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RESEARCH ARTICLE

RADIATION EFFECTS ON MHD BOUNDARY LAYER FLOW OF A NANOFLUID PAST AN EXPONENTIAL PERMIABLE STRETCHING SHEET EMBEDDED IN A POROUS MEDIUM

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ABSTRACT

In the present paper, an attempt is made to discuss the heat and mass transfer effects on a laminar, two dimensional, steady/unsteady, free/mixed convection flow of an incompressible electrically conducting and radiating viscous fluid (or nanofluid) past a linear/non-linear stretching sheet / stretching cylinder bounded by a porous (or non-porous) medium, in the presence of various effects such as MHD, chemical reaction, viscous dissipation, thermophoresis, Brownian motion, thermally stratified medium, variable thermal conductivity and partial slip. This paper deals with the study case. The governing equations of the flow under consideration were solved with the associated boundary conditions by using a widely used numerical method called Runge-Kutta fourth order scheme along with shooting technique. In order to get a physical insight into the problems, the effects of various thermo-physical and hydrodynamical parameters on the velocity, temperature, concentration, skin-friction, Nusselt number and Sherwood number are computed and represented in figures and tables, and discussed in detail.

INTRODUCTION

In view of the rising demands of modern technology, including chemical production, power station, and microelectronics, there is a need to develop new types of fluids that will be more effective in terms of heat exchange performance. Numerous methods have been tried to improve the thermal conductivity of base fluids such as water, ethylene glycol and oil by suspending nano/micro-sized particle materials in liquids. These nanofluids have exhibited unique properties which make them potentially useful in many applications in heat transfer, including microelectronics, fuel cells, pharmaceutical processes, and hybrid-powered engines. Initially, Choi and Eastman (Choi and Eastman, 1995) presented the concept of nanofluids for suspension of liquids containing ultra-fine particles. Khan and Pop (2010) in their first work on nanofluid have considered the problem on flow over stretching sheet. The natural convective boundary-layer flow of a nanofluid past a vertical plate is presented analytically by Kuznetsov and Nield (Kuznetsov and Nield, 2010). (Buongiorno *et al.,* 2009) analysed A benchmark study on the thermal conductivity of nanofluids. (Vajravelu*et al.,* 2011*)* presented the detailed analysis of convective heat transfer in the flow of viscous *Ag*–water and *Cu*–water nanofluids over a stretching surface. Recently, (Syahira Mansur and AnuarIshak, 2014) studied the magnetohydrodynamic boundary layer flow of a nanofluid past a stretching/shrinking sheet with slip boundary conditions. (Padam Singh and Manoj Kumar, 2014) analysed the free convection in heat transfer flow over a moving sheet in alumina water Nanofluid. The study of boundary layer flow and heat transfer over a stretching surface has achieved a lot of success because of its large number of applications in industry and technology. Few of these applications are materials manufactured by polymer extrusion, drawing of copper wires, continuous stretching of plastic films, artificial fibres, hot rolling, wire drawing, glass fibre, metal extrusion and metal spinning etc. After the pioneering work by Sakiadis (1961) a large amount of literature is available on boundary layer flow of Newtonian and non-Newtonian fluids over linear and nonlinear stretching surfaces (Liu, 2004; Vajravelu and Nayfeh, 1993; Khan *et al.,* 1993; Khan and Pop, 2010; Rana and Bhargava, 2012; Hamad and Ferdows, 2012; Kalidas Das, 2012). However, only a limited attention has been paid to the study of exponential stretching surface. Mention may be made to the works of (Magyari and Keller, 1999) (Sanjayanand and Khan, 2012) (Khan and Sanjayanand, 2005). Recently, (Sreenivasulu and Bhaskar Reddy, 2012) studied the Soret and Dufour effects on boundary layer flow past an exponential stretching sheet with thermal radiation and viscous dissipation. (Nadeem and Lee, 2012) presented the boundary layer flow of nanofluid over an exponentially stretching surface. (Santosh Chaudhary*et al.,* 2015) presented Thermal radiation effects on MHD boundary layer flow over an exponentially stretching Surface.

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Magnetic nanofluid is a unique material that has both the liquid and magnetic properties. Many of the physical properties of these fluids can be tuned by varying magnetic field. In addition, they have been wonderful model system for fundamental studies. As the magnetic nanofluids are easy to manipulate with an external magnetic field, they have been used for a variety of studies. (Chamkha and Aly, 2010) presented the MHD free convection flow of a nanofluid past a vertical plate in the presence of heat generation or absorption effects. (Hamad *et al.,* 2011) investigated magnetic field effects on free convection flow of a nanofluid past a vertical semi-infinite flat plate. (Hamad and Pop, 2011) presented an Unsteady MHD free convection flow past a vertical permeable flat plate in a rotating frame of reference with constant heat source in a nanofluid. (Kandasamy*et al.,* 2011) presented the Scaling group transformation for MHD boundary-layer flow of a nanofluid past a vertical stretching surface in the presence of suction/injection. (Shakhaoath Khan *et al.,* 2013), investigated the effects of magnetic field on radiative flow of a nanofluid past a stretching sheet. (Ibrahim and Shankar, 2013), presented the MHD boundary layer flow and heat transfer of a nanofluid past a permeable stretching sheet with velocity, thermal and solutal slip boundary conditions. Recently, (Bhattacharyya and Layek, 2014), studied the magnetohydrodynamic boundary layer flow of nanofluid over an exponentially stretching Permeable Sheet.

Thermal radiation heat transfer effects on different flows are very important in high temperature processes and space technology such as heating and cooling chambers, fossil fuel combustion and energy processes, evaporation from large open water reservoirs, astrophysical flows and solar power technology. Also, it plays an important role in some applications because of the manner in which radiant emission depends on temperature and nanoparticle volume fraction. The random motion of nanoparticles within the base fluid is called Brownian motion, and results from continuous collisions between the nanoparticles and the molecules of the base fluid. The nanoparticle concentration, base fluid, and particle size appear to be the most influential parameters for improving the heat transfer efficiency of the nanofluid. In view of this, (Olanrewaju *et al.,* 2012), studied theBoundary layer flow of nanofluids over a moving surface in a flowing fluid in the presence of radiation. (Hady*et al.,* 2012) presented Radiation effect on viscous flow of a nanofluid and heat transfer over a nonlinearly stretching sheet. (Gbadeyan*et al.,* 2011) investigated the boundary layer flow of a Nanofluidpast a stretching sheet with a convective boundary condition in the presence of magnetic field and thermal radiation. (Pal and Mondal, 2011) analysed, Effects of Soret and Dufour, chemical reaction and thermal radiation on MHD non-Darcy unsteady mixed convective heat and mass transfer over a stretching sheet. (Hossain*et al.,* 2001) studied the Effect of radiation on free convection flow of fluid with variable viscosity from a porous vertical plate. (Elbashbeshy, 2000) investigated the radiation effect on heat transfer over a stretching surface. But so far, no attempt has been made to analyze the effects of thermal radiation on MHD boundary layer flow of a nanofluid past a porous exponential stretching surface embedded in a porous medium. Hence an attempt is made to study this problem. In the present study, the combined effects of thermophoresis and Brownian motion are considered to get the gradient of nanoparticles volume fraction.

Mathematical Analysis

A steady laminar two-dimensional flow of a viscous incompressible electrically conducting and radiating nanofluid past a stretching surface embedded in a porous medium, coinciding with the plane $y = 0$, is considered. The flow is assumed to be confined to $y > 0$. The transverse magnetic field B is imposed perpendicular to the x - axis. The induced magnetic field is neglected as the magnetic Reynolds number of the flow is taken to be very small. It is also assumed that the external electric field is zero and the electric field due to polarization of charges is negligible. The temperature and the nanoparticle fraction at the stretching surface are deemed to have constant values T_w and C_w, respectively, while the ambient temperature and nanoparticle volume fraction have constant values T_∞ and C_∞ respectively. It is further assumed that the base (host) fluid and the suspended nanoparticles are in thermal equilibrium and no slip occurs between them. The physical model for this problem is shown in Fig. 1.

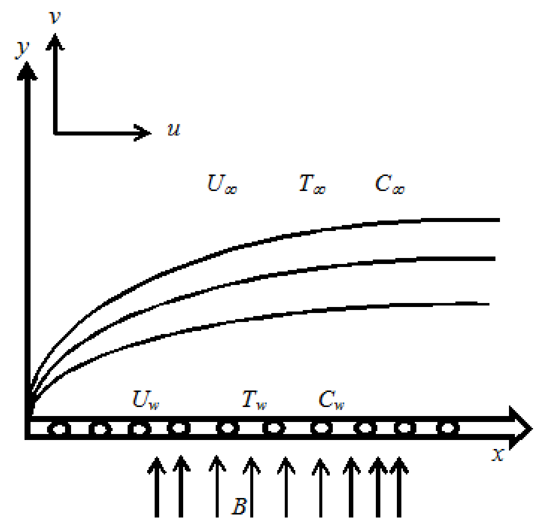

Fig. 1. Physical model and coordinate system

Under the above assumptions, the boundary layer equations governing the flow and temperature in the presence of heat source or heat sink are (using the boundary layer approximations and neglecting viscous dissipation).

Continuity Equation

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}=0 \qquad \ldots\ldots (1)$$

Momentum Equation

$$u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}=\nu\frac{\partial^2 u}{\partial y^2}-\frac{\sigma B^2(x)}{\rho_f}u-\frac{\nu}{k'}u \qquad \ldots\ldots (2)$$

Energy Equation

$$u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}=\alpha\frac{\partial^2 T}{\partial y^2}-\frac{1}{\rho C_p}\frac{\partial q_r}{\partial y}+\tau\left\{D_B\frac{\partial T}{\partial y}\frac{\partial C}{\partial y}+\frac{D_T}{T_\infty}\left(\frac{\partial T}{\partial y}\right)^2\right\} \qquad \ldots\ldots (3)$$

Species Concentration Equation

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

The boundary conditionsel for the velocity, temperature and concentration fields are

$$\begin{aligned} &u=u_w(x), \quad v=v_w, \quad T=T_w\,(x),\ C=C_w(x) \quad at \quad y=0 \\ &u\to 0, \quad T\to T_\infty, \quad C\to C_\infty \quad as \quad y\to\infty \end{aligned} \quad \ldots\ldots (5)$$

Where , x and y are the coordinates along and perpendicular to the surface of the sheet, u, v are the velocity components in the x and y directions, respectively, σ is the electrical conductivity, T is the local temperature of the fluid, C is the nanoparticle volume fraction(concentration of the species), ρ is the density of the fluid, $k'$is the permeability of the porous medium, q_r is the radiative heat flux, Cp is the specific heat, D_B is the Brownian diffusion coefficient, D_T is thermophoretic diffusion coefficient and τ is the ratio between the effective heat capacity of the nanoparticle material and heat capacity of the fluid. The stretching velocity u_w(x), exponential temperature distribution T_w(x) and exponential concentration distribution C_w(x) are defined as

$$u_w(x)=ae^{x/L} \quad \ldots\ldots (6)$$

$$T_w(x)=T_\infty+T_0e^{x/2L} \quad \ldots\ldots (7)$$

$$C_w(x)=C_\infty+C_0e^{x/2L} \quad \ldots\ldots (8)$$

Where a is the velocity parameter of the stretching surface, T_0 is the parameter of temperature distribution, whereas C_0 is the parameter of concentration distribution in the stretching surface and L is the characteristic length of the plate. The suction velocity is taken to be

$$v_w=v_0e^{x/2L} \quad \ldots\ldots (9)$$

Where v_0 is the wall mass flux with $v_0 < 0$ for suction and $v_0 > 0$ for injection, respectively. The radiative heat flux q_r is described by Rosseland (Brewster, 1992) approximation such that

$$q_r=-\frac{4}{3}\frac{\sigma^*}{k^*}\frac{\partial T^4}{\partial y} \quad \ldots\ldots (10)$$

Where σ^* is the Stefan-Boltzmann constant and k^* is the mean absorption coefficient. It should be noted that by using the Rosseland approximation, the present analysis is limited to optically thick fluids. If the temperature differences within the flow are sufficiently small, then equation (5.2.10) can be linearized by expanding T^4 into the Taylor series about T_∞, which after neglecting higher-order terms takes the form

$$T^4 \cong 4T_\infty^3T-3T_\infty^4 \quad \ldots\ldots (11)$$

In view of the equations (5.2.10) and (5.2.11), the equation (5.2.3) becomes

$$u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}=\left(\alpha+\frac{16\sigma^*T_\infty^3}{3k^*\rho Cp}\right)\frac{\partial^2 T}{\partial y^2}+\tau\left\{D_B\frac{\partial T}{\partial y}\frac{\partial C}{\partial y}+\frac{D_T}{T_\infty}\left(\frac{\partial T}{\partial y}\right)^2\right\} \quad \ldots\ldots (12)$$

To obtain similarity solutions, it is assumed that the magnetic field B(x) is of the form

$$B=B_0e^{x/2L} \quad \ldots\ldots (13)$$

Where B_0 is the constant magnetic field.

In view of the continuity equation (1), the stream function ψ is defined as

$$u=\frac{\partial\psi}{\partial y}, \quad v=-\frac{\partial\psi}{\partial x} \quad \ldots\ldots (14)$$

In order to write the governing equations and the boundary conditions in dimensionless form, the following non-dimensional quantities are introduced.

$$\psi=\sqrt{2\nu La}f(\eta)e^{x/2L}, \quad \eta=y\sqrt{\frac{a}{2\nu L}}e^{x/2L}, \ \theta(\eta)=\frac{T-T_\infty}{T_w-T_\infty}, \quad \phi(\eta)=\frac{C-C_\infty}{C_w-C_\infty} \quad \ldots\ldots (15)$$

In view of the relations in (15), the equations (1), (2), (4) and (12) become

$$f'''+ff''-2f'^2-(K+M)f'=0 \quad \ldots\ldots (16)$$

$$\frac{1}{\Pr}\left(1+\frac{4}{3}Nr\right)\theta''+f\theta'-f'\theta+Nb\theta'\phi'+Nt\theta'^2=0 \quad \ldots\ldots (17)$$

$$\phi''+Le(f\phi'-f'\phi)+\frac{Nt}{Nb}\theta''=0 \quad \ldots\ldots (18)$$

The corresponding boundary conditions are

$$f' = 1, \quad f = S, \quad \theta = 1, \quad \phi = 1 \quad at \quad \eta = 0$$
$$f' \to 0, \quad \theta \to 0, \quad \phi \to 0 \quad as \quad \eta \to \infty$$

.... (19)

Where $M = 2\sigma B_0^2 L / a\rho_f$ is the magnetic field parameter, $\Pr = \nu / \alpha$ is the Prandtl number, $Nr = 4\sigma^* T_\infty^3 / k^* k$ is the radiation parameter, $K = 2\nu L / ak' e^{x/L}$ is the permeable parameter of the porous medium, $S = -v_0 / \sqrt{a\nu / 2L}$ is the mass flux parameter (S > 0 corresponds to suction and s < 0 corresponds to blowing), $Le = \nu / D_B$ is the Lewis number, $Nb = \tau D_B (C_w - C_\infty) / \nu$ is Brownian motion parameter and $Nt = \tau D_T (T_w - T_\infty) / \nu T_\infty$ is the thermophoresis parameter. The wall shear stress, heat and mass transfers acting on the surface in contact with the ambient fluid of constant density are respectively given by

$$\tau_w = \mu \left[\frac{\partial u}{\partial y} \right]_{y=0}, \quad q_w(x) = -k \left[\frac{\partial T}{\partial y} \right]_{y=0}, \quad q_m(x) = -D \left[\frac{\partial C}{\partial y} \right]_{y=0}$$

.... (20)

where μ is the dynamic viscosity.

The skin friction at the plate can be obtained, which in non-dimensional form is given by

$$C_f = \frac{\tau_w}{\rho_f e^{2x/L} u_w^2} \qquad \Rightarrow C_f \sqrt{2\mathrm{Re}_x} = f''(0)$$

.... (21)

The rate of heat transfer coefficient can be obtained, which in the non-dimensional form, in terms of the Nusselt number, is given by

$$Nu_x = \frac{x q_w(x)}{k(T_w(x) - T_\infty)} \quad \Rightarrow \frac{Nu_x}{\sqrt{2\mathrm{Re}_x}} = -\sqrt{\frac{x}{2L}}\theta'(0)$$

.... (22)

The rate of mass transfer coefficient can be obtained, which in the non-dimensional form, in terms of the Sherwood number, is given by

$$Sh_x = \frac{x q_m}{D(C_w(x) - C_\infty)} \quad \Rightarrow \frac{Sh_x}{\sqrt{2\mathrm{Re}_x}} = -\sqrt{\frac{x}{2L}}\phi'(0)$$

.... (23)

Where $Re_x = u_w(x)\, x/\nu$ is the local Reynolds number.

METHOD OF SOLUTION

The set of non-linear ordinary differential equations (16) – (18) with boundary conditions (19) have been solved by using the Runge - Kutta fourth order method along with shooting technique. The step size $\Delta\eta$ = 0.01 is used while obtaining the numerical solution with η_{max}, and accuracy to the fifth decimal place is sufficient for convergence. A step size of $\Delta\eta$ = 0.01 was selected to be satisfactory for a convergence criterion of 10^{6}in nearly all cases. The value of η_∞ was found to each iteration loop by assignment statement $\eta_\infty = \eta_\infty + _{\Delta\eta}$. The maximum value of η_∞ to each group of parameters *Pr, Le, M, Nr, Nb, K* and *Nt*, determined when the values of unknown boundary conditions at η = 0 not change to successful loop with error less than 10^{6}. Effects of development of the steady boundary layer flow, heat transfer and nanoparticle volume fraction over a stretching surface in a nanofluid are studied for different values of Brownian motion parameter, thermophoresis parameter, radiation parameter, magnetic parameter, suction/injection parameter, porosity parameter and Lewis number.

RESULTS AND DISCUSSION

In order to test the accuracy of our results, we have compared our results with those of (Magyari and Keller, 1999) and (Bhattacharyya and Layek, 2014) for appropriate reduced cases, and found that there is an excellent agreement, as presented in Table 1 and Fig. 2.

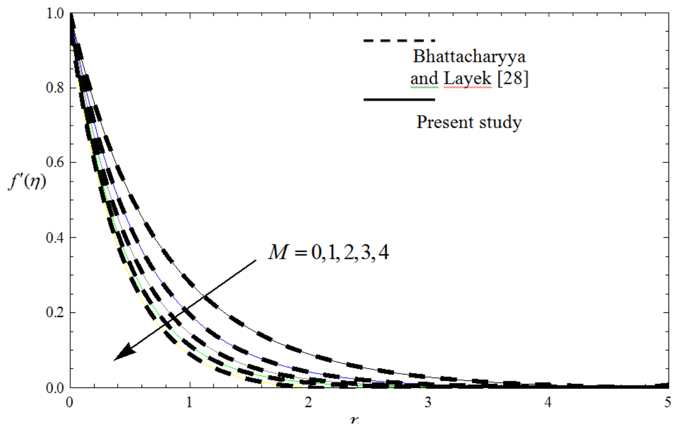

Fig. 2. Comparison of velocity profiles for different values of M with K = Nr = 0

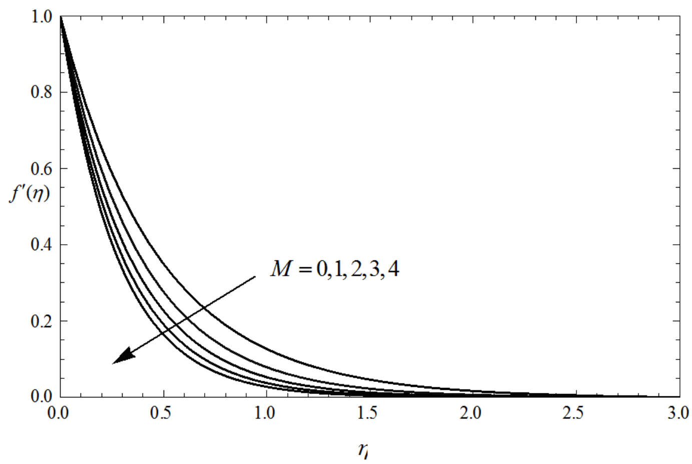

Fig. 3. Velocity profiles for different values of M

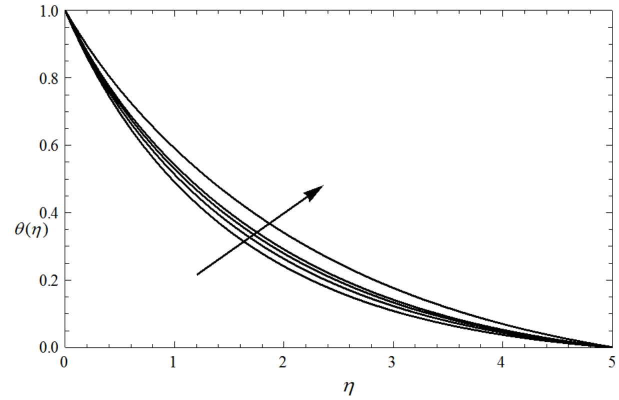

Fig. 4. Temperature profiles for different values of M

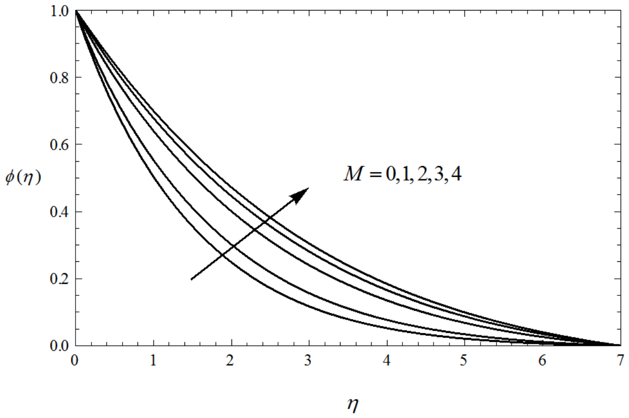

Fig. 5. Nanoparticle volume fraction profiles for different values of M

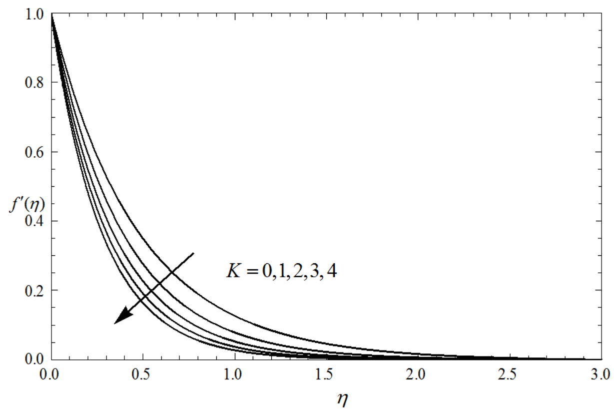

Fig. 6. Velocity profiles for different values of K

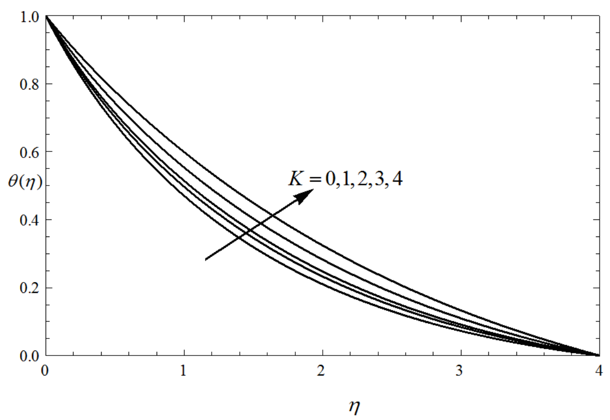

Fig. 7. Temperature profiles for different values of K

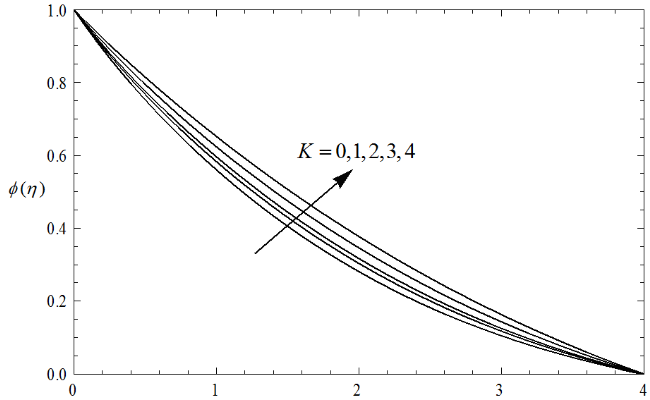

Fig. 8. Nanoparticle volume fraction profiles for different values of K

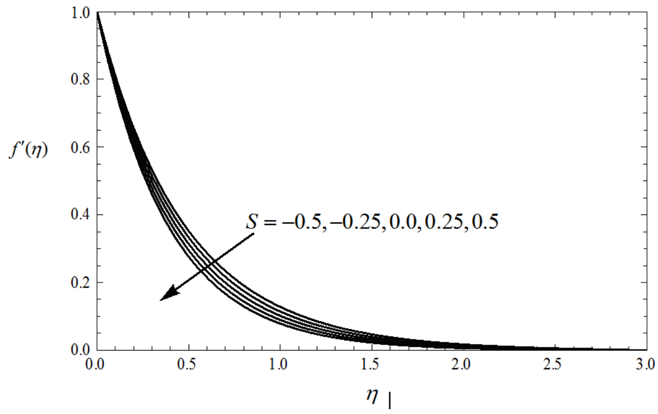

Fig. 9. Velocity profiles for different values of S

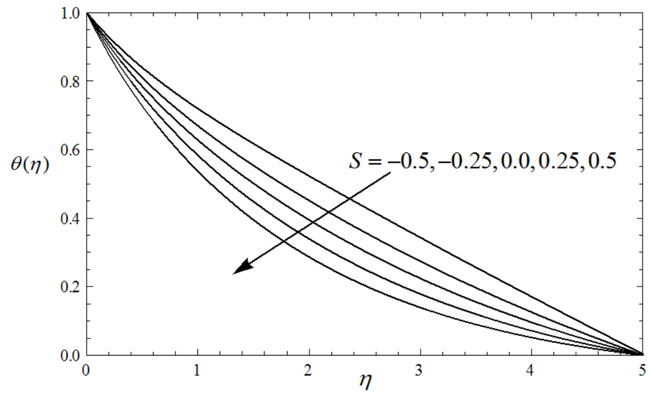

Fig. 10. Temperature profiles for different values of S

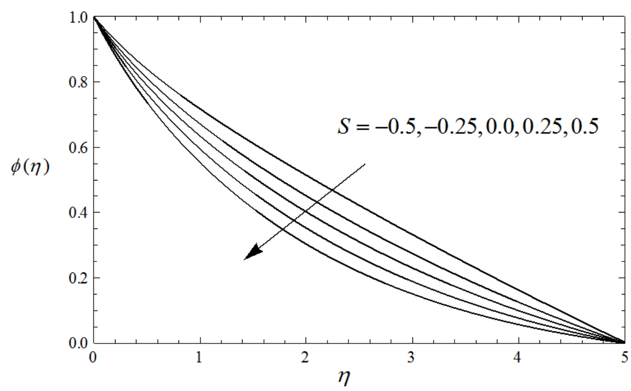

Fig. 11. Nanoparticle volume fraction profiles for different values of S

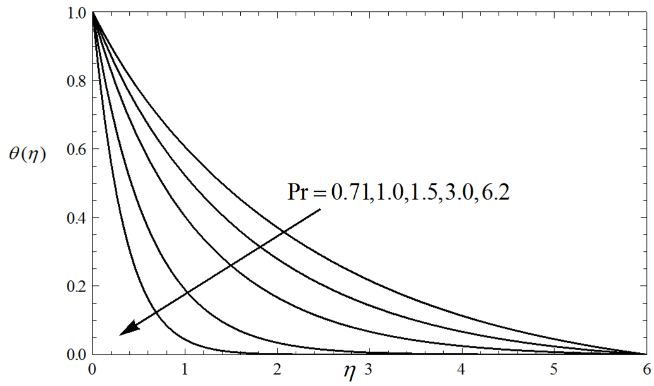

Fig. 12. Temperature profiles for different values of Pr

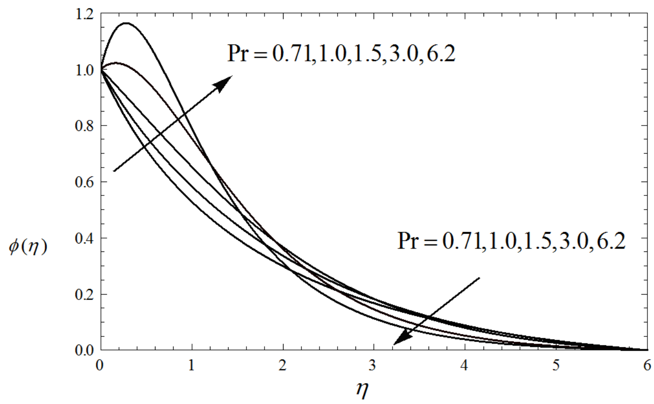

Fig. 13. Nanoparticle volume fraction profiles for different values of Pr

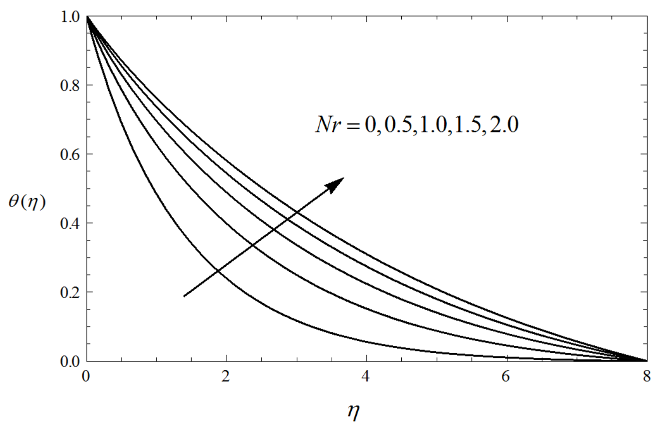

Fig. 14. Temperature profiles for different values of Nr

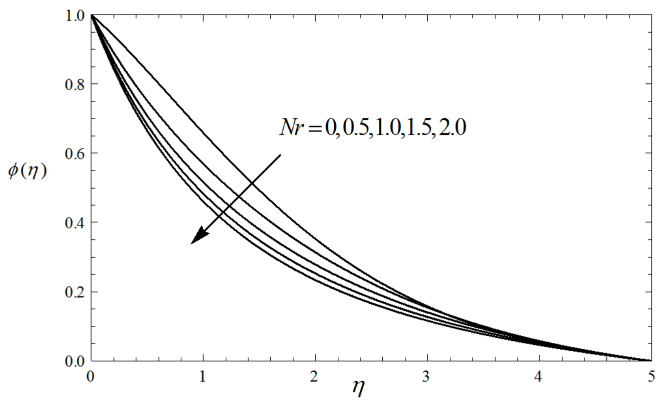

Fig. 15. Nanoparticle volume fraction profiles for different values of Nr

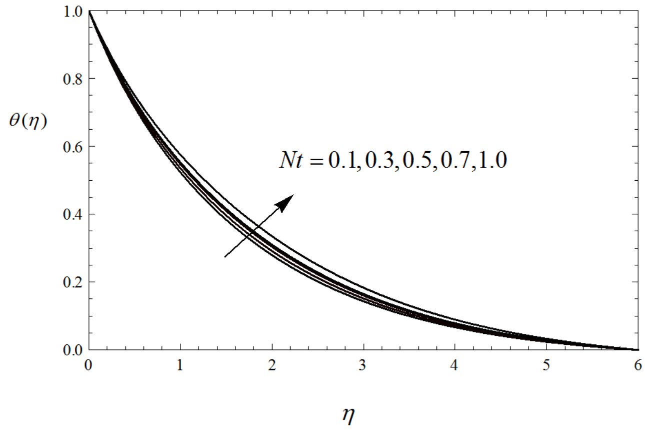

Fig. 16. Temperature profiles for different values of Nt

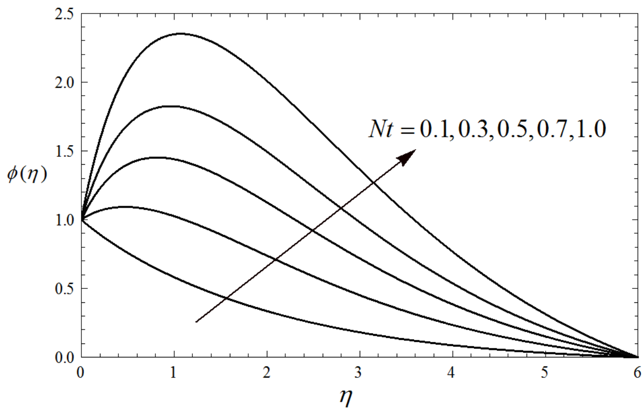

Fig. 17. Nanoparticle volume fraction profiles for different values of Nt

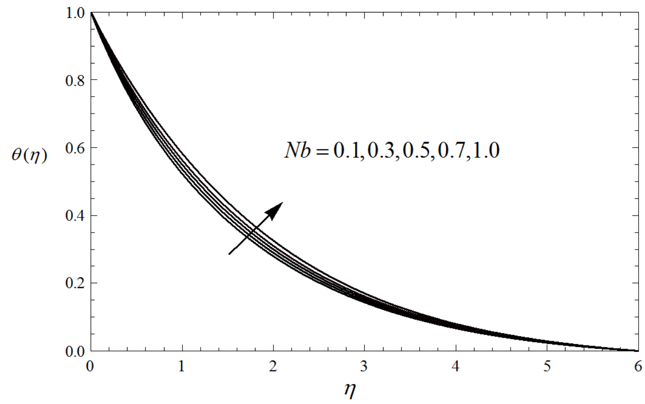

Fig. 18. Temperature profiles for different values of Nb

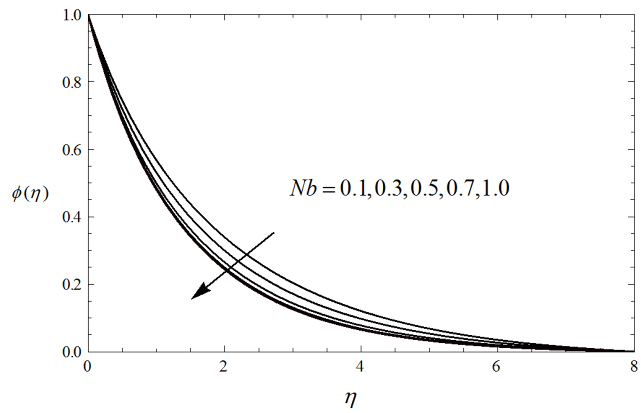

Fig. 19. Nanoparticle volume fraction profiles for different values of Nb

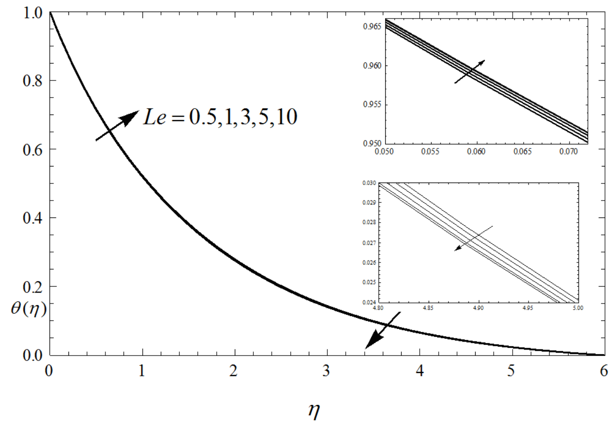

Fig. 20. Temperature profiles for different values of Le

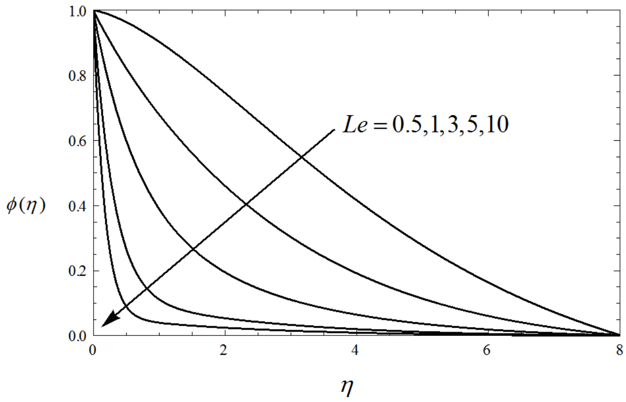

Fig. 21. Nanoparticle volume fraction profiles for different values of Le

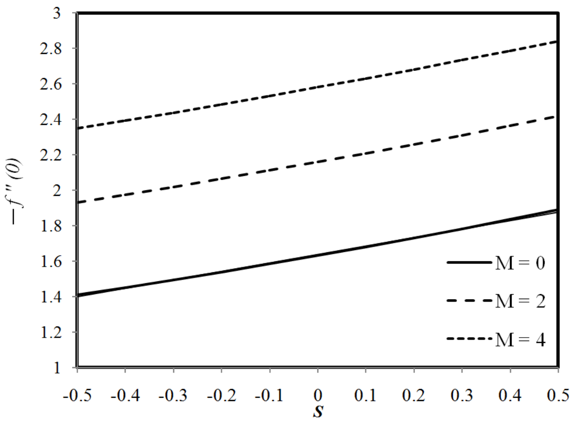

Fig. 22. Skin friction versus S for different M

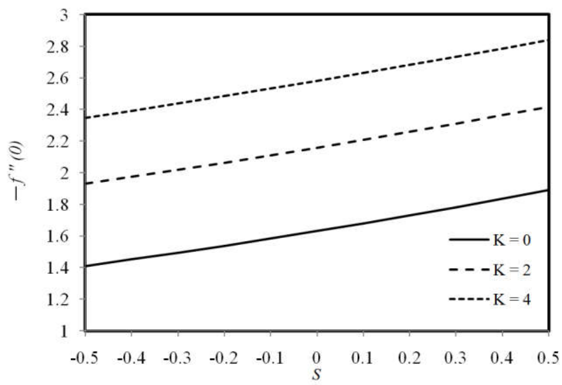

Fig. 23. Skin friction versus S for different K

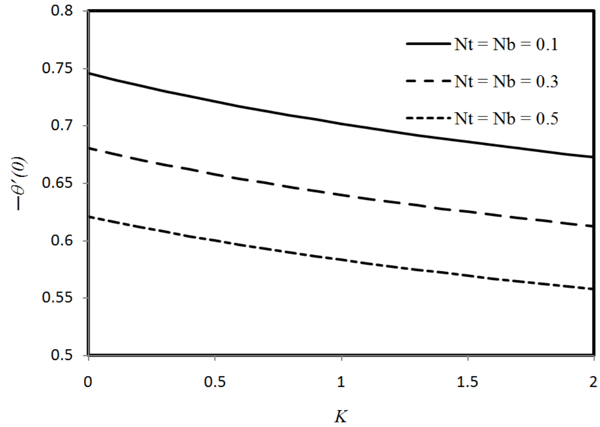

Fig. 24. Heat transfer versus K for different Nt and Nb

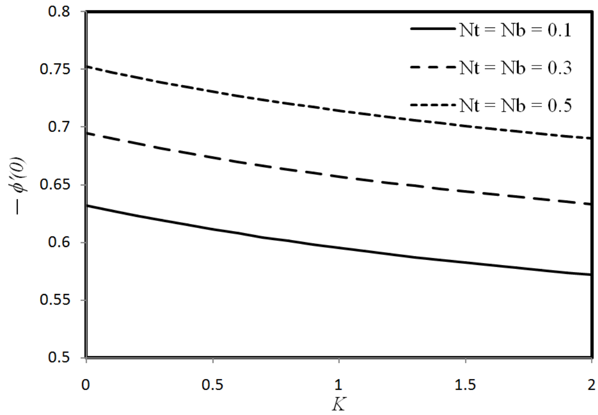

Fig. 25. Variation of with K for different Nt and Nb

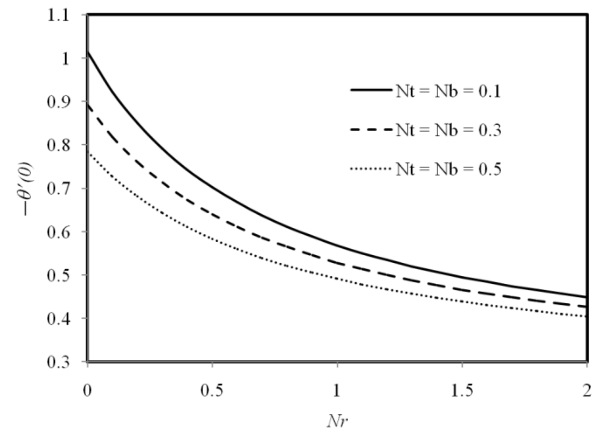

Fig. 26. Heat transfer versus Nr for different Nt and Nb

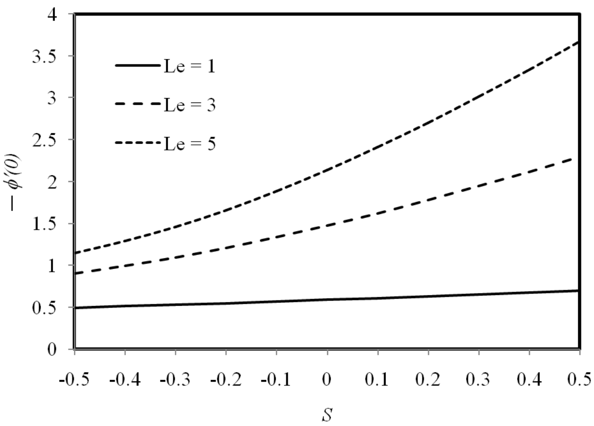

Fig. 27. Variation of with S for different Le

In order to bring out the salient features of the flow and the heat and mass transfer characteristics, the numerical results for different values of the governing parameters M, K, Pr, Nr, Nt, Nb and Le are plotted in Figs. 3 - 27. Throughout the calculations, the parametric values are taken to be Pr =1.0, S = 0.25, K = 1.0, Nt = 0.1, Nb = 0.1, Le =1.0, Nr = 0.5, M = 1.0. All the graphs correspond therefore these values unless specifically indicated on the appropriate graphs. Figs. 3, 4 and 5 depict the velocity, temperature and nanoparticle volume fraction profiles for different values of magnetic parameter M. Fig.3 shows that the velocity of the flow decreases with an increase in the magnetic parameter M. This can be explained physically as follows. As the strength of the magnetic field characterized by M increases, the Lorentz force which opposes the flow in the boundary layer also increases and leads to retardation of the motion of the fluid. From Figs.4 and 5, it is observed that the temperature as well as the concentration increases with an increase in M. The effect of transverse magnetic field on an electrically conducting fluid gives rise to a resistive type force called the Lorentz force. This force increases its temperature and nanoparticle volume fraction boundary layers.

Table 1. Comparison of results for $-f''(0)$ and $f(\infty)$ when $S=K=Nr=M=0$

	Magyari and Keller	Bhattacharyya and Layek	Present Results
$-f''(0)$	1.281808	1.28180838	1.2818123
$f(\infty)$	0.905639	0.90564328	0.9905636

The effect of permeability parameter K on the velocity, temperature and nanoparticle volume fraction is portrayed in Figs. 6 - 8. It is obvious that the presence of porous medium causes higher restriction to the fluid flow, which in turn slows its motion. Therefore, with increasing permeability parameter, the resistance to the fluid motion increases and hence velocity decreases (Fig.6). From Figs. 7 and 8, it is evident that both the temperature and concentration of the flow decrease with an increase in K. The velocity, temperature and nanoparticle volume fraction profiles for different values of suction or injection parameter S are shown in Figs. 9 - 11. With increasing values of the mass suction parameter (S> 0), the velocity, temperature and nanoparticle volume fraction in the boundary layer region decrease, whereas, due to the increase of mass injection (S< 0), all those increase. Due to mass suction, the fluids brought closer to the sheet and it thinner the velocity boundary layer thickness as well as the thermal and nanoparticle volume boundary layer thicknesses. Opposite effect is found for mass injection case i.e., the fluid is taken away from the sheet. Consequently, the velocity, thermal, and nanoparticle volume boundary layer thicknesses become broader. The influence of the Prandtl number Pr on the temperature and nanoparticle volume fraction are depicted in Figs.12 and 13, respectively. The increment of Prandtl number results in major effects on the temperature as well as on nanoparticle volume fraction. The thermal boundary layer thickness reduces with Prandtl number and it happens due to decrease of thermal diffusivity for the increment of Prandtl number. The nanoparticle volume fraction exhibits overshoot near the sheet for higher values of Pr, though the nanoparticle volume boundary layer thickness reduces. Hence, with uniform thermophoretic particle deposition, for larger values of Prandtl number the nanoparticle volume fraction is higher in the fluid adjacent to the sheet than the value at the wall. Fig. 14 and 15 explains the effect of radiation parameter on the temperature and nanoparticle volume fraction. It is observed that the temperature increases and nanoparticle volume fraction decreases for increasing values of Nr. This is because an increase in the radiation parameter Nr leads to decrease in the boundary layer thickness and enhances the heat transfer rate.

The effect of thermophoresis parameter Nt on the temperature and nanoparticle volume fraction are shown in Figs. 16 and 17 respectively. Thermophoresis parameter Nt is a key parameter for analysing the temperature distributions and nanoparticles volume fraction in nanofluid flow. From Figs. 16 and 17, it is evident that, the temperature of the fluid as well as the nanoparticle volume fraction increases with an increase in Nt. Increase in Nt causes increment in the thermophoresis force which tends to move nanoparticles from hot to cold areas and consequently it increases themagnitude of temperature profiles and nanoparticle volume fraction profiles. Ultimately, the thickness of nanoparticle volume boundary layer becomes significantly large for slightly increased value of thermophoresis parameter. The effect of Brownian motion parameter Nb on thetemperature and the nanoparticle volume fraction profiles is plotted in Figs. 18 and 19, respectively. From these figures, it is clear that the temperature of the fluid increases while the nanoparticle volume fraction decreases with an increase in Nb. In nanofluid system, due to the presence of nanoparticles, the Brownian motion takes place and for the increase in Nb the Brownian motion is affected and consequently the heat transfer characteristic of the fluid changes. Also, when the value of Nb increases, the nanoparticle volume boundary layer thickness decreases.

Figs. 20 and 21 depict that the temperature and nanoparticle volume fraction for different values of Lewis number Le. Very minor variation (initially increasing near the sheet and then decreasing away from the sheet) is observed in the temperature with the increase in the Lewis number. For large values of Le, the nanoparticle volume fraction significantly decreases and also the nanoparticle volume boundary layer thickness reduces. But, for smaller value of Le the overshoot is found in near the sheet. We now discuss the variations of the physical quantities of engineering importance, that is, the local skin friction coefficient C_f, the local Nusselt number Nu_x, and the local Sherwood number Sh_x for different values of $M, S, K, Le, Nb,$ and Nt. The quantities $-f''(0)$, $-\theta'(0)$, and $-\phi'(0)$ related to local skin friction coefficient, the local Nusselt number and the local Sherwood number, respectively, are plotted in Figs. 22-27. Fig. 22 shows that the variation of the skin friction (shear stress) versus the suction/injection parameter S for different values of magnetic parameter M. It is found that the skin friction increases with the simultaneous increase in $S$and M. The same behavior is observed in the case of porosity parameter K. It is evident from Fig. 23. The variation in dimensionless heat transfer rates and mass transfer rates at the wall versus the permeability parameter K is shown in Figs.24 and 25 respectively. It is noted that both the dimensionless heat and mass transfer rates decrease with an increase in K for different Nb and Nt. An increase in Nb and Nt together lead to an increase in the concentration rates. It is observed from Fig.26, the heat transfer rate decreases with an increase in radiation parameter *Nr.* Also it is evident that the rate of heat transfer decreases with the simultaneous increase in both *Nt* and *Nb*. Fig. 27 presents the effect of *Le* on the dimensionless mass transfer rate for blowing (S < 0) and suction (S > 0) cases. It is found for fixed value of *Le,* the value of heat transfer rate in the suction case is higher than it is in the blowing case. Also, in both cases of blowing and suction, an increase in *Le* leads to an increase in the heat transfer rate.

Conclusions

In the present investigation, the problem of a steady two dimensional hydromagneticboundary layer flow of a radiating nanofluid past an exponential stretching sheet embedded in a porous medium with suction/blowing is studied. The following conclusions may be drawn:

It is interesting to note that the impact of magnetic field, porosity parameter and thermal radiation in the presence of uniform thermophoresis and Brownian diffusion motion have a substantial effect on the flow field and, thus, on the heat transfer and nanoparticle volume fraction rate from the sheet to the fluid. Particularly, nanoparticles in the presence of Brownian diffusion motion with thermophoresis particle deposition have been the focus of much research recently because they possess attractive properties which could see potential use in catalysis, biomedicine, magnetic resonance imaging, data storage and environmental remediation. Hence, the subject of nanofluids is of great interest worldwide for basic and applied research.

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