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Effect of mixed convection flow of a Jeffrey nanofluid in a vertical channel with slip

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Abstract

Mixed convective flow of a Jeffrey nanofluid in a vertical channel with the effect of heat source/ sink, velocity slip, thermal conductivity variation and wall concentration variation is investigated. Exact solutions are obtained for dimensionless temperature, nanoparticle fraction and the velocity field. It is observed that the temperature of the fluid increases with increase the source or sink parameter. The wall concentration ratio decreases the rate of nanoparticle volume fraction. When the temperature ratio parameter (m_2), wall concentration ratio parameter (m_1), slip parameter (L), Jeffrey parameter (λ_1) tends to zero our results are good in agreement with the result of Michael O. Oni and Bagant K. Jha [21].

Keywords: Jeffrey nanofluid, vertical channel, Heat source or sink, slip, nanoparticle fraction

Nomenclature

λ_1	Jeffrey parameter	g	acceleration due to gravity
μ	dynamic viscosity	h	distance between two parallel walls
ρ	Density	Nb	Brownian motion parameter
υ	kinematic viscosity	Nr	buoyancy ratio parameter
T	dimensional temperature	Q_0	dimensional heat source/ sink parameter
θ	dimensionless temperature	Re	Reynolds number
K	thermal conductivity	S	dimensionless heat source/ sink parameter
ϕ	rescaled nanoparticle fraction	V	dimensional velocity vector
β_0	thermal expansion coefficient	u,v	velocity components
L	slip parameter	U	dimensionless velocity
p	Pressure	x,y	Cartesian coordinates
c	heat capacity at constant pressure	X,Y	Dimensionless Cartesian coordinates
C	nanoparticles volume fraction	m_2	wall temperature ratio
Gr	Grashof number	m_1	wall concentration ratio

D_B	Brownian diffusion coefficient	D_T	thermophoretic diffusion coefficient
Subscript f : Fluid		Subscript p : solid particle	

Introduction:

The significance of heat and mass transfer in modern engineering and scientific devices cannot be overstated. These applications encompass a wide range of areas, such as solar energy collection, cooling systems for electronics and micro-electronic equipment, heat sinks, nuclear waste disposal, exothermic reactions in catalytic beds, and the underground dispersion of chemical wastes and pollutants. Recent research and literature in this field have focused on comprehending heat and mass transfer phenomena in mixed convection flow within various geometries. Numerous articles have been dedicated to exploring and understanding these processes, considering their critical role in enhancing the performance and efficiency of innovative technologies and devices.

It has been demonstrated throughout the years that because of their weak thermal conductivity, common heat transfer fluids like water and oil perform poorly in heat transmission. This problem was addressed by researchers who tried to increase the fluid's thermal conductivity by suspending nanoparticles of metals, oxides, and carbides. The word "nanofluid" refers to these liquids that include nanometer-sized particles. These nanofluids provide superior attributes and applications to conventional fluids in terms of heat and mass transmission, heat exchanger, nuclear cooling, vehicle thermal management, and solar collecting.

Navier slip is a concept in fluid dynamics that describes the behavior of fluid flow near solid boundaries, such as walls or surfaces. It refers to the phenomenon where a fluid's velocity at the boundary does not match the velocity of the solid surface. Instead of adhering completely to the no-slip condition, where the fluid sticks to the solid surface and has zero velocity relative to it, the fluid exhibits a non-zero velocity at the boundary. In the context of Navier-Stokes equations, which describe the motion of fluid substances, Navier slip can be incorporated through a slip boundary condition. Navier slip has practical implications in various engineering applications, such as microfluidic devices, nanofluidic systems and thin film flows. It can significantly affect the overall behavior of fluid flow near boundaries, and understanding slip effects is crucial for accurately modeling and predicting fluid flow in such systems.

Beckett [1] investigated the combined natural and forced convection between parallel vertical walls. In a vertical channel with unequal wall temperatures, developing flow and flow reversal were examined by Aung and Work [2]. Choi [3] conducted a study focused on the augmentation of thermal conductivity in fluids through the use of nanoparticles. Choi et al. [4] demonstrated that the inclusion of a small quantity of nanoparticles in conventional heat transfer fluids can lead to an approximate doubling of the fluid's thermal conductivity. In order to study convective transport in nanofluids, Buongiorno [5] created a mathematical model and noted that the combined effect of the base fluid velocity and the slip velocity may be seen as the absolute velocity of nanoparticles. Srinivas and Muthuraj [6] investigated the peristaltic transport of a Jeffrey fluid in an inclined asymmetric channel, considering the influence of slip effects. Chamkha and Aly [7] have explored the MHD free convection flow of a nanofluid across a vertical plate while taking into account the effects of heat production and absorption. Prathap Kumar et al. [8] examined the behavior of magnetohydrodynamic (MHD) mixed convection flow in a vertical channel. The study focused on investigating the movement of a viscous fluid under the influence of magnetic fields and with the presence of both forced convection (induced by an external source) and natural convection effects. Grosan and Pop [9] investigated the steady, fully developed mixed convection flow in a nanofluid-filled space between two vertical parallel plates. The study focused on analyzing the effects of asymmetrical thermal and nanoparticle concentration conditions at the walls. Umavathi and Liu [10] conducted a study that explored the behavior of laminar magnetohydrodynamic convective flow in a vertical channel. The study specifically considered the presence of heat production and absorption within the system. The investigation aimed to understand how these factors influenced the flow characteristics and heat transfer processes in the channel. Kuznetsov and Nield [11] investigated the natural convective boundary-layer flow of a nanofluid across a vertical plate. Hayat et al. [12] conducted a study examining the mixed convection flow of a non-Newtonian nanofluid over a stretching surface. The investigation took into account the effects of thermal radiation, heat source/sink and a first-order chemical reaction. In their study, Oyelakin et al. [13] investigated the flow of an unsteady Casson nanofluid over a stretching sheet. They analyzed the impact of thermal radiation, convective boundary conditions, and slip at the boundaries on the flow behavior. Sheikholeslami and Oztop [14] studied numerical simulations and analyses of the fluid flow and heat transfer characteristics of the nanofluid inside the sinusoidal-walled cavity under the influence of magnetic fields using the CVFEM approach. The study might investigate how parameters such as nanoparticle volume fraction, magnetic field strength, and cavity geometry impact the flow and heat transfer behavior of the nanofluid. Sushma and Sreenadh [15] studied the flow of a Casson nanofluid between parallel plates in a vertical channel, specifically investigating its behavior under fully developed laminar mixed convection conditions. In a vertical micro-concentric annulus with a heat-generating/absorbing fluid, Jha et al. [16] examined steady fully developed mixed convection flow. Umavathi et.al. [17] analyzed mixed convective flow in a vertical channel with isothermal walls, filled with an electrically conducting viscous fluid, considering variable properties. It specifically examines the combined influence of temperature-dependent viscosity and temperature-dependent thermal conductivity on the flow behavior.

The study of nanofluid impacts on convection flows has received a lot of interest in recent years. Agbaje and Leach [18] studied the incompressible viscoelastic Jeffrey's nanofluid boundary layer flow from a vertical permeable flat plate while taking into account the impacts of heat production, thermal radiation, and chemical reaction on the fluid flow. The impact of Navier slip on natural convective flow and heat transfer of a viscous incompressible fluid contained within a channel made up of a long, vertically undulating wall and a parallel flat wall was examined by Gbadeyan et al. [19]. An analytical investigation on the impacts of Navier slip and heat transmission in a nanofluid flow across a stretching/shrinking sheet was given by Vishalakshi et al. [20]. In a vertical channel filled with a nanofluid, Oni and Jha [21] evaluated the effect of heat generation and absorption on mixed convection flow and found that the constant heat source/sink scenario transmits more heat than the temperature dependent heat source/sink case. Thanesh Kumar et al. [22] examined the influence of heat and mass transfer on a mixed convection flow field with a porous matrix in a vertical channel analytically. Using a constant boundary layer for the two-dimensional flow, Reddappa et al. [23] investigated the flow of a magnetohydrodynamic Jeffrey nanofluid across an exponentially stretched sheet in a porous medium.

In view of the above studies, we investigated the effect of heat source/ sink with and without dependent temperature and concentration ratio parameters on the mixed convective flow of a Jeffrey nanofluid in a vertical channel. The effects of different physical parameters on the Jeffrey nanofluid flow are analyzed through graphs.

Mathematical formulation

Consider the mixed convective flow of a Jeffrey nanofluid with the influence of dependent wall temperature, concentration and slip effect in a vertical channel. The channel is of width h and the slip condition is applied on fluid velocity. T_1 and C_1 are the temperature and nanoparticle concentration at the wall $y=0$ whereas T_2 and C_2 are the temperature and nanoparticle concentration at the wall $y=h$ with the condition $T_2>T_1$ and $C_2>C_1$. This temperature difference results to density difference at the walls which setups natural convection in the vertical channel.

The constitutive equations for an incompressible Jeffrey fluid are (Vajravelu *et al*. [24])

$$\tau=-pI+S \tag{1}$$

$$S=\frac{\mu_1}{1+\lambda_1}\left(\dot{\gamma}+\lambda_2\ddot{\gamma}\right) \tag{2}$$

where τ and S represent Cauchy stress tensor and extra stress tensor respectively, p is the pressure, I is the identity tensor, λ_1 is the ratio of relaxation to retardation times, λ_2 is the retardation time, $\dot{\gamma}$ is shear rate, and a dot over the quantities indicates differentiation with respect to time.

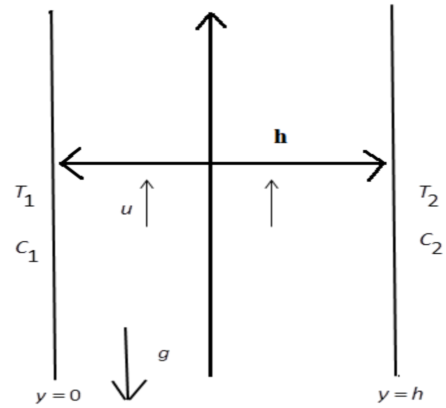

Fig. 1. Physical model

The fluid is heat conducting i.e., both heat generating (source) or absorbing (sink) fluid, viscous and Oberbeck - Boussinesq approximation is valid. Here we considered constant heat and source or sink. In this case a uniform heat source/sink is assume throughout the fluid formation and is independent on temperature increase or decrease.

$$\frac{\partial p}{\partial x}=\frac{dp}{dx}=constant, v=0, \frac{\partial u}{\partial x}=0, \frac{\partial T}{\partial x}=0, \frac{\partial c}{\partial x}=0, \frac{\partial p}{\partial y}=0.$$

The equations governing the fluid flow with above assumptions are given below:

$$\left(\frac{\mu}{1+\lambda_1}\right)\frac{d^2u}{dy^2}+\left\{\rho_{f_0}\beta_0\left(C-C_0\right)\left(T-T_0\right)-\left(\rho_f-\rho_{f_0}\right)\left(C-C_0\right)\right\}g=\frac{dp}{dx} \quad (3)$$

$$K\frac{d^2T}{dy^2}+\left(\rho c\right)_p\left[D_B\frac{dc}{dy}\frac{dT}{dy}+\left(\frac{D_T}{T_0}\right)\left(\frac{dT}{dy}\right)^2\right]+Q_0=.0 \quad (4)$$

$$D_B\frac{d^2C}{dy^2}+\left(\frac{D_T}{T_0}\right)\frac{d^2T}{dy^2}=0 \quad (5)$$

Here Q_0 is the dimensional constant heat source/sink parameter.

Boundary conditions for velocity, temperature and concentration fields are given as

$$\begin{aligned} &u-L\frac{du}{dy}=0, \quad T=T_1, \quad C=C_1 \quad at \quad y=0 \\ &u+L\frac{du}{dy}=0, \quad T=T_2, \quad C=C_2 \quad at \quad y=h \end{aligned} \quad (6)$$

Non-dimensional quantities are given as

$$Y=\frac{y}{h},\ X=\frac{x}{h},\ U=\frac{u}{u_0},\ P=\frac{p}{\rho u_0^{\ 2}},\ \theta=\frac{T-T_0}{T_2-T_0},\ \phi=\frac{C-C_0}{C_2-C_0},$$

$$T_0=\frac{T_1+T_2}{2},\ C_0=\frac{C_1+C_2}{2},\ Gr=\frac{(1-C_0)g\beta_0(T_2-T_0)h^3}{\nu^2},\ \mathrm{Re}=\frac{u_0h}{\nu}, \tag{7}$$

$$Nb=\frac{D_B(C_2-C_0)(\rho c)_p}{K},\quad Nt=\frac{D_B(T_2-T_0)(\rho c)_p}{KT_0},\quad S_0=\frac{Q_0h^2(\rho c)_p}{K(T_2-T_1)},\quad S=\frac{Q_0h^2(\rho c)_p}{K}.$$

Using the above parameters equations (3) to (5) are reduced to non-dimensional form

$$\left(\frac{1}{1+\lambda_1}\right)\frac{d^2U}{dy^2}=-\frac{dp}{dx}+Nr\phi-\frac{Gr}{\mathrm{Re}}\theta \tag{8}$$

$$\frac{d^2\theta}{dy^2}+Nb\frac{d\theta}{dy}\frac{d\phi}{dy}+Nt\left(\frac{d\theta}{dy}\right)^2+S_0=0 \tag{9}$$

$$\frac{d^2\phi}{dy^2}+\frac{Nt}{Nb}\frac{d^2\theta}{dy^2}=0 \tag{10}$$

The dimensionless parameter S_0 captures the constant heat source/sink effect.

The corresponding boundary conditions are given below

$$\begin{aligned} &U-L\frac{dU}{dy}=0,\quad \theta=-1,\quad \phi=-1 \quad at\ \ Y=0\\ &U+L\frac{dU}{dy}=0,\quad \theta=1+m_2,\quad \phi=1+m_1 \quad at\quad Y=1 \end{aligned} \tag{11}$$

where $m_2=\frac{2T_0-T_1-T_2}{T_2-T_0}$ is the wall temperature ratio and $m_1=\frac{2C_0-C_1-C_2}{C_2-C_0}$ is the wall concentration ratio.

The exact solutions to the coupled non-linear equations give the dimensionless velocity, temperature and nanoparticle concentration respectively as

$$U=(1+\lambda_1)\left[\left(-\frac{dp}{dx}\right)\frac{y^2}{2}+A\left(\frac{y^3}{3}-\frac{y^2}{2}\right)+B\left(\frac{y^3}{6}\right)-CB_1\left(\frac{y^2}{2}\right)+CB_2\left(\frac{e^{-(\alpha_1+\alpha_2)(Nb)y}}{-(\alpha_1+\alpha_2)^2(Nb)^2}+D\left(\frac{y^3}{6}\right)\right)\right] \tag{12}$$
$$+C_5y+C_6$$

$$\theta(y)=B_1+B_2e^{-(\alpha_1+\alpha_2)(Nb)y}-\frac{S_0y}{(\alpha_1+\alpha_2)(Nb)} \tag{13}$$

$$\phi(y)=\left(1+\frac{Nt}{Nb}\right)(2y-1)+\left(m_2\frac{Nt}{Nb}+m_1\right)y-\frac{Nt}{Nb}\theta(y) \tag{14}$$

Constants involved in (12) to (14) are given below

$$a_1 = 2\left(1+\frac{Nt}{Nb}\right); \quad a_2 = m_1 + m_2\left(\frac{Nt}{Nb}\right);$$

$$A = Nr\left(1+\frac{Nt}{Nb}\right); B = Nr\left(m_2\frac{Nt}{Nb}+m_1\right); C = Nr\left(\frac{Nt}{Nb}\right)+\frac{Gr}{\mathrm{Re}};\ D = \frac{C\rho_0}{(\alpha_1+\alpha_2)Nb};$$

$$B_1 = \frac{1+m_2+e^{-(\alpha_1+\alpha_2)Nb}+\dfrac{S_0}{(\alpha_1+\alpha_2)Nb}}{1-e^{-(\alpha_1+\alpha_2)Nb}}; B_2 = \frac{2+m_2+\dfrac{S_0}{(\alpha_1+\alpha_2)Nb}}{e^{-(\alpha_1+\alpha_2)Nb}-1};$$

$$C_1 = \frac{1}{-1-2L}\left[\frac{CB_2}{(\alpha_1+\alpha_2)^2 Nb^2}+\frac{LCB_2}{(\alpha_1+\alpha_2)Nb}+\frac{P}{2}-\frac{A}{6}+\frac{B}{6}-\frac{CB_1}{2}-(CB_2)\frac{e^{-(\alpha_1+\alpha_2)Nb}}{(\alpha_1+\alpha_2)^2 Nb^2}\right]$$

We have considered another model of Foraboschi and Federico as temperature dependent heat source or sink as

$$Q = Q_0(T-T_0) \tag{15}$$

Incorporating the above equation into (3-5) and using (11), the dimensionless equations governing this case is given as

$$\left(\frac{1}{1+\lambda_1}\right)\frac{d^2U}{dy^2} = -\frac{dp}{dx}+Nr\phi-\frac{Gr}{\mathrm{Re}}\theta \tag{16}$$

$$\frac{d^2\theta}{dy^2}+Nb\frac{d\theta}{dy}\frac{d\phi}{dy}+Nt\left(\frac{d\theta}{dy}\right)^2+S_0\theta = 0 \tag{17}$$

$$\frac{d^2\phi}{dy^2}+\frac{Nt}{Nb}\frac{d^2\theta}{dy^2} = 0 \tag{18}$$

The solution of the above equations by using the boundary conditions (11) is given by

$$U = \alpha\left(\frac{dp}{dx}\right)\frac{y^2}{2}+\frac{a_2}{6}\left(2y^3-3y^2\right)+\frac{a_3y^3}{6}-\frac{a_1}{\lambda_1^2\lambda_2^2}\left(C_3\lambda_2^2e^{\lambda_1 y}+C_4e^{\lambda_2 y}\lambda_1^2\right)+C_5y+C_6 \tag{19}$$

$$\theta(y) = C_3e^{(\lambda_1)y}+C_4e^{(\lambda_2)y} \tag{20}$$

$$\phi(y) = \left(1+\frac{Nt}{Nb}\right)(2y-1)+\left(m_2\frac{Nt}{Nb}+m_1\right)y-\frac{Nt}{Nb}\theta(y) \tag{21}$$

Constants involved in the above equations are

$$\alpha = 1+\lambda_1;\ a_1 = \alpha\left(Nr\frac{Nt}{Nb}+\frac{Gr}{\mathrm{Re}}\right); \quad a_2 = \alpha\left(Nr\left(1+\frac{Nt}{Nb}\right)\right);\ a_3 = \alpha Nr\left(m_2\frac{Nt}{Nb}+m_1\right);$$

$$a_4 = \frac{a_1C_3}{\lambda_1^2} + \frac{a_1C_4}{\lambda_2^2} - \frac{La_1C_3}{\lambda_1} - \frac{La_1C_4}{\lambda_2}; \quad a_5 = \frac{a_1C_3}{\lambda_1^2}e^{\lambda_1} + \frac{a_1C_4}{\lambda_2^2}e^{\lambda_2} + \frac{La_1C_3}{\lambda_1}e^{\lambda_1} + \frac{La_1C_4}{\lambda_2}e^{\lambda_2};$$

$$\lambda_{1,2} = \frac{-(\alpha_1+\alpha_2)Nb \pm \sqrt{((\alpha_1+\alpha_2)Nb)^2 - 4S}}{2}; C_3 = \frac{1+m_2+e^{\lambda_2}}{e^{\lambda_1}-e^{\lambda_2}}; C_4 = \frac{1+m_2+e^{\lambda_1}}{e^{\lambda_1}-e^{\lambda_2}};$$

$$C_5 = \frac{1}{1+2L}\left(-\alpha\frac{dp}{dx}\left(L+\frac{1}{2}\right) + \frac{a_2}{6} - \frac{a_3}{6}(1+3L) + a_5 - a_4\right); C_6 = a_4 + LC_5.$$

Results and discussion

We have obtained the dimensional expressions for the velocity U, temperature θ and nanoparticle volume fraction ϕ under the effect of velocity slip and heat source/ sink with dependent wall temperature and concentration in a vertical channel. The variations of the velocity temperature and concentration on Jeffrey fluid flow in a vertical channel are analyzed with respect to different physical parameters through graphs.

Figures 2 represents temperature distribution for constant heat source or sink for different values of source or sink parameter. It is observed that the temperature of the fluid increases with increase the source or sink parameter by fixing the other parameters $Nt = Nb = 0.5, m_1 = 1, m_2 = 1,$ $L = 0.3, Nr = 100$. Fig. 3 shows that an increase in the velocity is noted along with the rising values of slip parameter L. In figure 4, it is observed that the velocity distribution is increased by growing valuations of the Jeffrey fluid parameter λ_1. Fig. 5 shows the effect of buoyancy-ratio parameter and heat source/ sink parameter on velocity field. It is observed that the velocity increases at the left wall and decreases at the right wall. Fig. 6 shows the effect of wall temperature ratio m_2 on temperature field. For values of $m_2 < 0$ the temperature of the left wall is less than the temperature of the right wall, for m = 0 both walls are maintained at equal temperatures, and for values of $m_2 > 0$ the left wall is at higher temperature. Therefore as m_2 increases, rate of heat transfer also increases. Fig. 7 depicts temperature distribution for heat source/ sink parameter in two cases. In both the cases, temperature increases with increase in S. From Fig. 8, it is observed that the Nanoparticle volume fraction decreases with the increasing values of heat source/ sink parameter S.

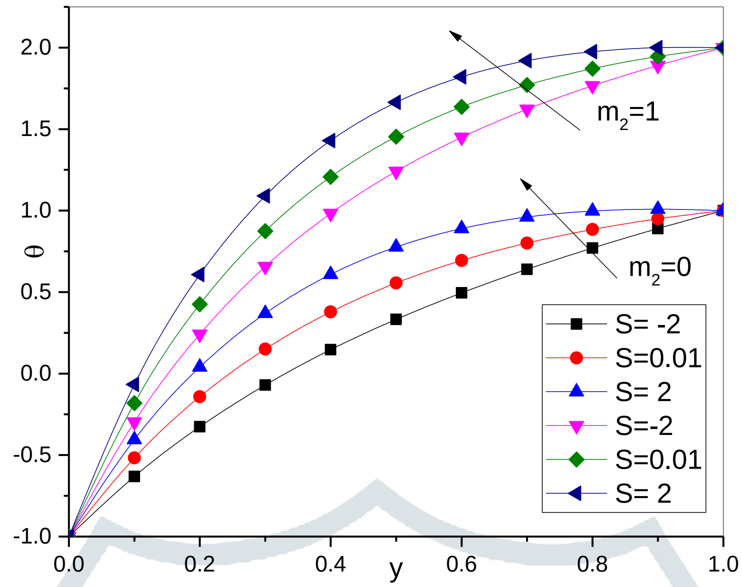

Fig. 2: Temperature profile for different values of heat source/ sink parameter S
(Constant heat source or sink)

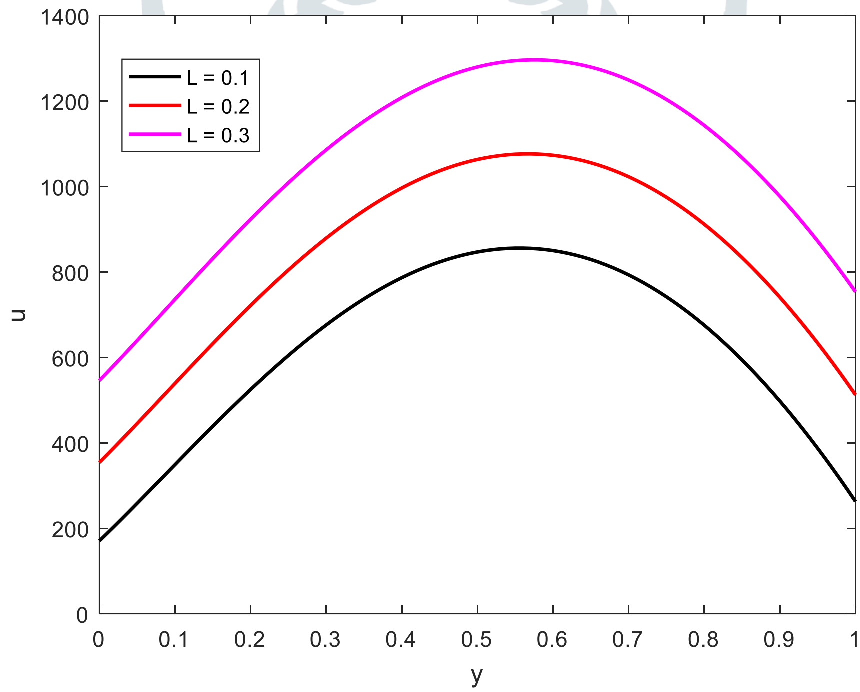

Fig. 3: Velocity profile for different values of slip parameter L.
(Temperature dependent heat source or sink)

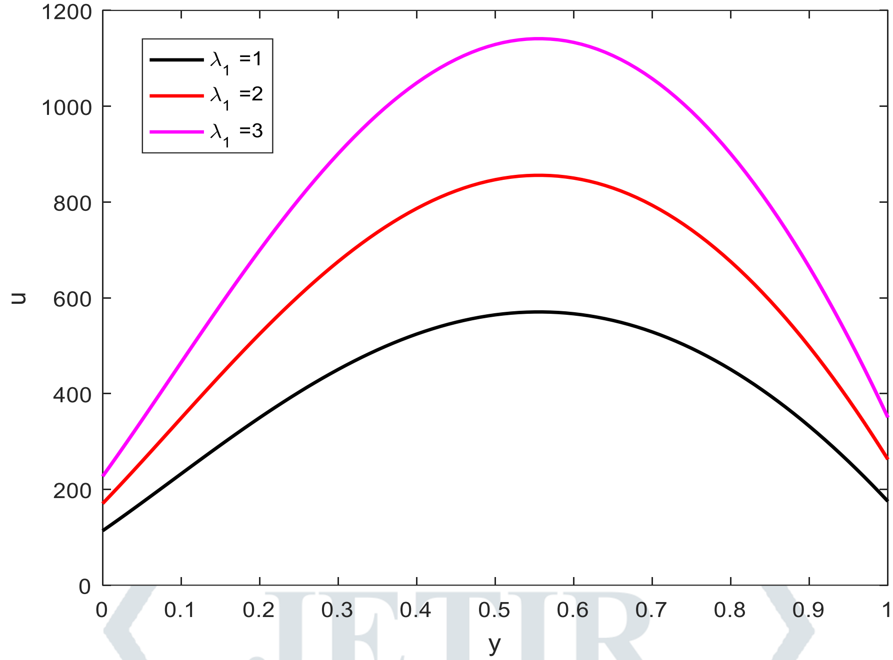

Fig. 4: Velocity profile for different values of Jeffrey parameter λ_1.
(Temperature dependent heat source or sink)

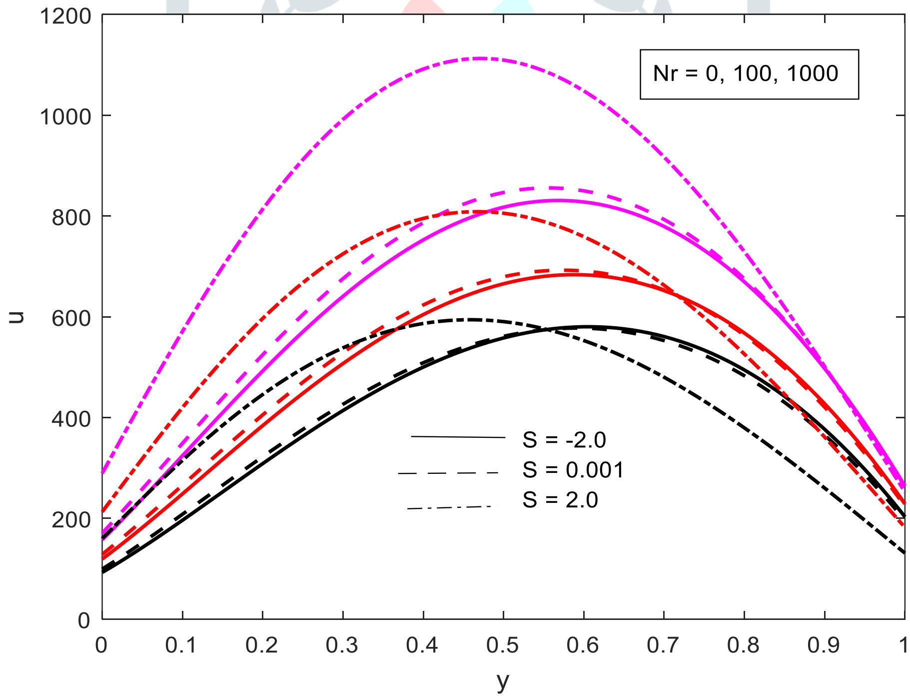

Fig. 5: Velocity profile for different values of heat source/ sink parameter S and buoyancy-ratio parameter Nr.
(Temperature dependent heat source or sink)

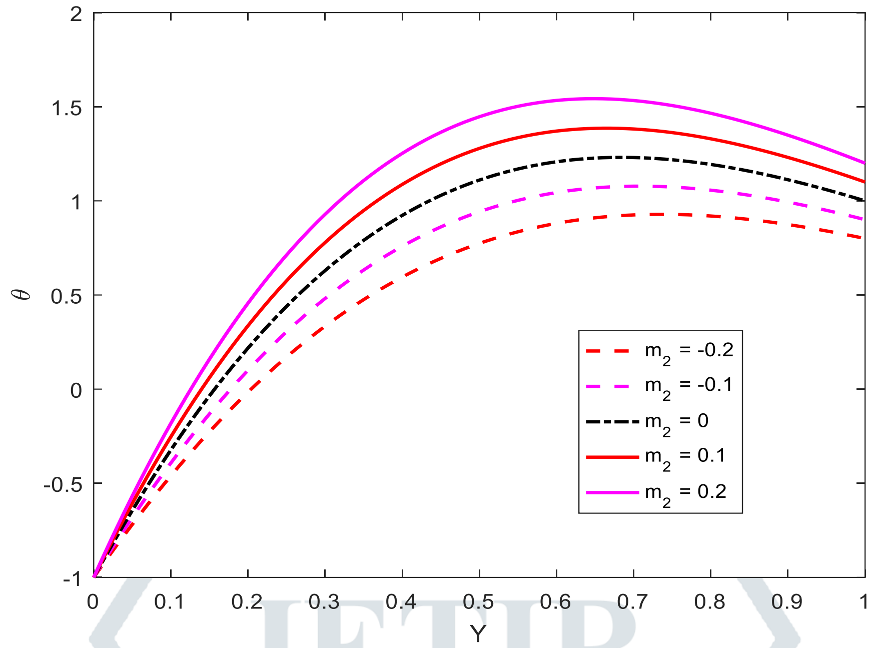

Fig. 6: Temperature profile for different values of wall temperature ratio m_2
(Temperature dependent heat source or sink)

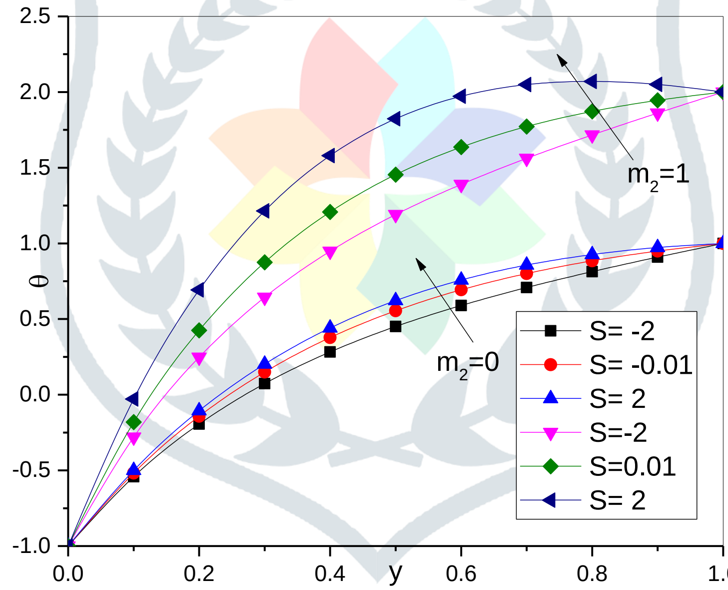

Fig. 7: Temperature profile for different values of heat source/ sink parameter S
(Temperature dependent heat source or sink)

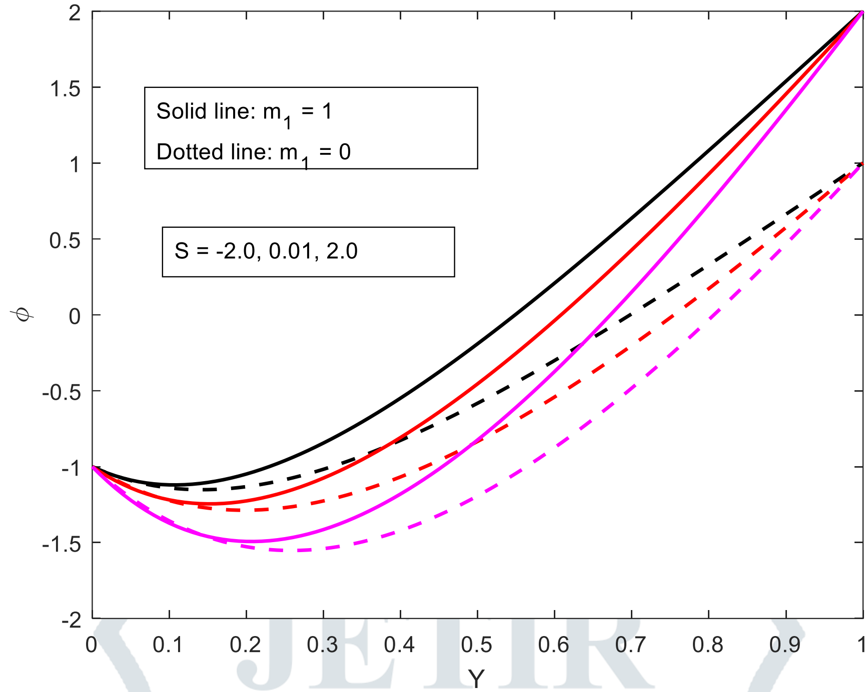

Fig. 8: Nanoparticle volume fraction for different values of heat source/ sink parameter S. (Temperature dependent heat source or sink)

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