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Inclined Magnetic Field on Second Grade Nanofluid Flow from an Inclined Stretching Sheet with Nonlinear Mixed Convection

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Present investigation aims to probe into the problem of nonlinear mixed convection flow of second grade nanofluid flow due to an inclined stretching sheet. The simultaneous impacts of inclined magnetic field of acute angle and convective boundary conditions are taken into deliberation. The system of highly nonlinear partial differential equations is transformed into non-linear ordinary differential equations with the aid of similarity transformation variables. The solutions are generated numerically via the Runge-Kutta-Fehlberg Method (RKF 45) and then presented in the form of graph. Obtained results are first authenticated by way of comparison with the documented results of previous publications. Finding reveals that the inclined angle together with magnetic parameter have decelerated the fluid flow. Besides, escalating both Brownian motion and thermophoresis diffusion parameters have enhanced the temperature. In contrast, the concentration profile has reduced owing to incremented Lewis number.

Keywords: inclined magnetic field; second grade nanofluid; inclined stretching sheet; nonlinear mixed convection; convective boundary conditions

I. INTRODUCTION

Experience gained through heat transport analysis has significant influence in engineering and industry technologies, for instance petroleum reservoirs, nuclear waste disposal and chemical reactor catalytic (Khan *et al.*, 2018). Extensive research activity in heat transport of fluid flow problem has garnered special focus from investigators due to the involvement in those build-up applications. Some of these efforts are concerned with the characteristic of heat transfer through convection in various conditions (Mohamed *et al.*, 2016; Zin *et al.*, 2016; Hussanan *et al.*, 2018; Zokri *et al.*, 2018; Zokri *et al.*, 2018). One of the popular convection modes known as mixed convection happens when the external sources like pump and fan together with buoyancy forces occur synchronously. This flow encompasses in diverse industrial applications including the exposure of solar central receivers to the wind currents, cooling the electronic devices and nuclear reactor, and installing the heat exchangers in low velocity environment (Imtiaz *et al.*, 2014). Despite of all the studies reviewed so far, improvement in the flow and heat transfer mechanisms have to be developed since the convectional flow only allows for linear relation of temperature-density. This is because, the involved process in thermal system operates at moderate to very high temperature which tends to render temperature to vary nonlinearly with density (Hayat *et al.*, 2018). In this connection, Motsa *et al.* (2014) addressed a theoretical study on the advancement of thermal transport by applying nonlinear mixed convection flow in nanofluid over a vertical surface under the influences of Brownian motion and thermophoresis. Meanwhile, Kameswaran *et al.* (2014) inspected the combined impact of nonlinear mixed convection and thermophoresis to observe the viscous fluid flow through porous medium. Khan *et al.* (2018) investigated the properties of flow behaviour displayed by nanofluid with the effects of entropy generation and nonlinear mixed convection in rotating disk. A recent study by Irfan *et al.* (2019) analyzed the nonlinear relationship between temperature and density for Carreau nanofluid with magnetic field effect. In addition, a few publications on nonlinear mixed

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convection flow have also been treasured in the literature for different types of fluid models in various circumstances (RamReddy and Pradeepa, 2016; Shaw *et al.*, 2016; Qayyum *et al.*, 2017; Mandal and Mukhopadhyay, 2018).

The investigation on boundary layer problem of magnetohydrodynamic (MHD) field involving fluid flow system has engaged the attention of some researchers. Evolution of the manufacturing industries such as nuclear reactor, cooling down metallic plate and extrusion polymers has led to the exploration of MHD flow, whereby it plays a crucial role in monitoring the heat loss in order to obtain a desired product quality. However, there is a considerable effort that has been embraced and suggested by researches to improve the understanding of fluid flow system. Sulochana *et al.* (2016) investigated the modified MHD flow by taking into account the inclined angle, in which the magnetic field is utilized at various angle from $30°-90°$ to the positive direction of flow. It is worth mentioning that the improvement of their study stems from the classical problems of transverse magnetic flow where the magnetic field is required to be at $90°$ on the flow region. In another article, Ilias *et al.* (2016) studied the convective flow of ferrofluids accompanied by inclined magnetic field at acute angle over a vertical plate. Sandeep (2017) scrutinized the distributions of nanofluid flow past a stretching sheet with the influences of inclined magnetic field and radiation. Several investigators have thoroughly explored the flow of modified MHD, as can be found in (Gaffar *et al.*, 2015; Hakeem *et al.*, 2016; Kasim *et al.*, 2019; Saravana *et al.*, 2019).

Referring to the literatures as discussed above, no study has reported a definite mathematical model of non-Newtonian second grade fluid problem for inclined magnetic field effect allied with nonlinear mixed convection flow. Therefore, this present research aims to undertake a numerical study by combining these two effects for second grade nanofluid flow due to vertical inclined stretching sheet.

II. MATHEMATICAL FORMULATION

A steady two dimensional inclined stretched flow of MHD second grade nanofluid is deliberated. Combined impacts of non-linear mixed convection and inclined magnetic field are taken into consideration. The physical model of the coordinate system is exemplified in Figure 1. The Cartesian coordinate is chosen such that the respective $x-$ and $y-$ axes are oriented along the stretched sheet and orthogonal to it. At $y=0$, the sheet is stretched vertically with velocity u_w in the $x-$ direction. The surface temperature and concentration, which are imposed to a convective boundary condition, are assumed to be greater than the free stream temperature and concentration, i.e. $T_f > T_\infty$ and $C_f > C_\infty$, respectively. The governing boundary layer equations for convectively heated second grade nanofluid flow are (Arifin *et al.*, 2017; Khan *et al.*, 2018; Irfan *et al.*, 2019)

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}=0 \tag{1}$$

$$\begin{aligned} u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y} &= \nu\frac{\partial^2 u}{\partial y^2}+\frac{\alpha_1}{\rho_f}\left(\frac{\partial}{\partial x}\left(u\frac{\partial^2 u}{\partial y^2}\right)-\frac{\partial u}{\partial y}\frac{\partial^2 u}{\partial x\partial y}+v\frac{\partial^3 u}{\partial y^3}\right) \\ &-\frac{\sigma}{\rho_f}uB_0{}^2\sin^2(\gamma)+\begin{bmatrix}\beta_T(T-T_\infty)+\beta_T^*(T-T_\infty)^2\\ +\beta_C(C-C_\infty)+\beta_C^*(C-C_\infty)^2\end{bmatrix}g\cos\alpha_0 \end{aligned} \tag{2}$$

$$u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}=\alpha\frac{\partial^2 T}{\partial y^2}+\tau\left[D_B\frac{\partial C}{\partial y}\frac{\partial T}{\partial y}+\frac{D_T}{T_\infty}\left(\frac{\partial T}{\partial y}\right)^2\right] \tag{3}$$

$$u\frac{\partial C}{\partial x}+v\frac{\partial C}{\partial y}=D_B\frac{\partial^2 C}{\partial y^2}+\frac{D_T}{T_\infty}\frac{\partial^2 T}{\partial y^2} \tag{4}$$

subject to the boundary conditions

$$\begin{aligned} &u=u_w(x)=ax,\ v=0,\ -k\frac{\partial T}{\partial y}=h_1\left(T_f-T\right), \\ &-D_B\frac{\partial C}{\partial y}=h_2\left(C_f-C\right)\ \text{at}\ y=0 \\ &u\to 0,\ v\to 0,\ T\to T_\infty,\ C\to C_\infty\ \text{as}\ y\to\infty \end{aligned} \tag{5}$$

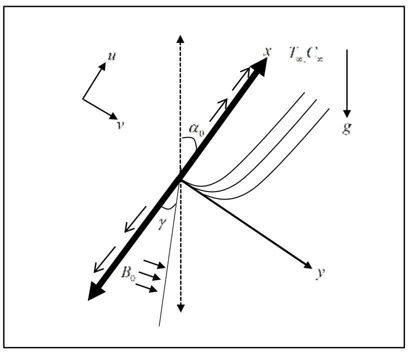

Figure 1. Physical model of the coordinate system

where u and v are the respective components of velocity in the $x-$ and $y-$ directions, ν is the kinematic viscosity, α is the thermal diffusivity, α_0 is the inclined angle for stretched sheet, α_1 is the material parameter for second grade fluid, β_T is the linear thermal expansion coefficient, β_T^* is the nonlinear thermal expansion coefficient, β_C is the linear concentration expansion coefficients, β_C^* is the nonlinear concentration expansion coefficients, T is the temperature of fluid, C is the concentration of fluid, ρ_f is the density of base fluid, ρ_p is the density for nanoparticles, B_0 is the magnitude of applied magnetic field, γ is the inclined angle for magnetic field, σ is the electrical conductivity, g is the gravitational acceleration, $\alpha = \frac{k}{(\rho C)_f}$ is the thermal diffusivity, $\tau = \frac{(\rho c)_p}{(\rho c)_f}$ is the ratio of heat capacity where $(\rho c)_p$ is the heat capacity of the nanoparticle while $(\rho c)_f$ is the heat capacity of the fluid, D_B is the Brownian diffusion coefficient, D_T is the thermophoretic diffusion coefficients, k is the thermal conductivity and h_1 and h_2 are the respective heat and mass transfer coefficients. Now, the succeeding similarity transformation variables are imposed

$$\eta = \sqrt{\frac{a}{\upsilon}}y, \quad u = axf'(\eta), \quad v = -\sqrt{a\upsilon}f(\eta), \quad \theta(\eta) = \frac{T - T_\infty}{T_f - T_\infty}, \quad \phi(\eta) = \frac{C - C_\infty}{C_f - C_\infty} \tag{6}$$

Upon implementing equation (6), the satisfaction of equation (1) is unavoidable, while equations (2) to (4) with boundary conditions (5) result in the subsequent equations

$$f''' + ff'' - f'^2 + \kappa\left(2ff''' - f''^2 - ff^{(iv)}\right) - Mf'\sin^2(\gamma) + \left(\lambda(1 + \lambda_T\theta)\theta + \lambda N(1 + \lambda_C\phi)\phi\right)\cos\alpha_0 = 0 \tag{7}$$

$$\theta'' + \Pr f\theta' + \Pr Nb\theta'\phi' + \Pr Nt\theta'^2 = 0 \tag{8}$$

$$\phi'' + Le\Pr f\phi' + \frac{Nt}{Nb}\theta'' = 0 \tag{9}$$

$$f(0) = 0, \; f'(0) = 1, \; \theta'(0) = -Bi_1(1 - \theta(0)), \; \phi'(0) = -Bi_2(1 - \phi(0)) \tag{10}$$
$$f'(\infty) \to 0, \; f''(\infty) \to 0, \; \theta(\infty) \to 0, \; \phi(\infty) \to 0$$

where $\kappa = \frac{\alpha_1 a}{\rho_f \nu}$, $\lambda = \frac{Gr_x}{\mathrm{Re}_x^2} = \frac{g\beta_T(T_f - T_\infty)x}{u_w^{\ 2}}$, $\lambda_T = \frac{\beta_T^*(T_f - T_\infty)}{\beta_T}$, $\lambda_C = \frac{\beta_C^*(C_f - C_\infty)}{\beta_C}$, $N = \frac{\beta_C}{\beta_T}\frac{(C_f - C_\infty)}{(T_f - T_\infty)}$, $M = \frac{\sigma B_0^2}{\rho_f a}$, $\Pr = \frac{\upsilon}{\alpha}$, $Nb = \frac{\tau D_B(C_f - C_\infty)}{\upsilon}$, $Nt = \frac{\tau D_T(T_f - T_\infty)}{\upsilon T_\infty}$, $Le = \frac{\upsilon}{D_B}$, $Bi_1 = \frac{h_1}{k}\sqrt{\frac{\upsilon}{a}}$, and $Bi_2 = \frac{h_2}{D_B}\sqrt{\frac{\upsilon}{a}}$ are the respective dimensionless second grade parameter, mixed convection parameter, nonlinear thermal mixed convection parameter, nonlinear concentration mixed convection parameter, ratio of concentration to thermal buoyancy forces, magnetic parameter, Prandtl number, Brownian motion parameter, thermophoresis parameter, Lewis number and heat and mass transfers of Biot number.

III. RESULTS AND DISCUSSION

The nonlinear system of equations (7) to (9) with boundary conditions (10) are tackled by means of the Runge-Kutta-Fehlberg Method (RKF 45) to explore the physical parameters of second grade, magnetic parameter and nonlinear thermal and concentration mixed convection. Specification of the physical parameters involved throughout this study is as follows: $\kappa = 1$, $M = 0.5$, $\Pr = 6.2$, $\lambda = \lambda_T = \lambda_C = N = 0.1$, $Bi_1 = Bi_2 = 0.3$, $\gamma = \alpha_0 = \frac{\pi}{4}$, $Nb = Nt = 0.2$ and $Le = 10$. Here, the selection of $Le = 10$ is based on the work of Pop *et al.* (2017), for which most nanofluid deliberated to date as mentioned by Kuznetsov and Nield (2013) has large value of Le, that is $Le > 1$. The numerical solutions are subsequently computed with the aid of MAPLE software. Validation of the present solutions is carried out by way of comparison with the formerly documented results in the literature for $-\theta'(0)$ and $-\phi'(0)$ as accessible through Tables 1 and 2. The comparative values are evidently in a good agreement with those of Khan and Pop (2010), Mabood *et al.* (2015), Rudraswamy *et al.* (2015), Gupta *et al.* (2018) and Nadeem *et al.* (2014), which bring in supreme conviction in all results as unveiled later. It is clear from Table 1 that the heat transfer increases as a result of increasing $\Pr$. Besides, Table 2 displays the reduction of heat transfer and enhancement of the nanoparticle concentration transfer by reason of rising Nt values.

Figures 2 to 7 are plotted to briefly discuss the impact of several dimensionless parameters on the profiles of velocity, temperature and concentration. An increasing impact of the velocity profile as a result of incremented κ values is demonstrated in Figure 2. A rise in κ means to reduce the fluid viscosity, hence subsequently accelerates the fluid flow. Figures 3 and 4 display the decremented velocity profile in consequence of rising inclined angle of magnetic field and magnetic parameter, respectively. Here, there exist no magnetic field impact in the flow region when $\gamma = 0°$ and the magnetic field behaves perpendicularly when $\gamma = 90°$. A rise of inclined angle from $0°$ to $90°$ has enhanced the strength of magnetic field which assisted the attendance of Lorentz force. This force type has an ability to reduce the boundary layer thickness, accordingly decelerate the flow of fluid.

Table 1. Comparison of $-\theta'(\eta)$ for several values of Pr when $\kappa = M = \lambda = Bi_2 = Nb = Nt = 0$ and $Bi_1 \to \infty$

Pr	Khan and Pop (2010)	Rudraswamy *et al.* (2015)	Gupta *et al.* (2018)	Present
0.7	0.4539	0.4539	0.4538682	0.454963
2	0.9113	0.9112	0.9113432	0.911305
7	1.8954	1.8953	1.8954124	1.895582
20	3.3539	3.3538	3.3538714	3.353720
70	6.4621	6.4621	6.4622357	6.462171

Table 2. Comparison of $-\theta'(\eta)$ and $-\phi'(\eta)$ for several values of Nt when $\Pr = 10$, $Nb = 0.1$, $Le = 1$, $Bi_1 \to \infty$ and $\kappa = \lambda = M = Bi_2 = 0$

	Nadeem *et al.* (2014)		Present	
Nt	$-\theta'(\eta)$	$-\phi'(\eta)$	$-\theta'(\eta)$	$-\phi'(\eta)$
0.1	0.9524	2.1294	0.952402	2.129311
0.2	0.6932	2.2732	0.692720	2.275542
0.3	0.5201	2.5286	0.520037	2.528833
0.4	0.4026	2.7952	0.402568	2.795256
0.5	0.3211	3.0351	0.321061	3.035104

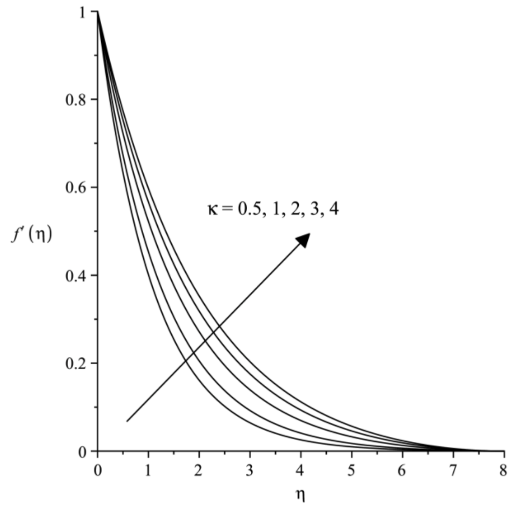

Figure 2. $f'(\eta)$ against η for several values of κ

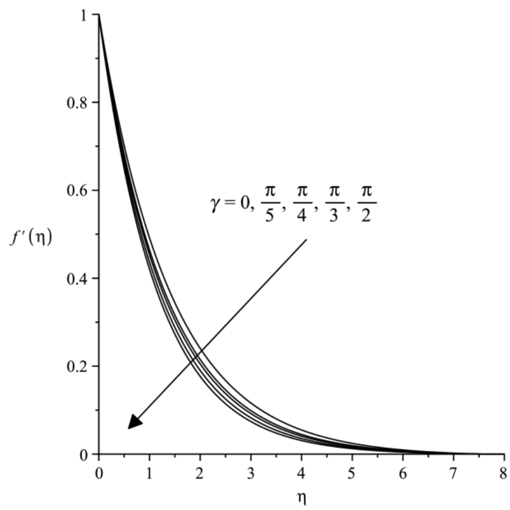

Figure 3. $f'(\eta)$ against η for several values of γ

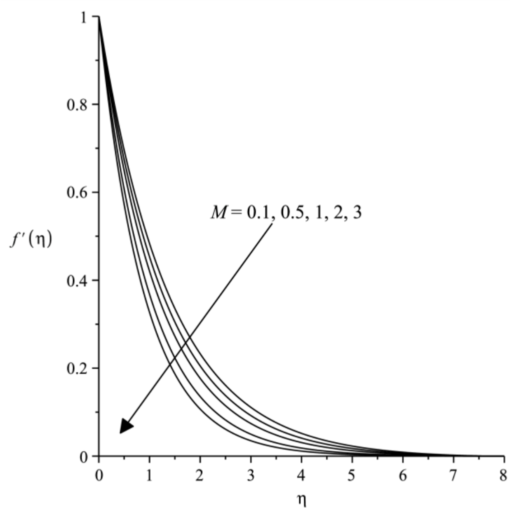

Figure 4. $\theta(\eta)$ against η for several values of M

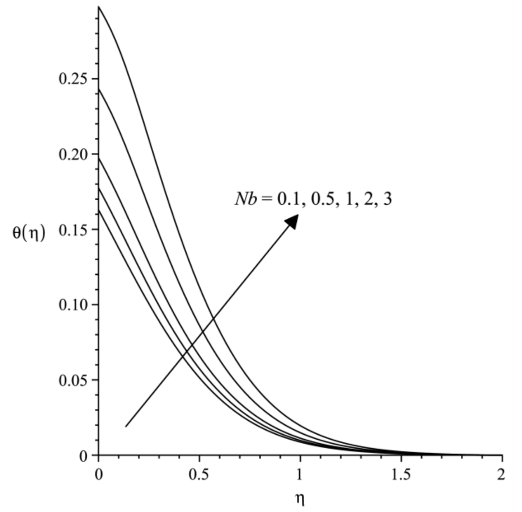

Figure 5. $\theta(\eta)$ against η for several values of Nb

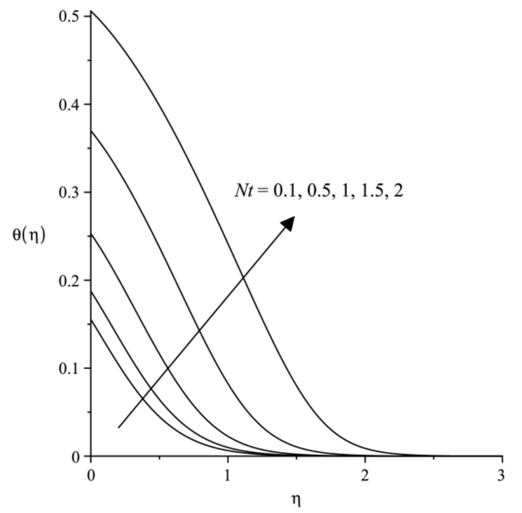

Figure 6. $\theta(\eta)$ against η for several values of Nt

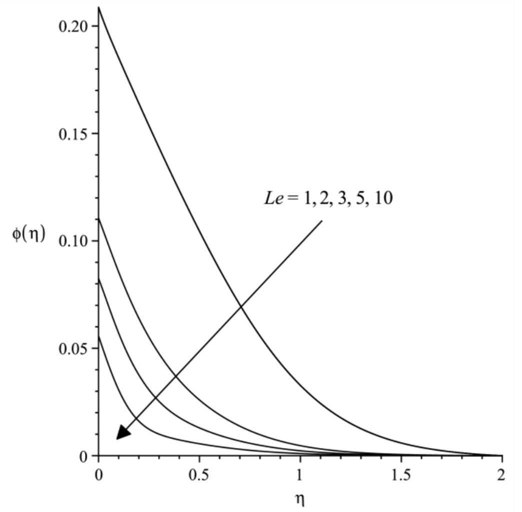

Figure 7. $\phi(\eta)$ against η for several values of Le

An illustration of the response of Brownion motion parameter, Nb over the temperature profile is elucidated in Figure 5, where the temperature profile displays rising function of Nb. This expected outcome can be associated with the increasing repetitive collision among the fluid particles and their random motions that result in the extra production of heat. Consequently, the temperature profile enhances. Figure 6 portrays an escalating behaviour of the temperature profile due to augmenting Nt values. Here, the thermophoresis phenomenon leads to the formation of a convective flow that triggers the movement of hot fluid molecules from warm to cold regions, which has subsequently increased the temperature profile.

From Figure 7, the rise of Lewis number, Le has significantly reduced the nanoparticle concentration profile. Fundamentally, Le relies upon Brownian diffusion coefficient. A small Le corresponds to a strong Brownian diffusion coefficient while a large Le corresponds to a weak Brownian diffusion coefficient. Therefore, the decremented nanoparticle concentration profile is anticipated.

IV. CONCLUSION

The present work has communicated the second grade nanofluid flow from a convectively heated inclined stretching sheet with combined impacts of inclined magnetic field and nonlinear mixed convection. The Buongiorno model representing the nanofluid flow was accounted. The numerical results have revealed how the second grade parameter, inclined angle, magnetic parameter, Brownian motion, thermophoresis diffusion and Lewis number affecting the velocity, temperature and concentration profiles. The salient outcome of this study can be outlined as below:

- The velocity profile accelerates with rising second grade parameter and decelerates with rising inclined angle and magnetic parameter.
- The temperature profile has enhanced because of incremented Brownian motion and thermophoresis diffusion parameters.
- The concentration profile has reduced owing to rising Lewis number.

V. ACKNOWLEDGEMENT

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