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Full Length Research Paper

Thermal Stratification on MHD Water Base Nanofluid Flow over a Porous Vertical Plate

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ABSTRACT: The study is on thermal stratification on Magnetohydrodynamics (MHD) water based nanofluid. The nonlinear governing equations and their related boundary conditions are initially looked into dimensionless forms by similarity variables. Fourth/fifth order Runge Kutta Fehlberg method with shooting scheme for numerical simulation is applied. Results obtained were plotted and analyzed in (Figures) and (Tables) for both the velocity, $f(\eta)$, and the temperature, $\theta(\eta)$. However, the reaction on the magnetic field, porous, thermophoresis, Brownian motion, Buoyancy and suction are given. The results obtained indicate that the temperature, $\theta(\eta)$, increase with an increase in thermal magnetic parameter on the nanofluid. It was also obtained that thermal stratification at $\epsilon_1 = 0.01$ parameters is higher than when is at $\epsilon_1 = 0.9$. Maple 18 is used at the software platform.

Keywords: Nanofluid, Nanoparticle, Thermal stratification and MHD

INTRODUCTION

In science and engineering, the study of magneto-hydrodynamic (MHD) flow has essential applications. MHD is deal with low frequency interactions of the plasma with the magnetic field such as Alfven wave (Sokolov et al., 2016). It is basically used in space plasmas (Chen and Zonca, 2016), magnetically confined fusion plasma (Cook et al., 2016; Cook et al., 2017). Industrial equipment, such as MHD generators, pumps, bearings and boundary layer control are affected by the interaction between the electrically conducting fluid and a magnetic field. MHD boundary layers are observed in various technical systems employing liquid metal and plasma flow transverse of magnetic fields. Heat transfer is thermal energy in transit due to a spatial temperature difference, which is classified into three major mechanisms, namely thermal conduction, thermal convection and thermal radiation. Thermal conduction and thermal convection involve particle, while radiation involves electromagnetics wave. Increasing the efficacy of fluid transfer (such as water, oil, and ethylene glycol) has been a huge research work in science and engineering in recent years. This has led to the discovery of additive to the base fluid because of its poor heat transfer properties.

Stephen U. S. Choi introduced an additive, which is called nanofluid (Choi and Eastman, 1995). This nanofluid comprises a dispersal of submicronic solid particle that is referred to as nanoparticle (Khan et al.,

2017). The main objective of this so called nanoparticle is to diffusing the solid particle in the fluid in order to boost thermal conductivity (Hwang et al., 2006; Jiang et al., 2009, Sheikholeslami et al., 2014). This has been further investigated by several researchers such as the works in (Hassani et al., 2015; Lee et al., 2017; Krahl et al., 2018; Zhao et al., 2008). Nanoparticles can be obtained from metals such as Al_2O_3 and single surface carbon nanotubes (SWCNTs).

On the other hands, nanofluid can be described as a single stage composite of nanometer sized solid suspended particles and fibers in traditional base fluids. The frequently utilized as based fluid are; oil, ethylene glycol mixture, toluene, etc. Nanofluids attempts many distinct assets in manufacturing employments including; fuel cell, nuclear reactors, transportation, microelectronics, and biomedicine (Wang and Mujumdar, 2008; Mohammed et al., 2017; Islam et al., 2016; Haq et al., 2015).

In industrial applications, nanoparticles have been used to avoid overheat of the instrument (Wong and De Leon, 2010). Thus, nanoparticle plays an important role as the coolant substance to transfer heat, an example of such is our computer system (Islam et al., 2016). The heat sink helps to absorb and cool the heat generated in the system, thereby avoid being overheated. This is because the diameter less than 100nm and this condition will affect the properties of the liquid surface area to enhance the heat transfer compare to the micron-size particle (Anderson et al., 2013). Various nanoparticle shapes have been utilized over the experiment (Xie et al., 2002; Murshed et al., 2005), which presented the first kind of experimental analysis. On top of that, the improvement of thermal conductivity is due to the form and appearance of the included nanoparticle into the suspension (Singh et al., 2009) analyzed role of the silicon carbide (SiC) nanoparticles where they admit the shape and appearance affirm disc or platelet, and consistently diffused in the water on mechanical assets and thermal conductivity enrichment.

Whenever there is a change in the lakes temperature more specifically at the different depths, which is referring to as thermal stratification. This of course, is due to the dynamic in density of water with the temperature. Lckey and Robert, (Lackey, 1972), obtained that cold water is denser than the warm water, where the epilimnion consist of water that is not as dense when compare with the warm water. The thermal stratification is not common in warm water. However, nanofluid has the ability to enhance the thermal properties when compare to the particle of conventional fluid suspension. However, and having known the impact and effort that thermal is contributing to industrial and engineering, it is therefore paramount for researchers to explore more on the impacts of thermal conductivity that would be better than the traditional method, such as Maxwell traditional theories (Sheikholeslami et al., 2016).

One of the challenges of the Maxwell's theories is that the cooling capacities is low and poor in thermal conductivity (Hatami et al., 2017; Torsater et al., 2012; Levidow et al., 2014). Besides these low cooling capacities, it is observed that its behavior is insufficient when compared to the nanoparticle thermal conductivity.

More works on these nanoparticles have been investigated with the connection of industrial and engineering application. Some of such investigations covers aspect including oscillatory enhancement (Zwick et al., 1997), nanoparticle effects on copper (Kim et al., 2011), stead and unsteady squeeze flow (Sheikholeslami et al., 2016) and lots more. And such have been applied to different aspect, which include chemical production (Baer et al., 2010), engineering (Macfarlane et al., 2011) power development of a power plant (Lu et al., 2012), automotive (Pal et al., 2011), beforehand nuclear systems.

Result obtained in (Wong and De Leon, 2010) considered the used of nanoparticles when one wants to avoid overheat. Islam et al. (2016) supported such and cited example of a computer system, where nanoparticles served as a coolant substance in heat transfers. It was revealed that the presence of heat sink helps in absorbing and cooling the heat that is generated from the system and however, avoid being overheated. This is made possible as a result of nanoparticle, which is (< 100nm) in diameter, which have impact in the liquid surface area properties in order to increase the transfer of the heat when compare to micron-side particle (Anderson et al., 2013). MHD Water based nanofluid flow over a porous vertical plate is considered in this paper. Local symmetry transformation is applied to convert the governing equations from Partial differential equations (PDEs) into Ordinary differential equation (ODEs). We thereafter applied the fourth/fifth order Runge Kutta Fehlberg method with shooting scheme for numerical simulation. Results obtained were plotted and analyzed for the velocity, $f(\eta)$, and temperature, $\theta(\eta)$.

FORMULATION OF MODEL AND METHODOLOGY

Here, the work in (Kandasamy et al., 2018) is adopted. The authors proposed a porous vertical plate that is position along the x axis, while the normal plate is stationed along the y axis, which is a steadier connective two- dimensional nanofluid flow. The non-negative direction along the B_0 as the non-negative direction along the x-axis is presented. The ambient temperature along with the nanofluid is taken into consideration, which is given as $T_\infty = T_{\infty,0} + Ax$ and $C_\infty = C_{\infty,0} + Bx$, respectively, where $T_{\infty,0}$ and $C_{\infty,0}$ are the depth of stratification. The surface of the temperature is considered to be constant rate, which is given as, T_w. C_w is the nanofluid. A and B remain constant values.

The proposed coordinate system and the flow structure as proposed is given in (Figure 1). The governing equations i.e. continuity, momentum and energy equations are given respectively in equation (1)-(3).

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

$$u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} = v\frac{\partial^2 u}{\partial y^2} - \left(\frac{v}{K} + \left(\frac{\sigma B_0^{\,2}}{\rho}\right)u + (1 + C_{\infty,0})\rho f_{\infty,0}\beta g(T - T_{\infty,0}) - (\rho - \rho f_{\infty,0})g(T - T_{\infty,0}) \quad (2)$$

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

where the boundary conditions are

$$u = 0, \quad v = -V_0, \quad T = T_w, \quad C = C_w, at\ \eta = 0$$
$$u = 0,\ T = T_\infty,\ C = C_\infty,\ and\ \eta = \infty \quad (4)$$

We have below the local Rayleigh number along with the stream function ψ, respectively

$$Ra_x = \frac{(1+C_{\infty,0})\rho f_{\infty,0}\beta g(T-T_{\infty,0})}{v\alpha},\ u = \frac{\partial \psi}{\partial y}, v = -\frac{\partial \psi}{\partial x} \quad (5)$$

The energy, momentum, as well as the equations of diffusion are transformed into the equivalent differential equation via the below similarity transformation;

$$\eta = \frac{y}{x}Ra_x^{\frac{1}{4}}, \psi = Ra_x^{\frac{1}{4}}\alpha f(\eta), \theta(\eta) = \frac{T-T_\infty}{T_w-T_{\infty,0}} - \frac{Ax}{T_w-T_{\infty,0}},\ \varphi(\eta) = \frac{C-C_\infty}{C_w-C_{\infty,0}} - \frac{Bx}{C_w-C_{\infty,0}} \quad (6)$$

where, $C_w - C_{\infty,0} = mx, T_w - T_{\infty,0} = nx, m, n$ are constants.

Pr = Prandtl number

Le = Lewis number

$Nr = \frac{(\rho\gamma)_0\rho f_{\infty,0})(C_w - C_\infty}{\rho f_\infty \beta(T_w - T_\infty)(1-C_\infty}$ - nanofluid buoyancy ratio,

$Nb = \frac{(\rho c)_p D_B (C_w - C_\infty}{(\rho c)_f \alpha}$ - nanofluid buoyancy ratio,

$Nt = \frac{(\rho c)_p D_T (T_w - T_\infty}{(\rho c)_f \alpha T_\infty}$ - Brownian motion parameter,

$\varepsilon_1 = \frac{4Ax}{(T_w - T_{\infty,0})} =$ - thermal stratification parameter,

$\lambda = \frac{L}{kRe_x}$ - porous parameter,

$M = \frac{\sigma_0 B_0^2}{\mu Re_x}$ - magnetic parameter,

However, the quantities parameters are;

C_f - skin friction coefficient,

$Nu_x = \frac{q_w x}{k_f(T_w -}$ - local Nusselt number,

where and are defined as;

$C_f(Re_x)^{\frac{1}{2}} = \frac{f''(0)}{(1-\zeta)^{3/2}}, \frac{2\varepsilon_{0x}}{Re_x^{\frac{1}{2}}} = -\frac{k_{nf}}{k_f}\theta'($

Re_x -The local Reynolds number.

Due to limited spaces, we skip some work here, but however, after much algebraic works, we solved simultaneously, using 2-dimensional boundary layer for the four fundamental fluid dynamics equations, which are; continuity equation, momentum equation and energy equation. In this study, the flow of the system is steady. Along the x-axis and y-axis, we considered u and v respectively as the velocity components, while and are the pressure and density respectively. The system of the equation is partially differential equations (PDEs) which are converted into the ODEs via similarity transformation.

We consider that

$$u = hf'p, \quad (7)$$

$$\frac{\partial u}{\partial x} = -\frac{3}{4}\alpha\frac{Rax^{\frac{1}{2}}}{x}\eta f'' - \frac{1}{2}\alpha\frac{Rax^{1/2}}{x^2}f', \quad (8)$$

$$v = \frac{Rax^{\frac{1}{4}}}{x}\alpha\left[\frac{3\eta}{4}f' - \frac{1}{4}f\right]. \quad (9)$$

It then follows that

$$\frac{\partial u}{\partial y} = hp^2 f'', \quad (10)$$

and

$$\frac{\partial^2 u}{\partial y^2} = hp^3 f''' \quad (11)$$

As earlier mentioned several algebraic works are skips here because of space. Therefore, the momentum, and energy equations are given respectively in equations (12) – (14) which in the form of PDEs is reduced to ODEs using Similarity Transformation as;

$$f''' + \frac{3}{4Pr}\left(ff'' - (f')^2\right) + \theta - N_r\varphi - f'(\lambda + M) = 0 \quad (12)$$

$$\theta'' - f'\theta + \frac{1}{4}f'\theta - \frac{\varepsilon_1 f'}{n} + Nb\varphi'\theta' + Nt(\theta')^2 = 0 \quad (13)$$

$$u = 0, v = -V_0, T = T_w, C = C_w at \eta = 0, \quad (14)$$
$$u = 0, T = T_\infty, C = C_\infty, and\ \eta = \infty.$$

RESULTS AND DISCUSSION

In this section, the numerical simulation is illustrated and discussed. The result was evaluating and analyzed with certain nanofluid flows. The Runge Kutta Fehnerg technique of order fourth/fifth was applied along with the shooting method. The software used in the analysis was Maple 18. Two figures are displayed for each including velocity $f(\eta)$ and temperature $\theta(\eta)$. The effect that involves in the magnetic field, radiation, heat source, heat sink, suction, injection, porous and volume fraction, is be analyzed.

Setting and analyzing of parameters

The computational outputs are pictured in terms of dimensionless velocity and temperature. The parameters

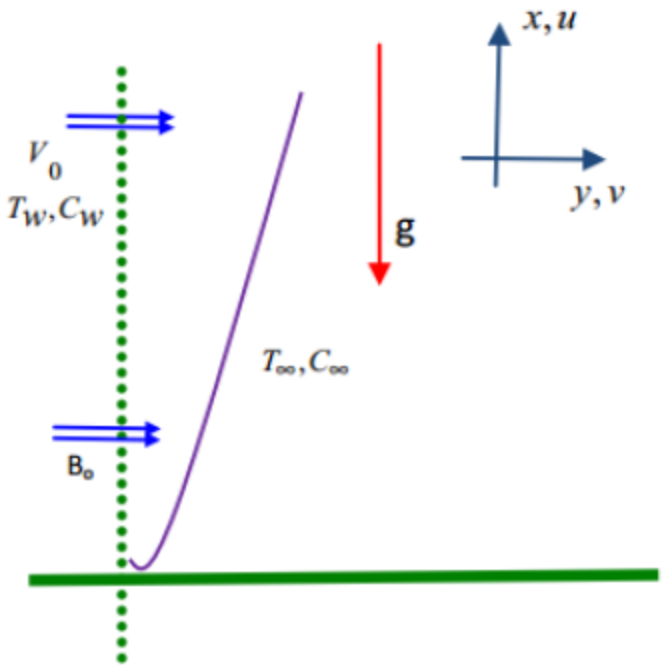

Figure 1. Flow structure and coordinate system (Kandasamy et al., 2018).

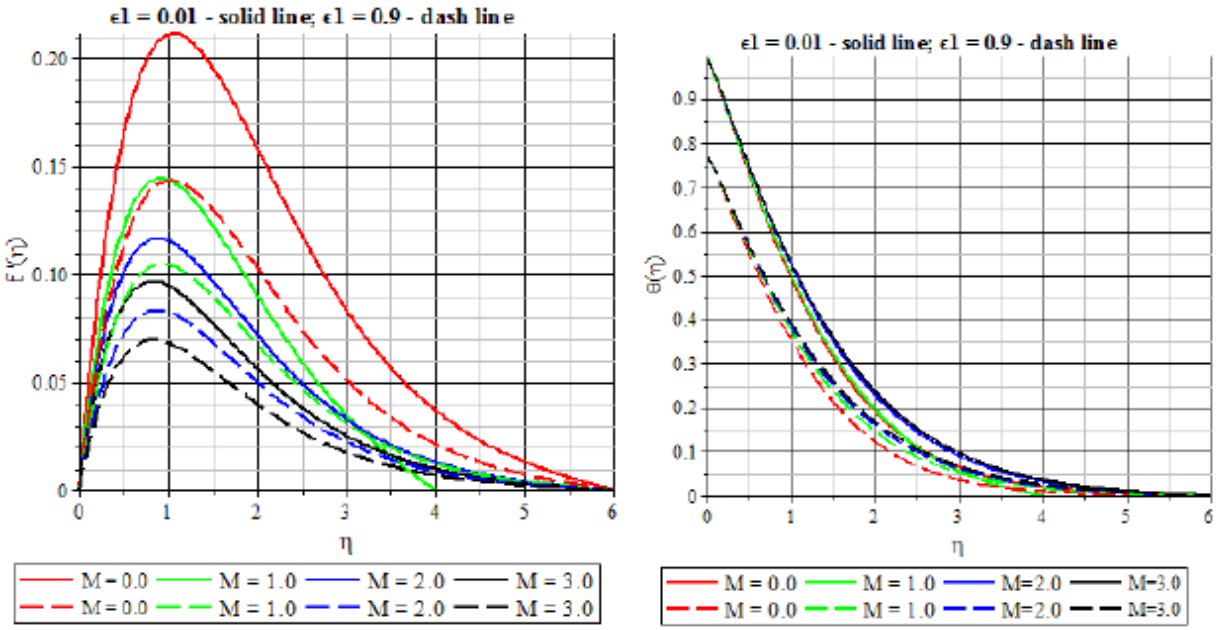

Figure 2. Comparison of magnetic strength velocity, $f(\eta)$, and temperature $\theta(\eta)$, with injection with Figure 5 in (Kandasamy et al., 2018).

M, λ, S, Nr, Nb, N are numerically executed for governing equations (ODEs) along with boundary conditions in equation. In this regard, the shooting technique is employed to solve the ODEs along with the conditions. This shooting technique was introduced by Runge Kutta in the nineteen century and has been recently studied by many researchers (Singh and M. Kumar, 2015; Kandasamy et al., 2016).

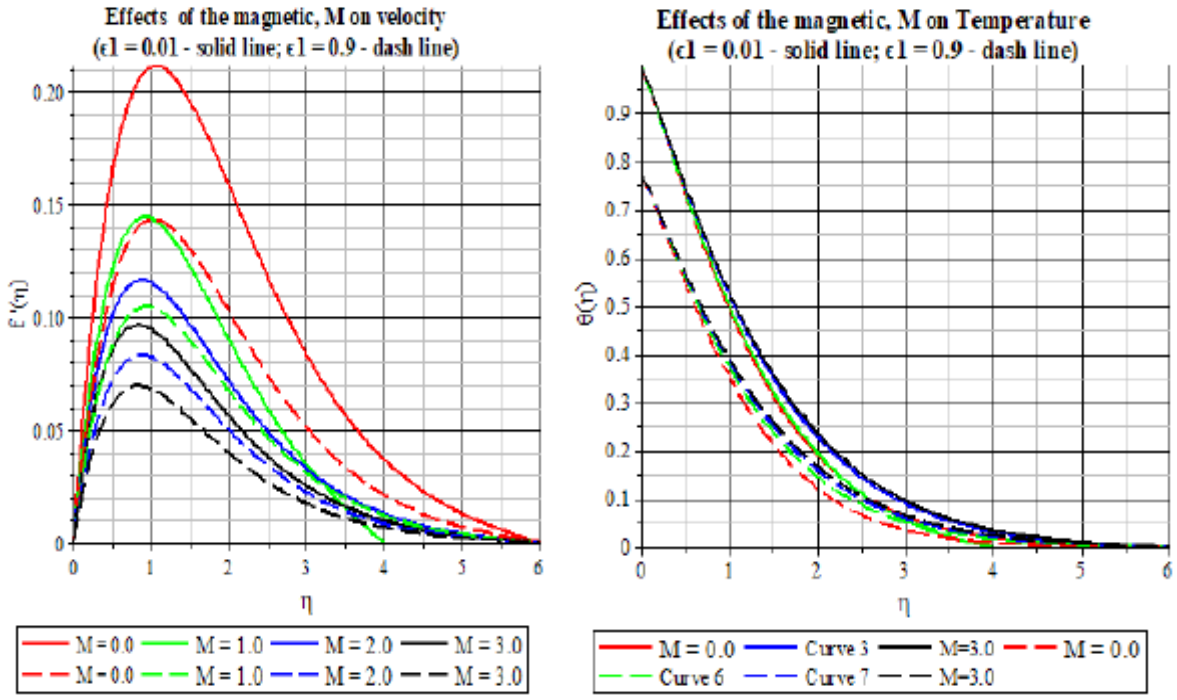

Figure 3. Thermal stratification on velocity, $f(\eta)$, and temperature $\theta(\eta)$, with Magnetic parameter M

The parameter to use is set. The analysis reports the parameters' effects on the thermal stratification on MHD water based nanofluid (water, $\rho(kg/m^3)$ = 997.1). In order to validate this method, the present work is compared in (Figure 2). It displays the result of comparison of the magnetic effects profile for velocity $f(\eta)$, and temperature $\theta(\eta)$. The obtained results are in good agreement with those results obtained in (Kandasamy et al., 2018). displayed the various values of magnetic field deposition. It indicated that thermal stratification parameter at when $\epsilon_1 = 0.01$ and $\epsilon_2 = 0.9$. It shows that when magnetic field, *M,* is increasing, velocity is reducing, but we observe fluctuation in the temperature $\theta(\eta)$. It is observed that the temperature dropped at when $M = 1.0$. The Effect of thermal stratification on velocity $f(\eta)$, and temperature $\theta(\eta)$ with magnetic parameter, M. The velocity $f(\eta)$ increase as a result of decrease in the magnetic strength in the presence of thermal stratification. Whereas, the temperature, $\theta(\eta)$, increase due to an increase in the thermal magnetic parameter (Figure 3). From the profile, it displays that the heat transfers rate MHD nanofluid has more impact in the circulation of stream system. The thermal magnetic has effect in the presence of thermal stratification parameter of the nanofluid.

The reaction of porous λ on thermal stratification along with the effect in the velocity and temperature are display in (Table 2). It is obtaining that the velocity decrease, which is due to the increase in the porous parameter. Whereas, the temperature increase with an increase in the porous parameter of the nanofluid for both when thermal stratification is fixed at $\epsilon_1 = 0.01$ and $\epsilon_2 = 0.9$. Figure 4 of $f(\eta)$, $\theta(\eta)$ circulation in the presence of thermal stratification, $\epsilon_1 = 0.01, \epsilon_2 = 0.9$ is displayed. The velocity, $f(\eta)$, increase with decrease in the porous strength. The temperature, $\theta(\eta)$, for nanofluids increase with the increase in the porous parameters. This is due to the strength of the density for the nanofluid. Tables 3. also displays the reaction of Buoyancy, N_T on thermal stratification, $\epsilon 1$ and the effect in both velocity and temperature. The thermal stratification shows more significant effect on Buoyancy, N_T. It is therefore obtaining that as the value of the Buoyancy, N_T increase, then velocity $f(\eta)$, decrease and temperature $\theta(\eta)$ increase as well. The thermal stratification at $\epsilon_1 = 0.01$ shows more significant effect on the thermal magnetic than when the thermal stratification is fixed at $\epsilon_2 = 0.9$.It is shown in Figure 5 that the velocity, $f(\eta)$, decrease with increase in the Buoyancy. The effect of buoyancy in the presence of electric field$\epsilon_1 = 0.01$ for the velocity is higher than the $\epsilon_2 = 0.09$. The temperature $\theta(\eta)$ increase for all nanofluids with increase in buoyancy strength. For the heat transfer when the electric field is low with increased of buoyancy, it is decreased, however, it is subsequently increase with high electric field. From the profile, it displays that the Buoyancy ration in MHD

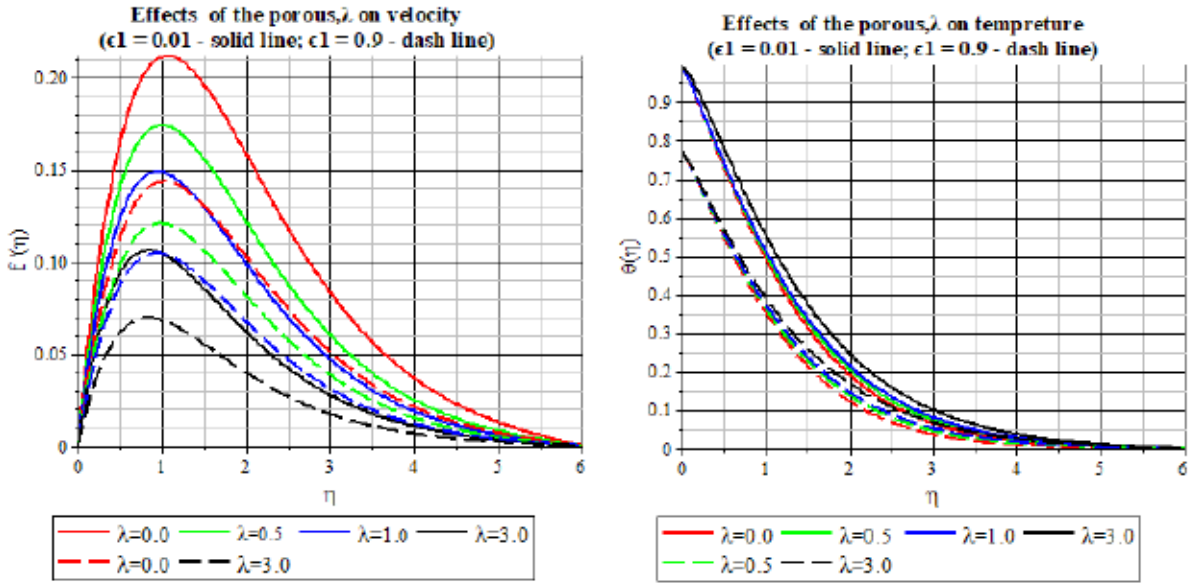

Figure 4. Effect of thermal stratification on velocity, $f(\eta)$, and temperature $\theta(\eta)$, with porous, λ

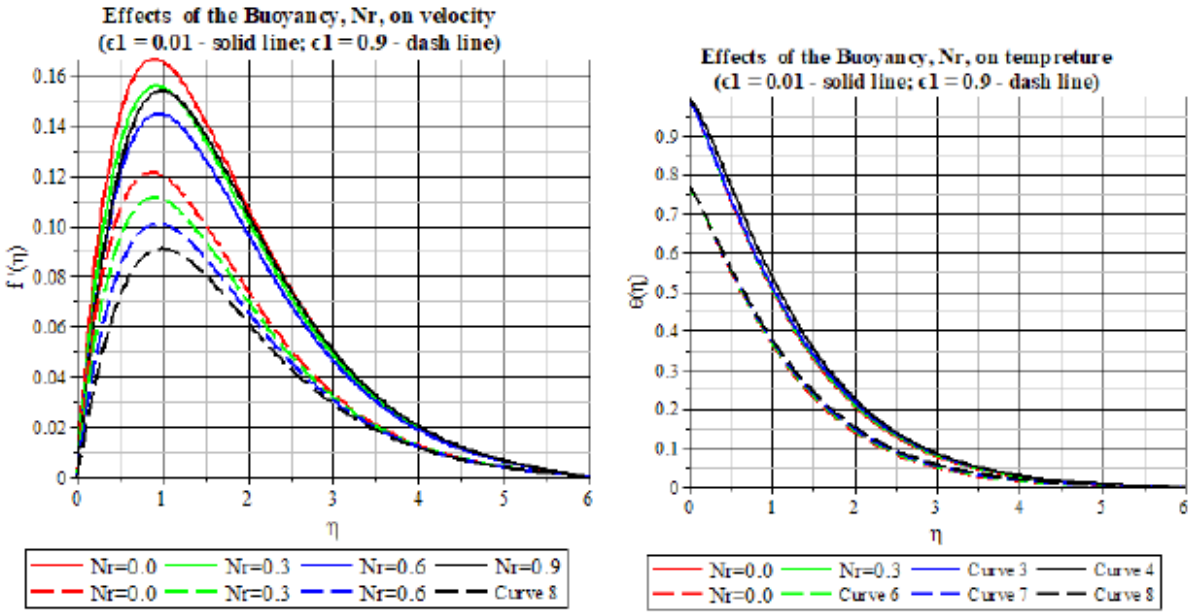

Figure 5: Effect of thermal stratification on velocity, $f(\eta)$, and temperature $\theta(\eta)$, with Buoyancy

nanofluid play a dominate role in temperature. Tables 4 displays the reaction of Brownian motion, Nb. It is indicated that the velocity and the temperature at $\epsilon_2 = 0.9$ increase, which is due to the increase in Brownian motion. Brownian motion is the accidental motion of particles in the base fluid.

In Figure 6, the velocity $f(\eta)$, increase, which is due to the increase in the Brownian motion. Also, it indicated that the Brownian motion parameter, $Nb = 0.1, 0.3, 0.5, 0.8$ is high in the presence of thermal stratification of the nanofluid, which subsequently increased the temperature when the Brownian motion is increasing. There is no significant different with the temperature. The $\theta(\eta)$ for nanofluids slightly increase.

Table 1. The effect of thermal stratification with the impact of Magnetic Field M.

M	$f(\eta)$	$\theta(\eta)$	Thermal
0.0	0. 46734	-0. 47395	
1.0	0. 36715	-0. 48086	
2.0	0. 32548	-0. 456190	$\epsilon_1 = 0.01$
3.0	0. 29029	-0. 45205	
0.0	0. 32005	-0. 40710	
1.0	0.26090	-0.39176	$\epsilon_2 = 0.9$
2.0	0.22537	-0.38321	
3.0	0. .20090	-0.37769	

Table 2. The effect of thermal stratification with the impact of porous, λ.

λ	$f(\eta)$	$\theta(\eta)$	Thermal
0.0	0. 44847	-0. 48855	
0.5	0. 40175	-0. 48409	$\epsilon_1 = 0.01$
1.0	0. 36715	-0. 48086	
3.0	0. 05164	-0. 31536	
0.0	0 31014	-0. 41427	
0.5	0. 27843	-0. 40813	$\epsilon_2 = 0.9$
1.0	0. 25465	-0. 40366	
3.0	0.19720	-0. 39349	

Table 3. The effect of thermal stratification with the impact of Buoyancy, .

Nr	$f(\eta)$	$\theta(\eta)$	Thermal
0.0	0.48577	-0.46707	
0.3	0.42098	-0.46438	$\epsilon_1 = 0.01$
0.6	0.35565	-0.46163	
0.9	0.32936	-0.30598	
0.0	0.36732	-0.39888	
0.3	0.30360	-0.39464	$\epsilon_2 = 0.9$
0.6	0.23948	-0.39030	
0.9	0.17497	-0.38583	

Table 4: The effect of thermal stratification with the impact of Brownian motion,

Nr	$f(\eta)$	$\theta(\eta)$	Thermal
0.1	0.25733	-0.64962	
0.3	0.34408	-0.56261	
0.5	0.30091	-0.48086	$\epsilon_1 = 0.01$
0.9	0.42384	-0.15013	
0.1	0.16381	-0.53592	
0.3	0.23536	-0.47025	
0.5	0.25465	-0.40366	$\epsilon_2 = 0.9$
0.9	0.27438	-0.29377	

The effect of Brownian motion in the presence of $\epsilon_2 = 0.9$ for the temperature, $\theta(\eta)$, is lower than when $\epsilon_1 = 0.1$. Table 5 displays the reaction of Brownian motion, Nb, on thermal stratification, $\epsilon 1$, layers. The reaction indicated

Table 5. The effect of thermal stratification with the impact of suction, .

S	$f(\eta)$	$\theta(\eta)$	Thermal
0.0	0. 36013	-0. 21476	
0.5	0. 38163	-0. 33193	$\epsilon_1 = 0.01$
1.0	0. 36715	-0. 48086	
2.0	0. 31272	-0. 83918	
0.0	0. 20994	-0. 189970	
0.5	0. 25366	-0. 28498	$\epsilon_2 = 0.9$
1.0	0. 22368	-0. 20708	
2.0	0. 22303	-0. 69011	

Table 6. The effect of thermal stratification with the impact of thermophoresis, .

Nt	$f(\eta)$	$\theta(\eta)$	Thermal
0.0	0. 37360	-0. 56732	
0.2	0. 37448	-0. 52205	$\epsilon_1 = 0.01$
0.5	0. 37749	-0. 46255	
0.8	0. 41573	-0. 41573	
0.0	0. 26417	-0. 45962	
0.2	0. 26241	-0. 43070	$\epsilon_2 = 0.9$
0.5	0. 26090	-0. 39176	
0.8	0. 26090	-0. 39176	

that the increase in suction parameter ($s > 0$) indicates decrease in the temperature. The interpretation means that layer shows more significant effect on Brownian motion. Figure 7 indicates effects of thermal stratification ($\epsilon = 0.01, 0.09$) on velocity $f(\eta)$, and temperature $\theta(\eta)$ with suction parameter, S. Similarly, the velocity $f(\eta)$, decrease with increase in the suction strength. whereas, the temperature $\theta(\eta)$ of heat transfer rate for all nanofluids decrease with increase in suction parameter *S*.

Table 6 displays the reaction of thermophoresis, Nt. The reaction indicated that the increase in thermophores effect the increase in the temperature. The thermal stratification parameter layer shows more significant effect on the thermophores thermal stratification parameter. The circulation in the presence of thermal stratification $\epsilon_1 = 0.01, \epsilon_2 = 0.9$ is presented in Figure 8. The velocity, $f(\eta)$, slightly increase with increase in the thermophore's strength. Also, it indicated that the thermophores parameters $Nt = 0.0, 1.0, 2.0, 3.0$ effect with high electric field.

The temperature $\theta(\eta)$ increase due to increase in thermophores of the nanofluid. This implies that the thermophore is dominate on the transfer of heat. Particularly, between boundary layer at when $Nb = 0.0, 1.0, 2.0, 3.0$.

The profile also displays the rate of heat transfers MHD nanofluid which is more dominated.

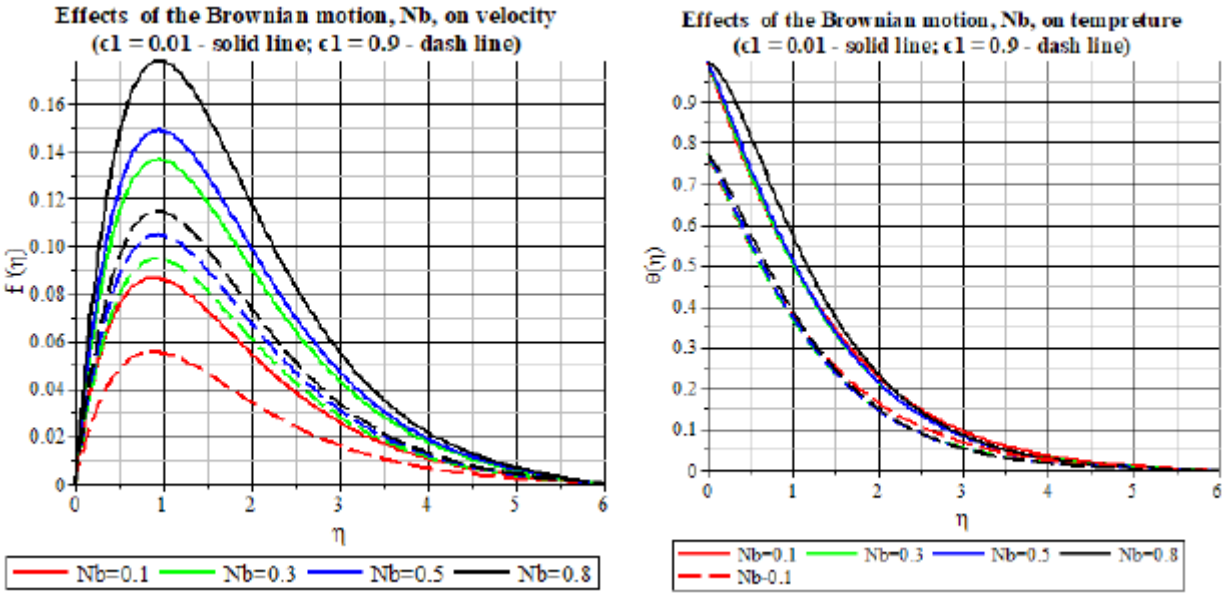

Figure 6: Effect of thermal stratification on velocity, $f'(\eta)$, and temperature $\theta(\eta)$, with Brownian motion,

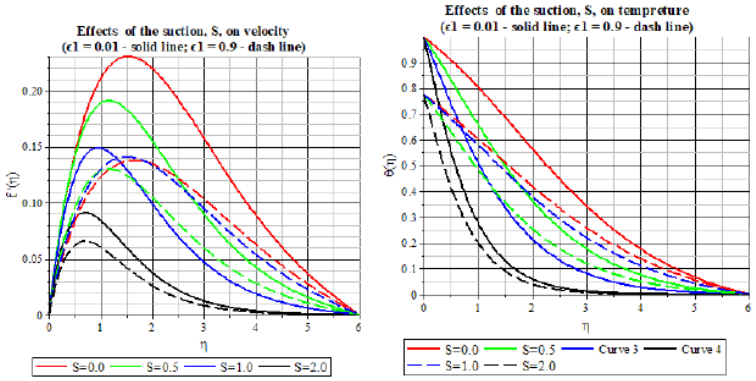

Figure7: Effect of thermal stratification on velocity, $f'(\eta)$, and temperature $\theta(\eta)$, with suction parameter, .

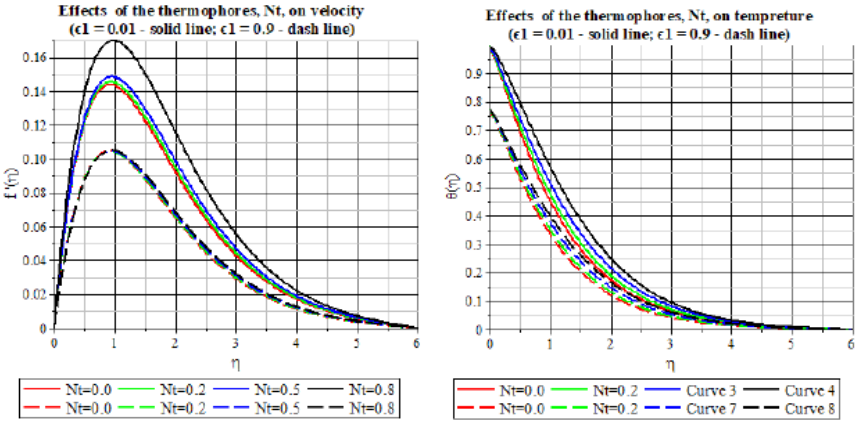

Figure 8: Effect of thermal stratification on velocity, $f'(\eta)$, and temperature $\theta(\eta)$, with thermophores parameter,

Conclusion

In this present paper, thermal stratification on MHD water base nanofluid was investigated. The local symmetry transformation is applied to convert the governing equations from PDEs into ODEs. The fourth/fifth order Runge Kutta Fehlberg method with shooting scheme for numerical simulation is also applied. Results obtained were plotted and analyzed in Figures and Tables for both velocity $f(\eta)$, and temperature $\theta(\eta)$. However, the reaction on magnetic field, porous, Thermophoresis, Brownian motion, Buoyancy and section or injection were obtained and discussed. The results obtain indicated that the temperature, $\theta(\eta)$, increase due to increase in the thermal magnetic parameter of the nanofluid. It was also obtained that thermal stratification at increase at $\epsilon_1 = 0.0$ than when it was fixed at $\epsilon_2 = 0.9$. Therefore, the thermal stratification of the nanofluid alongside of high strength of magnetic field is applicable to transport mechanism. This application, however include the use of conservation of the principle law of diffusion energy with the Fick and thermodynamic of diffusion. This application has however attracted various interests in thermal application, such as heating of water, application of air-conditioning, active and passive solar heating, cooling capacities (Kandasamy et al., 2018). The heat sink helps to absorb and cool the heat generated in the system, thereby avoid being overheated.

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Nomenclature

B_0	Flux density for the magnetic $kgs^{-2}A^1$,		**Greek symbols and subscripts**
A, B	Non-negative constant s^{-1}	α	Thermal diffusivity m^2s^{-1},
C	Volume fraction of the nanoparticle K,	β	Thermal expansion coefficient
C_w	Volume fraction of the wall nanoparticle K,	K^{-1}	Density of the base fluid, kgm^{-3},
C_∞	Volume fraction far away from the wall nanoparticle K,	ρ	Heat capacitance of the nanofluid Jkm^2K^{-1},
$C_{\infty,0}$	Volume fraction due to stratification of the nanoparticle K,	ρc_p	Electrical conductivity $\Omega^{-1}m^{-1}$,
c_p	Specific heat at constant pressure $Jkg^{-1}K^{-1}$,	σ	Dynamic viscosity of the base fluid $kgm1m^{-1}s^{-1}$,
D_B	Specific diffusivity m^2s^{-1},	μ	Thermal stratification parameter, $\frac{4Ax}{T_\infty - T_{\infty,0}} = \frac{4A}{m}\left(\frac{s^{-1}}{s^{-1}}\right)$
D_T	Thermophoresis diffusion coefficient, m^2s^{-1},	ϵ_1	Solutal stratification parameter, $\frac{4Bx}{C_\infty - C_{\infty,0}} = \frac{4B}{m}\left(\frac{s^{-1}}{s^{-1}}\right)$
K	Permeability of the porous medium m^2,	v	Dynamic viscosity, m^2s^{-1}
k	Thermal conductivity of the base fluid $kgms^2K^{-1}$,	λ	Porous parameter, $\frac{v_f L}{k u_w}\left(\frac{m^2s^{-1}m}{m\,m^2s^{-1}}\right)$
Le	Lewis number, $\frac{v}{D_B}\left(\frac{m^2s^{-1}}{m^2s^{-1}}\right)$	Ω	Resistance $kgm2s^{-3}A^{-2}$,
M	Magnetic parameter, $\frac{\sigma B_0^2 L^2}{\mu R a_x^{\frac{1}{2}}}\left(\frac{\Omega^{-1}m^1(kgs^2A^1)\ \ ^2m^2}{kgm^{-1}s^1}\right)$	Ψ	Dimensionless stream function
Nb	Brownian motion parameter $\frac{(\rho c)_p D_B (C_w - C_{\infty,0})}{(\rho c)_f \alpha}\left(\frac{Jm^{-3}k^{-1}m^2s^{-1}}{kgm^{-3}k^{-1}kk}\right)$	η	Similarity variable
Nr	Buoyancy ratio, $\frac{(\rho_p - \rho_{f\infty})(C_\infty - C_{\infty,0})}{\rho_{f\infty}\beta(T_\infty - T_{\infty,0})(1 - C_{\infty,0})}\left(\frac{kgm^{-3}k}{kgm^{-3}k^{-1}kk}\right)$	f	Dimensionless stream function
Nt	Thermophoresis parameter, $\frac{(\rho c)_p D_T (T_w - T_{\infty,0})}{(\rho c)_f \alpha T_{\infty,0}}\left(\frac{Jm^{-3}k^{-1}m^2s^{-1}k}{Jm^{-3}k^{-1}m^2s^{-1}k}\right)$	θ, φ	Dimensionless stream function
Pr	Prandtl number $\frac{v}{\alpha} = \left(\frac{m^2s^{-1}}{m^2s^{-1}}\right)$	γ	Volume fraction
T	Temperature of the fluid K,		
T_w	Temperature of the wall K,		
T_∞	The temperature of the fluid far away from the wall K,		
$T_{\infty,0}$	The temperature of the fluid due to stratification K,		
$x; y$	Stream wise coordinate and cross-stream coordinate m,		
$u; v$	Velocity components in x and y direction ms^{-1},		
V_0	Velocity of suction/injection ms^{-1},		