Applied Science and Innovative Research
ISSN 2474-4972 (Print) ISSN 2474-4980 (Online)
Vol. 1, No. 2, 2017
www.scholink.org/ojs/index.php/asir

Effect of an Inclined Magnetic Field on the Flow of Nanofluids in a Tapered Asymmetric Porous Channel with Heat Source/Sink and Chemical Reaction

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Received: September 25, 2017 Accepted: October 4, 2017 Online Published: October 13, 2017

doi:10.22158/asir.v1n2p104 URL: http://dx.doi.org/10.22158/asir.v1n2p104

Abstract

This article deals with the effect of an inclined magnetic field with heat source/sink on the flow of nanofluids in a tapered asymmetric porous channel. Effect of chemical reaction has been taken into account. The blood is considered as an incompressible electrically conducting viscous fluid. The assumption of low Reynolds number and long wave length approximations has been adopted. Exact solutions for dimensionless axial velocity, concentration and temperature profile are obtained analytically. The obtained results are displayed and discussed in detail with the help of graphs for the variation of different emerging flow parameters.

Keywords

peristaltic flow, asymmetric porous channel, inclined magnetic field, heat and mass transfer, chemical reaction

1. Introduction

The nanofliuids have superior properties such as thermal conductivity, long-term stability, minimal closing in flow passages, and homogeneity due to small size and very large specific surface areas of nanoparticles. Hence, the nanofliuids have broad range of potential applications in pharmacological administration mechanisms, solar collectors, nuclear applications and peristaltic pumps for diabetic treatments, etc. The flow characteristics with heat and mass transfer over a stretching surface in porous channel have been attracted by many researchers in the recent path due to its enormous applications in different branches of biological and engineering fields such as wire drawing, hot rolling, metal extrusion, artificial fibers, etc. (Rana & Bhargava, 2002; Kothandapani & Srinivas, 2008; Bhattacharyya, 2013).

Several experimental and theoretical investigations have been done by the researchers for the flow analysis of nanofluids under various aspects. Nadeem et al. (2014) analyzed heat transfer of water-based nanofluid over an exponentially stretching sheet. Baheta and Woldeyohannes (2013) have studied the effect of particle size on thermal conductivity of nanofluids. Mutuku-Njane and Makinde (2014) analyzed the effects of MHD nanofluid flow over a permeable vertical plate with convective heating. The effects of slip and heat generation/absorption on MHD stagnation flow of nanofluid past a stretching/shrinking surface with convective boundary conditions has been discussed by Nandy and Mahapatra (2009). The flow and heat transfer of nanofluid past shrinking/stretching sheet with partial slip boundary conditions were also investigated by Mansur et al. (2014). Javed et al. (2011) investigated the heat transfer analysis for a hydromagnetic viscous fluid over a non-linear shrinking sheet. The MHD boundary-layer flow of a micropolar fluid past a wedge with constant heat flux was described by Anuar Ishak et al. (2013). Akbar and Nadeem (2010) reported the simulation of heat and chemical reactions on Reiner Rivlin fluid model for blood flow through a tapered artery with a stenosis. The MHD flow has got considerable attention in the last few decades due to its effect on the boundary layer flow control and applications in various branches of physical and engineering fields. Tripathi and Anwar (2012) considered a study of unsteady physiological magneto-fluid flow and heat transfer through a finite length channel by peristaltic pumping. Chamkha et al. (2011) analyzed the melting effect on unsteady hydromagnetic flow of a nanofluid past a stretching sheet. The influence of heat source/sink on a Maxwell fluid over a stretching surface with convective boundary condition in the presence of nanoparticles has been demonstrated by Ramesh and Gireesha (2014). Analytical solution for heat and mass transfer of MHD slip fluid in nanofluids has been derived by Nohreh abadi and Ghalambaz (2012). Kameshwaran et al. (2012) examined the hydromagnetic nanofluid flow due to stretching or shrinking sheet with viscous dissipation and chemical reaction effects. The radiation and inclined magnetic field effects on unsteady hydromagnetic free convection flow past an impulsively moving vertical plate in a porous medium has been analyzed by Sandeep and Sugunamma (2014). The radiation effect on the flow and heat transfer over an unsteady stretching sheet was investigated by El-Aziz (2009). Some other important investigations in the direction of radiation and mass transfer effect in various aspects were made by Rohni et al. (2012), Motsumi and Makinde (2012), Kumaran et al. (2011). Thermal diffusion, radiation and inclined magnetic field effects on oscillatory flow in an asymmetric channel in presence of heat source and chemical reaction has been studied by Ajaz and Elangovan (2016). The effect of inclined magnetic field and Hall current on the micropolar fluid model of blood flow through stenotic arteries in a porous medium has been studied by Ajaz and Elangovan (2016). Recently, Ajaz and Elangovan (2016a, 2016b) observed the influence of inclined magnetic field on the peristaltic flow of blood by considering blood as a micropolar fluid. Ajaz and Elangovan (2017) studied the influence of an inclined magnetic field on heat and mass transfer of the peristaltic flow of a couple stress fluid in an inclined channel.

In thermal convection, the effects of temperature field as modified by heat source/sink in moving fluids are considerable attention in many physical problems. Krishnamurthy et al. (2015) have studied the effect of viscous dissipation on hydromagnetic fluid flow and heat transfer of nanofluid over an exponentially stretching sheet with fluid-particle suspension. Hakeem et al. (2014) illustrated the effect on partial slip on hydromagnetic flow over a porous stretching sheet with non-uniform heat source/sink, thermal radiation and wall mass transfer past a stretching porous sheet in presence of radiation. Mukhopadhyay and Layek (2008) have discussed the effects of thermal radiation and variable fluid viscosity on the free convective flow and heat transfer past a porous stretching surface. Anjali Devi and Ganga (2009) have studied the viscous dissipation effects on non-linear MHD flow in a porous medium over a stretching porous surface. Norihan and Arifan (2011) investigated the viscous flow due to a permeable shrinking/stretching sheet in a nanofluid. The effect of chemical reaction and thermal radiation on heat and mass transfer flow of MHD micropolar fluid in a rotating frame of reference was investigated by Das (2011). Many researchers contributed the important investigations in this direction (Muthucumaraswamy et al., 2006; Pal et al., 2012; Pal & Mandal, 2014). More recently, Raju et al. (2015) investigated the radiation, and inclined magnetic field and cross-diffusion effects on flow over stretching surface. The radiation and magnetic field effects on unsteady natural convection flow of a nanofluid past an infinite vertical plate with heat source was studied by Mohankrishna et al. (2014).

In view of the above facts, the aim of the present investigation is to study the effect of an inclined magnetic field on the flow of nanofluids in a tapered asymmetric porous channel with heat source/sink and chemical reaction. The highly non-linear differential equations are solved by simply using the low Reynolds number and high wavelength approximation approach. The expressions of velocity, temperature and concentration distribution are obtained which are shown and discussed with the help of graphs for the variations of different flow parameters.

2. Mathematical Formulations

Consider the peristaltic transport of nanofluid in an asymmetric non-uniform as shown in Figure 1. Let Y = -H_1 and Y = H_2 be the right and left wall boundaries of the tapered asymmetric channel respectively. The geometry of the wall surfaces is defined as

$$H_1'(X', t') = d + m'X' + a_2 sin\left[\frac{2\pi}{\lambda}(X' - ct')\right] \quad \text{left wall,} \tag{1}$$

$$H_2'(X', t') = -d - m'X' - a_1 sin\left[\frac{2\pi}{\lambda}(X' - ct') + \phi\right] \quad \text{right wall,} \tag{2}$$

where a_1, a_2 are the amplitudes of right and left walls respectively. c is the phase speed of the wave, d is the half-width of the channel, λ is the wave length, the phase difference ϕ.

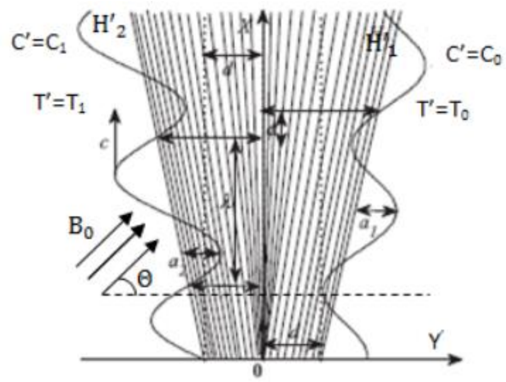


Figure 1. Geometry of the Problem

varies in the range $\phi(0 \leq \phi \leq \pi)$, $\phi = 0$ corresponds to symmetric channel with waves out of phase, that is both walls move towards inward or outward simultaneously and $m'(<<< 1)$ is the non-uniform parameter respectively. Moreover, a_1, a_2, d, and ϕ satisfy the following relation

$$a_1^2 + a_2^2 + 2a_1a_2\cos\phi \leq (2d)^2 \tag{3}$$

The field equations governing the flow are described as

$$\frac{\partial U'}{\partial X'} + \frac{\partial V'}{\partial Y'} = 0 \tag{4}$$

$$\rho_f\left[\frac{\partial U'}{\partial t'} + U'\frac{\partial U'}{\partial X'} + V'\frac{\partial U'}{\partial Y'}\right] = -\frac{\partial P'}{\partial X'} + \mu\left(\frac{\partial^2 U'}{\partial X'^2} + \frac{\partial^2 U'}{\partial Y'^2}\right)$$

$$-\sigma B_0^2 s\Theta[U'\cos\Theta - V'\sin\Theta]$$

$$-\frac{\mu}{K'}U' + (1 - C_0)\rho_f g\alpha(T' - T_0) + (\rho_p - \rho_f)g\beta(C - C_0) \tag{5}$$

$$\rho_f[\frac{\partial V'}{\partial t'} + U'\frac{\partial V'}{\partial X'} + V'\frac{\partial V'}{\partial Y'}] = -\frac{\partial P'}{\partial Y'} + \mu(\frac{\partial^2 V'}{\partial X^2} + \frac{\partial^2 V'}{\partial Y'^2}) - \frac{\mu}{K'}V'$$

$$+\sigma B_0^2\sin\Theta\,[U'\cos\Theta - V'\sin\Theta] \tag{6}$$

$$(\rho c')_f[\frac{\partial T'}{\partial t'} + U\frac{\partial T'}{\partial X'} + V\frac{\partial T'}{\partial Y'}] = k(\frac{\partial^2 T'}{\partial X'^2} + \frac{\partial^2 T'}{\partial Y'^2}) + Q'(T' - T_0)$$

$$+(\rho c')_p D_B(\frac{alC'}{\partial X'}\frac{\partial T'}{\partial X'} + \frac{\partial C'}{\partial Y'}\frac{\partial T'}{\partial X'}) + \frac{D_T(\rho c')_p}{T_m}[(\frac{\partial^2 T'}{\partial X'^2} + \frac{\partial^2 T'}{\partial Y'^2})] \tag{7}$$

$$[\frac{\partial C'}{\partial t'} + U'\frac{\partial C'}{\partial X'} + V'\frac{\partial C'}{\partial Y'}] = D_B[\frac{\partial^2 C'}{\partial X'^2} + \frac{\partial^2 C'}{\partial Y'^2}] + \frac{D_T}{T_m}[\frac{\partial^2 T'}{\partial X'^2} + \frac{\partial^2 T'}{\partial Y'^2}] \tag{8}$$

where U' and V' are the velocity components along X, Y directions respectively. Moreover, ρ_f, ρ_p, μ, σ, K, Θ, B_0, g, β, T, t, k, c_p, are density of the fluid, density of the particle,viscosity, electrical conductivity of the fluid, porous parameter, inclination angle of magnetic field, applied magnetic field, acceleration due to gravity, volumetric expansion co-efficient, temperature, time, thermal conductivity, specific heat at constant pressure respectively. In order to derive the fluid flow, let us introducing the dimensionless variables and parameters as follows:

$$x=\frac{X'}{\lambda}, y=\frac{Y'}{d}, u=\frac{U'}{c}, v=\frac{V'}{\delta c}, p=\frac{d^2p'}{c\lambda\mu}, t=\frac{ct'}{\lambda}, h_1=\frac{H_1{}'}{d}, h_2$$

$$=\frac{H_2{}'}{d}, a=\frac{a_1}{d},$$

$$b=\frac{a_2}{d}, \delta=\frac{d}{\lambda}, Re=\frac{\rho_f cd}{\mu}, Pr=\frac{\mu c_f}{k}, \theta=\frac{T-T_0}{T_1-T_0}, G_r=\frac{(1-C_o)\rho_f g\alpha(T_1-T_0)d^2}{c\mu},$$

$$K=\frac{K'}{d^2}, m=\frac{\lambda m'}{\mu}, M^2=\frac{\sigma B_0^2 d^2}{\mu}, B_r=\frac{(\rho_p-\rho_f)g\beta(C_1-C_0)d^2}{c\mu}, N_b=\frac{\tau D_B(C_1-C_0)}{\nu},$$

$$N_t=\frac{\tau D_T(T_1-T_0)}{\nu}, \Phi=\frac{C'-C_0}{C_1-C_0}. \tag{9}$$

where x and y are the axial co-ordinate, transverse co-ordinate respectively. u and v denotes the axial velocity and transverse velocity respectively. Moreover, δ, ϕ, R_e, Pr, G_r, M, N_b, N_t and B_r are wave number, phase difference, Reynolds number, Prandtl number, Grashof number, Hartmann number, Brownian motion parameter, thermophoresis parameter and local nanoparticle Grashof number respectively. By using the above non-dimensional variables and parameters from Equation (9) in Equations. (5)-(8) and applying the low Reynolds number and high wavelength approximation approach, we arrive at

$$0=\frac{\partial p}{\partial x}+\frac{\partial^2 u}{\partial y^2}-(\frac{1}{K_1}+M^2cos^2\Theta)u+G_r\theta+B_r\phi \tag{10}$$

$$0=\frac{\partial p}{\partial y} \tag{11}$$

$$0=(\frac{\partial^2\theta}{\partial y^2})^2+P_rN_b(\frac{\partial\phi}{\partial y}\frac{\partial\theta}{\partial y})+N_t(\frac{\partial^2\theta}{\partial y^2})^2+Q\theta \tag{12}$$

$$0=(\frac{\partial^2\phi}{\partial y^2})+(\frac{N_t}{N_b})(\frac{\partial^2\theta}{\partial y^2})^2 \tag{13}$$

The corresponding dimensionless boundary conditions are

$$\begin{gathered} u=0,\ \theta=0,\ \Phi=0 \ \text{ at} \\ y=h_1=-1-mx-a\sin[2\pi(x-t)+\phi] \end{gathered} \tag{14}$$

$$\begin{gathered} u=0,\ \ \theta=1,\ \ \Phi=1 \ \text{ at} \\ y=h_2=1+mx+b\sin[2\pi(x-t)] \end{gathered} \tag{15}$$

3. Method of Solution

Integrating Equation (13) twice with respect to y, and applying the boundary conditions (14), (15), the value of Φ becomes

$$\Phi+\frac{N_t}{N_b}\theta+\frac{N_b+N_t}{(h_1-h_2)N_b}y-\frac{h_1(N_b+N_t)}{(h_1-h_2)N_b}=0 \tag{16}$$

Solving Equation (12) after substituting the value of Φ and applying the boundary conditions (14), (15), we have

$$\theta = A_3\left(-e^{\frac{1}{2}A_2(y-h_2)}\right)\sinh\left(A_4(y-h_1)\right) \tag{17}$$

$$A_2 = \frac{P_r(N_b+N_t)}{h_1-h_2}$$

$$A_3 = \mathrm{Csch}\left[\frac{1}{2}A_4(h_1-h_2)\right]$$

$$A_4 = \frac{1}{2}\sqrt{}\left(-4Q+{A_2}^2\right)$$

Using Equation (17) in Equation (16), we have

$$\Phi = A_5(-U) - A_6(y-h_1) \tag{18}$$

where

$$A_5 = \frac{N_t}{N_b}$$

$$A_6 = \frac{(N_b+N_t)}{(h_1-h_2)N_b}$$

Using the values of θ and Φ in Equation (10) and applying the boundary conditions, the velocity expressions becomes

$$\begin{aligned} u = {} & e^{\sqrt{A_5}(-y)}\left(A_5\left(C_1\left(e^{\sqrt{A_5}(h_1+2y)} - e^{\sqrt{A_5}(2h_1+y)} - e^{\sqrt{A_5}(h_2+2y)} + e^{\sqrt{A_5}(2h_2+y)} + A_9\right)\right)\right) \\ & + e^{\sqrt{A_5}(-y)}\left(A_5\left(A_2G_r\left(e^{\sqrt{A_5}(2h_1+y)} - e^{\sqrt{A_5}(2h_2+y)}\right)\sinh\left(A_1(y-h_1)\right)\right)\right) \\ & + e^{\sqrt{A_5}(-y)}\left(A_5\left(A_5A_7left(-\left(e^{\sqrt{A_5}(h_1+h_2)} + e^{2\sqrt{A_5}y}\right)\right) + A_{10}\left(e^{\sqrt{A_5}(h_2+2y)} - e^{\sqrt{A_5}(2h_1+h_2)}\right)\right) \\ & + e^{\sqrt{A_5}(-y)}\left(A_7A_1^2\left(C_1e^{\sqrt{A_5}(h_1+y)} + C_1e^{\sqrt{A_5}(h_2+y)} - C_1e^{2\sqrt{A_5}y} \right.\right. \\ & \left.\left. + A_5e^{2\sqrt{A_5}y} + A_8\right)\right)/A_6 \end{aligned} \tag{19}$$

where

$$A_7 = (G_r - A_5B_r)A_3$$
$$A_8 = B_rA_6$$
$$A_9 = \left(A_1\left(4A_1 - 4\sqrt{A_1}A_2 + A_2^2 - 4A_4^2\right)\left(4A_1 + 4\sqrt{A_1}A_2 + A_2^2 - 4A_4^2\right)\right)$$
$$A_{10} = 16A_1^2A_8h_1 - 8A_1A_2^2A_8h_1 + A_2^4A_8h_1 - 32A_1A_4^2A_8h_1 - 8A_2^2A_4^2A_8h_1 + 16A_4^4A_8h_1$$

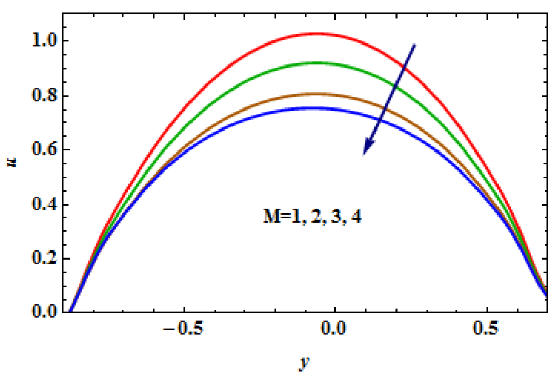
4. Results and Discussion

The purpose of this section is to discuss the numerical and computational results with the help of graphical illustrations. The influence of different emerging physical parameters has been discussed with particular importance. Figure 2 illustrates the variation of axial velocity for different values of the Hartmann number (M), Brownian motion parameter (N_b), thermophoresis parameter (N_t), heat source/sink parameter (Q), non-uniform parameter (m), local nanoparticle Grashof number (B_r), and permeability parameter (K_1).

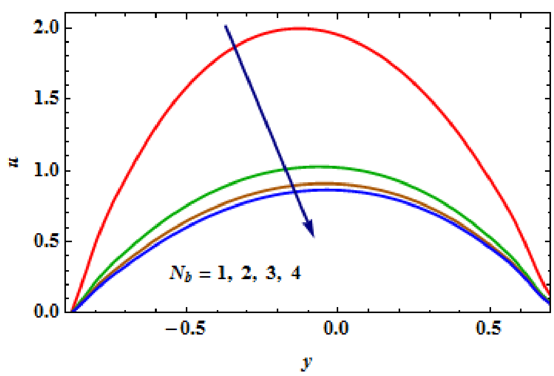
From Figures 2(a)-(b), it is observed that the axial velocity decreases by increasing the Hartmann number (M) and Brownian motion parameter (N_b). From Figures 2(c)-(h), it is depicted that the velocity increases by increasing thermophoresis parameter (N_t), heat source/sink parameter (Q), non-uniform parameter (m), local nanoparticle Grashof number (B_r), and permeability parameter (K_1).

Figure 3 illustrates the variation of temperature profile (θ) for different values Brownian motion parameter (N_b), thermophoresis parameter (N_t) and Prandtl number P_r. From Figure 3(a)-(c), It is observed that the temperature increases by increasing the values of Brownian motion parameter (N_b) and thermophoresis parameter (Nf_t) and Prandtl number (P_r). Figures 3(d)-(e), it is depicted that the temperature profile decreases by increasing the values heat generation and absorption parameter (Q).

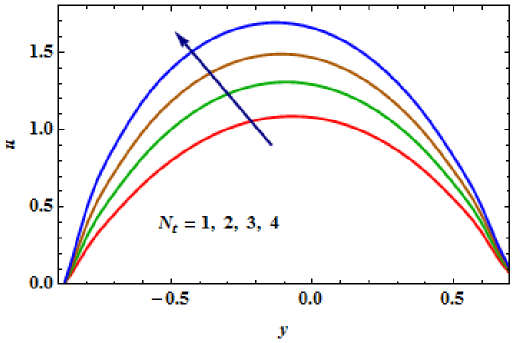
The variation of concentration profile for different values of physical parameters has been illustrated in Figure 4. From Figures 4(a)-(c), It is observed that the concentration profile decreases by increasing Brownian motion parameter (N_b), thermophoresis parameter (N_t) and Prandtl number P_r. From Figures 4(d)-(e), we can find that the concentration profile increases by increasing the heat source/sink parameter (Q).

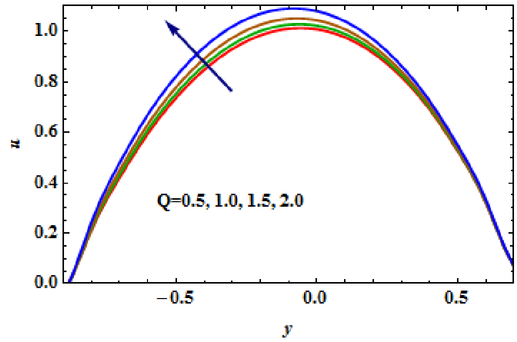


2(a)

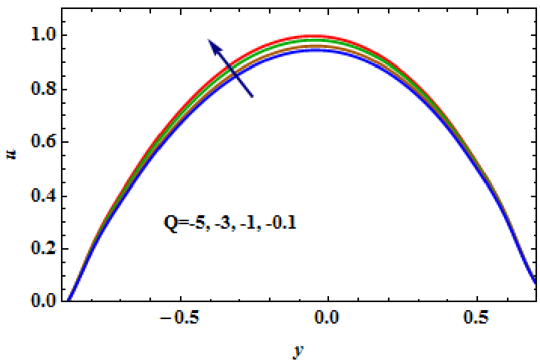


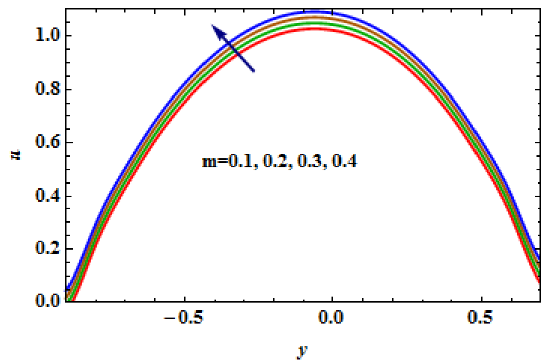
2(b)



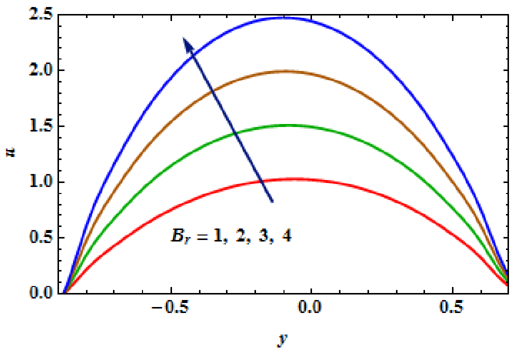


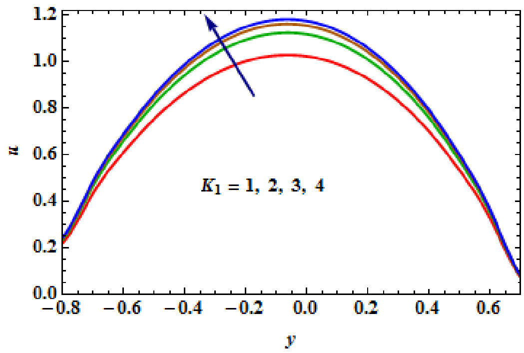
2(c) **2(d)**





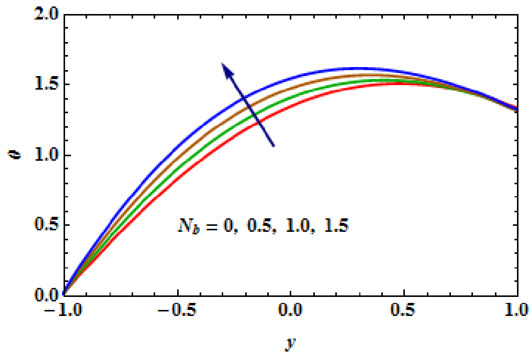
2(e) **2(f)**



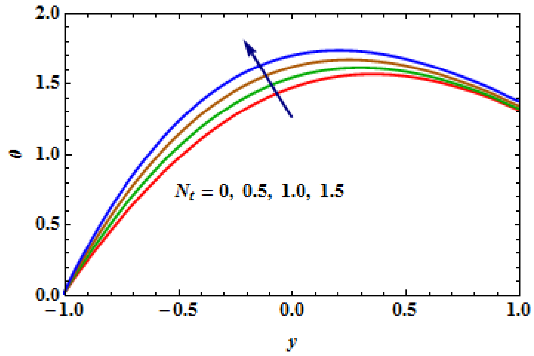


2(g) **2(h)**

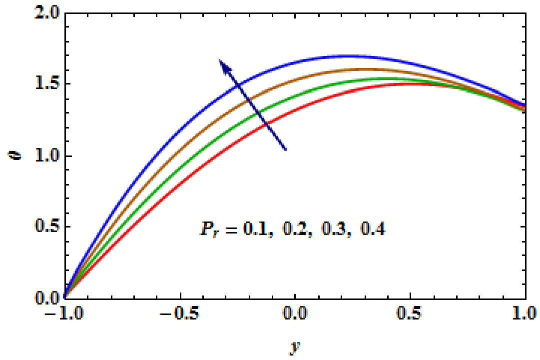
Figures 2(a-h). Variation of M, N_b, N_t, $\pm Q$, m, B_r and K_1 over the Axial Velocity (u) with Respect to y at $a = 0.5, b = 0.5, d = 2, \frac{dp}{dx} = -3, x = 0$



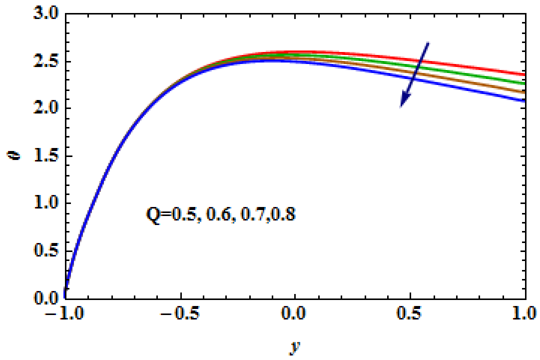
3(a)



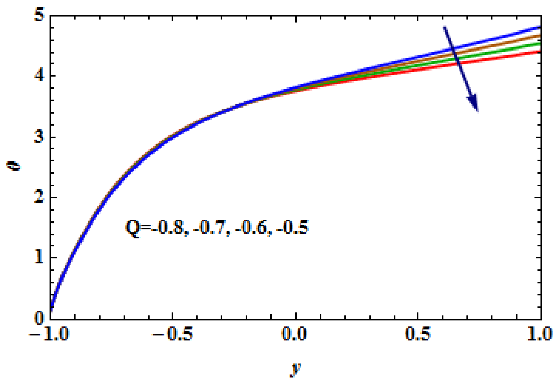
3(b)



3(c)

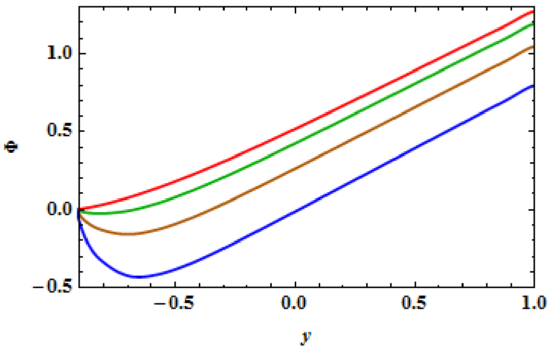


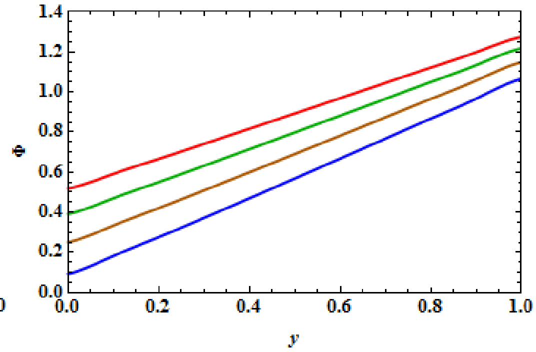
3(d)



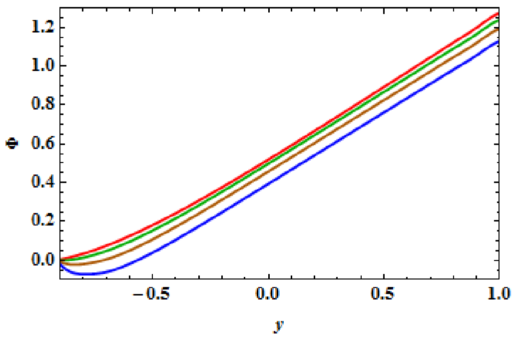
3(e)

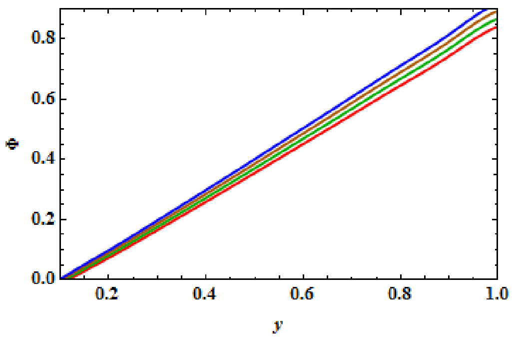
Figures 3(a-e). Variation of N_r, ϕ, P_r, Q **over the Temperature Profile** (θ) **with Respect to y with** $a = 0.5, b = 0.5, d = 2, x = 0$



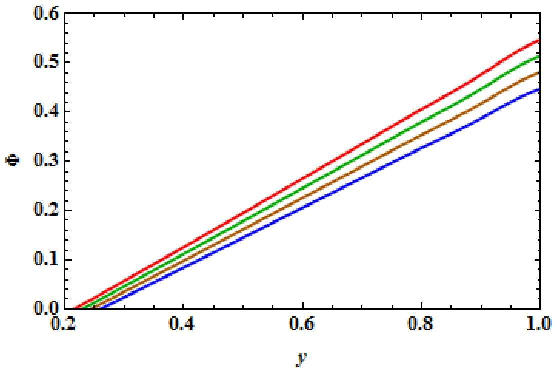


4(a) **4(b)**





4(c) **4(d)**



4(e)

Figures 4(a-e). Variation of N_r, ϕ, P_r, Q **over the Concentration Profile** Φ **with Respect to y with** $a = 0.5, b = 0.5, d = 2, x = 0$

4. Conclusion

In this article, we have studied the effect of an inclined magnetic field on the flow of nanofluids in a tapered asymmetric porous channel with heat source/sink. The governing equations of the flow are solved analytically and the effects of various flow parameters on axial velocity, temperature profile and concentration profile are discussed finally. We conclude the main observations are enlisted below:

a) By increasing the values of Brownian motion parameter, the axial velocity decreases.

b) The axial velocity of a fluid increases by increasing the thermophoresis parameter, heat source/sink parameter, non-uniform parameter (m), local nanoparticle Grashof number and porous parameter.

c) The Grashof number and thermal radiation parameter show similar behavior on the axial velocity.

d) The temperature of the fluid increases by increasing Brownian motion parameter, thermophoresis parameter and Prandtl number.

e) Heat source and heat sink parameters show similar effects on temperature profile.

f) The concentration profile decreases by increasing Brownian motion parameter, thermophoresis parameter and Prandtl number.

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