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Numerical analysis has been carried out on the problem of three-dimensional magnetohydrodynamic boundary layer flow of a nanofluid over a stretching sheet with convective boundary conditions through a porous medium. Suitable similarity transformations were used to transform the governing partial differential equations into a system of ordinary differential equations. We then solved the resultant ordinary differential equation by using the spectral relaxation method. Effects of the dimensionless parameters on velocity, temperature and concentration profiles together with the friction coefficients, Nusselt and Sherwood numbers were discussed with the assistance of graphs and tables. The velocity was found to decrease with increasing values of the magnetic, stretching and permeability parameters. The local temperature was observed to rise as the Brownian motion, thermophoresis and Biot numbers increased. The concentration profiles diminish with increasing values of the Lewis number and chemical reaction parameter.

Keywords: numerical analysis, MHD nanofluid, stretching sheet, convective boundary conditions, porous medium

1. Introduction

Many researchers have over the past few years paid significant attention to the study of boundary layer flow heat and mass transfer over a stretching sheet due to its industrial and engineering applications. These applications include cooling of papers, glass-fibre production, plastic sheets and polymer extrusion, hot rolling wire drawing, metal spinning, stretching of
rubber sheets and crystal growing. The quality and final product formation in these processes are dependent on the rate of stretching and cooling.

Since the pioneering study by Crane [1] who presented an exact analytical solution for the steady two-dimensional flow due to a stretching surface in a quiescent fluid many studies on stretched surfaces have been done [1–5].

Thermal conductivity of nanoparticles has been shown in recent research on nanofluid to change the fluid characteristics. The thermal conductivity of the base liquid with the enhanced conductivity of nanofluid and the turbulence induced by their motion contribute to a remarkable improvement in the convective heat transfer coefficient. This feature of nanofluid makes them attractive to a wide variety of industries, ranging from transportation to energy production and supply to electronics. They can be used in welding equipment, high heat flux and to cool car engines, among other applications. Many researchers [6–10] have studied the boundary layer flow of a nanofluid caused by a stretching surface.


The main objective of this chapter is to numerically analyse the influence of convective boundary conditions on the model of three-dimensional magnetohydrodynamic, nanofluid flow over a stretching sheet through a porous medium in the presence of thermophoresis and Brownian
motion as well as thermal radiation. The governing partial differential equations use suitable similarity transformations. The transformed governing equations are solved numerically using the spectral relaxation method (SRM). The effects of dimensionless parameters on velocity components, temperature and concentration profiles together with the skin friction coefficients, local Nusselt and Sherwood numbers are discussed with the aid of tables and graphs.

2. Mathematical formulation

We consider a three-dimensional steady incompressible MHD nanofluid flow, heat and mass transfer over a linearly stretching sheet through a porous medium. The sheet is assumed to be stretched along the $xy$-plane while the fluid is placed along the $z$-axis. A uniform magnetic field $B_0$ is applied normally to the stretched sheet and the induced magnetic field is neglected by assuming very small Reynolds number. We assume that the sheet is stretched with linear velocities $u = ax$ and $v = by$ along the $xy$-plane, respectively, with constants $a$ and $b$. Under the above assumptions and the boundary approximation, the governing equations for the current study are given by:

\[
\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0, \tag{1}
\]

\[
u \frac{\partial u}{\partial x} + \nu \frac{\partial u}{\partial y} + \nu \frac{\partial u}{\partial z} = \frac{\partial^2 u}{\partial z^2} - \frac{\sigma B_0^2}{\rho} u, \tag{2}
\]

\[
u \frac{\partial v}{\partial x} + \nu \frac{\partial v}{\partial y} + \nu \frac{\partial v}{\partial z} = \frac{\partial^2 v}{\partial z^2} - \frac{\sigma B_0^2}{\rho} v, \tag{3}
\]

\[
u \frac{\partial T}{\partial x} + \nu \frac{\partial T}{\partial y} + \nu \frac{\partial T}{\partial z} = \frac{\partial^2 T}{\partial z^2} - \frac{\tau D_T \left( \frac{\partial T}{\partial z} \right)^2}{C_p}, \tag{4}
\]

\[
u \frac{\partial C}{\partial x} + \nu \frac{\partial C}{\partial y} + \nu \frac{\partial C}{\partial z} = \frac{\partial^2 C}{\partial z^2} + \frac{D_B \left( \frac{\partial C}{\partial z} \right)^2}{C_p}, \tag{5}
\]

where $u$, $v$ and $w$ are the velocity components in the $x$, $y$ and $z$-directions, respectively, $T$ is the fluid temperature, $C$ is the fluid concentration, $k_1$ is the permeability, $\nu$ is kinematic viscosity, $\rho$ is the fluid density, $\tau$ is the ratio of the heat capacitances, $D_B$ and $D_T$ are the Brownian motion and thermopheric diffusion coefficients and $c_p$ is the specific heat capacity.

The corresponding boundary conditions for the flow model are:

\[
u = ax, \quad v = by, \quad w = 0, \quad -k_1 \frac{\partial T}{\partial z} = h_f (T_f - T), \quad -D_B \frac{\partial C}{\partial z} = h_s (C_f - C) \text{ at } z = 0, \tag{6}
\]

\[
u \rightarrow 0, \quad v \rightarrow 0, \quad w \rightarrow 0, \quad T \rightarrow T_\infty, \quad C \rightarrow C_\infty, \quad \text{as } z \rightarrow \infty. \tag{7}
\]

We have $h_f$ as the convective heat transfer coefficient, $h_s$ is the convective mass transfer coefficient and $T_f$ and $C_f$ are the convective fluid temperature and concentration below the moving sheet.
3. Similarity transformation

In order to non-dimensionalise the governing equations, we introduce the following similarity equations [24]. These transformations also transform the partial differential equations into a system of ordinary differential equations which is then solved using the spectral relaxation method:

\[ \eta = \sqrt{\frac{a}{v}}, u = axf(\eta), v = byg(\eta), w = -\sqrt{w}f(\eta) + cg(\eta), \theta(\eta) = \frac{T-T_w}{T_f-T_w}, \phi(\eta) = \frac{C-C_\infty}{C_\infty-C_\infty} \]  

Upon substituting the similarity variables into Eqs. (2)-(5), we obtain the following system of ordinary equations

\[ f'' + (f + cg)f' - f^2 - (M + K)f' = 0, \] 
\[ g'' + (f + cg)g' - g^2 - (M + K)g' = 0, \] 
\[ \left( \frac{3 + 4R}{3 \alpha R} \right) \theta' + (f + cg) \theta' + Nb \theta' \phi' + Nt(\theta')^2 = 0, \] 
\[ \phi' + Le(f + cg) \theta' + \frac{Nt}{Nb} \theta' = 0. \] 

The corresponding boundary conditions are

\[ f = 0, f' = 1, g = 0, g' = 1, \theta' = -Bi_0(1-\theta), \phi' = -Bi_0(1-\phi), \text{ at } \eta = 0, \] 
\[ f(\infty) \to 0, g(\infty) \to 0, \theta(\infty) \to 0, \phi(\infty) \to 0. \] 

Primes denote differentiation with respect to \( \eta \) and parameters appearing in Eqs (9)–(14) are defined as: \( Pr = v/a \) is the Prandtl number, \( Le = v/D_b \) is the Lewis number, \( Nb = \tau D_b(C_\infty - C_w)/v \) is the Brownian motion parameter, \( Nt = \tau D_f(T_f - T_w)/vT_w \) is the thermophoresis parameter, \( Bi_0 = \frac{h_0}{k} \sqrt{\tau/a} \), \( Bi_0 = \frac{h_0}{D_b} \sqrt{\tau/a} \) are the Biot numbers and \( c = b/a \) is the stretching parameter. The quantities of engineering interest are the skin-friction coefficient \( C_f \) along the x- and y-direction (\( C_{fx} \) and \( C_{fy} \)), the Nusselt number and Sherwood number. These quantities are defined as follows:

\[ C_{fx} = \frac{\tau_{wx}}{\rho u_{sw}^2}, C_{fy} = \frac{\tau_{wy}}{\rho u_{sw}^2}, Nu = x \frac{q_w}{k(T_f - T_w)}, Sh = x \frac{q_w}{D_b(C_f-C_w)}. \]  

where \( \tau_{wx}, \tau_{wy} \) are the wall shear along x- and y-directions, respectively, and \( q_w \) and \( q_w \) are the heat flux and mass flux at the surface, respectively. Upon using the similarity variables into the above expressions, we obtain the following:

\[ Re^2 C_{fx} = f'(0), Re^2 C_{fy} = g''(0), Re^2 Nu = -\theta'(0), Re^2 Sh = -\phi(0). \]
4. Method

To solve the set of ordinary differential Eqs. (9)–(12) together with the boundary conditions (13) and (14), we employ the Chebyshev pseudo-spectral method known as spectral relaxation method. This is a recently developed method, and the details of the method are found in Motsa et al. [25]. This method transforms sets of non-linear ordinary differential into sets of linear ordinary differential equations. The entire computational procedure is implemented using a program written in MATLAB computer language. The nanofluid velocity, temperature, the local skin-friction coefficient and the local Nusselt and Sherwood numbers are determined from these numerical computations.

To apply the SRM to the non-linear ordinary differential equations, we first set \( f(\eta) = p(\eta) \) and \( g(\eta) = q(\eta) \). We then write the equations as follows:

\[
\begin{align*}
\dot{f} &= p, \\
p'' + (f + c_\eta) p' - p^2 - (M + K)p &= 0, \\
\dot{g} &= q, \\
q'' + (f + c_\eta) q' - q^2 - (M + K)q &= 0,
\end{align*}
\]

\[
\left(\frac{3 + 4R}{3PrR}\right) \theta' + (f + c_\eta) \theta' + Nb \theta' \varphi + Nt \theta'^2 = 0,
\]

\[
\varphi + Le(f + c_\eta) \varphi' + \frac{Nt}{Nb} \theta'' = 0.
\]

The boundary conditions become

\[
\begin{align*}
f(0) &= 0, g(0) = 0, p(0) = 1, q(0) = 1, \\
\theta'(0) &= -Bit(1-\theta), \varphi(0) = -Bic(1-\varphi), \\
p(\infty) &= 0, q(\infty) = 0, \varphi(\infty) = 0, \theta'(\infty) = 0.
\end{align*}
\]

In view of the SRM, we then obtain the following iterative scheme:

\[
\begin{align*}
\dot{f}_{r+1} &= p_{r+1}, f_{r+1}(0) = 0, \\
p''_{r+1} + (f_{r+1} + c_{\eta r+1}) p'_{r+1} - p^2_{r+1} - (M + K) p_{r+1} &= 1, p_{r+1}(\infty) = 0, \\
\dot{g}_{r+1} &= q_{r+1}, g_{r+1}(0) = 0, \\
q''_{r+1} + (f_{r+1} + c_{\eta r+1}) q'_{r+1} - q^2_{r+1} - (M + K) q_{r+1} &= 1, q_{r+1}(\infty) = 0,
\end{align*}
\]

\[
\left(\frac{3 + 4R}{3PrR}\right) \theta'_{r+1} + (f_{r+1} + c_{\eta r+1}) \theta'_{r+1} = -Nb \theta', \varphi, -Nt \theta'^2_{r+1}, \theta'_{r+1}(0) = -Bit(1-\theta_{r+1}(0)), \varphi_{r+1}(\infty) = 0,
\]

\[
(30)
\]
\[ \dot{\theta}_{r+1} + Le(f_{r+1} + c_8 r_{r+1})\dot{\theta}_{r+1} = \frac{-Nt}{Nb} \dot{\phi}_{r+1}, \quad \dot{\phi}_{r+1}(0) = -Bic(1-\phi_{r+1}(0)), \quad \theta_{r+1}(\infty) = 0. \]  

The above equations form a system of linear decoupled equations which can be solved iteratively for \( r = 1, 2, \ldots \). Starting from initial guesses \( \left(p_0(\eta), q_0(\eta), \theta(\eta), \phi(\eta)\right) \). Applying the Chebyshev pseudo-spectral method to the above equations, we obtain

\[ A_1 f_{r+1} = B_1 f_{r+1}(\tau N) = 0, \]
\[ A_2 p_{r+1} = B_2 p_{r+1}(\tau N) = 1, p_{r+1}(\tau_0) = 0, \]
\[ A_3 q_{r+1} = B_3 q_{r+1}(\tau N) = 0, \]
\[ A_4 q_{r+1} = B_4 q_{r+1}(\tau N) = 1, q_{r+1}(\tau_0) = 0, \]
\[ A_5 \theta_{r+1} = B_5 \theta_{r+1}(\tau N) = \frac{Bi_t}{1 + Bi_t}, \quad \theta_{r+1}(\tau_0) = 0, \]
\[ A_6 \phi_{r+1} = B_6 \phi_{r+1}(\tau N) = \frac{Bi_t}{1 + Bi_t}, \quad \phi_{r+1}(\tau_0) = 0. \]

where, \( A_1 = D, B_1 = p, \quad A_2 = D^2 + \text{diag}(f_{r+1} + c_8 r_{r+1})D - (M + K)I, \quad A_3 = D, B_3 = q, \quad A_4 = D^2 + \text{diag}(f_{r+1} + c_8 r_{r+1})D - (M + K)I, \quad A_5 = \frac{(k^2 Bic)}{Nt}D^2 + \text{diag}(f_{r+1} + c_8 r_{r+1})D, \quad A_5 = -Nt \theta, \quad A_6 = D^2 + \text{diag}[Le f_{r+1} + cLe r_{r+1}]D, \quad B_6 = -\frac{Nt}{Ng} \theta r_{r+1}, \)

where \( I \) is the identity matrix of size \((N + 1)(N + 1)\). The initial guesses are obtained as:

\[ p_0(\eta) = e^n, \quad q_0(\eta) = e^n, \quad \theta_0(\eta) = \frac{Bi_t e^n}{1 + Bi_t}, \quad \phi_0(\eta) = \frac{Bic e^n}{1 + Bi_t}. \]  

5. Results and discussion

The system of ordinary differential Eqs. (9)-(12) subject to the boundary conditions (13) and (14) is numerically solved by applying the spectral relaxation method. The SRM results presented in this chapter were obtained using \( N = 40 \) collocation points, and also the convergence was achieved after as few as six iterations. We also use these default values for the parameters \( Pr = 0.71, \quad Nt = Nb = 0.3, \quad Le = 2, \quad R = 1, \quad M = 1, \quad K = 0.5, \quad C = 0.1, \quad Bit = 0.2 = Bi_t. \)

Table 1 displays the validation of the present results with those obtained by the bvp4c results. As can be clearly observed from this table, there is an excellent agreement between the results obtained by bvp4c method giving confidence in the findings of this study. Table 1 also shows the influence of the magnetic, permeability and stretching parameters on the skin friction coefficients. It is noticed that the skin friction coefficient increase with the increasing values of the parameters.

Table 2 depicts the influence of Brownian motion thermophoresis, parameters and the Biot numbers on the Nusselt and Sherwood numbers. Both the rates of heat transfer and mass...
transfer are increasing functions of the Brownian motion parameter. By definition, thermophoresis is the migration of a colloidal particle in a solution in response to a microscopic temperature gradient. The heat transfer is reduced while the mass transfer increases

\[
\langle \gamma \rangle - f'(0) / i \quad \langle \gamma \rangle - g'(0) / i
\]

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<th>C</th>
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<th>SRM</th>
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Table 1. Variation of the magnetic, permeability and stretching parameters on the skin friction coefficients.

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Table 2. The influence of the Brownian motion and thermophoresis parameters as well as that of the Biot numbers on the Nusselt and Sherwood numbers.
with increasing values of the thermophoresis parameter. Lastly, Table 2 shows the influence of the Biot numbers on the heat transfer and mass transfer rates and they both increase with increasing values of the thermal Biot number. But we noticed opposite effects when the solutal Biot number increases.

Figures 1 and 2 display the effect of permeability parameter on the velocity profiles. We observe that the tangential velocity profiles decrease as the values of the permeability parameter. Also, the transverse velocity \( f(\eta) \) is reduced by the increasing values of the permeability parameter as more nanofluid is taken away from the boundary layer. This explains the thinning of the velocity boundary layers as the values of \( K \) increases (Figure 1). Figures 3 and 4 depict the effect of the magnetic field parameter on the velocity profiles. As expected, we observe that both velocity components are greatly reduced as the values of the magnetic parameter increase. This is because physically increasing the values of magnetic field strength produces a drag-like force known as the Lorentz force. This force acts against the flow when the magnetic field is applied in the normal direction, as in this chapter. Figures 5 and 6 display the influence of the stretching parameter on the velocity fields. It is seen from Figure 5 that the tangential velocity profiles \( f(\eta) \) are reduced by increasing values of the stretching parameter \( c \). The transverse velocity is enhanced with the increasing values of the stretching parameter.

Figure 7 displays the influence of the Biot number \( Bi \), on the temperature profiles. It is clearly observed on this figure that the nanofluid temperature field rapidly increases near the boundary with increasing values of the Biot number, \( Bi \). It is also observed that as the Biot number increases the convective heating of the sheet also increases.

Figures 8 and 9 reveal the effect of the stretching ratio parameter \( c \) on the temperature and concentration profile. It is observed that the temperature and concentration profiles are

![Figure 1. Effect of permeability parameter on the tangential velocity profiles.](image)
reduced with increasing values of the stretching ration parameter. Figures 10 and 11 display the effects of thermophoresis parameter on the dimensionless temperature and concentration profiles. It is observed that the temperature and concentration profiles increase as the values of
the thermophoresis $Nt$ increase. Figure 12 depicts the influence of the Brownian motion parameter $Nb$ on the temperature profiles. Increasing the values of the Brownian motion parameter $Nb$ results in thickening of the thermal boundary layer, thus enhancing the

Figure 4. Influence of the magnetic parameter on the transverse velocity.

Figure 5. Influence of the stretching parameter on the tangential velocity.
temperature of the nanofluid. \textbf{Figures 13 and 14} are plotted to depict the influence of the permeability $K$ and magnetic $M$, parameters on the temperature profiles. The temperature of
Figure 8. Effect of varying the stretching parameter on the temperature.

Figure 9. Effect of varying the stretching parameter on the temperature.
Figure 10. Effect of thermophoresis parameter on the temperature profiles.

Figure 11. Effect of thermophoresis parameter on the concentration profiles.
the nanofluid increases with increases values of the permeability parameter. From Figure 14, we observe that the temperature profiles increase with the increasing values of the magnetic field parameter. Figure 15 displays the effect of thermal radiation parameter $R$ on the
Figure 14. Influence of the permeability parameter on the nanofluid temperature.

Figure 15. Influence of thermal radiation on the temperature.
temperature profiles. We observe in this figure that increasing the values of the thermal radiation produces a significant reduction in the thermal condition of the fluid flow.

Lastly, the effect of the Lewis number on the concentration profiles is depicted on Figure 16. Large values of the Lewis number implies increased values of the Schmidt number which results in the thinning of the solutal boundary layer.

6. Conclusion

A three-dimensional magnetohydrodynamic nanofluid, heat and mass transfer over a stretching surface with convective boundary conditions through a porous medium. The transformed governing equations are solved numerically using the spectral relaxation method. The accuracy of the SRM was validated against the MATLAB in-built bvp4c routine for solving boundary value problems. The following conclusions are driven from this study:

- The effect of increasing the magnetic field parameter is to reduce the momentum boundary layer there and to increase the thermal and solutal boundary layer thickness. The same effect on the flow characteristics is also experienced by increasing values of the stretching parameter ($c$).
- We observed that the local temperature rises as the Brownian motion, thermophoresis, permeability parameter and Biot numbers intensify. But opposite influences are observed when the values of the thermal radiation and stretching parameters increase.
Increasing values of the Lewis number \((Le)\) diminishes the concentration of the nanoparticles.

The rise in the stretching ratio parameter increases the Nusselt and Sherwood number.

Lastly, the Nusselt number decreases, while the Sherwood number increases as the Brownian motion and thermophoresis effects increase.

**Nomenclature**

- \(a, b\) positive constants
- \(B_0\) uniform magnetic field strength
- \(B_{it}, B_{tc}\) Biot numbers
- \(c\) stretching parameter
- \(C\) fluid concentration
- \(C_f\) skin friction coefficient
- \(C_s\) convective fluid concentration below the moving sheet
- \(C_w\) concentration on the wall
- \(C_w\) free stream concentration
- \(D_B\) Brownian motion coefficient
- \(D_T\) thermophoretic diffusion coefficient
- \(f\) dimensionless stream function
- \(g\) acceleration due to gravity
- \(h_f\) convective heat transfer coefficient
- \(h_s\) convective mass transfer
- \(k_1\) permeability of the porous medium
- \(k\) thermal conductivity
- \(K\) permeability parameter
- \(Le\) Lewis number
- \(M\) magnetic parameter
- \(N_b\) Brownian motion parameter
- \(N_t\) thermophoresis parameter
- \(Nu\) Nusselt number
Pr Prandtl number

$q_{w}, q_{m}$ heat and mass fluxes at the surface

$q_{r}$ radiative heat flux

$R$ thermal radiation

$Re$ Reynolds number

$Sh$ Sherwood number

$T$ fluid temperature

$T_{f}$ convective fluid temperature

$T_{w}$ temperature

$u, v, w$ velocity components

$x, y, z$ Cartesian coordinates

**Greek symbols**

$\alpha$ thermal expansion coefficient

$\rho$ fluid density

$\nu$ kinematic viscosity

$\sigma$ electrical conductivity

$\theta$ dimensionless temperature

$\phi$ dimensionless concentration

$\tau$ ratio of heat capacities

$\tau_{ux}, \tau_{uy}$ wall shears

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References


