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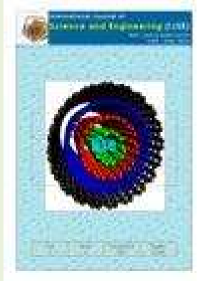

Effects of aligned magneticfield and radiation on the flow of ferrofluids over a flat plate with non-uniform heat source/sink

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Abstract *- In this study we analyzed the influence of radiation and aligned magneticfield on the flow of ferrofluids over a flat plate in presence of non-uniform heat source/sink and slip velocity. We considered Fe_3O_4 magnetic nano particles embedded within the two types of base fluids namely water and kerosene. The governing partial differential equations are transformed into nonlinear ordinary differential equations by using similarity transformation and solved numerically using bvp5c Matlab package. The effects of dimensionless quantities on the flow and temperature profiles along with the friction factor and Nusselt number is discussed and presented through graphs and tables. It is found that present results have an excellent agreement with the existed studies under some special assumptions. Results indicate that a raise in the aligned angle enhances the skin friction coefficient and heat transfer rate.*

Keywords — *MHD, Radiation, Ferrofluids, Non-uniform heat source or sink, Convection*

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I. Introduction

Magnetic nanofluids are also called as ferrofluids. Ferrofluids are in the size of 5-15 nm. The main aim of ferrofluids is to controlling the heat transfer and fluid flow. It has potential applications in the field of industrial engineering, aerospace, aeronautical, medical, science and technology (Rosersweig, 1985), Hiegeister *et al.,* 1999). (Jafari *et al*., 2008) illustrated the heat transfer analysis in ferrofluids by using computational fluid dynamics technique. The mesoscale structure analysis of ferrofluids with magnetic nano particles in presence of Brownian motion was discussed by (Xuan *et al.,* 2005). (Lajvardi *et al.,* 2010) examined the convective heat transfer in ferrofluids over a heated copper tube in presence of magneticfield. The influence of external magneticfield on the free convection ferrofluids flow and heat transfer was studied by (Sheikholeslami and Bandpy, 2014).

(Arulmurugan *et al.,* 2006) presented an experimental study on the thermal magnetic properties on ferrofluid flow in presence of Mn-Zn particles. The heat transfer analysis of thermophoretic radiative MHD nanofluid flow past an exponentially stretching porous sheet with heat generation/absorption was discussed by (Sandeep and Sulochana, 2015) and concluded that an increase in the exponential parameter enhances the heat and mass transfer rate. (Raju *et al.,* 2015) illustrated the cross-diffusion effects on steady two dimensional flow over a stretching surface in presence of radiation and magneticfield effects and found that heat and mass transfer rate increase with the increase in Biot number. The effects of elevating laser power on the structural stability and chemical composition of magnetite nano particles in ferrofluids was experimentally analyzed by (Abrashev *et al.,* 2010). (Aminfar *et al.,* 2011) investigated the mixed convection flow of a nanofluid past a vertical tube in presence of non-uniform magneticfield. MHD effect on natural convective heat transfer of Cu-water nanofluid through hot elliptic cylinder was studied by (Sheikholeslami *et al.*, 2014).

(Aminfar *et al.,* 2013) illustrated the non-uniform transverse magneticfield effect of ferrofluid flow and heat transfer analysis past a rectangular duct. A numerical analysis of the magnetic and thermal buoyancy effects on ferrofluid was examined by (Jue, 2006). The convective heat transfer analysis of ferrofluid flow past a micro channels was considered by (Xuan *et al.*, 2007).

(Jothimani and Anjali Devi, 2000) discussed the interface of two superposed viscous ferrofluids past an infinite plate in presence of an oblique uniform magneticfield. Recently, heat transfer analysis of ferrofluids past a flat plate in presence of uniform heat flux and slip velocity was investigated by (Khan *et al.,* 2015). In this paper they found that an increase in slip parameter enhances the heat transfer rate and declines the friction factor. (Felicia and Philip, 2015) was studied the influence of hydrophilic silica on the magneto rheology of an oil-based ferrofluid in presence of Fe_3O_4 nano particles. (Murali et al., 2015) discussed the heat and mass transfer in MHD flow past a vertical porous plate.

The soret driven ferro thermo convective instability of multi component fluid in a porous medium heated from below and salted in above in presence of dust particles was examined by (Sekhar and Raju, 2015). (Raju *et al.,* 2015) investigated the magneticfield, radiation and soret effects on the nanofluid flow through a moving vertical plate in presence of porous medium and found that soret number and buoyancy parameters are helps to enhance the heat transfer rate. (Seo *et al., 2015*) presented an analytical method to find the thermo physical characteristics of ferrofluids past a vertical rectangle with variations of intensity of magneticfield and viscosity. The numerical analysis of magnetic dipole effect on natural convective flow in a ferrofluids past a triangular cavity is studied by (Fatish and Oztop, 2015). (Zhou and Yan, 2015) investigated the effect of MHD nanofluid flow and heat transfer analysis by applying lattice Boltzmann procedure. The effects of rotation and aligned magneticfield in free convective unsteady MHD flow through porous medium with appearance of moving vertical plate were discussed by (Sandeep *et al.,* (2014). Very recently, (Sulochana *et al.,* 2015; Jones *et al.*, 2015) discussed the influence of aligned magneticfield on MHD boundary layer flow through different channels.

In this study we analyzed the influence of aligned magneticfield and radiation on the flow of ferrofluids over a flat plate in presence of non-uniform heat source/sink and slips velocity. We considered Fe_3O_4 magnetic nano particles embedded within the two types of base fluids namely water and kerosene. The governing partial differential equations are transformed into nonlinear ordinary differential equations by using similarity transformation and solved numerically using bvp5c Matlab package. The effects of dimensionless quantities on the flow and temperature profiles along with the friction factor and Nusselt number is discussed and presented through graphs and tables.

II. MATHEMATICAL FORMULATION

Consider a steady, incompressible two dimensional forced convection flow of ferrofluids over a stationary flat plate with uniform surface heat flux and non-uniform heat source/sink. The base fluids and ferroparticles are assumed to be in thermal equilibrium. The spherical shaped ferroparticles are considered. Volume fraction of ferroparticles is taken into account. An aligned magneticfield with an acute angle α is applied to the flow as shown in the Fig.1. At the fluid solid interface the hydromagnetic slip is assumed. Viscous dissipation effect is neglected. Here the ferroparticle moments are quickly randomize with the absence of magneticfield.

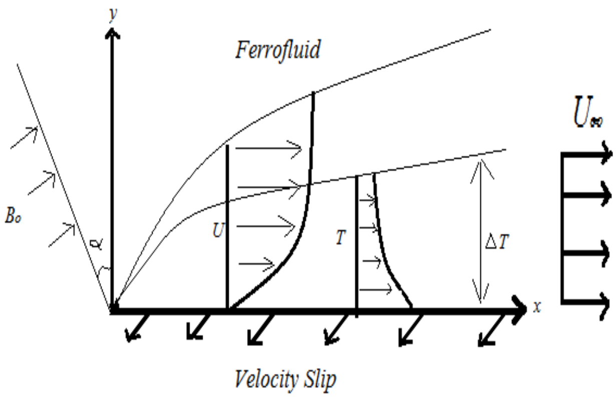

Figure 1.Flow Configuration

The boundary-layer equations that govern the present flow are:

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

$$\rho_{nf}\left(u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}\right)=\mu_{nf}\frac{\partial^2 u}{\partial y^2}-\sigma B^2\sin^2\alpha\left(u-U_\infty\right), \quad (2)$$

$$u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}=\alpha_{nf}\frac{\partial^2 T}{\partial y^2}-\frac{1}{(\rho c_p)_{nf}}\frac{\partial q_r}{\partial y}+\frac{1}{(\rho c_p)_{nf}}q''', \quad (3)$$

with the boundary conditions

$$\left.\begin{array}{l} u=\gamma\dfrac{\partial u}{\partial y},\ v=0,\ -k_{nf}\dfrac{\partial T}{\partial y}=q_w \text{ at } y=0, \\ u\to U_\infty, v\to 0,\ T\to T_\infty, \qquad \text{as } y\to\infty, \end{array}\right\} \quad (4)$$

where u, v are the velocity components in x, y directions, α is the inclined angle, ρ_{nf} and μ_{nf} are the ferrofluid density and dynamic viscosity respectively, σ is the electrical conductivity, $(\rho c_p)_{nf}$ is the specific heat capacitance of ferrofluid, T is the fluid temperature, k_{nf} is the effective thermal conductivity of ferrofluid, α_{nf} is the effective thermal diffusivity of the ferrofluid, q_r is the radiative heat flux, γ is the slip parameter and U_∞ is the free stream velocity. The transverse magneticfield assumed as $B=B_0x^{-1/2}$ with $B_0\neq 0$ where x is the coordinate along the plate, B_0 is the magnetic-field strength.

The radiative heat flux is defined as

$$q_r=-\frac{4\sigma_1}{3k_1}\frac{\partial T^4}{\partial y}, \quad (5)$$

In the above equation σ_1 is the Stefan-Boltzmann constant and k_1 is the coefficient of mean absorption. Assuming T^4 as a linear combination of temperature, then

$$T^4 \cong -3T_\infty^{\ 4} + 4T_\infty^{\ 3}T, \tag{6}$$

The temperature dependent heat generation/absorption (non uniform heat source/sink) q''' is defined as

$$q''' = \frac{k_f U(x)}{lv}\left(A^*(T_w - T_\infty) f' + B^*(T - T_\infty)\right), \tag{7}$$

where A^* and B^* are parameters of the space and temperature dependent internal heat generation/absorption. The positive and negative values of A^* and B^* represents heat generation and absorption respectively and l is the characteristic length scale.

The ferrofluids constants are given by

$$(\rho\beta)_{nf} = (1-\phi)(\rho\beta)_f + \phi(\rho\beta)_s,$$

$$(\rho c_p)_{nf} = (1-\phi)(\rho c_p)_f + \phi(\rho c_p)_s,$$

$$\frac{k_{nf}}{k_f} = \frac{(k_s + 2k_f) - 2\phi(k_f - k_s)}{(k_s + 2k_f) + \phi(k_f - k_s)},$$

$$\mu_{nf} = \frac{\mu_f}{(1-\phi)^{2.5}},\ \rho_{nf} = (1-\phi)\rho_f + \phi\rho_s, \tag{8}$$

where ϕ is the volume fraction of the ferroparticles. The subscripts f and s refer to fluid and solid properties respectively.

For similarity solutions of equations (1)-(3), subject to the boundary conditions (4) we are introducing

$$\eta = \frac{y}{x}(\mathrm{Re}_x)^{1/2},\ \theta(\eta) = \frac{T - T_\infty}{q_w x / k_f}\sqrt{\mathrm{Re}_x},$$

$$u = \frac{\nu_f}{x}\mathrm{Re}_x\, f'(\eta), \psi = \nu_f\sqrt{\mathrm{Re}_x}\, f(\eta),$$

$$v = -\left(-\frac{y}{2x^2}\mathrm{Re}_x\, f'(\eta) + \frac{1}{2x}(\mathrm{Re}_x)^{1/2} f(\eta)\right), \tag{9}$$

Where η is the similarity variable, ψ is the stream function and $\mathrm{Re}_x = U_\infty x / \nu_f$ is the Reynolds number.

Using equations (5)-(9) equations (2) and (3) transformed into the ordinary differential equations of the form

$$\frac{1}{(1-\phi)^{2.5}} f''' + \left(1 - \phi + \phi\left(\frac{\rho_s}{\rho_f}\right)\right)\frac{ff''}{2} + M(1-f')\sin^2\alpha = 0, \tag{10}$$

$$\left(\frac{k_{nf}}{k_f} + \frac{4}{3}R\right)\theta'' + \frac{1}{2}\Pr\left(1 - \phi + \phi\left(\frac{(\rho c_p)_s}{(\rho c_p)_f}\right)\right)(f\theta' - f'\theta) + A^* f' + B^*\theta = 0, \tag{11}$$

Subject to the boundary conditions

$$f(0) = 0,\ f'(0) = \frac{\beta}{(1-\phi)^{2.5}} f''(0), \theta'(0) = -\frac{k_f}{k_{nf}},$$

at $\eta = 0$, $\quad f'(\infty) \to 1, \theta(\infty) \to 0$ as $\eta \to \infty$, (12)

where β is the slip parameter, $\Pr$ is the Prandtl number parameter, M is the magneticfield parameter, R is the radiation parameter and A^* and B^* are the non-uniform internal heat generation/absorption coefficients, which are given by

$$M = \frac{\sigma B_0^{\ 2}}{\rho U_\infty}, \Pr = \frac{(\mu c_p)_f}{k_f}, \beta = \frac{U_\infty \gamma}{\nu_f}, R_a = \frac{4\sigma_1 T_\infty^{\ 3}}{k^* k_f}, \tag{13}$$

The physical quantities are interest of the skin friction C_f and the local Nusselt number Nu_x are defined by

$$C_f = \frac{\tau_{wx}}{\rho_f U_\infty^{\ 2}}, Nu_x = \frac{x q_w}{k_f (T_w - T_\infty)}, \tag{14}$$

where τ_{wx} is the shear surface stresses along the $x-$ directions and q_w is the heat flux which are given by

$$\tau_{wx} = \mu_{nf}\left(\frac{\partial u}{\partial y}\right)_{y=0}, q_w = -k_{nf}\left(\frac{\partial T}{\partial y}\right)_{y=0}, \tag{15}$$

Reduced the non-dimensional forms after fixing $\mathrm{Re} = \frac{U_w x}{\nu_f}$,

$$C_f \mathrm{Re}_x^{1/2} = \frac{1}{(1-\phi)^{2.5}} f''(0), Nu_x \mathrm{Re}_x^{-1/2} = \frac{k_{nf}}{k_f}\frac{1}{\theta(0)}, \tag{16}$$

III. NUMERICAL SOLUTION

Equations (10) and (11), subject to the boundary conditions (12) are solved numerically by using bvp5c Matlab package. We consider $f = x_1$, $f' = x_2$, $f'' = x_3$, $\theta = x_4$, $\theta' = x_5$. Equations (10) and (11) are transformed into system of first order differential equations. Subject to the following initial conditions

$$x_1(0) = 0, x_2(0) = \lambda, x_3(0) = s_1, x_4(0) = 1, x_5(0) = s_2, \tag{17}$$

we assumed the unspecified initial conditions s_1, s_2 in equation (17), transformed first order differential equations are integrated numerically as an initial valued problem to a given terminal point. We can check the accuracy of the assumed missing initial condition, by comparing the calculated value of the different variable at the terminal point with the given value by the existence of the difference in improved values so that the missing initial conditions must be obtained. The calculations are carried out by the program using Matlab.

IV. RESULTs AND DISCUSSION

The system of nonlinear ordinary differential equations (10) and (11), subject to the boundary conditions (12) are solved numerically using bvp5c Matlab package. For numerical results we considered the dimensionless parameter values $R = M = 1$, $\alpha = \pi/2, A^* = B^* = 0.5, \Pr = 6.2, \phi = 0.1$. These values are kept as common in entire study except the variations in the values as displayed in respective figures and tables. Results depicts the influence of non-dimensional parameter values namely magneticfield parameter M , inclined angle α , radiation parameter R , non-uniform heat source/sink parameters A^*, B^* and volume fraction of nano particles ϕ on the velocity and temperature profiles of the flow.

Figs. 2 and 3 show the effect of inclined angle on velocity and temperature profiles of both Fe_3O_4-water and Fe_3O_4-kerosene ferrofluids. It is evident from the figures that an increase in the aligned angle enhances the velocity profiles and depreciates the temperature profiles for both ferrofluids. Further it is observed that increasing in α causes to enhance the momentum boundary layer and declines the thermal boundary layer of Fe_3O_4-kerosene ferrofluid. This is due to the fact that a raise in the value of aligned angle strengthen the applied magneticfield. At $\alpha = \pi / 2$ level this aligned magneticfield acts like transverse magneticfiled and ferroparticles are attracted by the magneticfield due to change in the positions of aligned angle. The similar type of results has been observed in Figs. 4 and 5 for magneticfiled parameter case. Generally increase in magneticfiled arranges the ferroparticles in order. Due to this reason we noticed hike in velocity profiles of the flow.

Figs. 6 and 7 depict the influence of volume fraction of nano particles on velocity and temperature profiles of both Fe_3O_4-water and Fe_3O_4-kerosene ferrofluids. It is clear that with the increase in the volume fraction of nano particles we seen a raise in the momentum boundary layer and reduce in thermal boundary layer near the wall after wards it takes reverse action in both cases. Physically, increase in the volume fraction of nano particles enhances the thermal conductivity of the fluid. This helps to enhance the momentum and thermal boundary layer thickness. Fig.8 displays the effect of radiation parameter on temperature profiles of the flow. It is observed from the figure that an increase in radiation parameter enhances the temperature profiles of the flow. This is due to the fact that increasing the radiation parameter releases the heat energy to the flow, which causes to develop the temperature profiles. It is also noticed that the influence of radiation is significant in water based ferrofluids.

Figs. 9 and 10 illustrate the effect of non-uniform heat source/sink on temperature profiles of both Fe_3O_4-water and Fe_3O_4-kerosene ferrofluids. It is observed that with the increase in the values of non-uniform heat source/sink parameters A^* and B^* , we seen a raise in the temperature profiles of the flow in both cases. Generally, the positive values of A^* and B^* acts like heat generators and this will help to enhance the thermal boundary layer thickness in both ferrofluids. It is significant to mention here that the thermal conductivity levels are more in water based ferrofluids compared with kerosene based ferrofluids. Figs. 11 and 12 show the influence of slip parameter on velocity and temperature profiles of both Fe_3O_4-water and Fe_3O_4-kerosene ferrofluids. It is clear that an increase in slip parameter enhances the velocity and depreciates the thermal boundary layers in both cases. Physically, increase in slip parameter causes to reduce the flow resistance. This help to develop the momentum boundary layer thickness.

Table 1 depicts the comparison of the present results with the existed results of Khan et al. (2015). We found an excellent agreement with the existed results under some special assumptions. This shows the validity of the present results and the accuracy of the numerical technique we used in this study. Table 2 shows the thermophysical properties of the base fluids along with the Fe_3O_4 ferroparticles. Tables 3 and 4 displays the influence of non-dimensional governing parameters on friction factor and local Nusselt number for Fe_3O_4-water and Fe_3O_4-kerosene ferrofluids respectively. It is evident from the tales that with the increase in aligned angle, volume fraction of nano particle and magneticfield parameter we observed a raise in friction factor along with the heat transfer rate. An increase in the values of non-uniform heat source/sink parameters and radiation parameter does not shown significant variation in friction factor. But this causes to reduce the heat transfer rate.

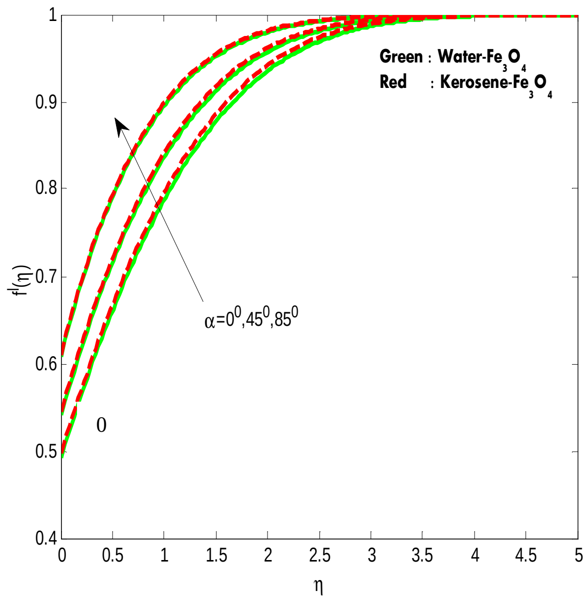

Figure 2. Velocity Profiles for Different Values of Inclined Angle α

Table 1. Comparison of the skin friction coefficient for different values of Volume fraction of nano particles

		$M = \beta = 0$	$A^* = B^* = R = 0$	$M = \beta = 2$	$A^* = B^* = R = 0$
	ϕ	Khan et al. (2015)	Present Study	Khan et al. (2015)	Present Study
Fe_3O_4-Water	0.01	0.34324	0.3432413	0.37573	0.3757321
	0.1	0.45131	0.4513102	0.38832	0.3883210
	0.2	0.59517	0.5951712	0.40242	0.4024202
Fe_3O_4-Kerosene	0.01	0.34557	0.3455732	0.37580	0.3758001
	0.1	0.47336	0.4733621	0.38896	0.3889631
	0.2	0.63950	0.6395023	0.40356	0.4035641

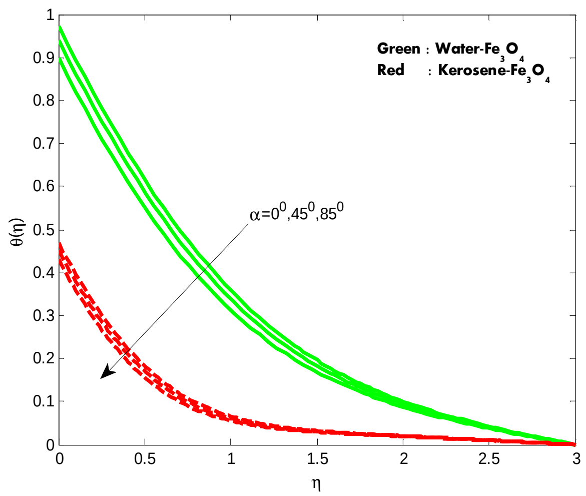

Figure 3. Temperature Profiles for Different Values of Inclined Angle α

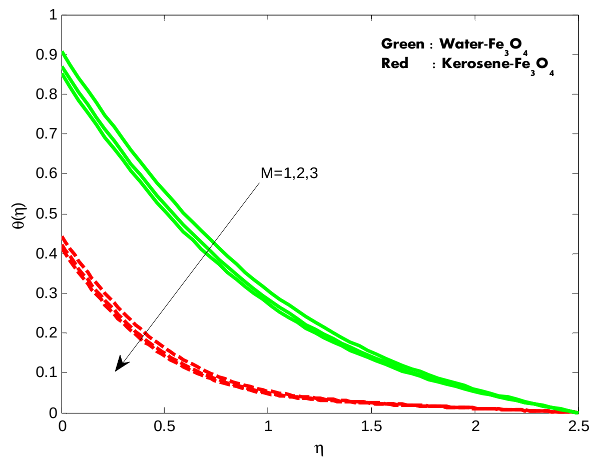

Figure 5. Temperature Profiles for Different Values of Magneticfield Parameter M

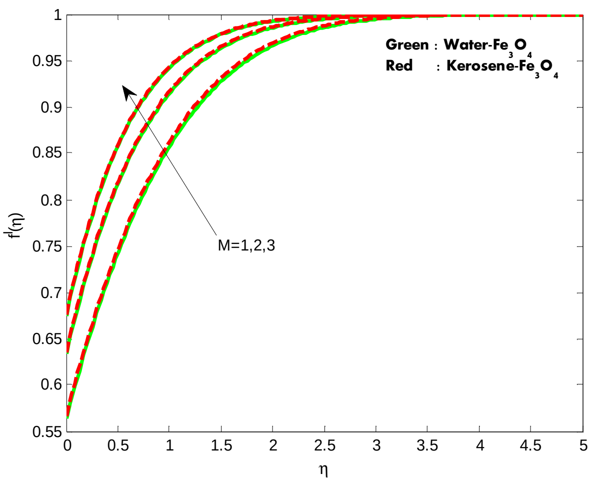

Figure 4. Velocity Profiles for Different Values of Magneticfield Parameter M

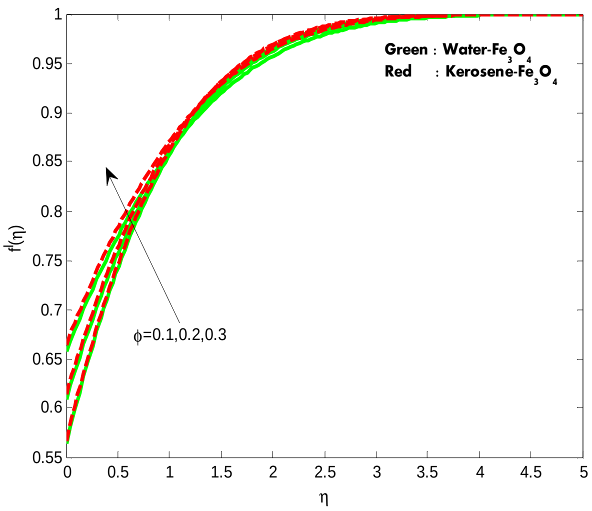

Figure 6. Velocity Profiles for Different Values of Volume fraction of Nano Particles ϕ

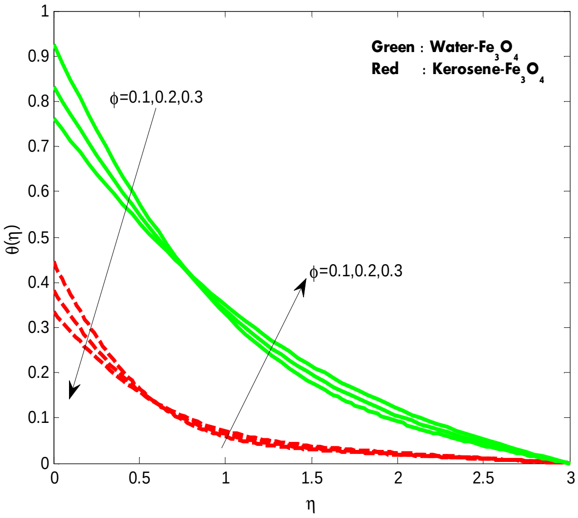

Figure 7. Temperature Profiles for Different Values of Volume Fraction of Nano Particles ϕ

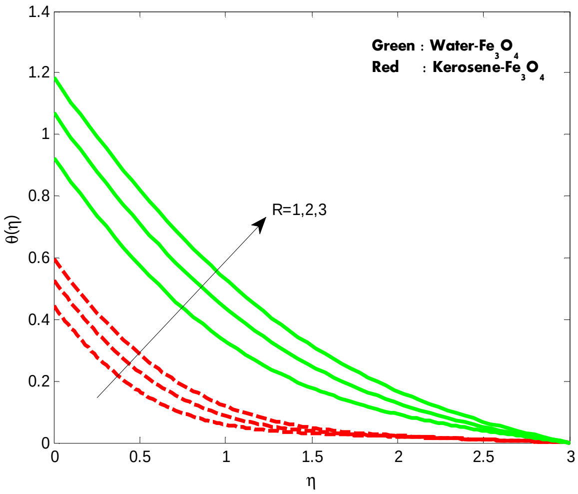

Figure 8. Temperature Profiles for Different Values of Radiation Parameter R

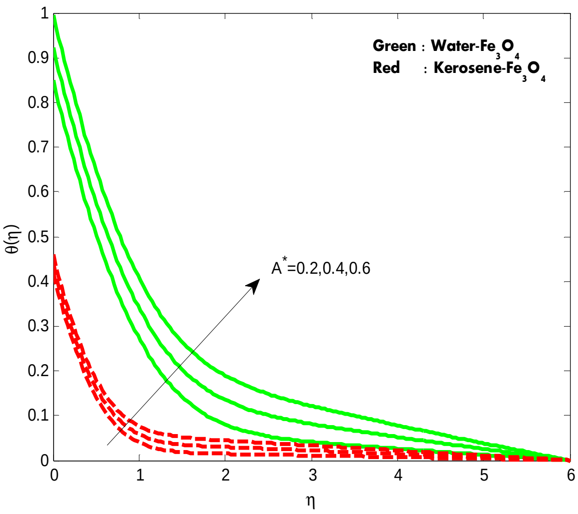

Figure 9. Temperature Profiles for Different Values of Non-Uniform Heat Source/Sink A^*

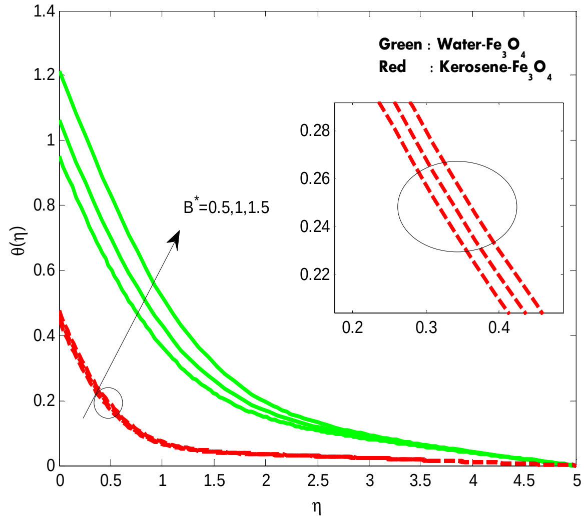

Figure 10. Temperature Profiles for Different Values of Non-Uniform Heat Source/Sink B^*

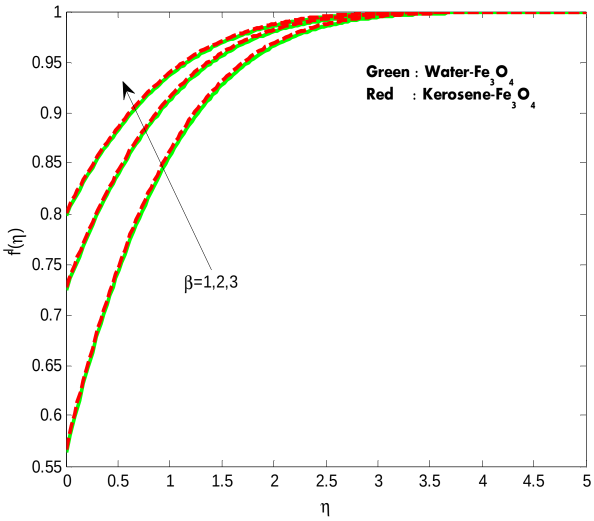

Figure 11. Velocity Profiles for Different Values of Slip Parameter β

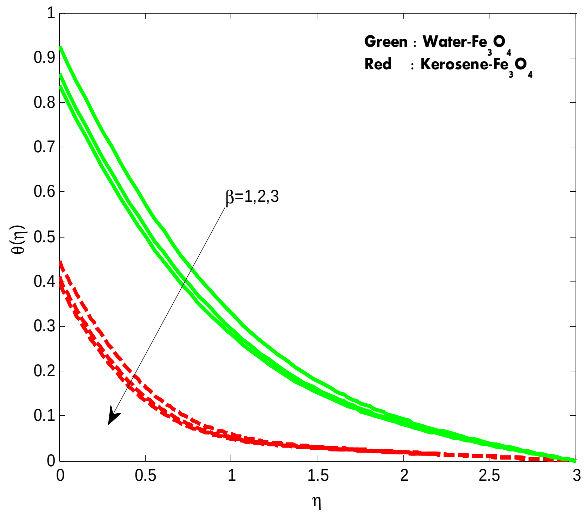

Figure 12. Temperature Profiles for Different Values of Slip Parameter β

Table 2. Thermophysical Properties of Water, Kerosene and Fe_3O_4 Nano Particles

	ρ (Kgm^{-3})	c_p $(JKg^{-1}K^{-1})$	k $(Wm^{-1}K^{-1})$
Water	997	4179	0.613
Kerosene	783	2090	0.15
Fe_3O_4	5180	670	9.7

Table 3. Variation in skin friction coefficient and Nusselt number for Fe_3O_4-water Ferrofluids at different non-dimensional parameters

α	ϕ	R	A^*	B^*	M	$C_f Re_x^{1/2}$	$Nu_x Re_x^{-1/2}$
0^0						0.452075	1.221365
45^0						0.501115	1.273556
85^0						0.536236	1.308496
	0.1					0.563371	1.334185
	0.2					0.608601	1.840748
	0.3					0.656644	2.468652
		1				0.563371	1.334185
		2				0.563371	1.149903
		3				0.563371	1.031799
			0.2			0.563369	1.495423
			0.4			0.563369	1.377009
			0.6			0.563369	1.275972
				0.5		0.563371	1.334185
				1.0		0.563372	1.195712
				1.5		0.563371	1.047710
					1	0.563371	1.334185
					2	0.632996	1.395142
					3	0.674215	1.427955

Table 4. Variation in skin friction coefficient and Nusselt number for Fe_3O_4-kerosene Ferrofluid at different non-dimensional parameters

α	ϕ	R	A^*	B^*	M	$C_f Re_x^{1/2}$	$Nu_x Re_x^{-1/2}$
0^0						0.459194	2.684769
45^0						0.505997	2.796946
85^0						0.539908	2.874053
	0.1					0.566289	2.931796
	0.2					0.614121	4.422842
	0.3					0.664211	6.497952
		1				0.566289	2.931796
		2				0.566289	2.472948
		3				0.566289	2.188651
			0.2			0.566287	3.137646
			0.4			0.566287	2.993513
			0.6			0.566287	2.862040
				0.5		0.566289	2.931796
				1.0		0.566289	2.849712
				1.5		0.566289	2.766036
					1	0.566289	2.931796
					2	0.634540	3.072665
					3	0.675233	3.151072

V. CONLUSIONS

This study presents the influence of radiation and aligned magneticfield on the flow of ferrofluids over a flat plate in presence of non-uniform heat source/sink and slip velocity. The governing partial differential equations are transformed into nonlinear ordinary differential equations by using similarity transformation and solved numerically using bvp5c Matlab package. The effects of dimensionless quantities on the flow and temperature profiles along with the friction factor and Nusselt number is discussed and presented through graphs and tables. Conclusions of the present study are made as follows:

- Heat and mass transfer rate in Fe_3O_4-kerosene ferrofluid is more compared with Fe_3O_4-water ferrofluid.
- A raise in inclined angle enhances the friction factor and heat transfer rate.

- Slip parameter have tendency to enhance the momentum boundary layer thickness.
- Positive values of non-uniform heat source/sink parameters acts like heat generators and enhance the temperature profiles of the flow.
- Volume fraction of nano particles have tendency to improve the momentum and thermal boundary layers.

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