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Insight into the significance of Joule dissipation, thermal jump and partial slip: Dynamics of unsteady ethelene glycol conveying graphene nanoparticles through porous medium

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Abstract: In the production of ethelene glycol, graphene nanoparticles is inevitable and even suggested due to monomolecular layer of carbon atoms which are bounded like honey comb structure is known as graphene due to this structure, graphene has several types of exceptional and unique structural, optical and electronic properties. However, little is known on the enhancement of the transport phenomenon when Joule dissipation, inclined magnetic field, thermal jump and partial slip are apparent. With emphasis to the inherent aforementioned concepts together with heat source/sink and thermal radiation, this paper presents insight into the dynamics of unsteady Ethelene glycol conveying graphene nanoparticles through porous medium. The dimensional governing equation was non-dimenzionalized using fitting similarity variables and solved the dimensionless equations using Runge-Kutta Fehlberg algorithms along with the shooting technique. Also, a statistical method was implemented for multiple quadratic regression estimation analysis on the numerical figures of wall velocity gradient and local Nusselt number to establish the connection among heat transfer rate and physical parameters. Our numerical findings reveal that the magnetic field and porosity parameters boost the graphene Maxwell nanofluid velocity while Maxwell parameter has a reversal impact on it. The regression analysis confers that Nusselt number is more prone to heat absorption parameter as compared to Eckert number. The rate of heat transfer is higher in case of with slip compare to without slip flow in the presence of thermal radiation, viscous dissipation and unsteady parameter. The fluid velocity and temperature distribution is higher in without slip compare to with slip flow.

Keywords: Dynamics of ethelene glycol, graphene nanoparticles, thermal jump and partial slip, viscous dissipation, Joule dissipation

1 Introduction

In the present scenario, owing to overwhelming significance in industry and public endeavor, the nanofluid problems have received notable attention from researchers working in the domain of nanotechnology. The nanofluid foremost termed by Choi [1] is a kind of fluid that consists of extremely fine metallic or non-metallic particles (up to 50 nm in radius). The addition of extremely fine metallic or non-metallic particles in convectional fluid influences the fluid characteristics like heat transfer rate and thermal conductivity Eastman *et al.* [2]. For example, in the modern nuclear system addition of nano-scale metal particles in the convectional fluid augments the heat transfer rate characteristics. Nanofluids are enormously useful in various applications including energy conversion, microsystem cooling (due to change in heat capacity of base fluid by adding metal or metal oxide particle of nano-sized), nanomedical industry, etc. The easiest way to enhance the thermophysical properties of base fluid is by adding the nano-sized particle (metal or non-metal). The suspension of nano-sized (less than 100 nanometers) particles (both metal and non-metal) into the base fluid results in the extreme enhancement in the temperature gradient of the

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fluid Hsiao [3]. The report of Shah et al. [4] shows that optimal Nusselt number is ascertained at a larger value of stretching ratio and suction in the dynamics of water conveying (less dense nanoparticles) multiple wall CNT and silicon dioxide.

Some relevant researches related to nanofluids under various conditions are given by Sheikholeslami [5], Li et al. [6], Mamatha et al. [7], and Patil Mamatha et al. [8]. The carbon atom's monomolecular layer having a similar structure to honeycomb is known as graphene. Owing to the fast mobility of electrons, high thermal conductivity, stability, and expanded surface area the graphene nanoparticles possess novel material, physical, electrical and chemical characteristics Netro et al. [9]. Therefore, it has a wide range of applications including but not limited to electronics, the energy sector, sensing outlets, medical sciences, etc.; see Chung et al. [10]. Upadhyay et al. [11] performed the theoretical investigation of magneto-Carreau fluid by adding the graphene and dust particles into it and observed that mixtures of ethylene glycol and graphene nanoparticles are noteworthy in improving the heat transport phenomena. Further, this study was prolonged by Mahesha et al. [12] assuming the significance of both heat generation and thermal radiation, and found that both temperature and velocity profiles are augmented owing to an increase in unsteadiness parameter values. The hydromagnetic heat transfer flow problems in the presence of porous medium have industrial useful applications, such as plasmas, extraction of energy from the earth, separation of metal from non-metals enclosure, polymer industries, etc. The significance of problems of the hydromagnetic flow of fluid along with heat transfer characteristics in the existence of a porous medium is reported by Shercliff [13], Brannover [14], Cramer and Pai [15], Sheremet and Pop [16, 17].

In the aforesaid published studies, the majority of the problems were confined to the flow of Newtonian fluids. In practical situations, it is found that numerous fluids in various engineering and industrial developments are non-Newtonian fluids in characteristics, for instance, molten plastics, polymers, nuclear fuel slurries, pulps, mercury amalgams, liquid metals, lubrication by heavy oil, etc. Owing to the complex characteristics of these fluids one can't find at least one constitutive equation that reveals all the characteristics of such non-Newtonian fluids. However, complex constitutive models for the non-Newtonian fluid's concept have been proposed by Jayachandra and Sandeep [18], Haroun [19], Sajid et al. [20], and Hayat et al. [21]. The proposed models are concerned with the second grade, third grade, and fourth-grade fluids which can estimate the impact of elasticity while these models are shear independent and unable to envisage the significance

of shear relaxation; see Hayat et al. [22, 23]. Moreover, the Maxwell model is proposed for the rate type fluids which can estimate shear stress relaxation and consequently become a popular model among the researchers. These models can also depict the significance of shear-dependent viscosity of boundary layer problems.

In the same direction, Farooq et al. [24], Imran et al. [25], Fetecau [26], and Heyhyat and Khabazi [27] reported their investigations on Maxwell fluid flow problems considering different geometrical configurations to analyze the significance of different germane parameters on the flow field. Heat generation/absorption models of fluid flow driven by permeable stretched sheet have been investigated by many authors because of its numerous industrial applications viz. hot rolling, a chemical reaction that discharges heat, endothermic reactions, heat exchange due to nuclear fuel wastage, glass fiber production, paper production, etc. Following this, the quiescent fluid flow over an exponentially stretched sheet amid the significance of heat source/ sink is investigated numerically by Elbashbeshy [28]. Satya et al. [29] solved numerically non-uniform heat source problem fluid flow over a stretching sheet. This study illustrates that suction can be employed to cool down the moving continuous surface. Further, this problem was extended by Elbashbeshy and Bazid [30] considering unsteady state conditions. Subsequently, the influence of suction/blowing on magnetohydrodynamic flow assuming both heat generation and heat absorption over the oblique stretched surface is reported by Eldahab and Aziz [31].

In the above studies, the effect of viscosity is ignored but in the practical situation its effect has a novel role Mamatha et al. [32] and due to viscosity, viscous dissipation impact has not been considered as the same is supposed to be low but its relevance in food processing, instrumentations, lubrications, polymer manufacturing, etc., is considered as very significant as it enhances the characteristics of temperature distribution which induce the heat transfer rate. Some important studies dealing with the viscous dissipative flow problem induced by stretched sheets are reported by Partha et al. [33], Aziz [34], Rashidi and Erfani [35], Qasim and Noreen [36], Khader and Megahed [37]. Further, Joule dissipation shows the characteristics alike volumetric heat sources in magnetohydrodynamic fluid flows and the collective influence of viscous dissipation and Joule dissipations are imperative in the context of heat-treated materials. Following this, several researchers such as Anjali and Ganga [38], Pal [39], Seth and Singh [40], and Seth et al. [41] modeled their problems considering the impacts of Joule and viscous dissipations. A meticulous review of research papers reported in the lit-

erature reveals that the majority of the researchers have considered the no-slip conditions in their investigations and have ignored the slip conditions. But, in many physical problems such as low-pressure flows, micro/nano-scale flow, flow over coated surfaces, etc. Navier's partial slip took place. Owing to this reason, Mukhopadhyay and Gorla [42] Singh and Makinde [43], Seth et al. [44, 45] studied the boundary layer flow problems taking partial slip conditions into account.

In recent days, industries, manufacturing, and design of materials are looking for immediate cooling or heating. Therefore we included the graphene nanoparticles in this study with time-dependent to get the originality of the flow behaviour. This state of the art is an attempt to have an overview of recent research in the field of GR related to its synthesis and scope in multifarious applications in context to electronics and energy in general and related to field emission and sensors in particular. The scope of graphene nanoparticles in tribology and industrial automation has also been explored. Sequel to the aforementioned published facts, it is worth remarking that there is no report on the significance of Joule dissipation, thermal jump, and partial slip on the dynamics of unsteady Ethylene glycol conveying graphene nanoparticles through a porous medium. Hence, this study will provide answers to the following research questions:

1. In the case of dynamics subject to no-slip and partial slip, how do Maxwell parameter and permeability parameter influences the velocity of unsteady ethylene glycol conveying graphene nanoparticles?
2. What are the variations in the local skin friction and heat transfer rate in the flow of unsteady Ethylene glycol conveying graphene nanoparticles through porous medium?
3. How does the aforementioned transport phenomenon (velocity) vary for the case of no-slip and partial slip?
4. What is the effect of the thermal jump, unsteadiness parameter, viscous dissipation, heat absorption, and heat absorption affect the temperature distribution in the dynamics mentioned above?

2 Governing mathematical equations

The mathematical formulation of the physical problem has been done by considering the flow of an incompressible, electrically conducting, two-dimensional streamline and heat-absorbing non-Newtonian Maxwell graphene nanofluid over a linearly stretching sheet. The nanofluid

Figure 1: Geometrical illustration of the problem

consists of Ethylene glycol as a base fluid and graphene as a nanoparticle. The flow of fluid is considered on the two-dimensional Cartesian coordinate system in which the stretching sheet is along to x-axis while the y-axis is across it. The fluid flow is limited in the area $y > 0$. The nanofluid is induced over a stretching sheet owing to the unsteady magnetic field $B(t) = B_0(1 - \alpha t)^{-1/2}$ exerted along the y-axis. The influence of the induced magnetic field is assumed to be ignorable for the applied magnetic field due to the low Reynolds number. Moreover, it is presumed that the considered sheet is shrunk owing to two opposite but equal forces with the unsteady velocity $U_w(x, t) = cx(1 - \alpha t)^{-1}$, where c and $(1 - \alpha t)^{-1}$ (here $\alpha t < 1$) are respectively initial and notable stretching rate. The wall temperature of nanofluid is considered T_w while the temperature outside the boundary regime known as the free stream is denoted by T_∞ . The geometrical illustration of the problem is presented in Figure 1. The prevailing mathematical equations related to momentum and energy for the Maxwell nanofluids problem by Mukhopadhyay [46] under the assumptions as considered above are expressed as

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

$$\begin{aligned} \frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} &= \frac{\mu_{nf}}{\rho_{nf}} \frac{\partial^2 u}{\partial y^2} \\ &- \lambda \left(u^2 \frac{\partial^2 u}{\partial x^2} + v^2 \frac{\partial^2 u}{\partial y^2} + 2uv \frac{\partial^2 u}{\partial x \partial y} \right) - \frac{\mu_{nf}}{\rho_{nf} K} u - \frac{\sigma_{nf} B^2(t) u}{\rho_{nf}}, \end{aligned} \quad (2)$$

$$\frac{\partial T}{\partial t} + u \frac{\partial T}{\partial x} + v \frac{\partial T}{\partial y} = \frac{k_{nf}}{(\rho c_p)_{nf}} \left(\frac{\partial^2 T}{\partial y^2} \right) - \frac{Q_0 (T - T_\infty)}{(\rho c_p)_{nf}}$$

$$+ \frac{\sigma_{nf} B^2(t) u^2}{(\rho c_p)_{nf}} \sin^2(\gamma) + \frac{\mu_{nf}}{(\rho c_p)_{nf}} \left(\frac{\partial u}{\partial y} \right)^2 - \frac{1}{(\rho c_p)_{nf}} \frac{\partial q_r}{\partial y}. \quad (3)$$

boundary conditions for the above mathematical model are given as:

$$U(x, 0) = U_w(x, 0) + s\mu_{nf} \frac{\partial u}{\partial y}, \quad v = 0, \quad T(x, 0) = T_w + D \frac{\partial T}{\partial y}, \quad (4)$$

at

$$y \rightarrow \infty, \quad u \rightarrow 0, \quad T \rightarrow T_\infty. \quad (5)$$

Notations u , v are the graphene Maxwell nanofluid velocity in the x -direction (primary velocity) and y -direction (secondary velocity) respectively. μ_{nf} indicates the dynamic viscosity of nanofluid. $\lambda = \lambda_0(1 - \alpha t)$, where λ_0 is the initial relaxation rate. $K = K_0(1 - \alpha t)$ is the porosity parameter. σ_{nf} is a symbol of electrical conductivity of graphene Maxwell nanofluid. γ is the angle in anti-clockwise sense from stretching surface. T denotes the temperature of graphene Maxwell nanofluid. k_{nf} is the symbol of heat conductivity of nanofluid. $(\rho c_p)_{nf}$ is the symbol of specific heat capacitance of graphene Maxwell nanofluid. Q_0 is the heat absorption coefficient. $s = s_0\sqrt{1 - \alpha t}$ is the slipping factor of velocity and s_0 is the slip parameter at $t = 0$. $D = D_0(1 - \alpha t)$ is the slipping factor of temperature and D_0 is the thermal slip parameter at $t = 0$. By making use of Roseland approximation for an optically thick radiative graphene Maxwell nanofluid, thermal radiative heat flux q_r takes the following form:

$$q_r + \frac{4\sigma^*}{3k^*} \frac{\partial T^4}{\partial y} = 0. \quad (6)$$

Here, σ^* is the Stefan-Boltzmann constant and k^* signifies absorption coefficient.

3 Numerical solution of the problem

By making use of stream functions $\psi = \sqrt{\frac{\nu_f c}{1 - \alpha t}} x f(\eta)$, $\theta = \frac{T - T_\infty}{T_w - T_\infty}$ and similarity variables $\eta = \sqrt{\frac{c}{\nu_f(1 - \alpha t)}} y$, the mathematical model is represented by Eqs. (2)-(3) along with boundary conditions (4) and (5) with the help of equation (6) and above similarity transform are converted to the following non-dimensional forms

$$A \left(f' + \frac{\eta}{2} f'' \right) + (f'^2 - ff'') - \phi_a \frac{f'''}{\phi_b} + \beta (f^2 f''' - 2ff' f'') + \frac{\phi_e}{\phi_b} M f' + K_1 f' = 0, \quad (7)$$

$$\theta'' (\phi_d + Nr Pr) - Q Pr \theta + \frac{Pr \phi_c}{\phi_d} \left(\frac{\phi_e}{\phi_c} M E^* c f'^2 - \frac{A\eta}{2} \theta' + f\theta' + E^* c \frac{\phi_a}{\phi_c} f'^2 \right) = 0. \quad (8)$$

The dimensionless form of boundary conditions is given as:

$$f'(0) = 1 + A_1 f''(0), \quad f(0) = 0, \quad \theta(0) = 1 + \varepsilon \theta'(0), \quad (9)$$

as

$$\eta \rightarrow \infty, \quad f'(\eta) \rightarrow 0, \quad \theta(\eta) \rightarrow 0, \quad (10)$$

where

$$\left. \begin{aligned} \phi_a &= \frac{\mu_{nf}}{\mu_f} = (1 - \phi)^{2.5}, \quad \phi_b = \frac{\rho_{nf}}{\rho_f} = (1 - \phi) + \frac{\rho_s}{\rho_f} \phi, \\ \phi_c &= \frac{(\rho c_p)_{nf}}{(\rho c_p)_f} = (1 - \phi) + \phi \frac{(\rho c_p)_s}{(\rho c_p)_f}, \\ \phi_d &= \frac{k_{nf}}{k_f} = \frac{(k_s + 2k_f) - 2\phi(k_f - k_s)}{(k_s + 2k_f) + \phi(k_f - k_s)}, \\ \phi_e &= \frac{\sigma_{nf}}{\sigma_f} = \left(1 + \frac{3 \left(\frac{\sigma_s}{\sigma_f} - 1 \right) \phi}{\left(\frac{\sigma_s}{\sigma_f} + 2 \right) - \left(\frac{\sigma_s}{\sigma_f} - 1 \right) \phi} \right) \end{aligned} \right\} \quad (11)$$

In above expressions ρ_{nf} represents the graphene Maxwell nanofluid's density, ρ_f is the base fluid's density, μ_{nf} denotes dynamic viscosity of graphene Maxwell nanofluid, μ_f is the density of Maxwell fluid (base fluid), σ_s represents the electrical conductivity of graphene nanoparticle, σ_f represents the electrical conductivity of ethylene glycol, k_s represents heat conductivity of graphene particles, k_f represents the heat conductivity of Maxwell fluid (base fluid), $A = \frac{\alpha}{c}$ is unsteadiness parameter, ϕ is the volume fraction of nanoparticle in nanofluid, $\beta = c\lambda_0$ denotes the Maxwell parameter, $M = \frac{\sigma_f B_0^2}{c\rho_f}$ presents the magnetic parameter, $K_1 = \frac{\nu_f}{cK}$ denotes the porous medium parameter, $Pr = \frac{\nu_f}{\alpha_f}$ indicates the thermal diffusivity parameter, $Nr = \frac{16}{3} \frac{\sigma^* T_\infty^3}{k^* \nu_f (\rho c_p)_f}$ implies radiation parameter, Q is the heat absorption parameter, $E^* c = \frac{U_w^2}{(c_p)(T_w - T_\infty)}$ is local Eckert number, $A_1 = s_0 \sqrt{\frac{c}{\nu_f}}$ denotes velocity slip parameter and $\varepsilon = D_0 \sqrt{\frac{c}{\nu_f}}$ represents thermal slip parameter. The thermophysical properties of Ethelene glycol (base fluid) and graphene nanoparticles are mentioned in Table 1.

From the engineering applications viewpoint, the expressions for S_f characterizes skin friction coefficient and local Nusselt number Nu_x are defined as:

$$S_f = \frac{\tau_w}{\rho_f U_w^2}, \quad Nu_x = \frac{x q_w}{k_f (T_w - T_\infty)},$$

where τ_w and q_w are $\tau_w = \mu_{nf} \frac{\partial}{\partial y} \left(u + \lambda v \frac{\partial u}{\partial y} \right)_{y=0}$, $q_w = -k_{nf} \left(1 + \frac{16}{3} \frac{\sigma^* T_\infty^3}{k^* \nu_f (\rho c_p)_f} \right) \left(\frac{\partial T}{\partial y} \right)_{y=0}$.

Table 1: Thermophysical properties of Ethelene glycol and graphene nanoparticles; sources Asim *et al.* [47] and Elbashbeshy and Bazid [48].

Thermo-physical properties	ρ (kg/m ³)	c_p (J/kgK)	K (W/mK)	σ (S/m)
Ethelene glycol	1114	2415	0.252	5.5×10^{-6}
Graphene	2250	2100	2500	1×10^{-7}

Applying the similarity transformation (9), we obtained

$$\left. \begin{aligned} S_f \sqrt{\text{Re}_x} &= (1 - \phi)^{-2.5} (f''(0) - \beta f(0)f'''(0) + \beta f'(0)f''(0)), \\ Nu_x &= -(1 + Nr) \phi_d \sqrt{\text{Re}_x} \theta'(0), \end{aligned} \right\} \quad (12)$$

where $\lambda_1 = \lambda_0 c$ is the fluid relaxation parameter and $\text{Re}_x = \frac{x U_w(x, t)}{\nu_f}$ is the local Reynolds number.

3.1 Implementation of the numerical method

The complexity of the mathematical model reported in segment 3 is very high, so the analytical solution of the model can't be obtained. Therefore, to analyze the solution of highly non-linear ordinary differential equations mentioned by equations (7) and (8) along with conditions (9) and (10), a numerical solution is analyzed employing the Runge-Kutta Fehlberg scheme with shooting technique. At first, equations (7) and (8) are converted to the form of five first-order differential equations. After this, the Runge-Kutta Fehlberg method is used to solve this set of five differential equations in which the initial functional values of $f''(0)$ and $\theta'(0)$ are obtained with the help of shooting technique. The value of similarity variable η is chosen $\eta = 7$ as aimed at infinity boundary conditions whereas the step size is considered as 0.001 during the numerical computation. To achieve a precise result the tolerance error is taken as 10^{-6} . The complete method is repeated until the anticipated correctness in the results is attained.

3.2 Validation of numerical solution

For the validation of the numerical solution obtained in this paper, we have done a comparison of $-f_1(0)$ for various values of Prandtl number Pr and unsteadiness parameter A and with that of Elbashbeshy and Bazid [48] when $\beta = M = K_1 = Q = Ec = A1 = \epsilon = 0$ and are presented in Table 2. Table 2 shows excellent conformity of numerical results which validates the correctness of our numerical solution.

From an engineering interest viewpoint, the numerical findings of the coefficient of skin friction and Nusselt number are also presented in Tables 3 and 4. This is in good

agreement with the observation reported by Elbashbeshy and Bazid [48] that unsteady stretching affects the transfer of heat across the fluid flow. For this, values of non-dimensional parameters are considered as Prandtl number $Pr=150$, unsteadiness parameter $A = 0.1$, thermal slip parameter $\epsilon = 0.1$, Eckert number, magnetic parameter $M = 0.7$, Maxwell parameter $\beta = 0.5$, heat absorption parameter $Q = 3$, and porosity parameter $K_1 = 0.1$. These values remain unchanged throughout the analysis. It is obvious from Table 3 that skin friction is getting enhanced due to an increase in Magnetic field, porosity, and unsteadiness parameters for both conditions (slip and without slip flow). It is also evident from Table 3 that skin friction is getting reduced due to an increase in Maxwell parameter for both conditions (slip and without slip flow). It is noticed from Table 4 that the Nusselt number gets enhanced owing to an increase in heat absorption and thermal slip parameters for both conditions (slip and without slip flow) while it gets reduced due to an increase in viscous dissipation, radiation parameter, and unsteadiness parameters for both conditions (slip and without slip flow). Notably, the rate of heat transfer is higher in the case of slip compare to without slip flow in the presence of thermal radiation, viscous dissipation, and unsteady parameter.

3.3 Multiple regression analysis: Estimation of Nusselt number and skin friction coefficients

Multiple regression analysis is a statistical tool that is used to estimate the relationship between two or more variables. Generally, regression analysis is beneficial to distinguish in what way the specific value of dependent variable changes owing to variation in independent variable though other independent variables are assumed constant. In this portion, quadratic regression estimation analysis for Nusselt number and skin friction coefficients has been presented. The model of multiple quadratic regression estimation for the coefficient of skin friction is mentioned for 100 different values of M and K_1 , obtained arbitrarily from the intervals $[1,7]$ and $[0.1, 0.5]$ respectively for two different values of $\beta = 0.1$ and $\beta = 0.5$. Apart from

Table 2: Comparison of $-f''(0)$ with the previously published paper

A Pr	0.8		1.2		2	
	Elbashbeshy and Bzid [48]	Present result	Elbashbeshy and Bzid [48]	Present result	Elbashbeshy and Bzid [48]	Present result
0.01	1.3321	1.3382	1.4691	1.4637	1.7087	1.6979
0.1	1.3321	1.3382	1.4691	1.4637	1.7087	1.6979
1	1.3321	1.3382	1.4691	1.4637	1.7087	1.6979
10	1.3321	1.3382	1.4691	1.4637	1.7087	1.6979

Table 3: Skin friction coefficient under both slip ($A_1 = 0$) and no-slip ($A_1 = 0.3$) conditions

M	K_1	β	A	$A_1 = 0$ Skin friction coefficient	$A_1 = 0.3$ Skin friction coefficient
1				-1.550280	-1.091902
2				-1.795996	-1.224990
3				-2.018683	-1.336651
	0.1			-1.464016	-1.055576
	0.3			-1.550862	-1.10089
	0.5			-1.629970	-1.142603
		0.1		-1.504320	-1.062202
		0.3		-1.493485	-1.059860
		0.5		-1.464016	-1.055576
			0.1	-1.550280	-1.091902
			0.9	-1.751600	-1.201253
			1.7	-1.938760	-1.297035

Table 4: Heat transfer rate at the stretched sheet under both no-slip ($A_1 = 0$) and slip ($A_1 = 0.3$) conditions

Nr	Ec	ε	A	Q	$-Nu_x$ (Nusselt Number)	
					$A_1 = 0$	$A_1 = 0.3$
0.1					1.793817	1.782474
0.3					1.609518	1.569714
0.5					1.352808	1.286409
	0.10				1.493379	1.439736
	0.25				0.680038	0.656444
	0.40				0.580038	0.473152
		0.10			1.024231	1.030984
		0.25			1.215093	1.201549
		0.40			1.493379	1.439736
			0.1		1.493379	1.439736
			0.4		1.341298	1.253572
			0.7		1.157093	0.995805
				1	0.805981	0.813852
				3	0.935618	0.944211
				5	1.027387	1.035966

this, a model of multiple quadratic regression estimation for the Nusselt number is provided for a set of 100 values of Ec and Q analyzed arbitrarily from the intervals $[0.1, 0.3]$ and $[1, 3]$ for two different values of $Pr = 5$ and $Pr = 10$. During the estimation process, the remaining parameters are kept constant as stated. The estimated quadratic regression model for $Cf_x Re_x^{1/2}$ corresponding to the magnetic field and the porous medium parameter is given as

follows

$$Cf_{est} = Cf + b_1 M + b_2 K_1 + b_3 M^2 + b_4 K_1^2 + b_5 M K_1. \quad (13)$$

While the regression formula for $Nu_x Re_x^{1/2}$ corresponding to Eckert number Ec and heat absorption parameter Q is given as

$$Nu_{est} = Nu + c_1 Ec + c_2 Q + c_3 Ec^2 + c_4 Q^2 + c_5 Ec Q. \quad (14)$$

Table 5: Error bound ε and multiple quadratic regression coefficients for the estimated $Cf_x Re_x^{1/2}$ with variations in M and K_1 .

B	Cf	b_1	b_2	b_3	b_4	b_5	ε
0.1	-0.9310	-0.2160	-0.3164	0.0070	0.0417	0.0227	0.0042
0.5	-0.8742	-0.2352	-0.3806	0.0089	0.0655	0.0317	0.0066

Figure 2: Velocity profiles due to variation in the magnetic parameter. **Figure 3:** Velocity profiles due to variation in the permeability parameter.

Tables 5 and 6 present the coefficients of multiple quadratic regression estimated findings of skin friction coefficients and Nusselt number for different parameters. The maximum relative error bound for skin friction $\varepsilon = |Cf_{est} - Cf| / Cf$ and Nusselt number $\varepsilon_1 = |Nu_{est} - Nu| / Nu$ are also obtained and presented in Tables 5 and 6 respectively. From the tabulated values, it is evident that the coefficient of the porous medium parameter is higher than that of the magnetic field parameter, which suggests that the variation in skin friction is more sensitive for the values of K_1 than M for both values of β . In the same way, we can observe that the Nusselt number is more prone to heat absorption parameter Q for both values of Pr as compared to Eckert number Ec .

Figure 4: Velocity profiles due to variation in Maxwell parameter.

4 Result and discussions

In this section, numerical computation is executed and the results are reported to demonstrate a comparative analysis revealing the impacts of several parameters on the flow field. Throughout the numerical computation, values of various non-dimensional parameters are assumed as Prandtl number $Pr=150$, unsteadiness parameter $A = 0.1$, thermal slip parameter $\varepsilon = 0.1$, Eckert number $Ec = 0.1$,

magnetic parameter $M = 0.7$, Maxwell parameter $\beta = 0.5$, heat absorption parameter $Q = 3$, radiation parameter $Nr = 0.2$, and porosity parameter $K_1 = 0.1$. These values remain unchanged throughout the analysis while the varying values of parameters are specified in respective figures. In all the figures, solid lines indicate the impact of pertinent flow parameters under no-slip conditions while dashed lines denote the impact under slip conditions.

Table 6: Error bound and multiple quadratic regression coefficients for the estimated $NuRe_x^{1/2}$ with variations in Ec and Q .

Pr	Nu	c_1	c_2	c_3	c_4	c_5	ϵ_1
5	-1.3931	-0.7258	1.6353	0.0768	0.4318	-0.2417	0.000024
10	-1.7862	-0.9962	2.6242	0.1319	0.6564	-0.4804	0.000028

Figure 5: Velocity profiles due to variation in the unsteadiness parameter. **Figure 7:** Temperature profiles due to variation in heat absorption parameter. **Figure 6:** Temperature profiles due to variation in heat radiation parameter. **Figure 8:** Temperature profiles due to variation of viscous dissipation.

Figures 2-5 illustrate the effects of the magnetic field, porous medium, Maxwell, and unsteadiness parameters on the velocity of graphene Maxwell nanofluid. Figures 6-10 describes the significance of thermal radiation, heat absorption, viscous dissipation, thermal slip, and unsteadiness parameter on the temperature of graphene Maxwell nanofluid. Figure 2 shows that graphene Maxwell fluid velocity decreases due to magnetic field parameter

(M) enhancement under both slip ($A1 = 0.3$) and no-slip ($A1 = 0$) velocity conditions. This type of behaviour is happened due to resistive Lorentz force; which enhances slowing to increase the strength of the magnetic field. Figure 3 explores the effect of porosity medium (K_1) on nanofluid velocity. It is seen that due to an increase in porosity the fluid velocity is decreasing. The reason behind this nature of velocity is that resistance opposes the fluid flow is

Figure 9: Temperature profiles due to variation in thermal slip parameter.

Figure 10: Temperature profiles due to variation in the unsteadiness parameter.

experienced due to increment in a porous medium. Figure 4 shows that the velocity of graphene Maxwell fluid increases due to an increase in the Maxwell parameter (β). Since Maxwell fluid is non-Newtonian fluid, therefore, it generates repulsion forces between molecules, due to this, there is a velocity increment. Figure 5 exhibits that graphene Maxwell fluid velocity is getting reduced owing to an increase in unsteadiness parameter (A). As increasing unsteady parameter, improve the unsteadiness of the flow. Further, it is to be noted from Figures 2-5 that graphene Maxwell nanofluid velocity is higher in case of the no-slip condition than that of slip condition.

Figure 6 shows that the temperature of graphene Maxwell nanofluid is boosting due to an increase in a radiation parameter (Nr). As raising values of thermal radi-

ation, generates collision between molecules of the fluid. Figure 7 depicts that graphene Maxwell nanofluid temperature is reduced due to enhancement in the heat absorption parameter (Q). This is owing to the reason that increment in heat absorption parameter results in the heat-absorbing capacity of fluid throughout the boundary layer region. It is apparent from Figure 8 that by enhancing the Eckert number (Ec), graphene Maxwell nanofluid temperature can also be increased. The reason behind this behaviour of graphene Maxwell nanofluid is that Eckert number signifies the ratio of kinetic energy to enthalpy and the total work is done against viscosity where the kinetic energy is converted into internal energy. Hence, viscous dissipation has a nature to increase the temperature of the fluid in the whole boundary layer. Figure 9 presents that graphene Maxwell fluid temperature is reducing due to enhancing the thermal slip parameter ϵ . The reason for this tendency of fluid temperature presented by Figure 9 is that due to increment in thermal slip parameter less heat is flowing from surface to fluid. Hence, the temperature is reducing. It can be noticed from Figure 10 that, due to an increase in unsteadiness parameter, graphene Maxwell temperature is also increasing. Increasing unsteady parameters, improve the chaotic behaviour of the flow. Hence that will help in increment in the collision between molecules. It is to be noted from Figures 6-10 that graphene Maxwell nanofluid temperature is higher in the case of the no-slip condition than that of slip conditions.

5 Concluding remarks

In this report, the significance of Joule dissipation, thermal jump, and partial slip on the dynamics of unsteady ethylene glycol conveying graphene nanoparticles through porous medium had been examined. Based on the outcome of the analysis, it is worth concluding that the graphene Maxwell nanofluid velocity gets reduced owing to enhancement in a magnetic field, the inclination angle of the magnetic field, the porosity of porous medium, and unsteadiness parameters whereas the behaviour of fluid velocity gets reversed due to Maxwell parameter. The heat absorption and thermal slip parameters reduce the temperature of graphene Maxwell nanofluid in the boundary layer regime while the temperature of Maxwell nanofluid is increased owing to an increase in inclination angle of the magnetic field, viscous dissipation, and unsteadiness parameters. The magnetic field, porosity, angle of inclination of the magnetic field, and unsteadiness parameters improve the shear stress at the stretched sheet. The rate of

heat transfer of nanofluid is augmented owing to heat absorption and thermal slip parameters while it is reduced due increase in viscous dissipation and unsteadiness parameters.

The extension of this study to the cases of nanofluid flow due to radially elongated disk with Coriolis and Lorentz forces by Mahanthesh *et al.* [49], Quadratic convective flow of Casson fluid in a micro-channel by Kunnegowda *et al.* [50], dynamics of ethylene glycol conveying graphene nanoparticles rotating stretchable disk by Mahanthesh *et al.* [51], increasing effects of the haphazard motion of graphene nanoparticles in ethylene glycol by Animasaun *et al.* [52] and dynamics of blood - graphene nanoparticles Carreau nanofluid induced by partial slip and buoyancy by Koriko *et al.* [53] are recommended as a future study.

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