Bioconvection Flow of MHD Viscous Nanofluid in the Presence of Chemical Reaction and Activation Energy

Muhammad Imran Asjad, Muhammad Zahid, Fahd Jarad, and Abdullah M. Alsharif

1Department of Mathematics, University of Management and Technology, Lahore 54770, Pakistan
2Department of Mathematics, Cankaya University, Etimesgut, Ankara, Turkey
3Department of Mathematics, King Abdul Aziz University, Jeddah, Saudi Arabia
4Department of Medical Research, China Medical University Hospital, China Medical University, Taichung, Taiwan
5Department of Mathematics and Statistics, College of Science, Taif University, Taif 21944, Saudi Arabia

Correspondence should be addressed to Fahd Jarad; fahd@cankaya.edu.tr

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Enhancement of heat transfer due to stretching sheets can be appropriately controlled by the movement of the nanofluids. The concentration and settling of the nanoparticles in the viscous MHD fluid and bioconvection are addressed. In this scenario, the fluid flow occurring in the presence of a normal and uniform magnetic field, thermal radiation, and chemical reaction is taken into account. For the two-dimensional flow with heat and mass transfer, five dependent variables and three independent variables constitute the system of partial differential equations. For this purpose, similarity functions are involved to convert these equations to corresponding ODEs. Then, the Runge–Kutta method with shooting technique is used to evaluate the required findings with the utilization of MATLAB script. The fluid velocity becomes slow against the strength of the magnetic parameter. The temperature rises with the parameter of Brownian motion and thermophoresis. The bioconvection Lewis number diminishes the velocity field. Compared with the existing literature, the results show satisfactory congruences.

1. Introduction

The convoluted and quick process in massive machinery and little gadgets has produced a significant problem of thermal imbalance. Varied extraneous techniques like fins and fans are used; however, their utility is restricted because of their giant size. In 1995, the scientist Choi and Eastman [1] introduced that the nanosized particles mixed in the fluid called nanofluid have more capacity of heat transfer as compared with fluid without nanosized particles. Das et al. [2] explained the recent and future applications of fluid involving nanosized particles. Khan et al. [3] using the shooting method analyzed flow features of Williamson nanofluid influenced by variable viscosity depending on temperature and Lorentz force past an inclined nonlinear extending surface. Koo and Kleinstreuer [4] described influences of convection, conduction, viscous dissipation, and thermal transportation on nanofluid flow in a microchannel. Sui et al. [5] introduced the Cattaneo–Christov model with double diffusion to analyze the influence of slip velocity, Brownian motion, and variable viscosity on the transportation of an upper convected Maxwell nanofluid through stretching sheet. Imran et al. [6] determined an unsteady stream of Maxwell fluid through an accelerated exponentially vertical surface with influences of radiation, Newtonian heating, MHD, and slip condition taken into account. Khan et al. [7] investigated the flow of micropolar base nanofluid through stretching sheet with thermal radiation and magnetic dipole. Sheikholeslami and Rokni [8] scrutinized magnetic field impacts on the thermal transport rate in a nanofluid. Seyyedi et al. [9] analyzed the entropy generation for Cu-water nanofluid having a semi-annulus porous wavy cavity in the presence of a magnetic field. Molana et al. [10] discussed the characteristics of heat transfer and natural
convection of nanofluid past a porous cavity with a constant inclined magnetic field. Dogonchi et al. [11] explained the characteristics of natural convection and magnetic field on nanofluid flow through porous medium with effects of Hartmann number, Rayleigh number, and Darcy number taken into account. Shaw et al. [12] scrutinized the impact of nonlinear thermal and entropy generation on Casson nanofluid flow with rotating disk and also described the brain function. Chamkha et al. [13] explained MHD nanofluid flow through cavity using the control-volume-based finite element method with effects of natural convection, thermal radiation, and shape factor of nanoparticles taken into account. Dogonchi et al. [14] numerically introduced the importance of the Cattaneo–Christov theory of heat conduction through triangular semicircular heater with viscosity dependent on the magnetic field. Seyyedi et al. [15] analyzed the thermal behavior of magnetic buoyancy-driven flow in ferrofluid-filled wavy cavity. Sadeghi et al. [16] analyzed the thermal behavior of heat conduction through triangular semicircular heater with effects of heat flux, cross-diffusion, and Cattaneo–Christov.

Inspired by the above literature survey, our interest pertains to extending the results of Goud et al. [26] to investigate a more general problem, including bioconvection of nanofluid transportation with the effects of chemical reaction and radiation to avoid probable settling of nanoparticles. The connotation of such meaningful attributes can be a useful extension, and the results can be utilized for desired effective thermal transportation in the heat exchanger of various technological processes.

2. Problem Formulation

Here, we considered steady incompressible magnetohydrodynamic nanofluid flow through exponentially stretching sheet along the x-axis and y-axis taken to be normal with velocity $U_w = x e^{yl}$ as shown in Figure 1. A magnetic field is applied to the flow region and acts in the y-direction. A mild diffusion of microorganisms and nanoparticles is set in the fluid. Thermal radiation is considered, and bioconvection takes place because of microorganisms’ movement. The fluid velocity for two-dimensional flow is $\vec{u}, \vec{v}$.

Under the above conditions, the governing equations are as follows [20, 26]. Continuity equation is as follows:

$$\vec{u}_x + \vec{v}_y = 0, \quad (1)$$

momentum equation is as follows:

$$\vec{u} \vec{u}_x + \vec{v} \vec{u}_y = \nu \vec{u}_{yy} - \frac{\sigma}{\rho} (B_0^2 \vec{u}) + \frac{1}{\rho} \left[ g \beta_p (1 - \bar{C}_\infty) (\bar{T} - \bar{T}_\infty) - g \left( \rho_p - \rho_f \right) (\bar{C} - \bar{C}_\infty) - g \gamma (\rho_m - \rho_f) (\bar{N} - \bar{N}_\infty) \right], \quad (2)$$

energy equation is as follows:
Concentration equation is as follows:

\[ \bar{u}\bar{T}_x + \bar{v}\bar{T}_y = a\bar{T}_{yy} - \frac{1}{\rho C_p} \frac{\partial q_r}{\partial y} + \tau \left( D_{xy}\bar{T}_y \bar{C}_x + \frac{D_T(T)}{T_c} \right)^2, \]  

(3)

Bioconvection equation is as follows:

\[ \bar{u}\bar{C}_x + \bar{v}\bar{C}_y = D \bar{C}_{yy} - K_r(\bar{C} - \bar{C}_\infty) - K_p(\bar{C} - \bar{C}_\infty) \left( \frac{T}{T_c} \right)^n \exp \left( -\frac{E_a}{kT} \right) + \frac{D_T(T)}{T_c} \bar{T}_{yy}, \]  

(4)

With constraints

\[ \bar{u}\bar{N}_x + \bar{v}\bar{N}_y + dW \frac{\partial}{\partial y} \left( \frac{\bar{N}}{\Delta \bar{C}_y} \right) = \bar{N}_{yy}D_n, \]  

(5)

Now, introducing

\[ \bar{U}_w = a_0 \bar{v}^{-1/2}, \bar{T}_w = \bar{T}_c + \bar{T}_0 e^{-x/2}, \bar{C}_w = \bar{C}_c + \bar{C}_0 e^{-x/2}, \bar{N}_w = \bar{N}_c + \bar{N}_0 e^{-x/2}, \]  

(7)

Under the Rosseland approximation \( q_r \), equation (3) can be written as
\[ \bar{u}T_x + \bar{v}T_y = \bar{T}_{yy} \left( \alpha + \frac{16\sigma^* T_{\infty}^3}{\rho C_p 3k_1} \right) + \bar{T} \left( D_h \bar{T}_x \bar{C}_y + \frac{D_T}{T_{\infty}} (\bar{T}_y)^2 \right). \] (8)

Introducing similarity transformation,

\[ \eta = y \sqrt{\frac{a_0}{2v \ell}} e^{x/2} \ell, \quad \bar{u} = a_0 e^{x/2} f'(\eta), \quad \bar{v} = -\sqrt{\frac{a_0}{2v \ell}} e^{x/2} f(\eta) + \eta f''(\eta), \quad \phi = \sqrt{2v \ell} a_0 f(\eta) e^{x/2} \ell, \quad \bar{T} = \bar{T}_{\infty} + \bar{T}_0 e^{x/2} \ell, \quad \bar{C} = \bar{C}_{\infty} + \bar{C}_0 e^{x/2} \ell, \quad \bar{N} = \bar{N}_{\infty} + \bar{N}_0 e^{x/2} \ell. \] (9)

In view of the above appropriate relations, equation (1) is satisfied identically and equations (2)–(5), respectively, become

\[ f'''' - M f' - 2 f'' + f f'' + \lambda (\theta - N r \phi - R b \chi) = 0, \]
\[ \left( 1 + \frac{4}{3} K \right) \theta'' + Pr f' \theta' - Pr \theta f' + \theta' (N b \phi' + N t \theta') = 0, \]
\[ \phi'' + \left[ f \phi' - C r \phi - \phi f' - \sigma_m \phi (1 + \delta \theta) \exp \left( \frac{-E}{1 + \delta \theta} \right) \right] \theta'' = 0, \]
\[ \chi'' (\xi) + L b P r f(\xi) \chi'(\xi) - L b P r f'(\xi) \chi(\xi) - P e (\sigma_1 \phi''(\xi) + \chi(\xi) \phi''(\xi) + \chi'(\xi) \phi'(\xi)) = 0, \]

and the constraints reduce to

\[ f' (0) = 1, \quad f (0) = 0, \quad \phi (0) = 1, \quad \theta (0) = 1, \quad \chi (0) = 1, \quad \text{at} \ \eta = 0, \]
\[ f' (\infty) \longrightarrow 0, \quad \phi (\infty) \longrightarrow 0, \quad \theta (\infty) \longrightarrow 0, \quad \chi (\infty) \longrightarrow 0, \quad \text{as} \ \eta \longrightarrow \infty. \]

The associated parameters are

\[ M = \frac{2 \sigma B_0^2 \ell}{\rho U_w}, \]
\[ Pr = \frac{\gamma}{\alpha}, \]
\[ \lambda = \frac{(1 - C_{\infty}) \beta g (T_w - T_{\infty}) 2 \ell}{U_w^2}, \]
\[ N_r = \frac{\rho_p - \rho_f}{\beta (1 - C_{\infty}) p (T_w - T_{\infty})}, \]
\[ N_r = \frac{\rho_m - \rho_f}{\rho (1 - C_{\infty}) \beta (T_w - T_{\infty})}, \]
\[ N_t = \frac{T_{\infty}}{v T_{\infty}}, \]
\[ N_b = \frac{T_{\infty}}{v}, \]
\[ \sigma_m = \frac{2 K^2 \ell}{U_w^2}, \]
\[ \delta = \frac{(T_w - T_{\infty})}{T_{\infty}}, \]
\[ K = \frac{4 \sigma^* T_{\infty}^3}{k^b K}, \]
\[ \sigma_1 = \frac{N_{\infty}}{N_w - N_{\infty}}. \]
Table 1: Comparison of $\theta' (0)$ with changed values of $K$, $M$, and $Pr$.

| $K$ | $M$ | $Pr$ | Ishak [23] | Goud et al. [26] | Bidin and Nazar [34] | Our results |
|-----|-----|------|------------|------------------|----------------------|-------------|
| 0.0 | 0.0 | 1.0  | 0.9548     | 0.954784         | 0.9547               | 0.9548106   |
|     | 2.0 | 1.0  | 1.4715     | 1.471462         | 1.4714               | 1.4714540   |
|     | 5.0 | 1.0  | 2.5001     | 2.500111         | 2.5001280            | 2.5001280   |
|     | 10.0| 1.0  | 3.6604     | 3.660346         | 3.6603693            | 3.6603693   |
| 1.0 | 1.0 | 0.0  | 0.5312     | 0.53117          | 0.5312               | 0.5313112   |
| 1.0 | 1.0 | 1.0  | 0.4505     | 0.450687         | 0.450687            | 0.4506955   |

Figure 2: Influences of $M$ on $f'$.  

Figure 3: Influences of $\lambda$ on $f'$.  

Figure 4: Influences of $Nb$ on $\theta$.  

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\[
E = \frac{Ea}{kT_{\infty}}, \\
Sc = \frac{\nu}{D}, \\
Lb = \frac{\alpha}{D_n}, \\
Pe = \frac{dW_c}{D_n}, \\
Cr = \frac{2\ell_k}{U_w},
\]

(16)

where \( M \) is the magnetic field parameter, \( Pr \) is the Prandtl number, \( \lambda \) is the mixed convection parameter, \( Nr \) is the buoyancy ratio number, \( Rb \) is the bioconvection Rayleigh number, \( Nt \) is the thermophoresis diffusion factor, \( Nb \) is the Brownian factor, \( \sigma_m \) denotes the dimensionless reaction rate, \( \delta \) is used as the temperature distinction parameter, \( K \) is the radiation parameter, \( \sigma_1 \) is the bioconvective difference parameter, \( E \) means the nondimensional energy activation, \( Sc \) is the Schmidt number, \( Lb \) is the bioconvection Lewis number, \( Pe \) is the peclet number, and \( Cr \) is the chemical reaction parameter.

The wall shear stress, thermal flux, and mass flux, respectively, are given as

\[
\tau_w - \mu \left( \frac{\partial u}{\partial y} \right)_{y=0} = 0, \quad q_w + k \left( \frac{\partial T}{\partial y} \right)_{y=0} = 0, \quad j_w + D \left( \frac{\partial c}{\partial y} \right)_{y=0} = 0.
\]

(17)

\[C_f \text{ (skin friction)}, \quad Nu_x \text{ (Nusselt number), and} \quad Sh_x \text{ (sherwood number) in dimensionless form are}
\]

\[
C_f = \frac{f''(0)}{\sqrt{2Re_x}}, \quad Nu_x = -\left( \sqrt{Re_x} \right) \theta'(0), \quad Sh_x Re^{-1/2} = -\phi'(0).
\]

(18)

3. Results and Discussion

Physical meanings of the final nondimensional formulation of time-independent MHD flow of nanofluid due to stretch of an exponential sheet in the presence of chemical reaction along the boundary constraints are solved numerically. Table 1 contains results for \(-\theta(0)\) (Nusselt number). Comparison of the results indicates acceptable agreement to validate this numeric procedure. In Figure 2, the velocity of the flow seems to be reduced significantly when magnetic parameter \( M \) (0.0 \( \leq M \leq 2.5 \)) is increased because high values of magnetic field parameter improve the contradictory force known as Lorentz force. The improvement of mixed convection parameter \( \lambda \) causes to boost the flow velocity \( f'(\eta) \) as shown in Figure 3. From Figures 4 and 5, significant rising behavior of \( \theta(\eta) \) is noticed with an enhanced value of Brownian motion parameter \( Nb \) and thermophoresis parameter \( Nt \). The fast random motion of nanoparticles characterized by larger \( Nb \) is responsible for enhanced heat transfer to raise \( \theta(\eta) \). Similarly, the higher \( Nt \) means a greater thermophoretic effect which moves the nanoparticles hotter regime to the colder one and increases the thermal distribution. The similarly larger value of \( E \) provides strength to \( \phi(\eta) \) as depicted in Figure 6. Figure 7 displays the decrement in \( \phi(\eta) \) due to the larger value of chemical reaction, and the chemical reaction becomes faster to recede nanoparticles concentration. The bioconvection Rayleigh \( Rb \) and parameter are responsible for given direct increment to \( \chi(\eta) \) as demonstrated in Figure 8.
4. Conclusions

Theoretical and numeric analysis for magnetohydrodynamic of nanofluid owing to sudden stretched in an exponential sheet has been made in this communication. Effects of the emerging parameters are enumerated on the physical field, namely, velocity, temperature, and microorganisms distribution. Significant outcomes are summarized as follows:

(i) The velocity reduces with $M$ and boosts with $\lambda$
(ii) The conclusion of nanoparticles characterized by parameters $Nb$ and $Nt$ shows an increment in the temperature profile
(iii) Concentration recurses with $Cr$ and is enhanced with $E$
(iv) Bioconvection parameter is increased with $Rb$

Nomenclature

$B_0$: Coefficient of magnetic field
$C$: Concentration
$T$: Temperature

$N$: Concentration of microorganisms
$Nt$: Thermophoresis parameter
$(x, y)$: Cartesian coordinates
$Cr$: Chemical reaction parameter
$(u, v)$: Velocity components along $(x, y)$-axes
$\tau$: Heat capacity ratio
$\xi$: Similarity variable
$D_T$: Thermophoretic diffusion coefficient
$\phi$: Dimensionless concentration
$q_r$: Radiative heat flux
$\rho$: Density
$K_r^2$: Chemical reaction rate constant
$\mu$: Dynamic viscosity of the fluid
$K_r$: Rate of chemical reaction
$\sigma$: Electrical conductivity
$D_B$: Brownian diffusivity
$\psi$: Stream function
$K$: Radiation parameter
$\delta$: Temperature distinction parameter
$Sc$: Schmidt number
$\lambda$: Mixed convection parameter
$U_w$: Stretching velocity
$\nu$: Kinematic viscosity
$Pr$: Prandtl number
$\theta$: Dimensionless temperature
$Pe$: Peclet number
$\chi$: Dimensionless microorganism factor
$M$: Magnetic parameter
$\rho_f$: Density of nanofluid
$Nr$: Buoyancy ratio number
$\rho_{m}$: Density of microorganisms particle
$Rb$: Bioconvection Rayleigh number
$\rho_p$: Density of nanoparticles
$Nb$: Brownian motion parameter
$\kappa$: Thermal conductivity
$n$: Fitted rate constant parameter
$\alpha$: Thermal diffusivity
$\beta$: Volumetric coefficient of thermal expansion
$E$: Nondimensional activation energy
$\gamma$: Average volume of microorganism
$Lb$: Bioconvection Lewis number
$Sh$: Local Sherwood Number
$W_c$: Maximum cell swimming speed
$\sigma_{m}$: Dimensionless reaction rate
$D_n$: Microorganisms diffusion coefficient
$\sigma$: Bioconvection difference parameter
$^\ast$: Stefan Boltzman constant
$Nu_x$: Local Nusselt number
$C_f$: Local skin friction number
$Re_x$: Local Reynolds number.

Data Availability

The data used to support this study are included within this article.
Conflicts of Interest
The authors declare that they have no known personal relationships or conflicts of interest that could have appeared to the work reported in this work.

Authors’ Contributions
All authors contributed equally and significantly in writing this paper. All authors read and approved the manuscript.

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