Numerical Study on the Influence of Thermophores and Magnetic Field on the Boundary Layer Flow Over a Moving Surface in a Nanofluid

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Abstract:- For the present research, an attempt was made to study the influence of magnetic field and thermophoresis on an existing mathematical model. The impacts made by both magnetic parameter and thermophoresis over the nanofluids flux as well as the characteristics of transfer of heat are studied and analyzed by using a suitable numerical method (Runge-Kutta- Fehlberg method together with shooting technique) in maple2020. Also the effects of some emerging physical parameters on the profiles of momentum and temperature have been studied and analyzed in tables and graphs. Two solutions are obtainable if the free stream and the plate moves conversely to each other. At the end it was found that the Nusselt number is mostly an increasing function, whereas, the momentum and the temperature fluctuates with different parameters.

I.   INTRODUCTION

The standard fluid's heat transfers particularly those that have very poor heat transfer properties compared to most of the solid particles are water, mineral oil and ethylene glycol. An effort was made to improve the heat transfer of fluids by suspending very small sized solid particles in the fluids. The fluid that contains such solid particles were given a new name as "nanofluids". This concept was first introduced by Chai in the year 1995. Nanofluid is considered as fluid that contains particles of Nano-meter size. These fluids bring about collision in the suspensions of nanoparticles to the base fluid. Nanofluids have put together some novelty usefulness in many applications in heat transfer, some of which are microelectronics, fuel cells, pharmaceutical processes, and hybrid- powered engines, engine cooling/ vehicle thermal management, domestic refrigerator etc. These, with their various potential applications, have recently attracted intensive studies of nanofluids. Abu- Nada (2008) discussed extensively on the application of nanofluids for heat transfer enhancement of separated flow encountered in a backward facing step, Backok et al. (2010), (2010), (2011), Yacob et al. (2011). The use of particles of nanometer dimension was continuously studied by a research group at the Argonne National Laboratory around some decades ago. The thermal properties of the base fluid as well as the transport properties of the nanofluids respectively are influenced when nanoparticles are added into a fluid. A book was lunched in the year (2007) authored by Dass, Choi, Yu titled "Science and Technology", in this book they discussed extensively about the references on nanofluids. Some of the related published papers are Buongiorno (2006), Daungthongsuk et al. (2007), Trisaksri et al. (2007), Wang et al. (2008), Rohni et al. (2010). Recently studies concerning the natural phenomenon of nanofluids, have been investigated by Madaki et al. (2017), (2018), (2020) and (2021). moreover, Pal and Mandal (2015) investigated the Nano fluid's MHD convective-radiative boundary layer flow of stretching/shrinking sheet with viscous dissipation numerically. Hussaini et al (2021), make an analysis on the convective MHD nanofluid flow.

The main motivation for this research is to modify an existing mathematical model [Norfifah et al. (2011)] to a new case were the model consist of magnetic field as well as thermophoresis. Firstly, the governing partial differential system was transformed into an ordinary differential system. Thereafter, the ordinary differential system is then solved numerically by Runge- Kutta Ferlberge method along with shooting technique by using maple. The obtained result is then compared with that of Backok et al. (2011) for validation, and it was found that the two results are in good agreement with each other. And then the influence of some emerging physical parameters were studied and analyzed graphically and table of values.

II. PROBLEM FORMULATION

The research Considered boundary-layer flow of a nanofluid in two-dimension, which is passed through a heated stretching surface along with water as a base fluid and Cu, Al_2O_3, and TiO_2 as nanoparticles, on which convective boundary conditions are applied. Furthermore, the movement of the plate is considered to be constant, such that $u_w = \lambda U$, λ, U are the velocity, as described by Weidman et al. (2006). X is the coordinate along the plate and y is the coordinate normal to the plate, the fluid flows in the direction $y \geq 0$. T_w, $T\infty$ are the wall temperature and the ambient nanofluid respectively, such that $T_w > T\infty$.

using the nanofluid model which was proposed by and the governing equations for the mathematical model can take the following shape as used by Dass (2007) and Tiwari (2007):

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

$$u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} = -\frac{1}{\rho_{nf}}\frac{\partial p}{\partial x} + \frac{\mu_{nf}}{\rho_{nf}}\left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial x^2}\right)$$
$$-\frac{\sigma_e B_0^2}{\rho_f}u \tag{2}$$

$$u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} = -\frac{1}{\rho_{nf}}\frac{\partial p}{\partial y} + \frac{\mu_{nf}}{\rho_{nf}}\left(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2}\right)$$
$$-\frac{\sigma_e B_0^2}{\rho_f}u \tag{3}$$

$$\frac{\partial T}{\partial x} + v\frac{\partial T}{\partial y} = \frac{\sigma_{nf}}{v_f}\frac{\partial^2 T}{\partial y^2} + \left(\frac{D_T}{T_\infty}\right)\left(\frac{\partial T}{\partial y}\right)^2 \tag{4}$$

Where we assumed that the boundary conditions are
$u=u_w=\lambda$, $v=v_w$, $T=T_w$, at y=0
$u=u_e=U$, $v=0$, $T=T_\infty$, $p=p_\infty$ as $y \longrightarrow \infty$. (5)

Here, u and v are the velocities in x, y directions, T represents nanofluid temperature, ρ is the fluid pressure, μ_{nf} is viscosity, α_{nf} representing the thermal diffusivity and ρ_{nf} nanofluid density, these are explained by Oztop et al. (2008), and hence:

$$\alpha_{nf} = \frac{k_{nf}}{(\rho Cp)_{nf}},$$
$$\rho_{nf} = (1-\varphi)\rho_f + \varphi\rho_s,$$
$$\mu_{nf} = \frac{\mu_f}{(1-\varphi)^{2.5}},$$
$$(\rho Cp)_{nf} = (1-\varphi)(\rho Cp)_f + \varphi(\rho Cp)_s,$$
$$\frac{k_{nf}}{k_f} = \frac{(k_s + 2k_f) - 2\varphi(k_f - k_s)}{(k_s + 2k_f) + (k_f - k_s)} \tag{6}$$

Here φ, $(\rho Cp)_{nf}$, k_{nf}, k_f, k_s, ρ_f, ρ_s are the nanoparticle volume fraction, the heat capacity of the nanofluid, the thermal conductivity of the fluid, the thermal conductivities of the fluid, the solid fractions, the fluid densities, solid fractions of the fluid. This was explained in Abu Nada et al. (2008). The viscosity of the fluid is given by μ_{nf}, μ_f is the viscosity of a base fluid.

The boundary layer variables, are given below

$x=x/L$, $y=Re^{1/2}$ (y/L), $u=u/L$, $v=Re^{1/2}(v/L)$, $u_e=u_e/U$, $\theta=(T-T_\infty)/(T_w-T_\infty)$, $p=(p-p_\infty)/(p_f U^2)$, $u=u_w/U$ (7)

such that L, p_∞, $Re= UL/v_f$ are the plate's characteristic length, the pressure of the ambient nanofluid and the Reynolds number with v_f being the kinematic viscosity of the nanofluid. We now consider the flow under zero pressure gradient, on which boundary layer approximation is applied, which yield this mathematical model for the mass, momentum and energy equations:

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0 \tag{8}$$

$$u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} = \frac{\mu_{nf}}{\rho_{nf}}\frac{\partial^2 v}{\partial y^2} - \frac{\sigma_e B_0^2}{\rho_f}u \tag{9}$$

$$\frac{\partial T}{\partial x} + v\frac{\partial T}{\partial y} = \frac{\alpha_{nf}}{v_f}\frac{\partial^2 T}{\partial y^2} + \left(\frac{D_T}{T_\infty}\right)\left(\frac{\partial T}{\partial y}\right)^2 \tag{10}$$

For y =0: $u=u_w=\lambda$, $v=v_w$, $\theta = 0$
for $y \longrightarrow \infty$: $u=u_e= \gamma$, $\theta= 1$ (11)

we now apply these dimensionless quantities into eqs (5- 8):
$$T(\eta) = \theta, \eta = y/(2x)^{1/2}, f(\eta) = \psi/(2x)^{1/2}. \tag{12}$$

Where ψ is the stream function and is defined in the usually way as $u = -\frac{\partial \psi}{\partial y}$, which identically satisfies eq.(5). In order that similarity solutions of eqs. (5- 8) exists, we take

$$v_w = -\frac{\tau}{(2x)^{1/2}} \tag{13}$$

Where $\tau= f(0)$ is a non-dimensional constant which determines the transpiration rate.

Now, we reduce the above equations into the ODEs below
$$f''' + (1-\varphi)^{2.5}[1-\varphi+\varphi(\rho_s/\rho_f)]\{ff'' - M^2 f'\} = 0 \tag{14}$$

$$\theta'' + \frac{[1-\varphi+\varphi(\rho Cp)_s/(\rho Cp)_f]Pr}{k_{nf}/k_f}\left(f\theta' + \frac{N_T}{N_b}\theta'^2\right) = 0 \tag{15}$$

The new boundary conditions are as follows:
$$f(0) = \tau, f'(0) = \lambda, \theta(0) =1, \quad as\ y=0$$
$$f'(\eta) =1, \theta(\eta) = 0\ as\ \eta \to \infty. \tag{16}$$

The physical quantities of interest are the skin friction coefficient and the Nusselt number which are each defined thus:

$$C_f = \frac{\tau_w}{\rho_f u_w^2}, \quad Nu = \frac{Lq_w}{k_f(T_w - T_\infty)}, \qquad (17)$$

Such that:

$$\tau_w = \mu_{nf}\left(\frac{\partial u}{\partial y}\right)_{y=0}, \qquad q_w = -k_{nf}\left(\frac{\partial T}{\partial y}\right)_{y=0} \qquad (18)$$

Which are the surface shear stress and the surface heat flux respectively.

III. RESULTS AND DISCUSSION

The ordinary differential equations together with the boundary conditions are solved numerically by the Runge-Kutta- Fehlberg method alongside, the shooting technique. The missing boundary conditions where named by $f''(0) = \alpha$ and $\theta'(0), = \beta$ and their values were found in relation to the emerging physical parameters such as φ, λ. f_o the nanoparticle volume fraction, the moving parameter, the suction/injection parameter respectively. In this research we will focus our attention basically on Three (3) viz (Cu) copper, (Al_2O_3) alumina and (TiO_2) titanium nanoparticles. The results are summarized in tables 1-4 including figures (1-8).

Table1 this is the validation table [with N. Backok et al. (2012)] for the values for λ_e when we considered different values for τ at Pr= 6.2 along with φ= 0.1.

Nanoparticles	τ	Backok et al. (2012)	Present
TiO$_2$	-0.3	-0.1887	-0.1886
	0	-0.3541	-0.3541
	0.3	-0.5617	-0.5621
Cu	-0.3	-0.1657	-0.1659
	0	-0.3541	-0.3541
	0.3	-0.5997	-0.5999
Al$_2$O$_3$	-0.3	-0.1903	-0.1906
	0	-0.3541	-0.3541
	0.3	-0.5592	-0.5590

Table2 effects of Magnetic parameter (M) on the momentum and temperature $\left(f'(0) \text{ and } \theta'(0)\right)$

M	0	1	3	6	9
$f'(0)$	-0.3055	-0.3179	-0.3550	-0.4395	-0.9415
$\theta'(0)$	4.6793	5.0297	6.3835	19.05	25.63

Table3 influence of Prandtl number (Pr) to Nusselt number $-\theta'(0)$ profile

Pr	5	10	20	40	80
$-\theta'(0)$	2.935	2.878	2.783	2.649	2.506

Table4 effects of thermophoresis (Nt) on temperature $\theta'(0)$

Nt	-2	-1	0	1	3
$\theta'(0)$	2.5191	2.6499	3.8519	3.1895	5.112

It can be seen from *table1* that there is an increase in momentum as well as the temperature of the system rises whenever there is an increment in the value of the magnetic parameter (M). It is also clearly visible in *table2* the decrease in the Nusselt number is as a result of increment in Prandtl number. It can be notice from *table3* that increase in the value of thermophoresis parameter increases the temperature of the system and hence it increases the heat transfer enhancement.
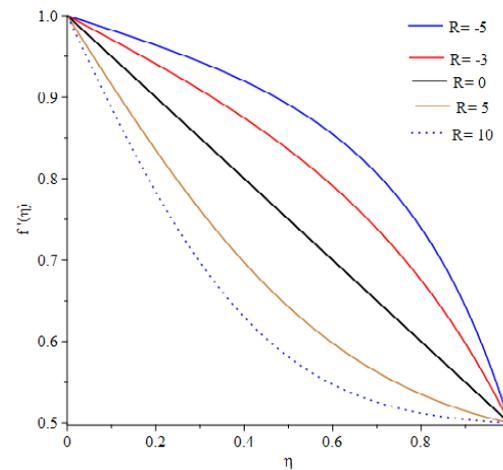

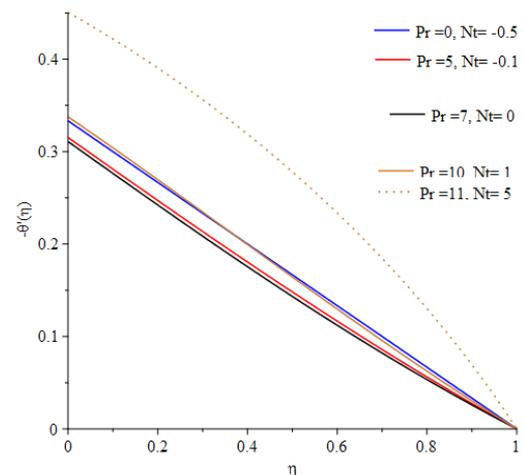Fig 1: influence of resistance parameter (R) on velocity.

Fig 2: influence of Prandtl number and thermophoresis to Nusselt number profile

Figure1 shows the effects of Resistance parameter on momentum, in which increment in the resistance parameter produces a drastic decrement in the velocity of the fluid. It is also seen from *figure2* above (the effects of Prandtl number and thermophoresis on the Nusselt number profile). There are basically two cases such that for negative values of thermophoresis parameter increase in the values of Prandtl number decreases the Nusselt number drastically, whereas, for positive values of thermophoresis increase in the values

of Prandtl number increases the Nusselt number of the system. *Figure3* (effects of Prandtl number on the temperature profile). Which depicted that increase in the values of Prandtl number increases the temperature of the system.
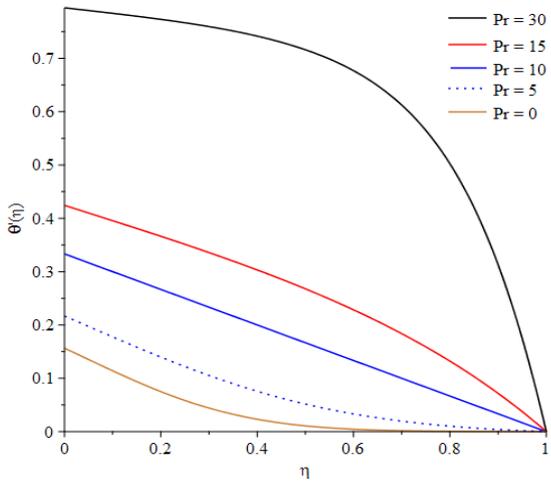

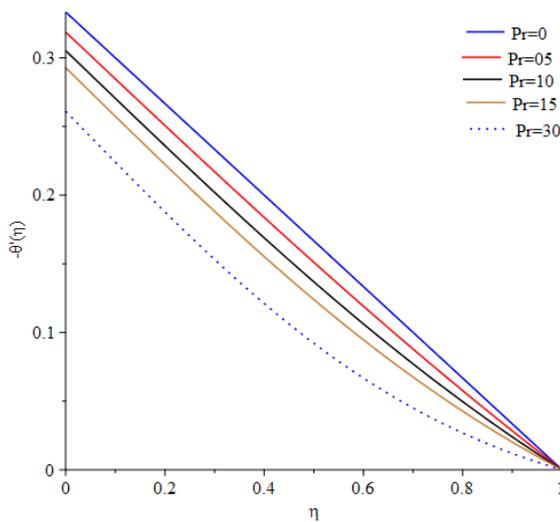Fig 3 influence of Prandtl number to the temperature profile

Fig 4: influence by Prandtl number on Nusselt number

It can be seen on *figure4* that for an increment in Prandtl number produces a decrement in the Nusselt number's profile. However, from *figure5* (thermal conductivity parameter on the profile of Nusselt number), two cases were recorded for different values of the thermal conductivity parameter, when the thermal conductivity is negative: increase in the parameter decreases the Nusselt number, while, for positive values of the thermal conductivity parameter, increase in thermal conductivity parameter drastically increase the temperature of the system.
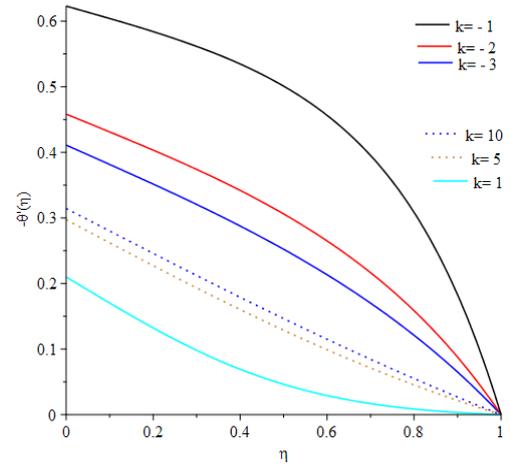

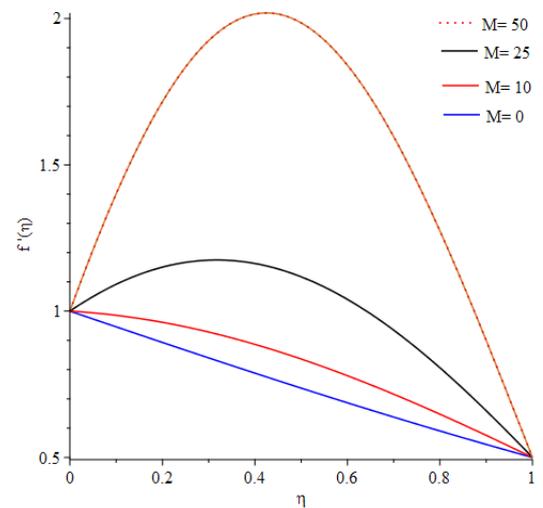Fig 5: Effects of thermal conductivity on Nusselt number.

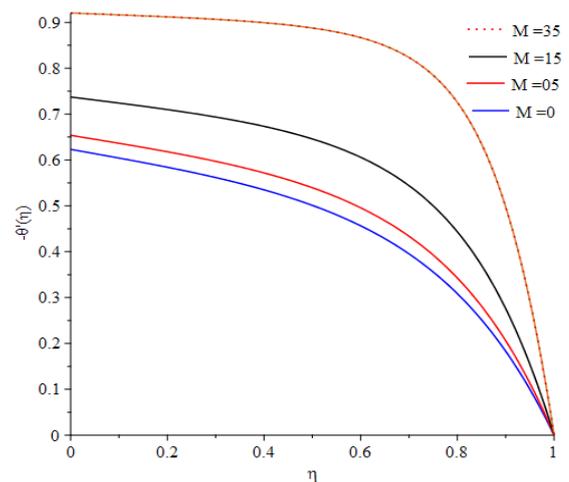Fig 6: influence of magnetic parameter on the momentum profile

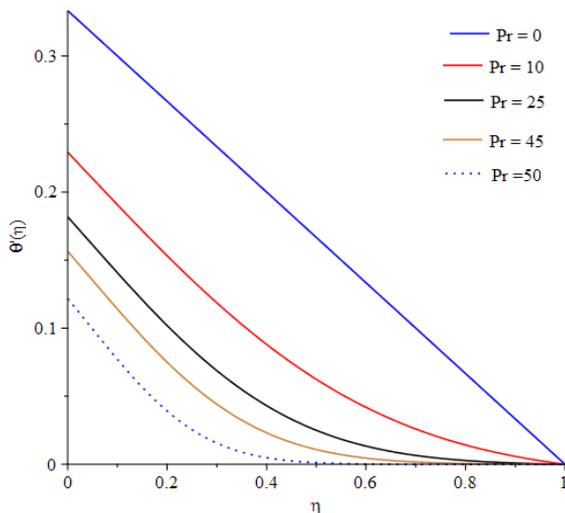Fig 7: influence of magnetic parameter (M) to the Nusselt number profile

Fig 8: effects of Prandtl number (Pr) on temperature (for a constant value of k=0.6089)

It was also observed that increase in the magnetic parameter increases the velocity of the system. Moreover, Increase in the value of magnetic parameter produces an increment in the Nusselt number profile.

IV.   CONCLUSION

We have successfully modified an existing mathematical model by adding the dual effects of magnetic field and thermophoresis. The partial differential system is converted to Ordinary differential system which was the solved numerically by a suitable method. table of values and graphs are used to Discuss the obtained results. It was found that: increasing magnetic parameter (M), bring about increment in the momentum profile as well as the temperature of the system rises. It is also clearly visible that increment in the value of the Prandtl number decreases the Nusselt number drastically. However, increase in the value of thermophoresis parameter increases the temperature of the system. Increment in the resistance parameter produces a decrement in the velocity of the fluid. The negative values of thermophoresis parameter increase in the values of Prandtl number decreases the Nusselt number drastically, whereas, for positive values of thermophoresis increase in the values of Prandtl number increases the Nusselt number of the system. It was also depicted that increase in the values of Prandtl number increases the temperature of the system. Increase in thermal conductivity parameter drastically increase the temperature of the system. Increase in the values of Prandtl number implies decrease in the Nusselt number profile. However, with regard to thermal conductivity parameter two cases were recorded for different values of the thermal conductivity parameter, when the thermal conductivity is zero is negative: increase in the parameter decreases the Nusselt number, while, for positive values of the thermal conductivity.

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