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"Study of Magnetohydrodynamic Nanofluid Boundary Layer Flow Past a Stretching Surface in a Porous Medium"

Bhavya N. P.[1,*], M. S. Gayathri [2], P. A. Dinesh [3], P. Gomathi [4]

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Abstract: The magnetic effects on nanofluid flow have significant industrial applications; particularly in the cooling sector. The present study numerically investigates the boundary layer flow created by the impact of magnetic field onto a stretching sheet in a porous medium. The flow governing partial differential equations have been transformed into ordinary differential equations using similarity transformations. These ordinary differential equations are then solved numerically using the shooting technique and the spectral collocation technique. The resulting equations include the effect of various parameters such as permeability, Hartmann number, Eckert number, Lewis number, Brownian motion, Prandtl number and thermophoresis. Numerical results are presented graphically to illustrate the effects of these parameters on velocity, thermal and concentration boundary layer. The velocity boundary layer thickness reduces with an increase in permeability and magnetic field strength whereas thermal boundary layer thickness increases with an increase in Brownian motion, Lewis number, thermophoresis and magnetic parameter and thickness of thermal boundary layer reduces with a rise in Eckert number and Prandtl number.

Key Words: *Magnetic field, Porous medium, Boundary layer, Joule heating, Spectral collocation method.*

Introduction

In current years, the utilization of nano fluids has attracted more attention because of their superior thermal conductivity and potential for improving energy transfer performance. Nanofluids, which are colloidal suspensions of nanomaterials in base fluids, have found widespread applications in various industrial sectors, especially in cooling systems and heat exchangers. Enhancing heat transfer in these systems is essential for advancing the efficiency and reliability of heat regulation across various industries requiring efficient heat dissipation.

1Department of Mathematics, Sapthagiri College of Engineering, Bangalore - 560057, Karnataka, India; bhavya201983@gmail.com
2Department of Mathematics, B.M.S College of Engineering, Bangalore - 560019, Karnataka, India; msgayathri.maths@bmsce.ac.in
3Department of Mathematics, Ramaiah Institute of Technology, Bangalore - 560054, Karnataka, India; dineshdpa@msrit.edu
4Department of Mathematics, B.M.S College of Engineering, Bangalore - 560019, Karnataka, India; pgomathi.maths@bmsce.ac.in
**Corresponding author Email: bhavya201983@gmail.com*

The magnetic field presence significantly influences the nano fluids behavior, particularly in magnetohydrodynamic (MHD) systems, where both the thermal and flow characteristics are altered by the magnetic forces. In MHD systems, the interaction between nanofluid particles and the applied magnetic field leads to a change in the temperature and velocity profiles, which are vital in optimizing cooling and heat transfer processes. The study of such magnetic field effects seems even more complex when the nanofluid flows over a stretching sheet embedded in a porous medium, as the porous medium affects both the temperature distribution and fluid velocity.

The boundary layer flow investigation in such systems is essential for the study of how various parameters, including the magnetic field strength, porous medium permeability and fluid properties such as Brownian motion and thermophoresis, influence the velocity, thermal and concentration profiles of nanofluids.

The Cassion nano fluid boundary layer flow onto a stretching sheet was observed by Tawade et.al [1] to notice Brownian motion thermophoresis effects onto concentration and temperature profiles and reported that there is a growth in energy distribution and reduction in concentration profiles. Anjali and Mekala [2] and Sami and Sabir [3] studied the analysis of local Nusselt number, Sherwood number, and non-Newtonian parameters on momentum boundary layer enhancement and nanoparticle temperature. It was observed that there is a periodic increase in skin-friction factor with the influence of non-Newtonian parameters. Zeeshan et.al [4]have studied 3D Brownian motion of nanofluid over a stretchable rotating surface.

Goswami and Sarma [6] conducted a numerical study of non-Newtonian fluid flow through a porous vertical plate and reported the influence of the magnetic field on the flow profiles. Swain et. al [5] and Jamaludin et.al [7] studied steady 3-D convection of nanofluids flow onto a permeable stretching surface. The influence of characteristic parameters on skin friction coefficients, local Nusselt number, velocity, and temperature profiles have discussed. Malik et.al [8] analysed the magneto hydrodynamic boundary layer flow of Sisko fluid over a continuously stretching cylinder, considering the effect of viscous dissipation.Oloniiju et.al [9] developed a precise numerical scheme for solving multi-dimensional time fractional partial differential equations using combination of Lagrange and Chebyshev polynomials for convergence analysis and error reduction.

Bhukta et.al [10], Rowlatt and Phillips [11] have studied the spectral element formulation of the immersed boundary method (IBM), showcasing its advantages in view of accuracy and efficiency. Jafar et.al [12] explored the flow of nano fluids past a porous medium stretching sheet subjected to frictional heating due to thermal radiation. The physical parameters impact on the flow field, skin friction, Nusselt number and temperature distribution have analysed and presented graphically. Tianet.al [13] experimented the effects of the variable viscosity parameter, Hartmann number and Prandtl number on fluid heat transfer behaviour. Fakour et.al [14],Khan and Azam [15] have studied the velocity and heat dissipation of laminar fluid flow through permeable channel subjected to a transverse magnetic field, using the least square method and comparing it with the numerical solutions considering the effects of the Reynolds number, Prandtl number, Eckert number and Hartmann number.

Shafeyet.al [16] have exercised numerical solutions to the characteristic equations and observed a decrease in thickness of thermal boundary layer proportional to a rise in Prandtl number, also there was an improved velocity field and diminished temperature and concentration profiles with increasing Reynolds number. Srinivas and Ramana Murthy[17] have reported the heat transfer in a horizontal conduit with two immiscible micropolar fluids subjected to magnetic field. An analytical profile for velocity, micro-rotation, and temperature are developed and entropy change and Bejan numbers are computed. An imposed magnetic field caused a reduction in entropy near the walls. Arshad et.al [18] and Sandeep et.al [19] experimented the boundary layer flow of nanofluid onto stretching sheet in a porous medium with coordinate and time-dependent internal heat sink and source. They presented numerical solutions and studied the various fluid properties. Misra and Shit [20] studied the bio-magnetic fluid flow over a stretching sheet in the presence of applied magnetic field generated by a magnetic dipole. Sinha [21]observed back flow of fluids near the centre of the channel due to stretching walls and noted that flow reversal could be ceased by creating a strong external magnetic field.

The current study intended to numerically analyze the boundary layer behaviour of nanofluid flow over a stretching sheet in a porous medium and subjected to magnetic field. The similarity transformations found appropriate to represent nonlinear partial differential equations in terms of ordinary differential equations. The shooting method and spectral collocation technique have been employed to solve ordinary differential equations. The variations in to the velocity, thermal and concentration boundary layers have been investigated in detail. This paper has discussed the significance of various parameters of nanofluid in optimizing cooling applications and improving the design of heat transfer systems.

Mathematical Formulation

A nanofluid, steady 2-D boundary layer flow onto a stretching sheet in a porous medium and subjected to a magnetic field and with a linear velocity $u_w(x) = ax$ where a is a positive real number, x is the spatial co-ordinate measured along the stretching surface has been considered. The nanoparticles volume fraction and temperature at the surface and the ambient values have denoted by $T_w,\ C_w,\ T_\infty,\ C_\infty$ respectively. A schematic sketch of flow problem is as shown Figure 1. The governing equations for the fluid flow, temperature and nanoparticle concentration can be presented by equations (1)–(5).

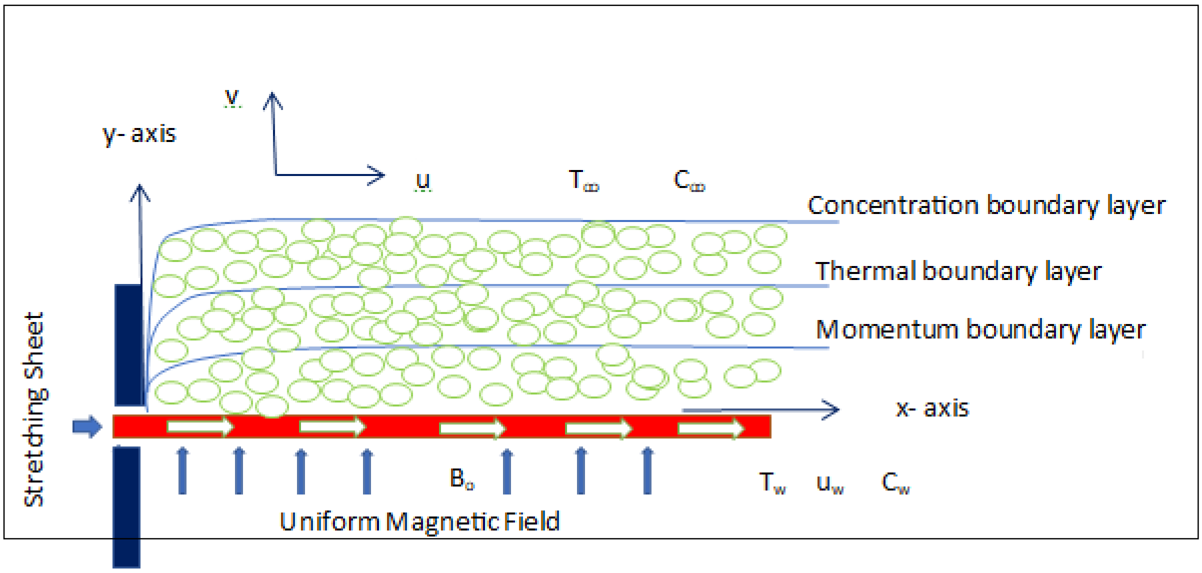


Figure 1 Geometrical interpretation of nanofluid flow; (a) Presence of porous medium and (b) Presence of Magnetic field.

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

$$u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} = -\frac{1}{\rho_f}\frac{\partial p}{\partial x} + \upsilon\left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2}\right) - \frac{\bar{\mu}}{k\rho_f}u - \frac{\sigma_f {B_0}^2 u}{\rho_f} \tag{2}$$

$$u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} = -\frac{1}{\rho_f}\frac{\partial p}{\partial y} + \upsilon\left(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2}\right) - \frac{\bar{\mu}}{k\rho_f}v \tag{3}$$

$$u\frac{\partial T}{\partial x} + v\frac{\partial T}{\partial y} = \alpha\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2}\right) + \tau\left\{D_B\left(\frac{\partial C}{\partial x}\frac{\partial T}{\partial x} + \frac{\partial C}{\partial y}\frac{\partial T}{\partial y}\right) + \left(\frac{D_T}{T_\infty}\right)\left[\left(\frac{\partial T}{\partial x}\right)^2 + \left(\frac{\partial T}{\partial y}\right)^2\right]\right\} - \frac{\sigma_f {B_0}^2 u^2}{(\rho c)_f} \tag{4}$$

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

Let u and v are velocity components along x and y directions respectively, p : fluid pressure, ρ_p: particle density, ρ_f: density of the fluid, υ: kinematic viscosity, α: thermal diffusivity, D_T: co-efficient of thermophoretic diffusion, D_B: co-efficient of Brownian motion diffusion, $\tau = {(\rho c)_p}/{(\rho c)_f}$:ratio between fluid heat capacity and nanoparticles effective heat capacity,

ρ : density, k: permeability of the porous medium, σ_f : electrical conductivity of the fluid, B_o : Magnetic field strength, c :

volumetric expansion coefficient, $\bar{\mu}$: effective dynamic viscosity of the nanofluid, T: Temperature of the fluid, C: Nanoparticle Concentration.

The Boundary conditions for the considered problem are given in equation (7) ;

$$At\ y = 0;\ v = 0, u = u_w(x) = ax, T = T_w, C = C_w$$

$$At\ y \longrightarrow \infty;\ u = 0, v = 0, T = T_\infty, C = C_\infty \qquad (6)$$

We have introduced the similarity variable to transform the physical quantities into dimensionless forms and presented by equations (8)–(10).

$$\eta = \sqrt{\frac{a}{\upsilon}}\ y\ , \Psi = \sqrt{a\upsilon}\ x\, f(\eta)$$

$$\theta(\eta) = \frac{T - T_\infty}{T_w - T_\infty}\ , \phi(\eta) = \frac{C - C_\infty}{C_w - C_\infty}$$

$$u = \frac{\partial \Psi}{\partial y} \quad \text{and} \quad v = -\frac{\partial \Psi}{\partial x} \qquad (7)$$

This will result in a set of dimensionless equations

$$f''' + ff'' - f'^2 - k_p f' - M^2 f' = 0 \qquad (8)$$

$$\frac{1}{Pr}\theta'' + f\theta' + Nb\phi'\theta' + Nt\theta'^2 - M^2 E f'^2 = 0 \qquad (9)$$

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

and the dimensionless boundary conditions are

$$f(0) = 0,\ f'(0) = 1,\ \theta(0) = 1\ , \phi(0) = 1$$

$$f'(\infty) = 0\ \ , \theta(\infty) = 0\ , \ \phi(\infty) = 0 \qquad (11)$$

Let $Pr = \frac{\upsilon}{\alpha}$: Prandtl number, $Le = \frac{\upsilon}{D_B}$: Lewis number, $Nb = \frac{(\rho c)_p D_B (C_w - C_\infty)}{(\rho c)_f \ \upsilon}$: Brownian motion parameter, $Nt = \frac{(\rho c)_p D_T (T_w - T_\infty)}{(\rho c)_f T_\infty \upsilon}$: thermophoresis parameter, $k_p = \frac{\overline{\mu}}{k \rho_f a}$: permeability parameter, $M = \sqrt{\frac{\sigma_m B_0{}^2}{\rho_f a}}$: Hartmann number and $E = \frac{a^2 x^2}{c_f (T_w - T_\infty)}$:Eckert number. The reduced boundary problem is given by equations [8] –[10] and applicable boundary conditions are given in equation [11].

The analytical solution of equation (8) with boundary conditions (11) is given by equation (12).

$$f(\eta) = \frac{1}{s}(1 - e^{-s\eta}) \tag{12}$$

where $s = \sqrt{1 + (M^2 + k_p)}$

The ordinary differential equations ; [8] – [10] subjected to the boundary constraints given in equation (11) have been solved using Runge-Kutta Fehlberg and Newton-Raphson method of fourth order strategy., The quasi-linear spectral collocation method using Gauss-Lobatto points has been applied to validate the accuracy of above methods .

Results And Discussions

The effect of Hartmann number, Eckert number, Lewis number, Prandtl number, Brownian motion parameter and thermophoresis parameter on the nanofluid flow characteristics have been discussed. Graphical representations of the velocity, temperature and nanoparticle concentration profiles are provided to visualize the influence of each parameter on the behaviour of the system.

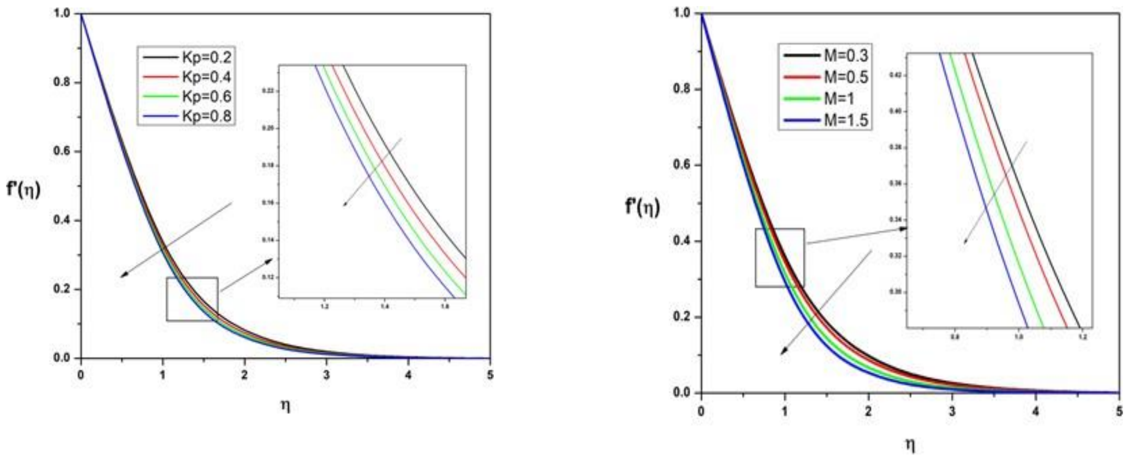


Figure 2 (a) and (b) Variation of fluid velocity; (a) As a function of Permeability Parameter (k_p) and (b) As a function of Hartmann Number (M)

It has noticed from Figure 2 (a) that for increasing values of porous parameter, there is a fall in nanofluid velocity which could be attributed to increased resistance of fluid flow in porous medium. As the resistance to flow rises, the nanofluid’s velocity diminishes, which leads to fall in the fluid molecular movement.

The influence of magnetic flux on velocity is demonstrated in the Figure 2 (b). As magnetic parameter increases, the velocity decreases. An increase in magnetic field strength generates a Lorentz force which reduces fluid movement. As the magnetic field intensifies, the retardation force also increases, creating resistance to the flow.

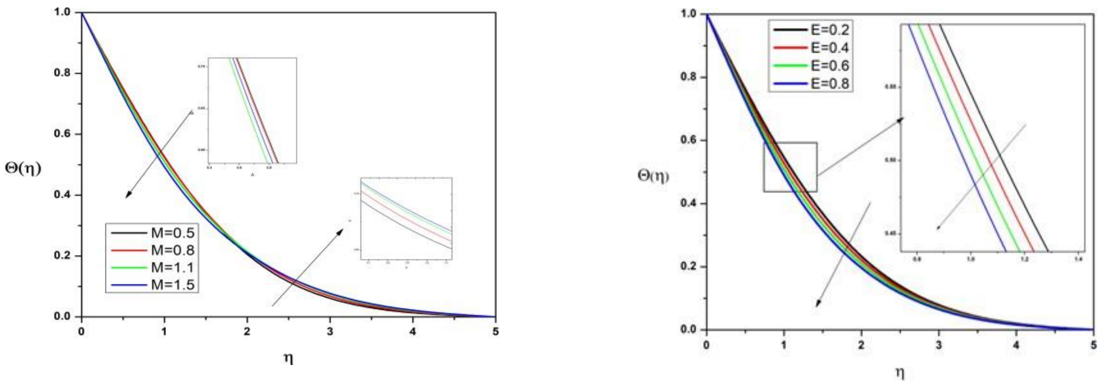


Figure 3 (a) and (b) Variation of fluid Temperature; (a) As a function of Hartmann Number (M) and (b) As a function of Eckert number (E)

Figure 3 (a) shows a distinct variation in temperature corresponding to magnetic number, both near and farther from the stretching sheet. It has observed that as the magnetic number increases, there was a decrease of temperature near the stretching sheet. The magnetic field creates a Lorentz force that dampens the velocity of the fluid, which reduces the convective energy transfer from the surface. This results, temperature decrease near the wall. However, moving farther away from the sheet, the thermal boundary layer becomes thicker due to the influence of the magnetic field on the velocity field, resulting in a temperature rise farther away from the surface.

The Eckert number effect on the temperature distribution can be noticed from Figure 3 (b). There is a fall in temperature distribution as the Eckert number increases. This is due to the increase in flow velocity for higher values of Eckert number, thereby hindering the heat dissipation between the fluid particles leading to decrease in temperature.

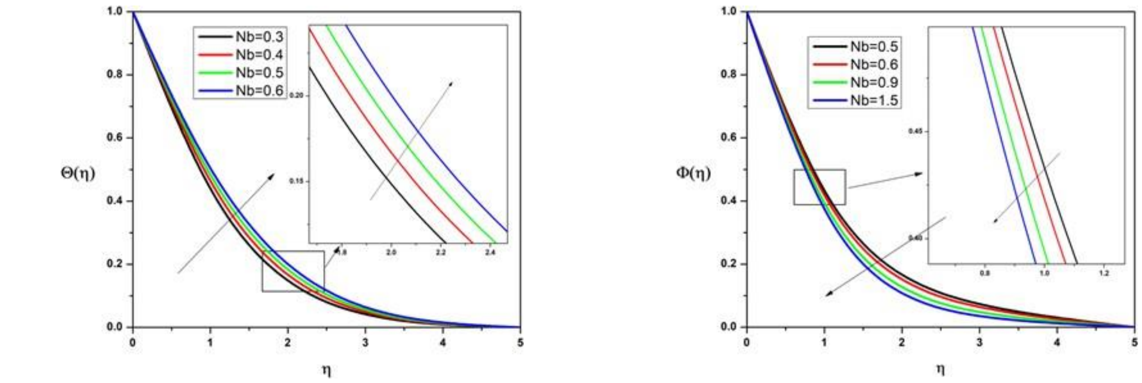


Figure 4 (a) & (b) Variation of fluid Temperature and Fluid Concentration; (a) Temperature Versus Brownian motion parameter and (b) Concentration Versus Brownian motion parameter

Figure 4 (a) shows that as Brownian motion intensifies, nanofluid temperature increases. This effect is amplified due to magnetic field. The rapid movement of fluid particles leads to an increase in acceleration, which in turn generates additional energy among particles. This results in increase in temperature gradient, thereby causing the thermal boundary layer to expand.

Figure 4 (b) illustrates the Brownian motion effect on nanoparticle concentration. As Brownian motion intensifies, the random movement and diffusion of nanoparticles increase. This enhanced diffusion leads to a more uniform dispersion of nanoparticles, thereby reducing the concentration gradient within the flow. Consequently, there is a shrink in concentration boundary layer.

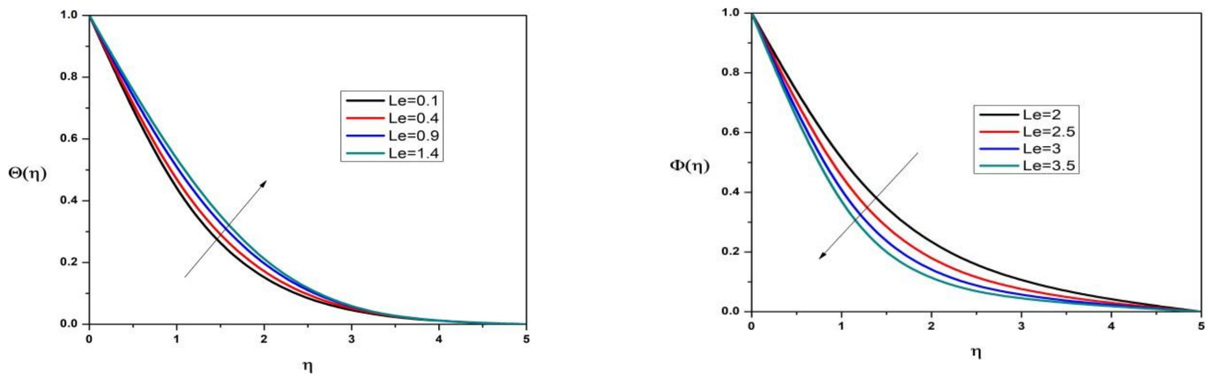
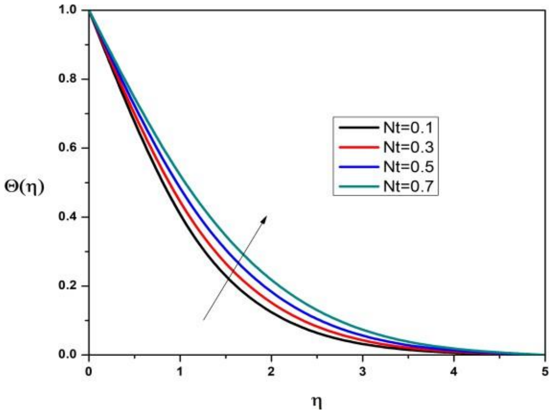


Figure 5 (a) & (b) Variation of fluid Temperature and Concentration; (a) Temperature Versus Lewis number and (b) Concentration Versus Lewis number

Figure 5 (a) shows that fluid temperature rises as the Lewis number increases which could be attributed to high momentum diffusivity than the mass diffusivity. The high momentum diffusivity causes friction between the layers hence more temperature. Also rise in Lewis number caused an increased thickness of temperature boundary layer.Figure 5 (b) indicates that the concentration of the nanoparticle decreases for the increase of Lewis number due to the decrease in mass diffusion rate relative to heat transfer. This causes the concentration boundary layer to weaken.



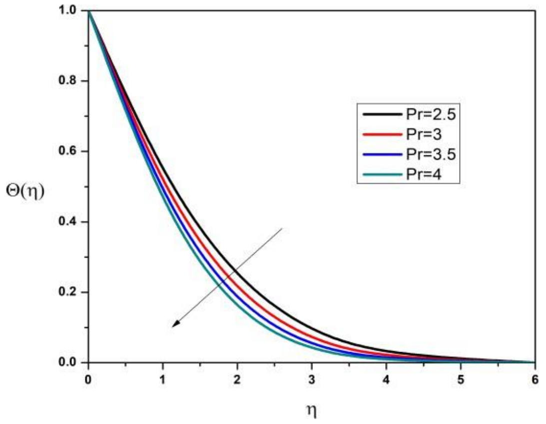


Figure 6 (a) & (b) Variation of fluid Temperature; (a) As a function of Thermophoresis parameter (Nt) and (b) As a function of Prandtl number (Pr)

Figure 6 (a) demonstrates a rise in temperature with the raising values of the thermophoresis parameter, which is influenced by the coefficient of thermal diffusion. As the thermophoretic effect strengthens, nanoparticles move deeper into the ambient fluid, leading to an enhanced local temperature and a thicker thermal boundary layer.

Figure 6 (b) illustrates the temperature distribution corresponding to Prandtl number. A rise in Prandtl number led to a reduction in thermal boundary layer thickness since higher Prandtl number controls the heat diffuse into fluid. Thus, there was a thinner thermal boundary layer which decreased overall heat transfer efficiency.

Conclusions

In this study, the magnetic field effects on nanofluids past a stretching sheet in porous medium have been investigated. The governing equations of fluid movement have been reduced to ordinary differential equations (ODEs) and solved with the help of shooting technique. The spectral collocation method has employed to validate the results obtained by shooting technique. The salient conclusions drawn from study are as follows:

1.Porous Parameter: The velocity profile decreases with an increase in the porous parameter, resulting in a reduction of molecular movement within the fluid.

2.Eckert Number: A rise in Eckert number has led to a decrease in the temperature profile when the fluid is subjected toa uniform magnetic field.

3.Magnetic Field Intensity: A stronger magnetic field exhibits dual behavior in the temperature distribution and reduces the flow velocity due to the influence of the Lorentz force.

4.Brownian Parameter: The rise in Brownian number significantly raises the temperature, decreases the concentration boundary layer by inhibiting the diffusion of nanoparticles in the flow.

5.Lewis Number: A rise in Lewis number enhances the temperature profile but reduces the concentration profile, leading to a thinning the concentration boundary layer.

6.Thermophoresis Parameter: Higher values of the thermophoresis parameter cause rise in temperature, which facilitates the deeper penetration of nanoparticles.

7.Prandtl Number: Higher Prandtl numbers resulted in a reduced temperature profile and thinner thermal boundary layer

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