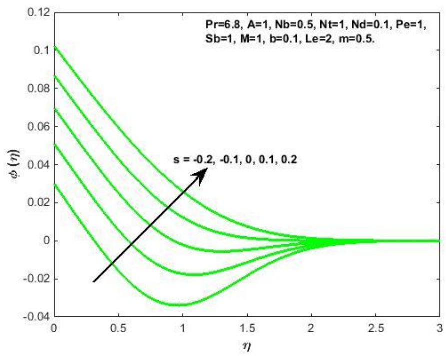
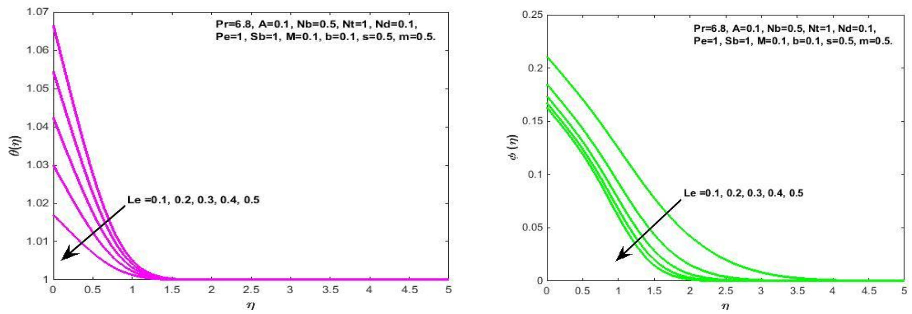


Figure 4. Effect of S onnanoparticles volume

field. **fraction.**

The concentration profile is plotted in Figure 4 for the different values of blowing parameter, s.With the increase of the blowing parameter, concentration profile increase and blown further away from the wall with thicker boundary layer. Figures 5(a) and 5(b) show the effect of Lewis number, Le on both temperature and nanoparticle volume fraction respectively. Clearly, an increase in Le values reduces thermal boundary layer thickness. This will be accompanied with a decrease in temperature as shown in figure 5(a). Then, in figure 5(b), it is observed that nanoparticle volume fraction distributions decelerate with the increasing values of Lewis number in the entire boundary layer region. By definition, the Lewis number represents the ratio of the thermal diffusivity to the mass diffusivity. Increasing the Lewis number means a higher thermal diffusivity and a lower mass diffusivity, and this produces thinner concentration boundary layer.



5(a) **5(b)**

Figure5. Effect of Le on (a) temperature and (b) nanoparticlesvolume fraction.

Figure 6 shows the effect of mass convective parameter on nanoparticle volume fraction profile. The graph of nanoparticle volume fraction increases with increasing of value *Nd*. Figure 7 exhibits the effect of Bioconvection Schmidt number, Sb on microorganism profile. Increasing value of Sb gives affects to microorganism graph profile to decrease.

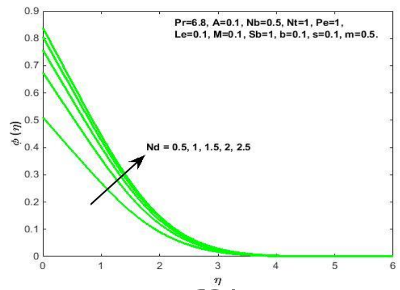


Figure6. Effect of Nd on nanoparticles volume fraction

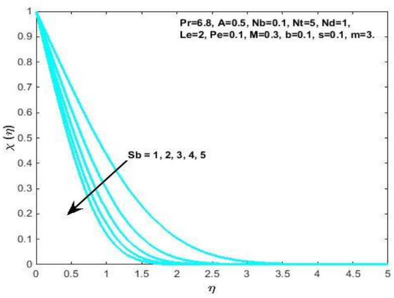


Figure 7. Effect of Sb on microorganism.

Figure 8 represents the effect of Péclet number, Pe on dimensionless microorganism graph. As the value of Pe increases, microorganism graph is decreasing.

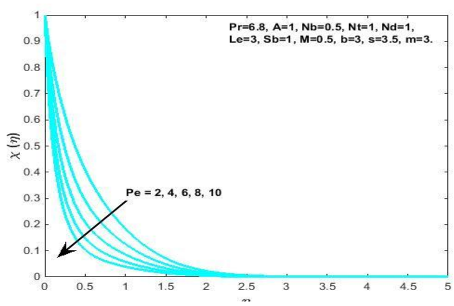
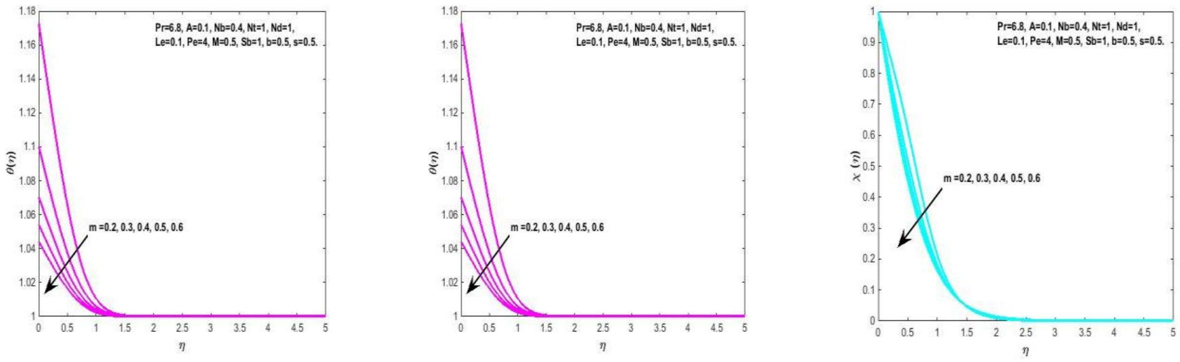


Figure 8. Effect of Pe on microorganism.

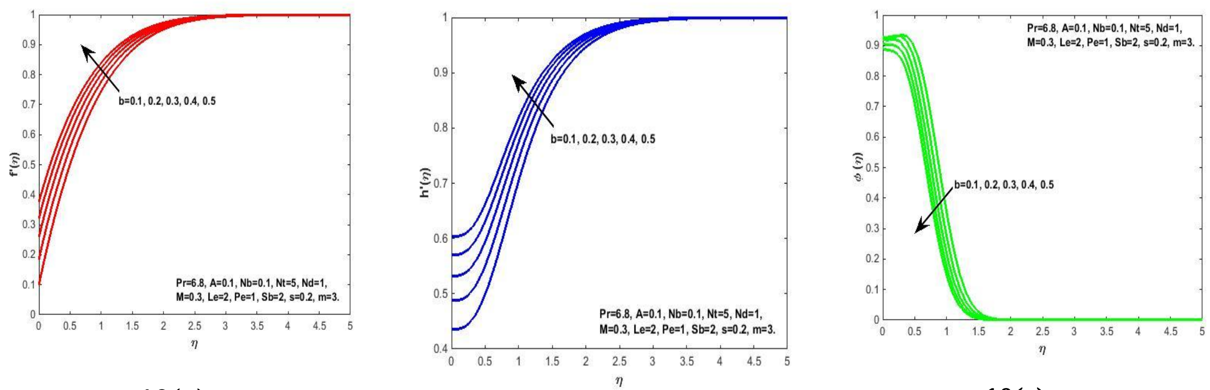
The effect of melting parameter, m on temperature, nanoparticles volume fraction and microorganism profile are plotted in figure 9(a)-(c) respectively. All graphs profile decreases with increasing of m. The temperature profile decreases with increasing melting parameter. The temperature difference between the ambient and melting surface increases and this reduces the fluid temperature. The thermal boundary layer thickness increases when melting parameter is increased.



9(a) **9(b)** **9(c)**

Figures9. Effect of m on the (a) temperature, (b) nanoparticles volume fraction and (c) microorganism.

Figures 10(a)-(c) represent the effect of b on dimensionless velocity, magnetic field and nanoparticle volume fraction. Firstly, as we can see from figure 12(a) that the velocity profile increases with increasing of velocity slip parameter. When the velocity slip parameter $a=0$ (conventional no-slip case), the fluid axial velocity at the plate surface is zero. The velocity at the wall enhances with the increase in linear velocity slip parameter. Physically, as the velocity slip parameter increases, the penetration of the stagnant surface through the fluid domain decrease leading to a decrease in the hydrodynamic boundary layer. Increasing the slip factor can be seen as a communication error between the fixed plate and fluid motion. In figure 12(b), magnetic field profile increase with increasing velocity slip parameter. Then, increasing velocity slip parameter lead nanoparticle volume fraction graph to decrease.



10(a) **10(b)** **10(c)**

Figures10.Effect of b on the (a) velocity, (b) magnetic field and (c) nanoparticles volume fraction.

Figure 11 exhibits the variations of the skin friction coefficient, $f''(0)$ with respect to velocity slip parameter, b and reciprocal magnetic Prandtl number, A for different values of magnetic parameter, *M*. Observe that $f''(0)$ decreases with increasing of b and A but decreases with rising of M.

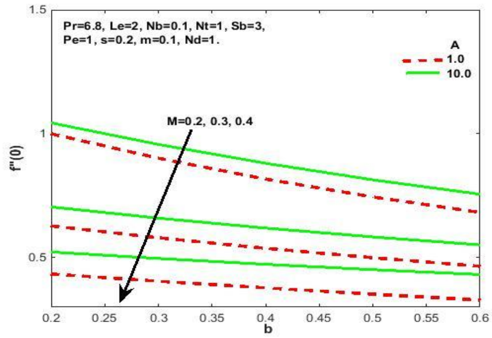


Figure 11. Skin friction coefficient, $f''(0)$ versus b and A for different values of M.

Figure 12 demonstrates the variations of local mass transfer rate, $-\phi'(0)$ versus blowing parameter, S and velocity slip parameter for a different values of convective mass parameter, Nd. It shows that $-\phi'(0)$ increase with increasing of b, S and Nd.

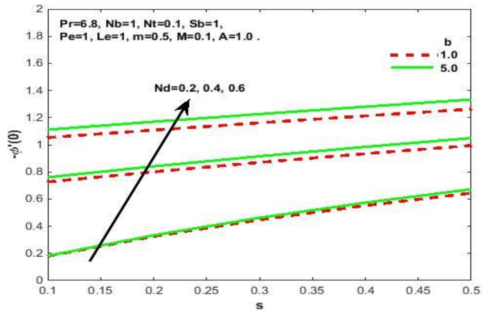


Figure 12. Local mass transfer rate, $-\phi'(0)$ versus S and b for different values of Nd.

Figure 13 illustrates the variations of local heat transfer rate, $-\theta'(0)$ with Brownian motion parameter, Nb and melting parameter, m for a different values of Lewis number, Le. It shows that $-\theta'(0)$ increases with increasing of Nb and Le but decreases with increment of m.

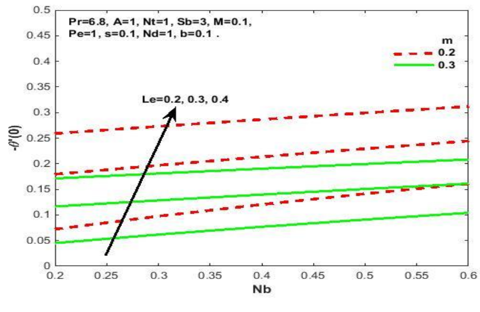


Figure 13. Local heat transfer rate, $-\theta'(0)$ versus Nb and m for a different values of Le.

Figure 14 represents the variations of local microorganisms transfer rate, $-\chi'(0)$ versus Péclet number, Pe and Lewis number, Le with different values of bioconvection Schmidt number, Sb. The graph shows that $-\chi'(0)$ increase with increasing of Pe, Le and Sb.

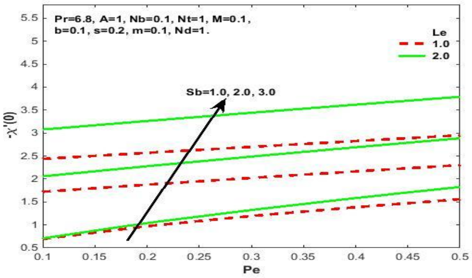


Figure 14. Local microorganisms transfer rate, $-\chi'(0)$ versus Pe and Le with different values of Sb.

7. Conclusion

In this work, magnetoconvective stagnation point flow of bionanofluid with melting heat transfer is investigated by including the Stefan blowing effects. The momentum, induced magnetic field, concentration, energy as well as microorganisms equations are solved numerically. The effects of various governing parameters on flow, heat, mass and microorganism characteristics are analyzed. It is found that magnetic parameter leads to decrease the thickness of momentum boundary layer. The temperature profile decreases with the increase of melting parameter. The blowing parameter enhances concentration. It is believed that the results of the present study are useful in many industrial applications such as heat exchangers, coolants, micro-channel heat sinks, lubricants and microbial fuel cells.

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