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THERMAL AND HYDRODYNAMIC ANALYSIS OF NANOFLUID FLOW BETWEEN ROTATING PLATES: AN APPLICATION TO TEMPERATURE CONTROL IN POLYMERIZATION REACTORS

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Abstract : Polymer solutions high viscous fluids and they are very sensitive to temperature gradients due to this reason controlling temperature is key research problem in polymerization reactors, mixers and coating system. Rotating parallel plate reactors used in viscous resins to maintain uniform heating and cooling effects during solvent removal and polymerization. This current study provides detailed mathematical analysis on improving heat transfer in rotating system and also preserving uniform temperature in the system. Hybrid nanofluid is prepared with copper and graphene oxide with base fluid as water. Mathematical model is developed by boundary layer approximation equations for momentum, temperature and similarity solution is obtained using MATLAB software. Casson rheological model is utilised to analyse non-Newtonian behaviour of hybrid nanofluid. Energy equation is embedded with thermal radiation and exponential heat source sink terms. Momentum, temperature profiles are visualised with respect to distinct fluid parameters and analysed. Friction co-efficient at the boundaries and rate of heat transfer is computed and tabulated. It is observed that radial velocity profile is suppressed for rotation parameter. Nusselt number increases with rise of volume fraction. Casson parameter increases velocity profile.

Key words: Hybrid nanofluid flow, rotating system, Shooting method, Numerical simulation

1. Introduction

The use of rotating plates in heat transfer applications involving engine oil–based nanofluids has attracted significant attention due to its relevance in engineering systems such as solar thermal devices and lubrication technologies. Rotating plates enhance convective heat transfer by inducing turbulence and promoting effective fluid mixing. Motivated by these practical applications, numerous researchers have investigated nanofluid flow between parallel plates. Mohsen Sheikholeislami et al. [1] examined heat transfer characteristics and nanofluid flow between two parallel horizontal plates in a rotating frame. Their findings revealed that the friction coefficient increases with the rotation parameter, while the heat transfer rate improves significantly with an increase in nanoparticle volume fraction. Subsequently, Mohsen Sheikholeislami, Hamid, and Ganji [2] revisited the rotating parallel plate problem by considering a modified configuration in which the lower plate was modeled as a stretching sheet and the upper plate as a solid surface. They concluded that the heat transfer rate is highly dependent on the type of nanomaterial used in the nanofluid preparation. This work was further extended by Syed Tauseef Mohyud-din et al. [3] to incorporate the effects of Coriolis force. Fazil Mabood et al. [4] analyzed nanofluid flow in a rotating vertical channel with variable viscosity. Zahir Shah et al. [5] investigated third-grade non-Newtonian fluid flow in a rotating system, considering a static upper plate and a stretching lower plate. A similar numerical study on hybrid nanofluid flow in a rotating channel was reported by Ghadekolaie et al. [6]. Sulochana and Prasanna [7] explored carbon nanotube–based hybrid nanofluid flow over a surface with nonlinear velocity.

Ali J. Chamkha et al. [8] studied hydromagnetic hybrid nanofluid flow in a rotating frame, accounting for viscous dissipation and Ohmic heating effects. Kumar and Uma [9] examined the Casson non-Newtonian fluid model and analyzed the influence of melting heat transfer on boundary layer flows. Debi Prasad Bhatta et al. [10] derived analytical solutions for a squeezed fluid flow problem and demonstrated that buoyancy effects play a crucial role in enhancing heat transport. More recently, Veera Krishna and Ali J. Chamkha [11] investigated the effects of Hall current and ion slip on rotational fluid flows, concluding that elasticity and magnetic fields oppose the velocity field. MM Rashidi et al. [12] conducted an irreversibility analysis of Casson nanofluid flow between rotating plates. Waqas Hasan et al. [13] analyzed the influence of electromagnetic field strength on rotating nanofluid flows. Sulochana and Kumar [14] examined mixed base hybrid fluids to analyze thermal behavior, while Pavithra et al. [15] studied rotating hybrid nanofluid flow over rotating geometries. Thermal radiation is energy transfer via electromagnetic waves due to temperature differences, without requiring a medium. Nonlinear thermal radiation effects on fluid flow involve the complex interplay between radiative heat transfer and the behaviour of a fluid under certain conditions. Nonlinear radiation intensifies heat transfer, especially at higher temperatures, by introducing stronger temperature gradients and also affects the temperature distribution in the fluid. This, in turn, can change the fluid's properties such as viscosity, thermal conductivity which are often temperature-dependent. Due to these reasons many researchers investigated nanofluid flows with thermal radiation effect. Shateyi and Motsa [16] studied magnetohydrodynamic fluid flow with thermal radiation effect and proved that temperature distribution boosts with inclusion of radiation term. Shiva Rao and Deka [17] simulated numerically the role thermal radiation on hybrid nanofluid heat transfer in boundary layer flows.Dulal Pal and Hiranmoy Mondal [18] studied about fluid flow and heat transfer in non-Darcy porous medium with thermal radiation effect. Yaseen et al.[19] reported thermal characteristics in parallel plates with thermal radiation for nanofluid and hybrid nanofluid. More detailed comparative study on linear and quadratic thermal radiation effect on hybrid nanofluid flow can be seen in research work by Yaseen et al.[20].Sulochana and Prasanna Kumar [21] investigated changes in friction coefficient with hybrid nanofluid and thermal radiation effect. Umar Farooq et al.[22] simulated hybrid nanofluid flow between two plates with radiation and dissipation effects. Motivated by the above research work , the present article is focused on the discussion about Casson nanofluid flow in a rotating system with upper surface being permeable plate and lower surface is a movable sheet with linear velocity. Most of the authors focused on nanofluid flow between parallel plates with nano and hybrid nanofluid models but no work is reported to analyse the Casson rheological model-based hybrid nanofluid flow in rotating plates with thermal radiation, ohmic heating effects.

2. CFD Model and Mathematical Formulation

Let us consider an incompressible Casson hybrid nanofluid flow between two parallel plates where one plate is stretchable, and the other is permeable. Detailed representative diagram is shown in Figure-1 with Cartesian coordinate system (x, y), where the x-axis lies along the surface, and the y-axis is perpendicular to it. The parallel plates are aligned horizontally along the x-axis. The lower plate is subjected to stretching, and the influence of solar radiation is examined and also the following assumption are taken into consideration:

- The plates are located at $y = 0$ and $y = H$ such that the permeable surface at $y = H$ is subjected to uniform suction/injection, while the stretchable surface at $y = 0$ aligns with the x-axis.
- The plates and fluid rotate simultaneously around the y-axis, which is perpendicular to the walls, with a constant angular velocity.
- The hybrid nanofluid is assumed to be incompressible and both the fluid phase and nanoparticles are in thermal equilibrium and are sufficiently small to neglect slip velocity between phases.
- The system includes the influence of a uniform magnetic field of constant strength $B_o$oriented perpendicular to the plates along the y-axis.

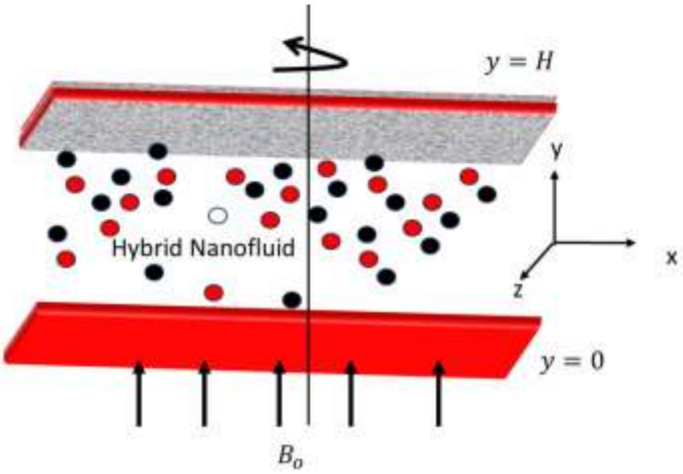

Figure -1: Geometrical representation of the fluid flow problem.

With the above assumptions and following the existing works on parallel plates flow problems the governing equation for nanofluid flow can be written as (See [23] ,[24]) :

$$\frac{\partial u}{\partial x} = -\frac{\partial u}{\partial y} \quad (1)$$

$$\rho_{hnf}\left(u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} + 2\Omega w\right) = -p_x + \mu_{hnf}\left(1+\frac{1}{\gamma}\right)\left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2}\right) - \sigma_{hnf} {B_o}^2 u \quad (2)$$

$$\rho_{hnf}\left(u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y}\right) = -p_y + \mu_{hnf}\left(1+\frac{1}{\gamma}\right)\left(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2}\right) \quad (3)$$

$$\rho_{hnf}\left(u\frac{\partial w}{\partial x} + v\frac{\partial w}{\partial y} - 2\Omega u\right) = -p_y + \mu_{hnf}\left(1+\frac{1}{\gamma}\right)\left(\frac{\partial^2 w}{\partial x^2} + \frac{\partial^2 w}{\partial y^2}\right) - \sigma_{hnf} {B_o}^2 w \quad (4)$$

$$\left(u\frac{\partial T}{\partial x} + v\frac{\partial T}{\partial y} + w\frac{\partial T}{\partial z}\right) = \alpha_{hnf}\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2}\right) - \frac{\frac{\partial q_r}{\partial y}}{(\rho c_p)_{hnf}} + \frac{\sigma_{hnf}}{(\rho c_p)_{hnf}}(u^2 + w^2) \quad (5)$$

The boundary conditions for upper and lower plate of the geometry are s follows

$$u = u_w(x) = ax, v = 0, w = 0, T = T_1 \text{ for the lower plate } y = 0. \quad (6)$$

$$u = 0,\ v = v_w, w = 0, T = T_2 \text{ for the lower plate } y = H. \quad (7)$$

Boundary layer equations are often complex and involve multiple independent variables. similarity variable combines these variables into a single dimensionless variable, simplifying the equations and allowing for easier analytical or numerical solutions. So let us introduces the similarity variable transformations

$$\eta = \frac{y}{H}, u = axF'(\eta), v = -aHF(\eta), w = axG(\eta), \theta(\eta) = \frac{T-T_1}{T_1-T_2} \quad (8)$$

The non dimensionalised ordinary differential equations are obtained by introducing the above similarity transformation can be written as:

$$\left(1+\frac{1}{\gamma}\right)\frac{\partial^4 F}{\partial \eta^4} + \Delta_1\Delta_2 Re\left(F\frac{\partial^3 F}{\partial \eta^3} - \frac{\partial F}{\partial \eta}\frac{\partial^2 F}{\partial \eta^2}\right) - 2\Delta_1\Delta_2 R_o\frac{\partial G}{\partial \eta} - M\Delta_1\frac{\partial^2 F}{\partial \eta^2} = 0 \quad (9)$$

$$\left(1+\frac{1}{\gamma}\right)\frac{\partial^2 G}{\partial \eta^2} + \Delta_1\Delta_2 Re\left(F\frac{\partial G}{\partial \eta} - \frac{\partial F}{\partial \eta}G\right) + 2\Delta_1\Delta_2 R_o\frac{\partial F}{\partial \eta} - M\Delta_1 G = 0 \quad (10)$$

$$\left(\frac{k_{hnf}}{kf}\left[1+\frac{4N_r}{3}\right]\right)\frac{\partial^2 \theta}{\partial \eta^2} + \Delta_3 PrReF\frac{\partial \theta}{\partial \eta} + MPrEc\left(\left(\frac{\partial G}{\partial \eta}\right)^2 + (G)^2\right) = 0 \quad (11)$$

Where $\Delta_1 = (1-\phi_1-\phi_2) + \frac{\phi_1\rho_1+\phi_2\rho_2}{\rho_f}$, $\Delta_2 = (1-\phi_1-\phi_2)^{2.5}$ and $\Delta_3 = (1-\phi_1-\phi_2) + \frac{\phi_1(\rho c_p)_1+\phi_2(\rho c_p)_2}{(\rho c_p)_f}$

The surface friction coefficient and Nusselt number are important dimensionless parameters used to characterize fluid flow and heat transfer between plates.

The skin friction coefficient quantifies the ratio of the wall shear stress to the dynamic pressure of the flow. It provides a measure of the resistance to flow caused by viscous forces.

$$C_f = -\frac{\mu_{hnf}}{\rho_f {v_w}^2}\left(1+\frac{1}{\gamma}\right)\left[\frac{\partial u}{\partial y}\right]_{y=0}.$$

By utilising similarity transformation mentioned in equation (8) ,

Skin friction coefficient will be $C_{fx} = \left|\frac{\left(1+\frac{1}{\gamma}\right)\left(\frac{\partial^2 F}{\partial \eta^2}\right)_{at\ \eta=0}}{\Delta_1}\right|$. (12)

The Nusselt number is a dimensionless parameter that characterizes the ratio of convective to conductive heat transfer at a boundary in a fluid flow system.

$$Nu_x = \frac{k_{hnf}h}{k_f(T_1-T_2)}\left(1+\frac{4N_r}{3}\right)\left[\frac{\partial T}{\partial y}\right]_{y=0}$$

In non-dimensional form Nusselt number can be expressed as $Nu = \left|\frac{k_{hnf}}{k_f}\left(1+\frac{4N_r}{3}\right)\left[\frac{\partial \theta}{\partial \eta}\right]_{\eta=0}\right|$ (13)

3. Results and Discussion

In this current numerical study, the authors have investigated the magnetohydrodynamic (MHD) flow and heat transfer of a hybrid nanofluid in a rotating system between two parallel plates using the shooting method implemented in MATLAB software. The upper plate of the system is permeable, while the lower plate is considered as linear velocity stretching sheet. The MATLAB code is verified with existing literature and results shows good agreement which is shown in Table-1. Effect of distinct fluid flow parameters such as Casson parameter (γ) ,radiation parameter (R_d), rotation parameter (R_o) ,Reynolds number (Re), magnetic parameter (M), suction and injection parameter (S) are discussed by computing skin friction and Nusselt number and also visualised through velocity and temperature profiles. Hybrid nanofluid is prepared by using nanoparticles Graphene oxide (GO) and molebdynum disulfide (MOS_2) with base fluid as engine oil. The rotation of a parallel plate system can significantly influence the fluid flow and temperature distribution due to the introduction of Coriolis and centrifugal forces. Figure-2 and Figure-3 explains the rotation parameter on primary and secondary velocity profiles. It is observed that rotation parameter causes diminishing profile on primary velocity and enhances the secondary velocity profile.

Figure 4 illustrates the influence of the Reynolds number on the primary velocity profile. It is evident that an increase in the Reynolds number leads to an enhancement of the primary velocity. In contrast, the secondary velocity profile exhibits an opposite trend, as shown in Figure 5, where it decreases with increasing Reynolds number. The Reynolds number significantly affects the flow regime, secondary flow characteristics, and the efficiency of the heat transfer mechanism, thereby influencing the temperature distribution. Figure 6 depicts the effect of the Reynolds number on the temperature profile, from which it is observed that higher Reynolds number values result in a reduction of the temperature distribution. Magnetic forces play a crucial role in controlling fluid motion in rotating plate systems, especially when the fluid is electrically conductive. This behaviour is commonly analysed within the framework of magnetohydrodynamics (MHD). Figures 7 and 8 illustrate the effect of the Hartmann number on the momentum boundary layer thickness. The interaction between the applied magnetic field and the moving conductive fluid generates a Lorentz force, which acts as an additional body force and alters the velocity and pressure distributions within the flow.

The Lorentz force opposes the motion of the conductive fluid, acting like a drag force. This suppression reduces flow velocity, particularly in regions where the magnetic field is strongest. In rotating plate systems, the damping effect can modify boundary layer behaviour and reduce the angular velocity of the flow near the plates.

The influence of suction and injection on fluid motion between rotating parallel porous plates is governed by their effects on the velocity, pressure, and temperature fields, as well as the associated boundary layer behaviour. Figures 9 and 10 illustrate the effects of suction and injection applied at the upper plate. The magnitude of the suction or injection velocity plays a crucial role in determining its impact on the flow; higher values produce more pronounced modifications to the boundary layer thickness and flow stability. It is evident from Figures 9 and 10 that the velocity profiles increase with the suction parameter, while they are suppressed under injection conditions. The Casson parameter is a key factor in the analysis of rotating fluid dynamics, particularly for fluids exhibiting non-Newtonian Casson behaviour. Such fluids, including blood, honey, and certain polymer solutions, require a finite yield stress to initiate motion. The Casson parameter strongly affects the flow structure, boundary layer development, and heat transfer characteristics under rotating flow conditions. Figure 11 reports the impact of Casson parameter on velocity profile and it shows an enhances momentum profile.

4. Conclusions

In the present numerical investigation, the thermal characteristics of Casson hybrid nanofluid flow between two horizontal surfaces are analyzed. The governing partial differential equations are transformed into a system of ordinary differential equations using similarity transformations, and the resulting system is solved numerically employing the shooting technique implemented in MATLAB. The key findings of this study are summarized as follows:

- An increase in the Casson parameter enhances the velocity profile while reducing the Nusselt number.
- Skin friction near the lower plate increases with higher nanoparticle volume fraction and increasing Reynolds number.
- The heat transfer rate improves with an increase in the Reynolds number.
- An increase in the rotation parameter leads to higher skin friction coefficients and a reduction in the Nusselt number.
- Enhancement of the exponential heat source/sink parameter results in an increase in the fluid temperature distribution.

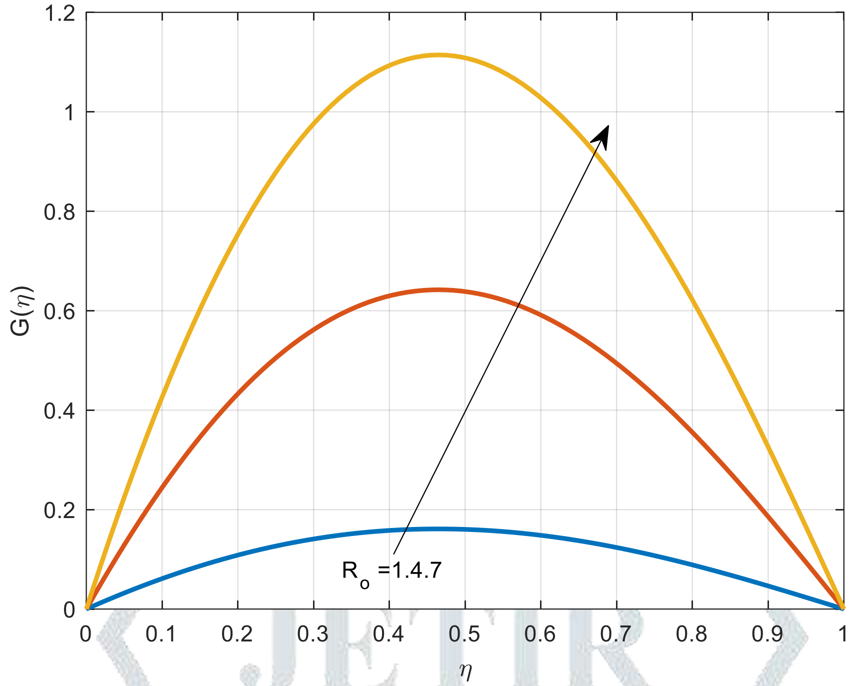

Figure-2 : Impact of rotation parameter on velocity profile.

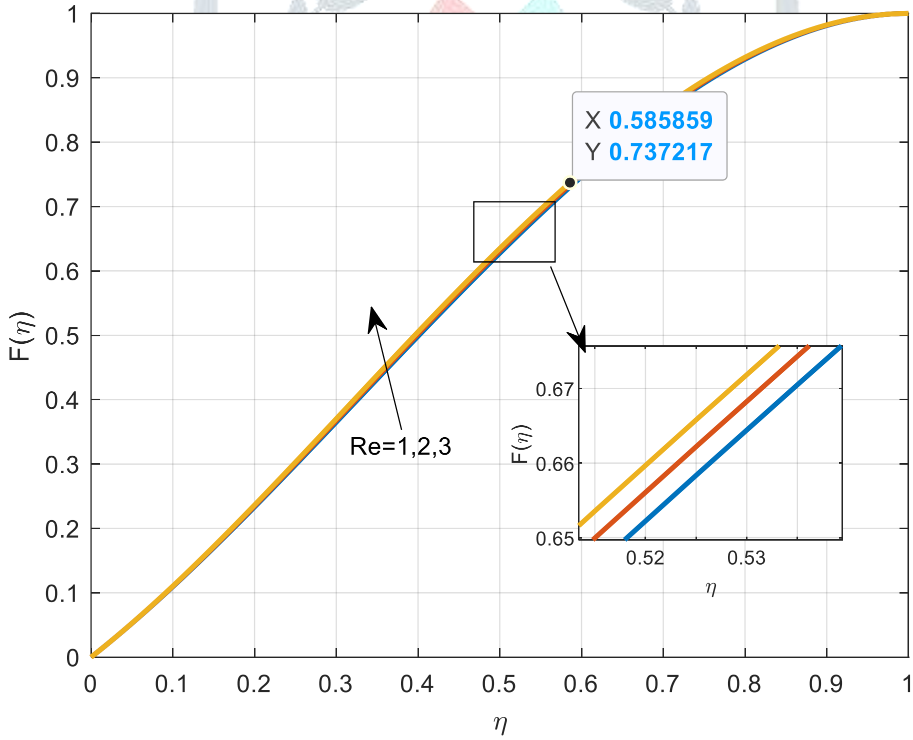

Figure-3: Impact of rotation parameter on velocity profile.

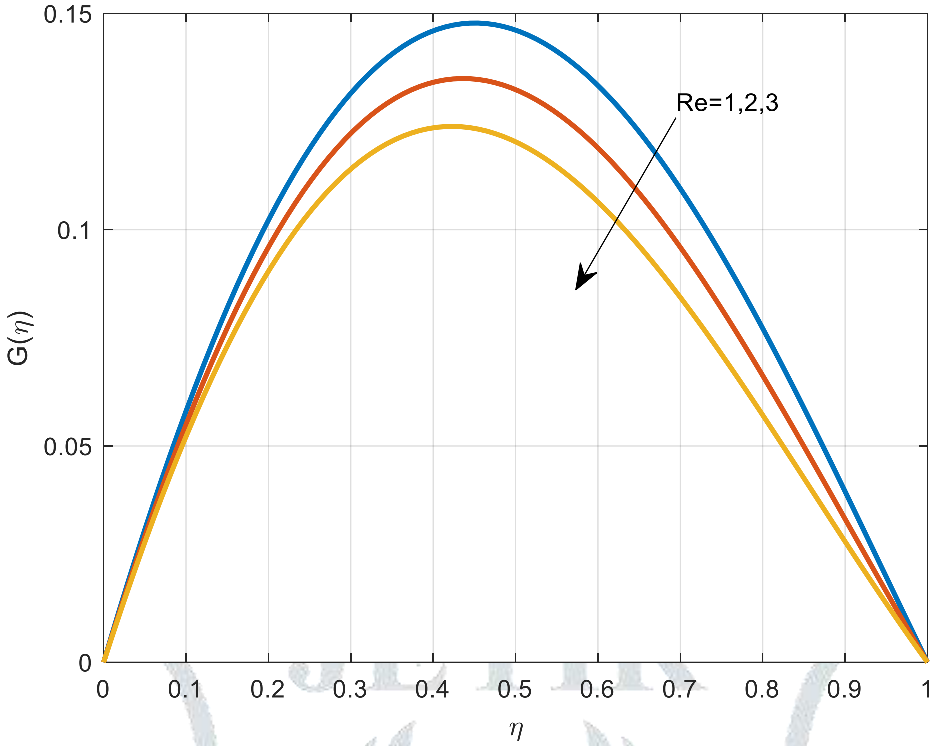

Figure 4: Rotation parameter effect on secondary velocity profile.

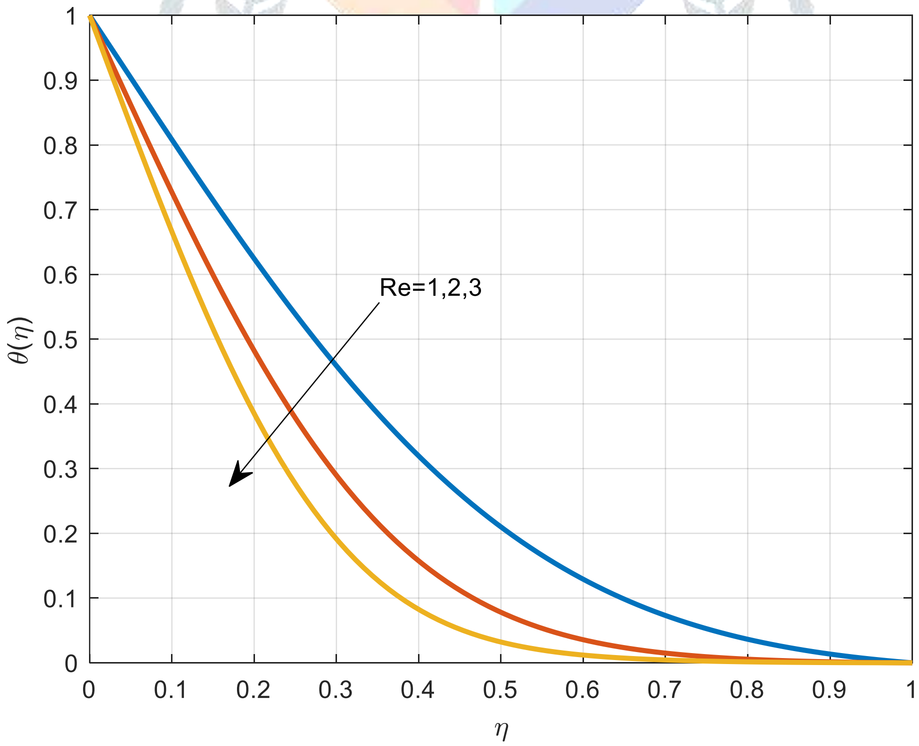

Figure-5: Impact of Reynolds number on secondary velocity.

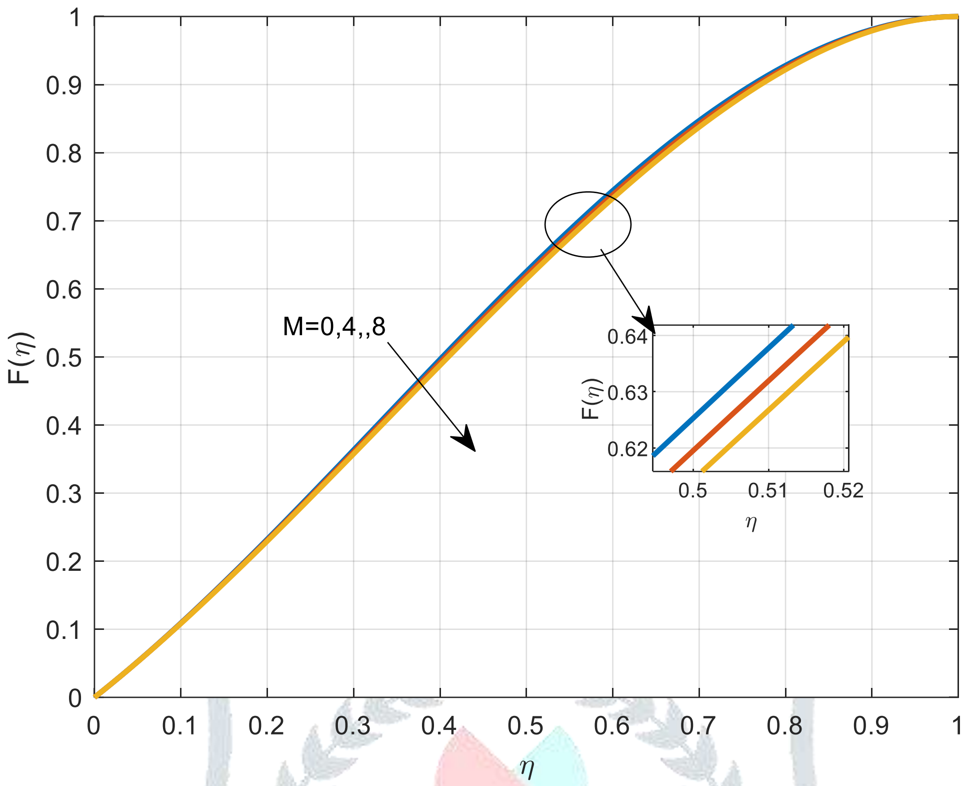

Figure-6: Impact of Reynolds number on temperature profile.

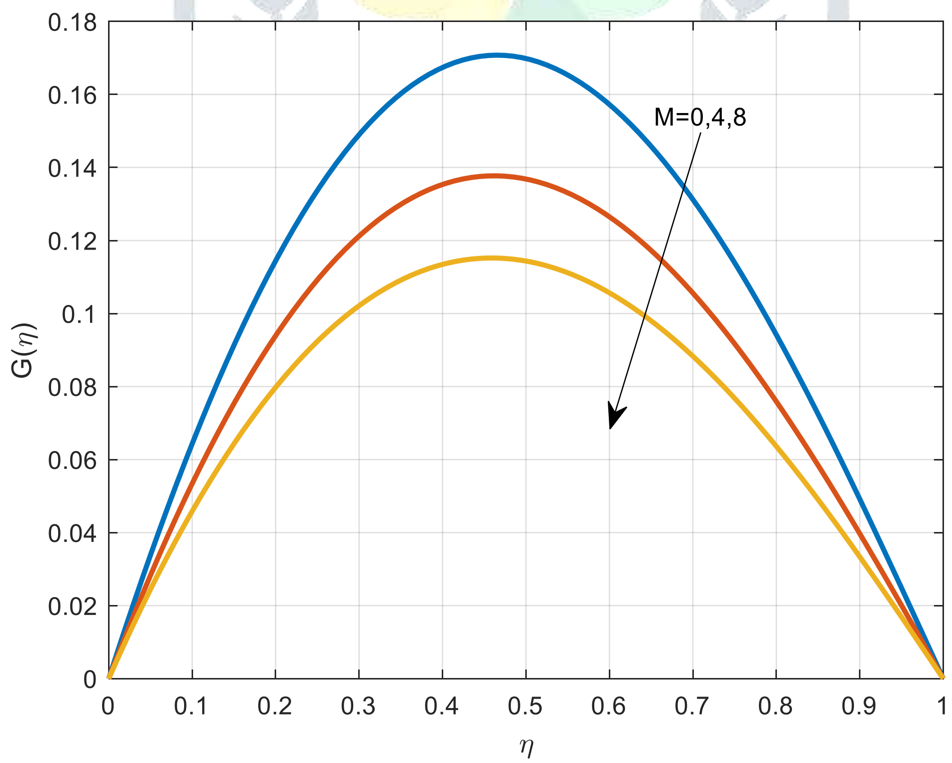

Figure-7: Impact of magnetic parameter on primary velocity profile.

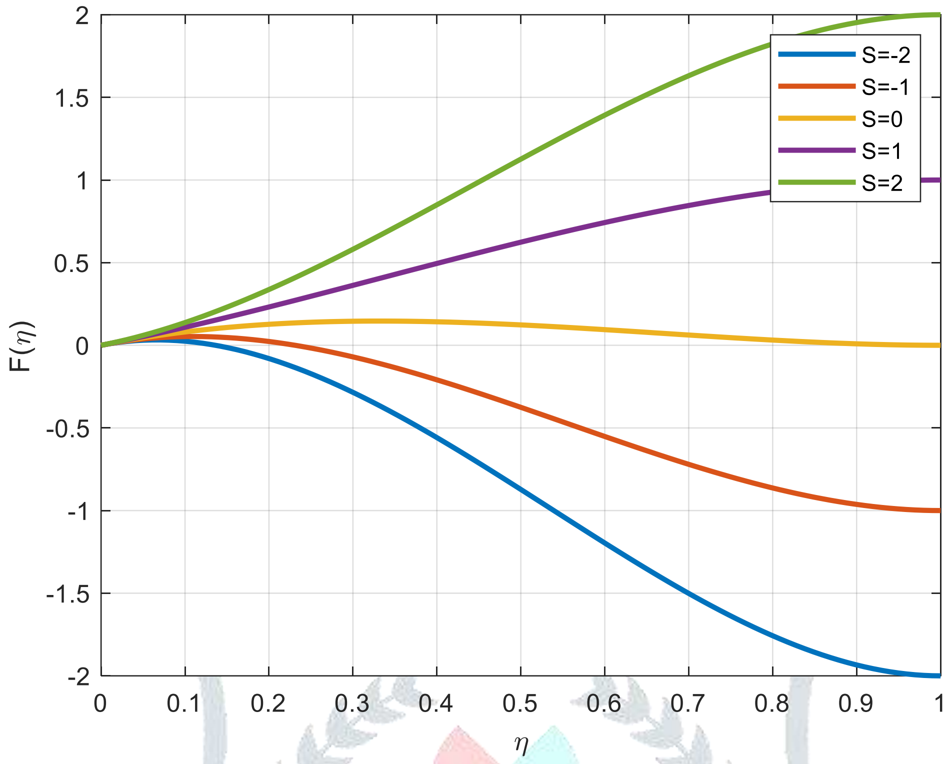

Figure-8: Impact of magnetic parameter on secondary velocity profile

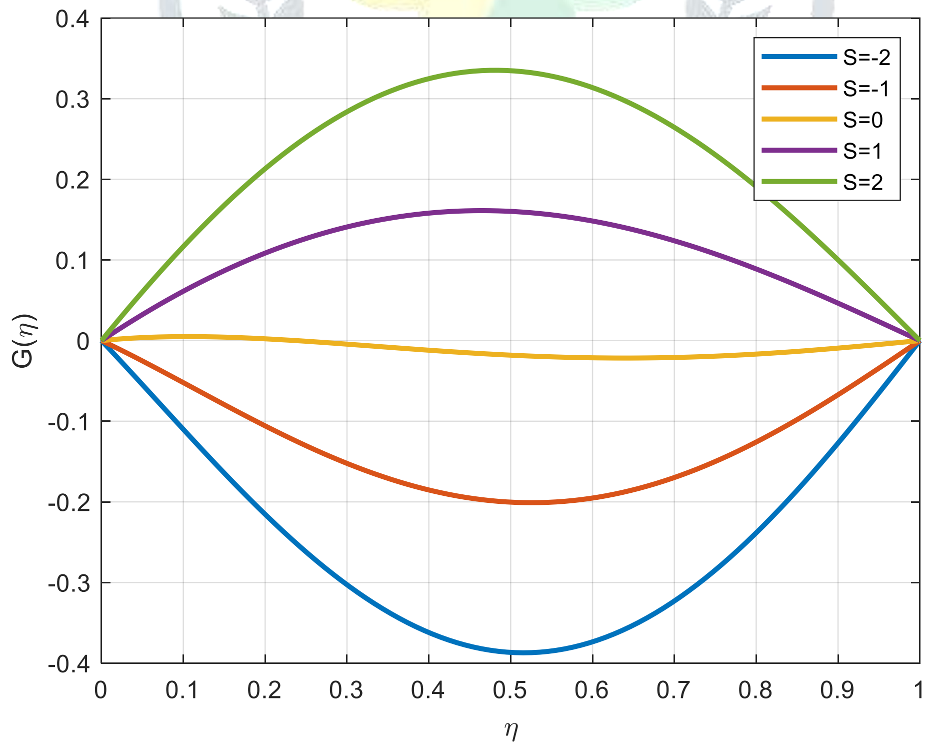

Figure-9: Suction and injection parameter effect on primary velocity profile

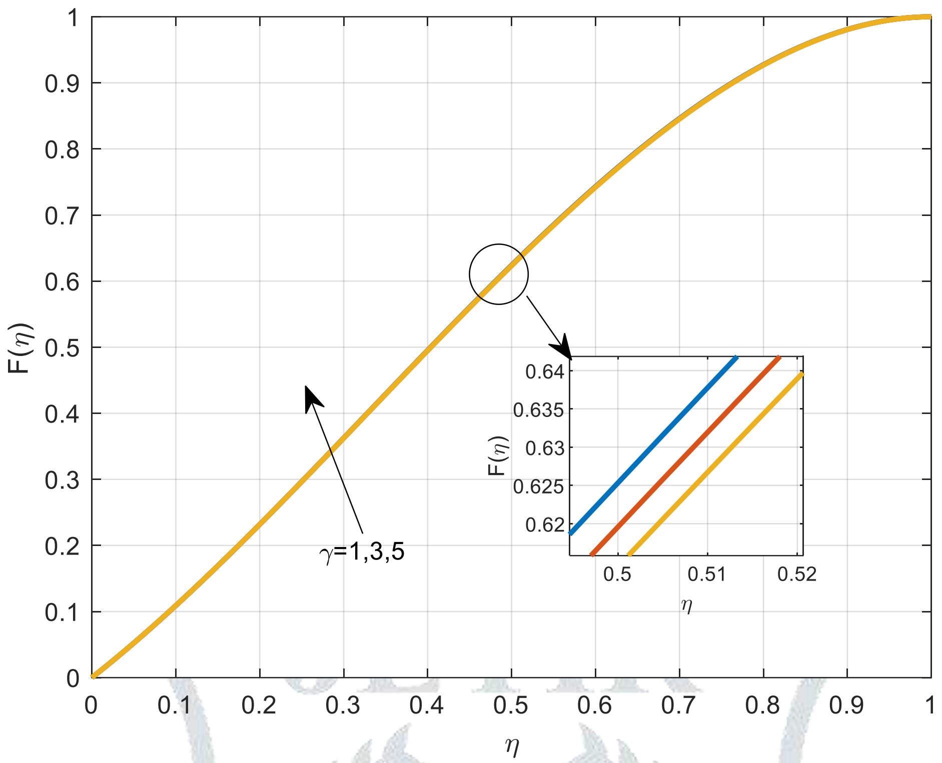

Figure-10: Suction and injection parameter effect on secondary velocity profile

Table-1: Thermophysical properties of nano particles and base fluid.[8]

Fluid Property	Graphene Oxide (GO)	Copper (Cu)	Water (H_2O)
Density $\rho(kg/m^3)$	1800	8933	997.1
Heat Capacity $C_p(J/kgK)$	717	385	4179
Thermal conductivity k(W/mK)	5000	401	0.613

Table 2: MATLAB code validation when $Rd = 0, Ec = 0, M = 0, \phi = 0.05$

Reynolds Number (Re)	Ali J Chamka et al.[8]	Present Results
0.1	1.29872	1.29760
0.5	1.61931	1.61920
1.5	2.42441	2.42364

Table-3: Computation of skin friction and Nusselt number for distinct flow parameter.

M	Rd	Re	R_o	γ	Ec	Skin friction coefficient (C_f)	Nusselt number (Nu)
0						3.460748	0.488708
4						3.330735	0.493443
8						3.218350	1.449202
	0					3.460748	1.009894
	2					3.460748	1.559063
	4					3.460748	4.231329
		1				3.620891	1.578200
		2				3.836232	2.718783
		3				4.049852	3.598861

			1			3.426361	0.240222
			4			3.710050	0.204320
			7			4.329037	0.126719
				1		4.107011	0.240856
				3		2.747038	0.239084
				5		2.475897	0.238363
					0.1	3.460748	-0.240222
					0.2	3.460748	0.007981
					0.3	3.460748	0.256195

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