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Unsteady MHD nonlinear radiative squeezing slip-flow of Casson fluid between parallel disks

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Abstract
Effect of nonlinear thermal radiation on theunsteady magnetohydrodynamic slip flow of Casson fluid between parallel disks in the presence of thermophoresis and Brownian motion effects are investigated numerically. A similarity transformation is employed to reduce the governing partial differential equations into ordinary differential equations. Further, Runge-Kutta and Newton's methods are adopted to solve the reduced ordinary differential equations. The effect of non-dimensional governing parameters, namely magnetic field parameter, Casson parameter, thermophoresis parameter, Brownian motion parameter, thermal radiation parameter, unsteadiness parameter, velocity slip parameter and temperature slip parameteron velocity, temperature and concentration fields are discussed and presented through graphs. Reduced Nusselt and Sherwood numbers are computed and presented through a table. It is found that rising values of nonlinear thermal radiation parameter depreciate the reduced Nusselt and Sherwood numbers. Thermophoresis and Brownian motion parameters have tendency to regulate the thermal and concentration boundary layers. Rising values of Casson parameter enhances the heat and mass transfer rate.

Nomenclature

u, w: Velocity components in x and z direction respectively (m/s)
x : Distance along the surface (m)
z : Distance normal to the surface (m)
r : Radial velocity
ρ : Density of the fluid (Kg/m^3)
σ : Electrical conductivity (S/m)
ν : Kinematic viscosity (m^2/s)
τ : Ratio of the effective heat capacity
α : Thermal diffusivity
$\sigma*$: Stefan-Boltzmann constant
$k*$: Mean absorption coefficient
c_p : Specific heat at constant pressure
D_B : Brownian motion coefficient (m^2/s)
D_T : Thermophoretic diffusion coefficient
T : Temperature of the fluid (K)
T_m : Mean fluid temperature
C : Concentration of the fluid
T_w, C_w : Temperature and concentration at lower disk

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T_h, C_h : Temperature and concentration at upper disk
p : Pressure
Cf_r : Skin friction coefficient
Nur : Reduced Nusselt number
Shr : Reduced Sherwood number
Re_r : Local squeeze Reynolds number
S : Squeeze number
Pr : Prandtl number
Le : Lewis number
M : Hartmann parameter
Nt : Thermophoresis parameter
Nb : Brownian motion parameter
A : Suction/injection parameter
δ : Dimensionless velocity slip parameter
γ : Dimensionless temperature slip parameter

1. Introduction

In nature, a non-Newtonian fluid acts as an elastic solid, i.e. the flow does not occur with small shear stress. Casson fluid is one of the non-Newtonian fluids. It is first invented by Casson in 1959. It is based on the structure of liquid phase and interactive behaviour of solid of a two-phase suspension. Some examples of Casson fluid are Jelly, honey, tomato sauce and concentrated fruit juices. Human blood can also be treated as a Casson fluid in the presence of several substances such as fibrinogen, globulin in aqueous base plasma, protein, and human red blood cells. Squeezing flows are generated by natural stresses or vertical velocities of the moving boundary layer. The practical examples of squeezing flow are compression, polymer processing, and injection molding. The system of lubrication can also be demonstrated by squeezing flow. By considering the lubrication, an approximation on squeezing flow was examined by Stefan [1]. The experimental and theoretical studies of squeezing flow have been led by many researchers [2-6]. Duwairi et al. [7] and Khan et al. [8] explained the effects of heat transfer on squeezing flow of viscous nanofluid. The effect of magnetohydrodynamic (MHD) Casson fluid flow in a lateral direction past linear stretching sheet was explained by Nadeem et al. [9].

Raju et al. [10] discussed the effects of nonlinear thermal radiation on Jeffery fluid in the presence of non-uniform heat sources/sink. The characteristics of heat and mass transfer in a viscous fluid with squeezing flow between the parallel plates were explained by Mustafa et al. [11]. Islam et al. [12] investigated the approximation solution on an MHD flow of squeezing fluid. The MHD three-dimensional steady flow of a Casson nanofluid past a stretching sheet was analysed by Nadeem et al. [13]. The effect of magnetic field on heat transfer analysis of nanofluid between parallel plates was explained by Hatami et al. [14]. Domairry and Aziz [15] investigated the MHD squeeze flow between the two parallel disks by the homotopy perturbation method. The heat transfer and stagnation-point flow of a Casson fluid in the region towards a stretching sheet was investigated by Mustafa et al. [16]. Rashidi et al. [17] explained the effects of radiation and buoyancy on heat and mass transfer for an MHD flow on a vertical stretching sheet. The hydromagnetic flow of a partial slip over a stretching sheet in the presence of thermal radiation was studied by Abdul Hakeem et al. [18]. Sheikholeslami and Ganji [19] discussed the effects of thermal radiation on an unsteady nanofluid flow and heat transfer in the presence of a magnetic field. MHD thermosolutal nanofluid flow over a vertical plate was investigated by Sulochana et al. [20]. Sheikholeslami et al. [21] explained the unsteady nanofluid flow and heat transfer in the presence of time-dependent magnetic field between parallel. Unsteady MHD flow in the presence of nonlinear thermal radiation between the parallel plates was analysed by Sathish Kumar et al. [22]. Very recently, the researchers [23-26] investigated the heat transfer nature of the non-Newtonian fluids by considering the various geometries.

To the author’s knowledge, no studies have been reported on the effect of nonlinear thermal radiation on the unsteady magnetohydrodynamic slip flow of Casson fluid between parallel disks in the presence of thermophoresis and Brownian motion effects. This study is useful to analyze the effect of non-dimensional governing parameters, namely magnetic field, Casson, thermophoresis, Brownian motion, radiation, unsteadiness, and slip parameters on velocity, temperature, and concentration fields. Which leads to control the heat and mass transfer rates of the flow between discs?

2. Mathematical formulation

Consider an electrically conducting axisymmetric flow of a Casson fluid between two parallel disks with a non-uniform distance $h(t)=H\sqrt{(1-\alpha t)}$, where α is the characteristic parameter. Lower disk locates at $z=0$ and upper disk ($z=h(t)$) approaches the lower disk at the velocity $v(t)=\frac{dh}{dt}$ until they touch each other. A uniform magnetic field $B(t)=B_0(1-\alpha t)^{-\frac{1}{2}}$ is applied to the flow as shown in Fig. 1. Nonlinear thermal radiation along with thermophoresis and Brownian motion effects are taken into account.

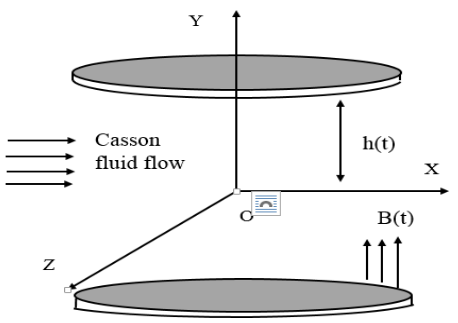

Fig. 1. Physical model of the problem.

As per the above assumption, the governing equations are as follows:

$$\frac{\partial u}{\partial r}+\frac{u}{r}+\frac{\partial w}{\partial z}=0, \tag{1}$$

$$\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial r}+w\frac{\partial u}{\partial z}=-\frac{1}{\rho}\frac{\partial p}{\partial r} +v\left(1+\frac{1}{\beta}\right)\left(\frac{\partial^2 u}{\partial r^2}+\frac{\partial^2 u}{\partial z^2}+\frac{1}{r}\frac{\partial u}{\partial r}-\frac{u}{r^2}\right)-\frac{\sigma B^2(t)}{\rho}, \tag{2}$$

$$\frac{\partial w}{\partial t}+u\frac{\partial w}{\partial r}+w\frac{\partial w}{\partial z}=-\frac{1}{\rho}\frac{\partial p}{\partial z} +v\left(1+\frac{1}{\beta}\right)\left(\frac{\partial^2 w}{\partial r^2}+\frac{\partial^2 w}{\partial z^2}+\frac{1}{r}\frac{\partial w}{\partial r}\right), \tag{3}$$

$$\frac{\partial T}{\partial t}+u\frac{\partial T}{\partial r}+w\frac{\partial T}{\partial z}=\alpha\left(\frac{\partial^2 T}{\partial r^2}+\frac{1}{r}\frac{\partial T}{\partial r}+\frac{\partial^2 T}{\partial z^2}\right) +\frac{16\sigma^*}{3k^*(\rho c_p)}\frac{\partial}{\partial z}\left(T^3\frac{\partial T}{\partial z}\right)+\tau\left[\begin{array}{l} D_B\left(\frac{\partial C}{\partial r}\frac{\partial T}{\partial r}+\frac{\partial C}{\partial z}\frac{\partial T}{\partial z}\right) \\ +\frac{D_T}{T_m}\left\{\left(\frac{\partial T}{\partial r}\right)^2+\left(\frac{\partial T}{\partial z}\right)^2\right\}\end{array}\right], \tag{4}$$

$$\frac{\partial C}{\partial t}+u\frac{\partial C}{\partial r}+w\frac{\partial C}{\partial z}=D_B\left(\frac{\partial^2 C}{\partial r^2}+\frac{1}{r}\frac{\partial C}{\partial r}+\frac{\partial^2 C}{\partial z^2}\right), +\frac{D_T}{T_m}\left(\frac{\partial^2 T}{\partial r^2}+\frac{1}{r}\frac{\partial T}{\partial r}+\frac{\partial^2 T}{\partial z^2}\right) \tag{5}$$

The boundary conditions for the problem are:

$$\begin{gathered} u=-\beta_1\frac{\partial u}{\partial z}, w=\frac{w_0}{\sqrt{1-\alpha t}}, T=-\gamma_1\frac{\partial T}{\partial z}+T_w, \\ C=C_w \quad at \quad z=0 \\ u=\beta_1\frac{\partial u}{\partial z}, w=w_h\left(\frac{\partial h}{\partial t}\right), T=\gamma_1\frac{\partial T}{\partial z}+T_h, \\ C=C_h \;\; at \;\; z=h(t), \end{gathered} \tag{6}$$

To solve the governing Eqs. (1) – (5) the following dimensionless quantities are introduced:

$$\begin{gathered} \eta=\frac{z}{H\sqrt{1-\alpha t}}, u=\frac{\alpha r}{2(1-\alpha t)}f'(\eta), \\ w=-\frac{\alpha H}{\sqrt{1-\alpha t}}f(\eta), \theta=\frac{T-T_h}{T_w-T_h}(or) \\ T=T_h\left(1+(\theta_w-1)\theta\right), C=\frac{C-C_h}{C_w-C_h} \end{gathered} \tag{7}$$

By using Eq. (7), the continuity of Eq. (1) is satisfied automatically and then Eqs. (2-5) are reduced to:

$$\left(1+\frac{1}{\beta}\right)f'''-S(\eta f''+2f''-2ff'')-M^2f'=0 \tag{8}$$

$$\left(1+\frac{1}{\beta}\right)g''-S\left(\eta g'+2g+2gg'\right)=0, \tag{9}$$

$$\theta''+\Pr S\left(2f\theta'-\eta\theta'\right)+\Pr Nb\theta'\phi'+\Pr Nt\theta'^2$$
$$+R\left[\left(1+\left(\theta_w-1\right)\theta\right)^3\theta''+3\left(\theta_w-1\right)\theta'^2\left(1+\left(\theta_w-1\right)\theta\right)^2\right]=0, \tag{10}$$

$$\phi''+LeS\left(2f\phi'-\eta\phi'\right)+\frac{Nt}{Nb}\theta''=0, \tag{11}$$

The boundary condition becomes:

$$f=A,\ f'+\delta f''=0,\ \theta+\gamma\theta'=1,\ \phi=0 \quad for\ \eta=0$$
$$f=\frac{1}{2},\ f'-\delta f''=0,\ \theta-\gamma\theta'=1,\ \phi=0 \quad for\ \eta=1, \tag{12}$$

Here, $S=\frac{\alpha H}{2v}$ is the squeeze number, $M=HB_0\sqrt{\frac{\sigma}{\mu}}$ is the Hartmann parameter, $\Pr=\frac{v}{\alpha}$ is the Prandtl number, $Le=\frac{v}{D_B}$ is the Lewis number, $Nb=\frac{\tau D_B\left(C_w-C_h\right)}{v}$ is the Brownian motion parameter, $Nt=\frac{\tau D_T\left(T_w-T_h\right)}{vT_m}$ is the thermophoresis parameter, $A=\frac{w_0}{\alpha H}$ is the suction/injection parameter, $\delta=\frac{\beta_1}{H\sqrt{1-\alpha t}}$ is the dimensionless velocity slip parameter and $\gamma=\frac{\gamma_1}{H\sqrt{1-\alpha t}}$ is the dimensionless temperature slip parameter.

The characteristics of flow, heat and mass transfer are skin friction coefficient, reduced Nusselt and Sherwood numbers, respectively which are defined by:

$$Nur=-\theta'(1) \text{ where } Nur=\sqrt{1-\alpha t}Nu, \tag{13}$$

$$C_{fr}=f''(1) \text{ where } C_{fr}=\frac{H^2\sqrt{1-\alpha t}\ \mathrm{Re}_r}{r^2}C, \tag{14}$$

$$Shr=-\phi'(1) \text{ where } Shr=\sqrt{1-\alpha t}Sh, \tag{15}$$

where $\mathrm{Re}_r=\frac{r\alpha H}{2v}$ is the local squeeze Reynolds number.

3. Numerical solution

The non-linear ordinary differential Eqs. (8-11) with boundary conditions (12) are solved using the Runge–Kutta and Newton's methods. A set of nonlinear ordinary differential equations are of third order in f, g, second order in θ and ϕ are first reduced into a system of simultaneous ordinary equations. In order to solve this system using Runge-Kutta and Newton's method, three more missed initial conditions are required. However, the values of $f'(\eta), g'(\eta),\ \theta(\eta)$, $\phi(\eta)$ are known when $\eta\to\infty$. These end conditions are used to obtain unknown initial conditions at $\eta=0$ using shooting technique. In shooting method, the boundary value problem is reduced to an initial value problem by assuming initial values. The calculated boundary values have to be matched with the real boundary values. Using trial and error or some scientific approaches, it can be attempted to get as close to the boundary value as possible. The most essential step of this method is to choose the appropriate finite value for far field boundary condition. In this study, infinity condition is taken at a large but finite value of η where no considerable variations in velocity, temperature and so on occur. Bulk computations are run out with the value at $\eta_{\max}=6$, which is sufficient to achieve the far field boundary conditions asymptotically for all values of the parameters considered.

4. Results and discussion

For numerical computations, the non-dimensional parameter values are chosen as follows:

$$\beta=0.5,\ \Pr=6,\ Nb=Nt=0.5, \mathrm{A}=-2,$$
$$Le=S=M=R=1, \theta_w=1.1, \delta=\gamma=0.1.$$

Throughout the analysis, these values are kept common except the varied values which are displayed in the respective graphs. In this discussion, the effects of pertinent parameter on the blowing case ($A<0$) are investigated.

Figs. 2 and 3 depict the behaviour of thermal radiation parameter on temperature and concentration profiles, respectively. Temperature profiles increases with increasing radiation parameter values while concentration profiles show opposite behaviour. Generally, increasing radiation parameter values enhances the temperature near the boundary; this causes concentration particle to move away from the surface.

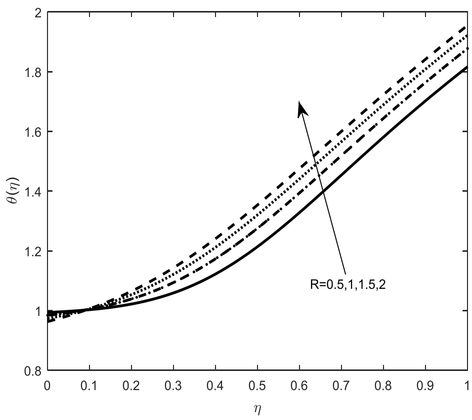

Fig. 2. The effect of R on temperature profile.

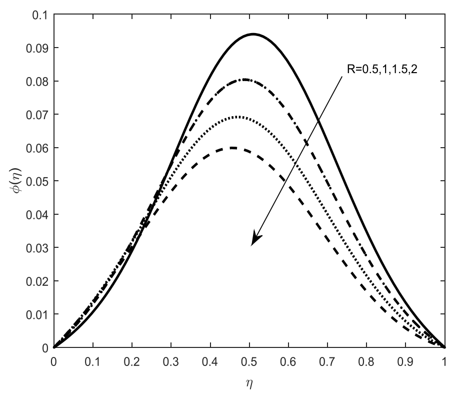

Fig. 3. The effect of R on concentration profile.

Figs. 4-6 show the behaviour of squeeze number on concentration, temperature, and velocity profiles. Decreasing in temperature profile is observed with increasing the squeeze number values. But velocity and concentration profiles enhance with increasing values of squeeze number. Generally, increasing the squeeze number value can be associated with the reduced kinematic viscosity and it enhances the distance between the plates and increase the speed at which the direction of the plate moves.

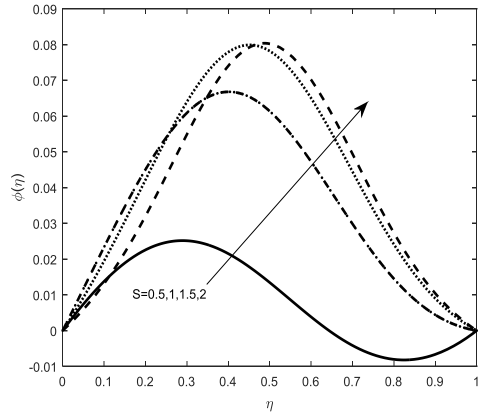

Fig. 4. The effect of S on concentration profile.

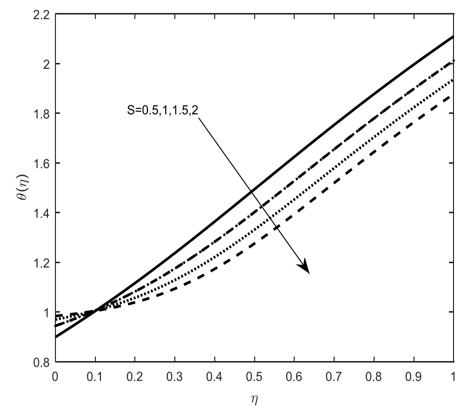

Fig. 5. The effect of S on temperature profile.

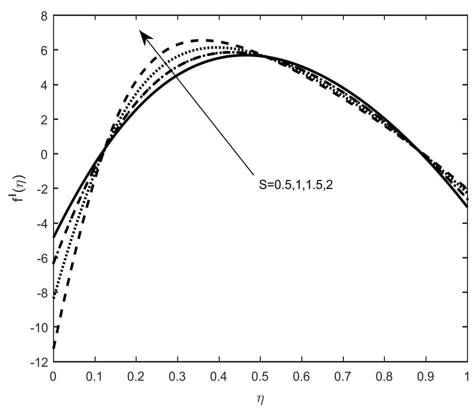

Fig. 6. The effect of S on velocity profile.

Figures 7-9 illustrate the behavior of concentration, temperature, and velocity profiles as a function of increasing value of Casson fluid parameter. It is observed a rise in the velocity profiles for increasing value of Casson fluid parameter. Temperature and concentration profiles show a reverse trend to above. Physically, rising values of Casson parameter develop the viscous forces. These forces have a tendency to decline the concentration and thermal boundary layer.

Fig. 10 depicts the effect of Brownian motion parameter on concentration profile. It is evident that increasing values of Brownian motion parameter decreases the concentration field. Generally, Brownian motion helps to heat the fluid in the boundary layer and instantaneously impair particle deposition away from the fluid on the surface. The effects of thermophoresis parameter on temperature and concentration profiles are shown in Figs. 11 and 12. It is observed that increasing values of thermophoresis parameter enhances the temperature and concentration profiles.

Figs. 13 and 14 demonstrate the effect of temperature slip parameter on temperature and concentration profiles. It is seen that the temperature and concentration fields increase with increasing values of slip parameter. The effect of velocity slip parameter on velocity, temperature, and concentration profile is shown in Figs 15-17. It is clear that an increase in the velocity enhances the velocity and temperature fields and declines the concentration filed. Physically, rising the value of slip parameter allows more fluid to slip over the surface because of which the flow close to the sheet decreases and the slip effect towards the free stream is less articulated.

Table 1 shows the effect of non-dimensional parameter values on local Nusselt and Sherwood numbers. It is evident that rising values of thermal radiation, thermophoresis parameter, and temperature slip parameter reduces the heat and mass transfer rates. However, an opposite trend is noticed to above for increasing values of unsteadiness parameter, Casson parameter, and velocity slip parameter. Interestingly, the effect of Brownian motion parameter on the heat transfer rate is negligible and it helps to boost the mass transfer rate.

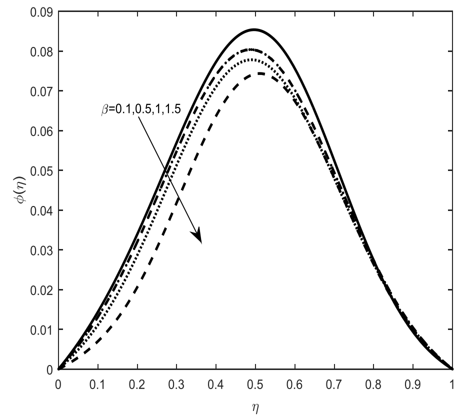

Fig. 7. The effect of β on concentration profile.

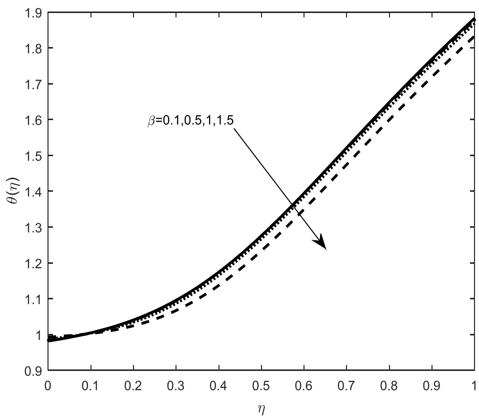

Fig. 8. The effect of β on temperature profile.

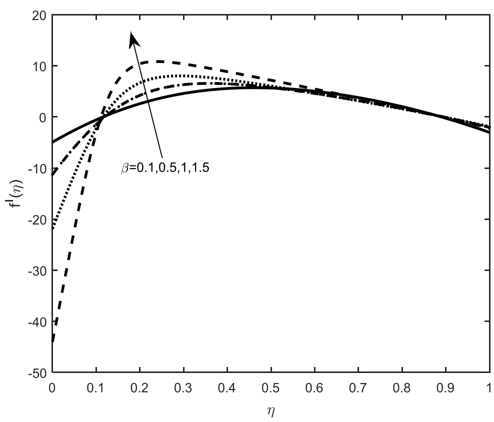

Fig. 9. The effect of β on velocity profile.

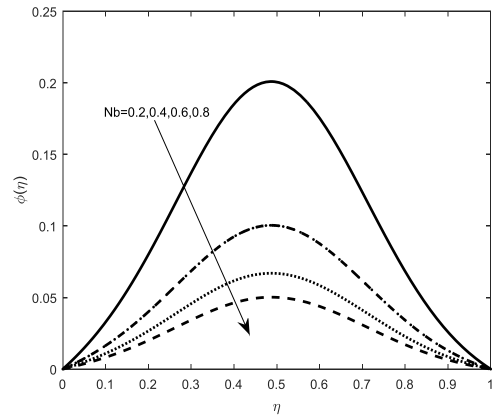

Fig. 10. The effect of Nb on concentration profile.

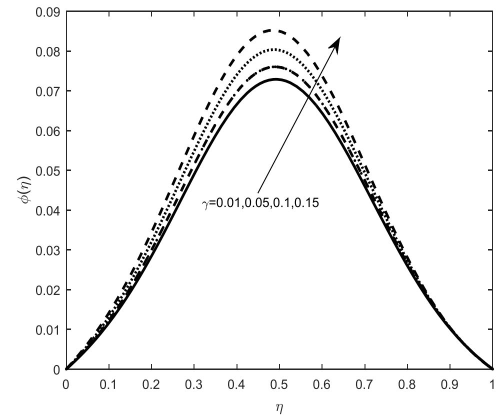

Fig. 13. The effect of γ on concentration profile.

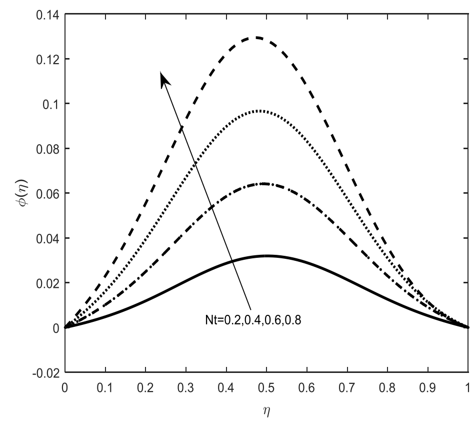

Fig. 11. The effect of Nt on concentration profile.

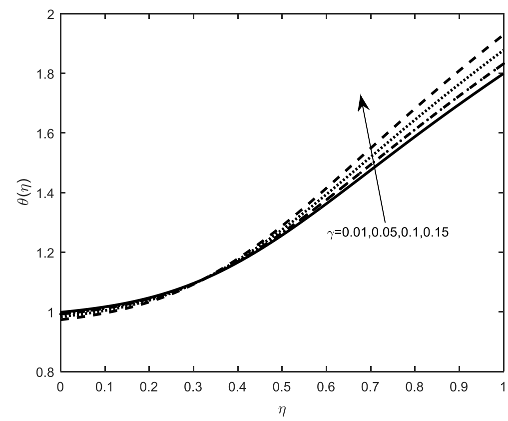

Fig. 14. The effect of γ on temperature profile.

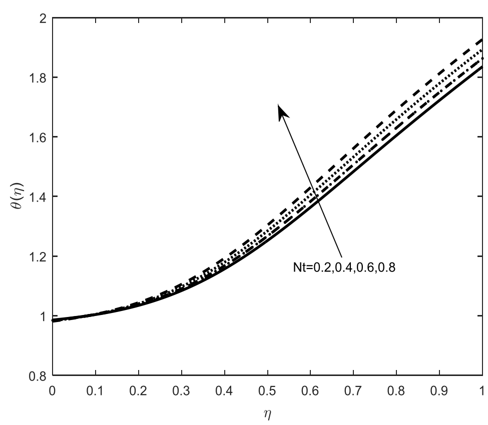

Fig. 12. The effect of Nt on temperature profile.

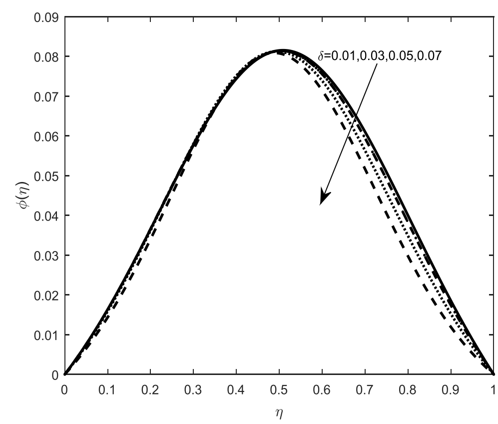

Fig. 15. The effect of δ on concentration profile.

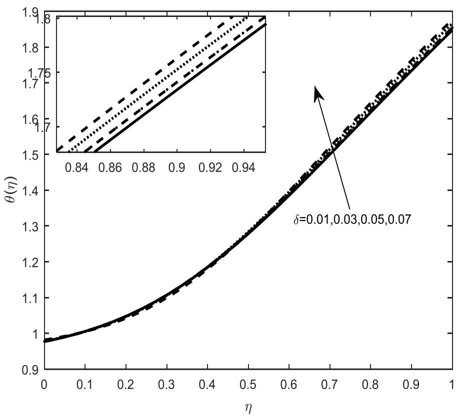

Fig. 16. The effect of δ on temperature profile.

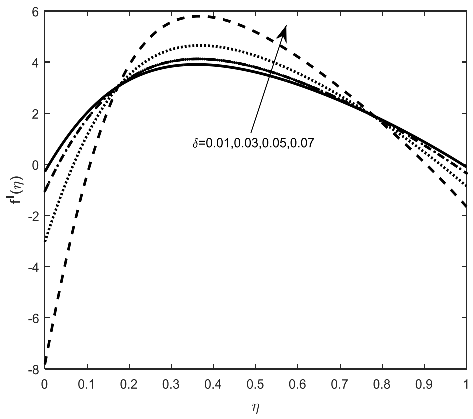

Fig. 17. The effect of δ on velocity profile.

Table 1. Physical parameter values of reduced Nusselt and Sherwood numbers.

R	S	β	Nb	Nt	γ	δ	$-\theta'(\eta)$	$-\phi'(\eta)$
0.5							-0.064964	-0.079919
1							-0.161588	-0.107289
1.5							-0.268392	-0.119753
	0.5						-1.010774	-0.156084
	1						-0.558427	-0.231937
	1.5						-0.305019	-0.175122
		0.1					-0.177447	-0.115960
		0.5					-0.167330	-0.110469
		1					-0.155513	-0.103869
			0.2				-0.161588	-0.268223
			0.4				-0.161588	-0.134112
			0.6				-0.161588	-0.089408
				0.2			-0.143121	-0.039022
				0.4			-0.154956	-0.083074
				0.6			-0.168763	-0.133151
					0.01		-0.142288	-0.094843
					0.05		-0.150270	-0.100001
					0.1		-0.161588	-0.107289
						0.01	-0.230797	-0.141072
						0.03	-0.227844	-0.140046
						0.05	-0.216398	-0.135215

5. Conclusions

The present study deals with the effect of nonlinear thermal radiation on unsteady magnetohydrodynamic slip flow of Casson fluid between parallel disks in the presence of thermophoresis and Brownian motion effects. A similarity transformation is employed to reduce the governing partial differential equations into ordinary differential equations. Furthermore, Runge-Kutta and Newton's methods are adopted to solve the reduced ordinary differential equations. Numerical findings are as follows:

- Magnetic field parameter regulates the flow field.
- Squeeze number have a tendency to enhance the heat and mass transfer rate.
- Rising values of Casson parameter boosts the local Nusselt and Sherwood numbers.
- Velocity and temperature slip parameters regulate the momentum, thermal, and concentration boundary layers.
- Brownian motion and thermophoresis parameters control the heat and mass transfer rates.

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