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Numerical Solution on MHD Stagnation Point Flow in Ferrofluid with Newtonian Heating and Thermal Radiation Effect

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ABSTRACT

This study aims to investigate MHD stagnation point flow of Magnetite (Fe_3O_4) with Newtonian heating and thermal radiation effect over a flat plate. The governing equation which is in the form of dimensional nonlinear partial differential equations are reduced to non-linear ordinary equations by using appropriate similarity transformation, then solved numerically by using Keller-box method, which programmed in Matlab software. The influenced of significant parameter such as the magnetic parameter, radiation parameter and volume fraction on velocity and temperature profiles will be obtained. The study reveals the radiation parameter will enhance the temperature of the flow. On the other hand, the skin friction and Nusselt number will increase with an increase magnetic parameter.

1. Introduction

The study of convective heat transfer has been investigated by many researchers in the past decade because requested from industries to develop various new types of heat transfer equipment with superior performance. Fluid will help the equipment to transfer the heat and prevent the equipment overheating (cooling system) when the thermal conductivity of the fluid increase. The first idea dispersion of solid particles in base fluid to improve the thermal conductivity by Maxwell [1] provided the research and development of heat transfer fluids. However, the utilized micrometre and millimetre-sized particles led some problems like sedimentation, clogging microchannel, surface abrasion, high pressure drop and particles are too large for micro system. The industrial revolution emerges multidisciplinary growth of miniaturization technology, for instance, microelectromechanical system (MEMS), nanoelectromechanical system (NEMS) and

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nanotechnology given the major effort for developing on advanced fluids and the concept of microchannel cooling technology proposed by Tuckerman and Pease [2].

Choi and Eastman [3] introduced the nanofluid term are shown containing nanoparticles exhibit high thermal conductivities and enhance the heat transfer. The nanofluid model proposed by Buongiorno [4] and Tiwari and Das [5] was very recently used by many researchers [6-10]. Like nanofluid, ferrofluid are composed of small particles (~3-15 nm) of solid, magnetic, single domain particles coated namely; Magnetite (Fe_3O_4), Hematite (Fe_2O_3), Cobalt Ferrite ($CoFe_2O_4$) and other compounds having iron with a molecular layer of a dispersant and suspended in a base fluid [11]. Ferrofluid or colloidal magnetic fluid is first invented in 1963 by NASA for use as a rocket fuel [12]. Ferrofluid is strongly and permanently magnetized in the presence of magnetic field and consists of a stable colloidal dispersion of subdomain magnetic particles in a base fluid (water, oil, ethylene glycol, etc.) due to the thermal Brownian motion of suspended particles [11]. The properties described ferrofluid are differ to the other fluid have a several applications in technological (eg. hard disks of computers, loudspeaker, sealing devices, electric motor, dampers) and biomedical (eg. magnetic drug targeting for healing the tumor) as well as help in material science and engineering research (eg. magnetic colloids used to dope liquid crystals) [13].

The features and benefits of ferrofluid attracted the researchers to investigate the fluid interaction and the other effect that can enhance the heat transfer such as magnetohydrodynamic (MHD) and thermal radiation. MHD is the study of the interaction between magnetic field and fluid conductors of electricity proposed by Alfvén [14] can control the rate of cooling and highly related to ferrofluid flow. According to Raju and Sandeep [15], the flow over a ferrofluid have a tendency to improve the thermal boundary layer as well as the momentum boundary layer thicknesses. They found the magnetic field and radiation parameter have tendency to decrease the skin friction coefficient. Therefore, radiation has significant impact in controlling the rate of heat transfer in boundary layer region [16-18]. In engineering system often included the effect of thermal radiation because it involved the heat transfer from electromagnetic waves that carry the energy away from the emitting object.

Neuringer and Rosensweig [19] studied a phenomenological treatment of fluid dynamics and thermodynamics interaction in magnetic fluid. Neuringer [20] extended his work by studied stagnation point flow and stationary horizontal flat plate of a heated saturated ferrofluid. Stagnation point (Hiemenz flow) was first presented by Hiemenz [21] studied the two dimensional stagnation flow and the problem of boundary flow along a stationary horizontal flat plate with a constant velocity was first proposed by Blasius [22]. Recently, numerous researchers investigated the stagnation point flow in ferrofluid but not applied Blasius flow assumption [23-26].

The boundary condition commonly applied are constant or prescribed wall temperature and constant or prescribed surface heat flux in modelling the convection boundary layer flow. Merkin [27] proposed the Newtonian heating (conjugate convection flow) where the surface heat transfer depends on the surface temperature and boundary layer assumed the heat is supplied to the convecting fluid through a bounding surface with a finite heat transfer. The Newtonian heating condition have been used recently in nanofluid by several authors [28-30] but not in ferrofluid.

Motivated by the above-mentioned studies, this study are focuses on MHD stagnation flow in ferrofluid with Newtonian heating and thermal radiation effect over a flat plate. In this study, we are considered Tiwari and Das [5] model because this model analyse the behaviour of nanofluid. To the best knowledge, this problem with Newtonian heating condition in ferrofluid has not been studied before, so that the reported results are new.

2. Mathematical Formulation

Consider a steady incompressible Ferrofluid on a stagnation point past a flat plate with ambient temperature T_∞. Assume that the free stream velocity $U_\infty = bx$ where b are constant. Further, a uniform magnetic field of strength B_o is assumed to be applied in the positive y-direction normal to the flat plate. The magnetic Reynolds number is assumed to be small, and thus the induced magnetic field is negligible. The physical model and coordinate system of this problem is shown in Figure 1. It is further assumed that the plate is subjected to a Newtonian heating as proposed by Merkin [27] and no slip velocity condition are considered. The boundary layer equations are [23, 31, 32]:

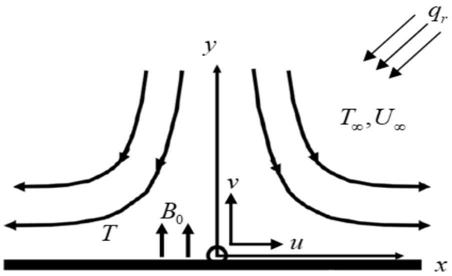

Fig. 1. Physical model and coordinate system

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

$$u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}=U_\infty\frac{dU_\infty}{dx}+\nu_{nf}\frac{\partial^2 u}{\partial y^2}-\frac{\sigma B_o^2(x)}{\rho_{nf}}(u-U_\infty), \tag{2}$$

$$u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}=\frac{k_{nf}}{\left(\rho C_p\right)_{nf}}\frac{\partial^2 T}{\partial y^2}-\frac{1}{\left(\rho C_p\right)_{nf}}\frac{\partial q_r}{\partial y}, \tag{3}$$

subject to the boundary conditions

$$\begin{aligned}&u=v=0,\ \frac{\partial T}{\partial y}=-h_s T\ \text{ at }\ y=0,\\ &u\to U_\infty,\ T\to T_\infty\ \text{ as }\ y\to\infty,\end{aligned} \tag{4}$$

where u and v are the velocity components along the x and y directions, respectively. Further, T is the ferrofluid temperature in the boundary layer, σ is the electrical conductivity, h_s is the heat transfer coefficient, $\left(\rho C_p\right)_{nf}$ is the heat capacity of ferrofluid, ρ_{nf} is the ferrofluid density, ν_{nf} is the kinematic viscosity of ferrofluid, α_{nf} is the thermal diffusivity of ferrofluid and μ_{nf} is the dynamic viscosity of ferrofluid which can be expressed in terms of the properties of base fluid, ferroparticles and solid volume fraction ϕ as follows [23, 33, 34]:

$$\nu_{nf}=\frac{\mu_{nf}}{\rho_{nf}},\quad \rho_{nf}=(1-\phi)\rho_f+\phi\rho_s,\quad \alpha_{nf}=\frac{k_{nf}}{\rho_{nf}\left(C_p\right)_{nf}},\quad \mu_{nf}=\frac{\mu_f}{(1-\phi)^{2.5}},$$
$$\left(\rho C_p\right)_{nf}=(1-\phi)\left(\rho C_p\right)_f+\phi\left(\rho C_p\right)_s,\quad \frac{k_{nf}}{k_f}=\frac{k_s+2k_f-2\phi(k_f-k_s)}{k_s+2k_f+\phi(k_f-k_s)}. \tag{5}$$

Note that k_{nf}, k_f and k_s are the thermal conductivity of the ferrofluid, base fluid and ferroparticles, respectively. According to Turkyilmazoglu [35], the Eq. (5) are restricted to nanoparticles with spherical shape as follow the classical model by Brinkman [36] and Maxwell [1]. The radiative heat flux q_r may simplified as

$$q_r=-\frac{4\sigma^*}{3k^*}\frac{\partial T^4}{\partial y} \tag{6}$$

where σ^* and k^* are the Stefan-Boltzmann constant and the mean absorption coefficient, respectively. Using Rosseland approximation (see [37]) , the Eq. (3) is reduce to

$$u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}=\left(\frac{k_{nf}}{\left(\rho C_p\right)_{nf}}+\frac{16\sigma^*T_\infty^3}{3k^*\left(\rho C_p\right)_{nf}}\right)\frac{\partial^2 T}{\partial y^2}, \tag{7}$$

From the above equation it is seen that the effect of radiation is to enhance the thermal diffusivity. If we take $N_R=\dfrac{4\sigma^*T_\infty^3}{k_{nf}k^*}$ as the radiation parameter, Eq. (7) becomes

$$u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}=\frac{k_{nf}}{\left(\rho C_p\right)_{nf}}\left(1+\frac{4N_R}{3}\right)\frac{\partial^2 T}{\partial y^2}, \tag{8}$$

The non-linear partial differential Eq. (1) - (3) contains many dependent variables which in dimensional forms and difficult to solve. Therefore, the following similarity variables are applied:

$$\eta=\left(\frac{b}{\nu_f}\right)^{1/2}y,\quad \psi=\left(b\nu_f\right)^{1/2}xf(\eta),\quad \theta(\eta)=\frac{T-T_\infty}{T_\infty}, \tag{9}$$

where η, θ and ψ are non-dimensional similarity variable, temperature and stream function. The Eq. (1) satisfied by definition $u=\dfrac{\partial\psi}{\partial y}$ and $v=-\dfrac{\partial\psi}{\partial x}$, respectively. Substitute the Eq. (5) and (9) into Eq. (2) and (8), then the following ordinary differential equations were obtained

$$\frac{1}{(1-\phi)^{2.5}\left[1-\phi+(\phi\rho_s)/(\rho_f)\right]}f'''+ff''-f'^2+1-M(f'-1)=0, \tag{10}$$
$$\frac{k_{nf}/k_f}{(1-\phi)+\phi(\rho C_p)_s/(\rho C_p)_f}\left(1+\frac{4N_R}{3}\right)\theta''+\Pr f\theta'=0, \tag{11}$$

where $M = \dfrac{\sigma B_o^{\,2}(x)}{b\rho_{nf}}$ is the magnetic parameter and $\Pr = \dfrac{\nu_f\left(\rho C_p\right)_f}{k_f}$ is the Prandtl number. The transformed boundary conditions are

$$\begin{aligned}&f(0)=0,\ f'(0)=0,\ \theta'(0)=-\gamma\big(1+\theta(0)\big),\\ &f'(\eta)\to 1,\ \theta(\eta)\to 0 \text{ as } y\to\infty.\end{aligned} \tag{12}$$

where $\gamma = h_s\left(\dfrac{\nu_f}{b}\right)^{1/2}$ is the conjugate parameter for Newtonian heating. The physical quantity interests are the wall temperature $\theta(0)$, the heat transfer rate $-\theta'(0)$, the reduced skin friction coefficient C_f and the reduced local Nusselt number Nu_x which given by

$$C_f = \frac{\tau_w}{\rho_f U_\infty^2},\ Nu_x = \frac{x q_w}{k_f(T_w - T_\infty)}, \tag{13}$$

with surface shear stress τ_w and the surface heat flux q_w given by

$$\tau_w = \mu_{nf}\left(\frac{\partial u}{\partial y}\right)_{y=0},\ q_w = -k_{nf}\left(\frac{\partial T}{\partial y}\right)_{y=0} + q_r, \tag{14}$$

Using the similarity variables in Eq. (9) gives

$$C_f \operatorname{Re}_x^{1/2} = \frac{f''(0)}{(1-\phi)^{2.5}},\quad Nu_x\big/\operatorname{Re}_x^{1/2} = \gamma\frac{k_{nf}}{k_f}\left(1+\frac{4}{3}N_R\right)\left(\frac{1}{\theta(0)}+1\right), \tag{15}$$

where $\operatorname{Re}_x = \dfrac{U_\infty x}{\nu_f}$ is the Reynolds number.

3. Results and Discussion

The non-linear ordinary differential Eq. (10) and (11) subjected to the boundary conditions (Eq. 12) were solved numerically using Keller-box method, which programmed in Matlab software. The effect of pertinent parameter namely volume fraction of ferroparticles ϕ, magnetic M and radiation N_R parameter on the velocity, temperature, reduced skin friction coefficient $C_f \operatorname{Re}_x^{1/2}$ and Nusselt number $Nu_x\big/\operatorname{Re}_x^{1/2}$ were analysed. We have considered water as a base fluid with ferroparticle of magnetite (Fe_3O_4). Table 1 show the thermophysical properties of base fluid and ferroparticles. The comparison present result with the previously reported numerical results has been made in Table 2 to validate the numerical method accuracy. Based on Table 2, the present result of the values of the wall temperature $\theta(0)$ and heat transfer coefficient $-\theta'(0)$ are found in good agreement with previous published result by Mohamed *et al.,* [38] with shooting method for various values of the Prandtl number Pr when $M=\phi=N_R=0$ and $\gamma=1$. Due to the decoupled boundary layer (Eq. (10)) and (Eq. (11)) when $M=\phi=N_R=0$ and $\gamma=1$, it is found that there is a unique value of the skin coefficient

$f'' = 1.232588$, which is the very good comparison with value $f'' = 1.232588$ for $\varepsilon = 0$ and $\phi = 0$ by Bachok *et al.,* [33]. The value of Prandtl number of water is taken 6.2 and the volume fraction effect of ferroparticles ϕ is studied in the range $0 < \phi < 0.2$ where $\phi = 0$ represent the pure fluid water.

Table 1
Thermophysical properties of base fluid and ferroparticles

Physical Properties	Water	Magnetite (Fe_3O_4)
ρ (kg/m^3)	997	5180
C_p (J/kg·K)	4179	670
k (W/m·K)	0.613	9.7

Table 2
Comparison values of $\theta(0)$ and $-\theta'(0)$ with previously published result when $M = \phi = N_R = 0$ and $\gamma = 1$.

Pr	Mohamed *et al.,* [38]		Present	
	$\theta(0)$	$-\theta'(0)$	$\theta(0)$	$-\theta'(0)$
5	23.0239	24.0239	23.0042	24.0042
7	5.6062	6.6062	5.6873	6.6873
10	2.9516	3.9516	2.9227	3.9227

Figures 2 and 3 illustrate the effect of volume fraction ϕ of ferroparticles when magnetic parameter *M* and radiation parameter N_R are applied on the distribution of velocity and temperature profiles respectively. Figure 2 show the velocity decrease with an increase the volume fraction of ferroparticles. Physically, the volume fraction of nanoparticles increase leads to an increase the thermal conductivity and viscosity of the nanofluid with the theoretical model by Brinkman [36] for viscosity and thermal conductivity model by Maxwell [1]. Hence, an increase the viscosity of nanofluid will cause the velocity decrease.

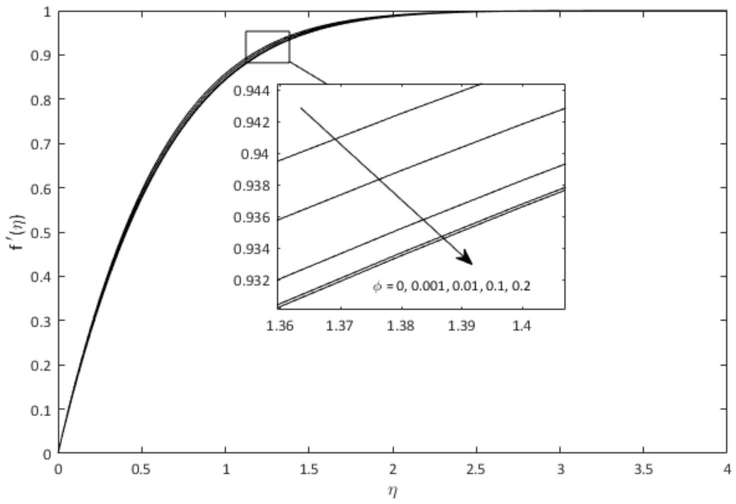

Fig. 2. Velocity Profile for increasing of Volume Fraction, ϕ for $\mathrm{Pr} = 6.2$, $M = N_R = 1$ and $\gamma = 0.5$

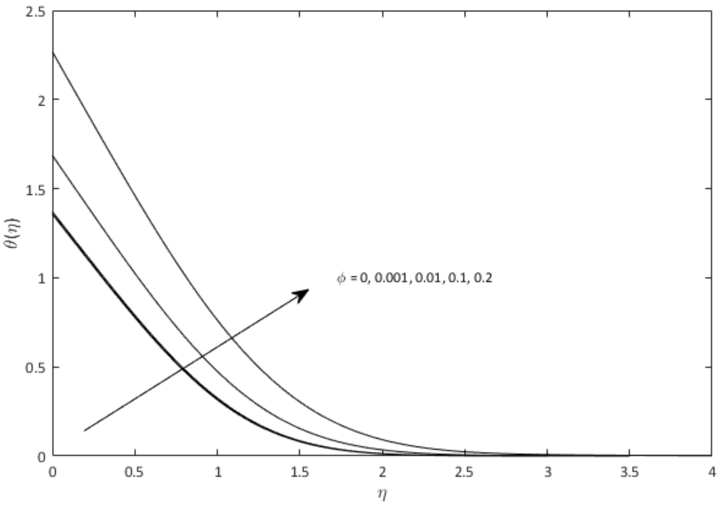

Fig. 3. Temperature profile for increasing of Volume Fraction, ϕ for $\Pr = 6.2$, $M = N_R = 1$ and $\gamma = 0.5$

From Figure 3, it can be seen increase the volume fraction had increase the fluid temperature due to an increase the volume of magnetite nanoparticles and adding it to water-based fluid had increase the ferrofluid capabilities in thermal conductivity and consequently enhances the heat transfer rate as well as increase the thickness of thermal boundary layer. In addition, it is observed the fact that magnetite has high thermal conductivity in line with ferroparticles physical behaviour as presented in Table 1.

Figures 4 and 5 illustrate the effect of magnetic parameter *M* on velocity and temperature profiles when $N_R = 1$, $\phi = 0.1$ and $\gamma = 0.5$. Figure 4 show an increase of magnetic parameter *M* had increase the velocity of the fluid flow. Ferrofluid known as colloidal magnetic fluid, therefore it highly affected by magnetic parameter. The physical situation with Blasius flow, it clearly shown an increase in magnetic parameter *M* the force known as Lorentz force makes the boundary layer thickness decrease. Ferrofluid are composed single-domain particle exist with magnetization in the same direction will decrease the viscosity as experimental result by Li *et al.,* [39] lead to the velocity increase as parameter *M* increase.

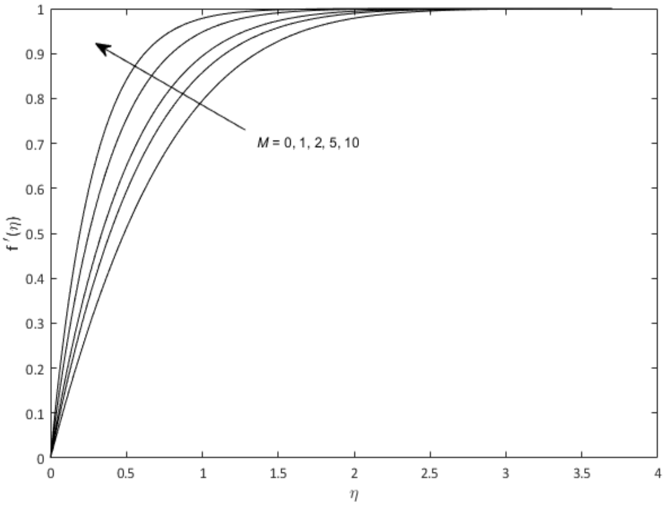

Fig. 4. Velocity Profile for increasing of Magnetic Field, M for $\Pr = 6.2$, $N_R = 1$, $\phi = 0.1$ and $\gamma = 0.5$

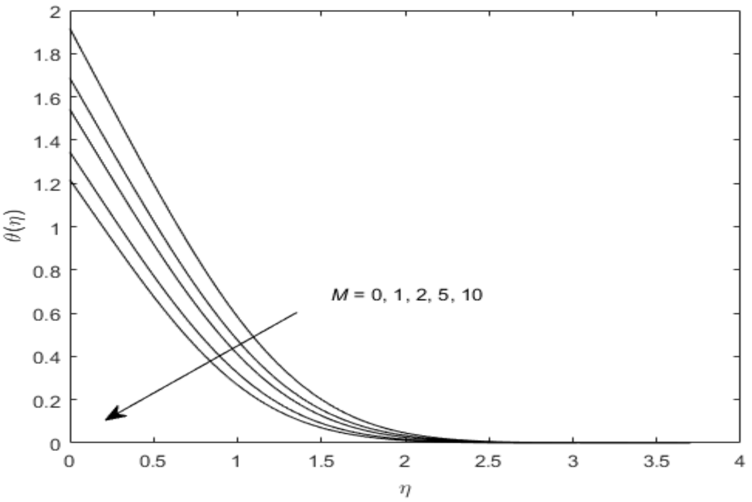

Fig. 5. Temperature Profile for increasing of Magnetic Field, M for $\mathrm{Pr}=6.2$, $N_R=1$, $\phi=0.1$ and $\gamma=0.5$

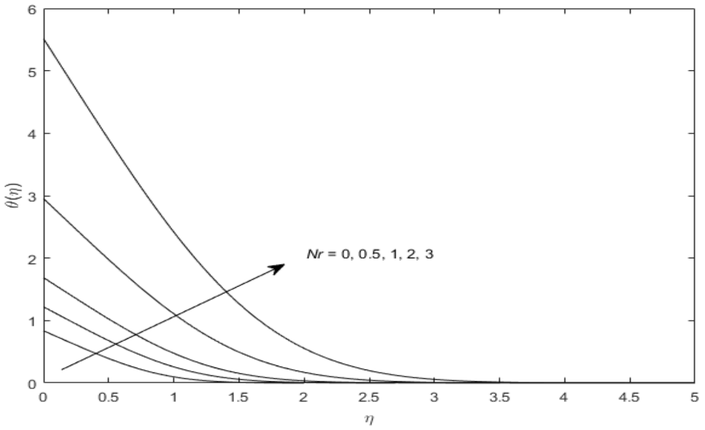

Fig. 6. Temperature Profile for increasing of radiation parameter, N_R for $\mathrm{Pr}=6.2$, $M=1$, $\phi=0.1$ and $\gamma=0.5$

Figure 5 observed the temperature decrease and reduced the thickness of boundary layer with the magnetic parameter M increase. As the magnetic field is applied in ferrofluid, it arranges the ferroparticles in order. Results from this study concurred well with the experiment result by Hangi *et al.,* [40]. That experiment result found the thermal boundary layer is naturally developing when no magnetic applied but when magnetic applied, the cold fluid moves towards the source of magnetic close to the hot wall which can lead the better cooling rate and enhance the heat transfer rate from wall to ferrofluid.

The effect of radiation parameter on temperature profile are shown in Figure 6 when $M=1$, $\phi=0.1$ and $\gamma=0.5$. Further, an increasing radiation parameter enhance the temperature of the flow and the thermal boundary layer thickness also increase due to thermal energy physically released to the flow. Table 3 are shows an increase in skin friction $C_f\,\mathrm{Re}_x^{1/2}$ with increase the magnetic parameter M and volume fraction ϕ but not effect to radiation parameter N_R due to the decoupled boundary layer Eq. (10) and (11). The skin fraction increase with an increase the volume fraction due to the density of ferroparticles increase. Lastly, Table 4 are shows that the Nusselt number increase with increasing the magnetic parameter M and radiation parameter N_R but the Nusselt number decrease with increasing volume fraction ϕ. The Nusselt number represent the ratio of amount of heat displaced by convection to conduction, it is noted that an increase the radiation parameter and magnetic parameter implies enhance the heat transfer.

Table 3

Variation of the skin friction $C_f \mathrm{Re}_x^{1/2}$ for ferrofluid at different parameter

N_R	ϕ	$M = 1$	$M = 2$	$M = 5$	$M = 10$
0	0.01	1.638754	1.936626	2.636552	3.505884
	0.1	2.154755	2.546461	3.466805	4.609891
	0.2	2.841629	3.358193	4.571913	6.079379
1	0.01	1.638754	1.936626	2.636552	3.505884
	0.1	2.154755	2.546461	3.466805	4.609891
	0.2	2.841629	3.358193	4.571913	6.079379
2	0.01	1.638754	1.936626	2.636552	3.505884
	0.1	2.154755	2.546461	3.466805	4.609891
	0.2	2.841629	3.358193	4.571913	6.079379
3	0.01	1.638754	1.936626	2.636552	3.505884
	0.1	2.154755	2.546461	3.466805	4.609891
	0.2	2.841629	3.358193	4.571913	6.079379

Table 4

Variation in of the Nusselt Number $Nu_x / \mathrm{Re}_x^{1/2}$ for ferrofluid at different parameter

N_R	ϕ	$M = 1$	$M = 2$	$M = 5$	$M = 10$
0	0.01	1.197017	1.244064	1.333180	1.420404
	0.1	1.183949	1.229307	1.312845	1.388555
	0.2	1.140645	1.181967	1.260795	1.331300
1	0.01	2.032165	2.101887	2.233811	2.351011
	0.1	2.002634	2.067371	2.186419	2.293742
	0.2	1.924522	1.984253	2.093139	2.187830
2	0.01	2.683687	2.768199	2.921986	3.057164
	0.1	2.637926	2.714575	2.854588	2.977672
	0.2	2.529667	2.599842	2.726939	2.836889
3	0.01	3.240047	3.334938	3.506722	3.657480
	0.1	3.179458	3.265229	3.417338	3.554035
	0.2	3.044135	3.122216	3.261713	3.381580

4. Conclusions

The present study investigates the MHD stagnation flow in ferrofluid over a flat plate with Newtonian heating. We can conclude that:

- The velocity profiles will increase with an increase in magnetic parameter.
- The temperature profiles will increase with an increase volume fraction of ferroparticles and radiation parameter and decrease with increasing magnetic parameter.
- The skin friction will increase with an increase in magnetic parameter and volume fraction of ferroparticles.

- The Nusselt number will increase with an increase in magnetic parameter and radiation parameter.

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