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Biomagnetic Flow and Heat Transfer with Magnetic/non-magnetic Particles through a Stretched Cylinder

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Mixed convection flow and heat transfer of Biomagnetic fluid with magnetic/non-magnetic particles due to a stretched cylinder in the presence of a magnetic dipole

In this paper, a steady two dimensional mixed convection boundary layer flow of biomagnetic fluid with magnetic ($CoFe_2O_4$) and non-magnetic (Al_2O_3) particles suspension within base fluid blood over a stretched cylinder in the presence of a magnetic dipole is studied. Where, thermal conductivity is considered temperature dependent. The governing PDEs are converted into a system of ODEs by applying some acceptable non-dimensional similarity variables and numerically solved them by utilizing an efficient numerical technique that consists with common finite difference along with central differencing, a tridiagonal matrix manipulation and on an iterative procedure. The impacts of ferromagnetic interaction parameter, particles volume fraction, mixed convection and Prandtl number is discussed for $CoFe_2O_4$-blood and Al_2O_3-blood by graphical demonstrations of velocity, temperature distributions as well as skin friction coefficient and the rate of heat transfer. It is found that the performance of magnetic particles ($CoFe_2O_4$) in blood flow and heat transfer is better than non-magnetic (Al_2O_3) particles. A comparison was made with previous existing literature to validate the current results.

1.1 Introduction

Due to the numerous applications of biomagnetic fluid dynamics (BFD) in medical and bio-engineering such as drug delivery, cancer treatment, eye treatment, magnetic resonance imaging (MRI) etc. [1-3], it has gained serious attention from the researchers in last few decades. With a spreading world race, medical and engineering sectors are required more effective advancement and its implementation. Based on this purpose, researchers was engaged themselves to evolve progression of fluid heat transfer with higher thermal conductivities. Such idea was first introduced by Choi [4] with the term "nanofluid" and shows that by applying this concept the barrier of thermal conductivity of base fluid is greater than regular fluid. Basically, nanofluid is a fluid where regular fluid such as blood, water, oil etc. are mixed with different types of nanoparticles.

In view of medical applications, BFD model was enchanted by many researchers because in BFD, all biological fluids are influenced by a strong applied magnetic field. One of the characteristics of biomagnetic fluid is blood. Blood treated as a magnetic fluid due to the presence of iron oxides which are present with highly concentration in the mature red blood cells. In bio-medical applications progression magnetic particles plays a vital role than non-magnetic particles due to its unique property. Because magnetic particles can easily manipulated by magnetic force, which can further enables fleet and simple detachment of target molecules bound to the particles from reaction mixtures than non-magnetic particles.

Hakim et al. [5] investigated the flow and heat transfer of Newtonian/Non-Newtonian fluid with Fe_3O_4 magnetic and Al_2O_3 non-magnetic particles over a flat plate. They found that the skin friction coefficient and rate of heat transfer becomes higher for non-Newtonian fluid than

Newtonian fluid. Shah et al. [6] was the first who introduce the concept of fractional derivatives to analyze the flow of blood along with magnetic particles through a circular cylinder. Sharma et al. [7] investigated the flow of artificial blood with Iron oxide magnetic particles under the influence of external magnetic field. A comprehensive study of non-Newtonian Casson and Carreau model were discussed by Dey et al. [8]. Where spiral component of blood circulation assumed pulsatile and parabolic characteristics of human blood flow. Using finite element method, Marwan et al. [9] analyzed the behavior of human heart to transport blood in the active vascular system. Hemmat Esfe et al. [10] performed a numerical analysis of mixed convection flow and heat transfer water-Al_2O_3 nanofluid in an inclined two-sided lid driven cavity. Recently, Ferdows et al. [11] examined the flow of blood with $CoFe_2O_4$ magnetic particles through an unsteady stretched/shrinking cylinder. In that study, they found that temperature of blood- $CoFe_2O_4$ is enhanced significantly in case of BFD compare than MHD and FHD. The impact of temperature dependent fluid viscosity and thermal conductivity on blood-Fe_3O_4 flow and heat transfer in the presence of magnetic dipole examined by Alam et al. [12] and shows that the blood flow can be controlled by applying a strong magnetic field.

A pioneering research has been already exists related to this model but still needed to improve the thermal enhancement of blood heat transfer. According to the best information of authors no study has been done yet about the impacts of variable fluid properties on mixed convection flow over a stretched cylinder where blood considered as base fluid and two different types of particles namely magnetic ($CoFe_2O_4$) and non-magnetic particles (Al_2O_3) is considered. The hope is that the results that obtained from this research can be useful in medical applications especially in drug delivery and cancer treatment.

1.2 Mathematical Modeling

Figure1 shows a stretched two dimensional cylinder considered for the present study. It is assumed that the radius of the cylinder is R and it's stretched with velocity $u_w = \frac{u_0 x}{l}$ along axial x–direction, while r–axis is normal to it. The temperature of cylindrical surface is considered T_w and the ambient temperature of a ferrofluid with particle is T_c that situated far away from the surface, where $T_w < T_c$. It is also assumed that ferrofluid flow is subjected to a magnetic field of strength H that creates a magnetic dipole at distance c from the sheet. However, heat transfer of ferrofluid analysis is carried out by assuming in presence of variable temperature dependent thermal conductivity.

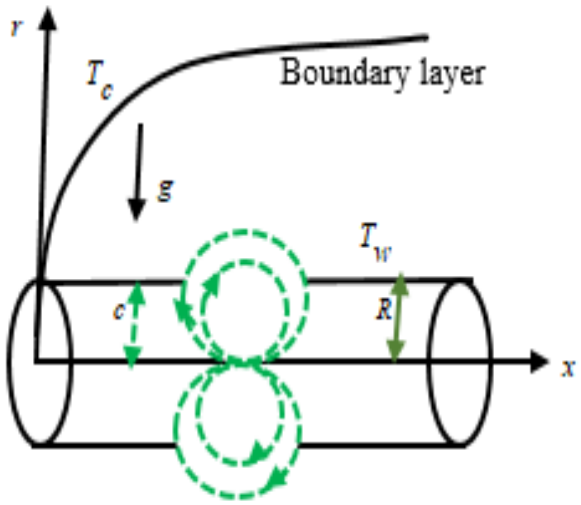


Figure1. Physical model and co-ordinate system

Under the above assumptions and using the Boussinesq approximations for mixed convection, the extended model of [13] can be written in the following equations:

$$\frac{\partial}{\partial x}(ru)+\frac{\partial}{\partial r}(rv)=0 \tag{1}$$

$$u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial r}=\frac{\mu_{mf}}{\rho_{mf}}\left(\frac{1}{r}\frac{\partial u}{\partial r}+\frac{\partial^2 u}{\partial r^2}\right)+\frac{(\rho\beta)_{mf}}{\rho_{mf}}g\left(\mathrm{T}_c-T\right)+\frac{\mu_0}{\rho_{mf}}M\frac{\partial H}{\partial x} \tag{2}$$

$$(\rho C_p)_{mf}\left(u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial r}\right)+\mu_0\,T\frac{\partial M}{\partial T}\left(u\frac{\partial H}{\partial x}+v\frac{\partial H}{\partial r}\right)=\frac{1}{r}\frac{\partial}{\partial r}\left(\kappa^*_{mf}(T)r\frac{\partial T}{\partial r}\right) \tag{3}$$

With applicable boundary conditions:

$$\begin{aligned} &at\ r=R:\ u=\frac{u_0 x}{l},\ v=0,\ T=T_w \\ &as\ r\to\infty:u\to 0,\ T\to T_c \end{aligned} \tag{4}$$

Where, the velocity components u and v are in the x-and r directions, respectively. Additionally, the symbols $\rho,\kappa,c_p,\mu,\mu_0,g,\beta,u_0,l$ are the blood densities, thermal conductivity, specific heat at constant pressure, magnetic permeability, fluid viscosity, acceleration due to gravity, coefficient of volumetric thermal expansion, referred velocity and characteristics length of the cylinder respectively. The third term of the momentum equation $\frac{\mu_0}{\rho_{mf}}M\frac{\partial H}{\partial x}$ represent the magnetic body force per unit volume along x–axis and depends on the existence of the magnetic gradient and the

term $\mu_0 T\frac{\partial M}{\partial T}\left(u\frac{\partial H}{\partial x}+v\frac{\partial H}{\partial r}\right)$ in equation (3) accounts for heating due to adiabatic magnetization. These two terms arise because of ferrohydrodynamics (FHD) [14].

According to the studies of [13], the thermal conductivity is considered to vary as linearly with temperature and given by:

$$\kappa_{mf}^{*}(T)=\kappa_{mf}(1+\varepsilon\theta) \tag{5}$$

Where ε is the thermal conductivity parameter which basically shows the influence of temperature on variable thermal conductivity.

Moreover, the variation of magnetization M that express as a linear function of temperature T as [14]:

$$M = K(T_C - T) \tag{6}$$

Where, K is the pyromagnetic coefficient constant and T_C is the Curie temperature.

Now following [14], we consider that the components of magnetic field of intensity $\vec{H}$ i.e. H_x and H_r due to a magnetic dipole is given by

$$H_x(x,r)=-\frac{\partial V}{\partial x}=\frac{\gamma}{2\pi}\frac{x^2-(r+c)^2}{\left(x^2+(r+c)^2\right)^2} \tag{7}$$

$$H_r(x,r)=-\frac{\partial V}{\partial r}=\frac{\gamma}{2\pi}\frac{2x(r+c)}{\left(x^2+(r+c)^2\right)^2} \tag{8}$$

Where $V=\frac{\alpha}{2\pi}\frac{x}{x^2+(r+c)^2}$

Thus, the magnitude of $\left\|\vec{H}\right\| = H$, of the magnetic field of intensity as analogous manner expressed by

$$H(x,r)=\left[H_x^2+H_r^2\right]^{1/2}\approx\frac{\gamma}{2\pi}\left[\frac{1}{(r+c)^2}-\frac{1}{2}\frac{x^2}{(r+c)^4}\right] \tag{9}$$

1.3 Similarity Transformation

Let us now introduce the following non-dimensional expressions [13]:

$$\eta = \frac{r^2 - R^2}{2R}\sqrt{\frac{u_0}{\upsilon_f l}}\,;\, u = \frac{u_0 x}{l} f'(\eta);\, v = -\frac{R}{r}\sqrt{\frac{u_0 \upsilon_f}{l}} f(\eta);$$
$$\theta(\eta) = \frac{T_c - T}{T_c - T_w} \tag{10}$$

Along with the thermal characteristics of magnetic fluid [10-11]:

$$\begin{cases} \rho_{mf} = (1-\varphi)\rho_f + \varphi\rho_s \\ \mu_{mf} = \mu_f\,(1-\varphi)^{-2.5} \\ (\rho C_p)_{mf} = (1-\varphi)(\rho C_p)_f + \varphi\,(\rho C_p)_s \\ (\rho\beta)_{mf} = (1-\varphi)(\rho\beta)_f + \varphi(\rho\beta)_s \\ \dfrac{\kappa_{mf}}{\kappa_f} = \dfrac{(\kappa_s + 2\kappa_f) - 2\varphi\,(\kappa_f - \kappa_s)}{(\kappa_s + 2\kappa_f) + \varphi\,(\kappa_f - \kappa_s)} \end{cases} \tag{11}$$

Where φ is the solid volume fraction of the magnetic/non-magnetic particles. The subscripts symbol $(\ )_f$ and $(\ )_s$ represents the base fluid (blood) and magnetic/non-magnetic particles ($CoFe_2O_4/Al_2O_3$), respectively.

Now, the continuity equation is identically satisfied and therefore the momentum and energy equations with boundary conditions are reduced as utilizing (9) to (11) as follows:

$$(1+2\eta D)f''' + \left(2D + A_1A_2 f\right)f'' - A_1A_2 f'^2 + A_1A_3\,\lambda\theta - A_1\frac{2B\theta}{(\eta+\alpha)^4} = 0 \tag{12}$$

$$(1+\varepsilon\theta)(1+2\eta D)\theta'' + \left(2D(1+\varepsilon\theta) + \varepsilon(1+2\eta D)\,\theta' + A_4A_5\,\mathrm{Pr}\,f\right)\theta' - A_4\frac{2B\lambda_1 f(\varepsilon_1 - \theta)}{(\eta+\alpha)^3} = 0 \tag{13}$$

Reduced boundary conditions are:

$$\begin{aligned} &at\ \eta = 0: f = 0,\ f' = 1, \theta = 1 \\ &as\ \eta \to \infty: f' \to 0, \theta \to 0 \end{aligned} \tag{14}$$

Where,

$$A_1 = (1-\varphi)^{2.5}, A_2 = \left(1-\varphi+\varphi\frac{\rho_s}{\rho_f}\right), A_3 = \left(1-\varphi+\varphi\frac{(\rho\beta)_s}{(\rho\beta)_f}\right)$$

$$A_4 = \frac{\kappa_f}{\kappa_{mf}}, A_5 = \left(1-\varphi+\varphi\frac{\left(\rho C_p\right)_s}{\left(\rho C_p\right)_f}\right)$$

In the above expressions, $B = \frac{\gamma}{2\pi}\frac{\mu_0 K\left(T_c - T_w\right)\rho_f}{\mu_f^2}$ is the ferromagnetic interaction parameter; $\lambda_1 = \frac{u_0\mu_f^2}{l\kappa_f\left(T_c - T_w\right)\rho_f}$ is the viscous dissipation parameter; $\varepsilon_1 = \frac{T_c}{T_c - T_w}$ is the Curie temperature; $D = \left(\frac{l\upsilon_f}{u_0 R^2}\right)^{1/2}$ is the Curvature parameter; $\alpha = \left(\frac{u_0}{l\upsilon_f}\right)^{\frac{1}{2}} c$ is the dimensionless distance; $\Pr = \frac{\left(\mu C_p\right)_f}{\kappa_f}$ is the Prandtl number; $\lambda = \frac{g\beta_f l^2\left(T_c - T_w\right)}{u_0^2 x}$ is the mixed convection parameter.

1.4 Physical Quantities: Surface Drag Coefficient and Thermal Gradient

One of the physical quantities interest of the present study in engineering point of view are the shear stress and the rate of heat transfer which are evaluated at the surface of the cylinder known as the skin friction coefficient C_f and rate of heat transfer Nu_x. The mathematical relation of C_f and Nu_x are defined by:

$$C_f = \frac{2\tau_w}{\rho_f u_w^2} \quad \text{and} \quad Nu_x = \frac{x q_w}{\kappa_f\left(\mathrm{T_c} - \mathrm{T_w}\right)} \tag{15}$$

Where, $\tau_w = \mu_{mf}\left(\frac{\partial u}{\partial r}\right)_{r=R}$ is the wall shear stress and $q_w = \kappa_{mf}\left(\frac{\partial T}{\partial r}\right)_{r=R}$ is the wall heat flux at the surface of the cylinder.

Now using (10) and (11), the equation (15) becomes:

$$C_f\sqrt{\mathrm{Re}} = \frac{1}{(1-\phi)^{2.5}} f''(0) \text{ and } Nu_x = \frac{\kappa_{mf}}{\kappa_f}\sqrt{\mathrm{Re}}\theta'(0) \tag{16}$$

Where, the ration of internal force to viscous force defined by $\mathrm{Re} = \frac{u_0 x^2}{l\upsilon_f}$ and known as local Reynolds number.

1.5 Numerical Procedure

Now the obtained highly non-linear ODEs of (12) and (13) with applicable boundary conditions (14) are solved by applying a new algorithm which has better stability characteristics than classical Runge-Kutta method and this new numerical technique is simple, accurate and efficient than others numerical procedure. The details study about this numerical technique is found in [12, 15]. According to [12, 15], this numerical technique consists with three necessary features, such as:

i. Common finite difference method with central differencing
ii. a tridiagonal matrix manipulation
iii. On an iterative procedure.

Keeping this into account, the given problem is solved by assuming a proper step size $h = \Delta\eta = 0.01$ where $\eta_\infty = 5$. This process is continued until the required convergence 10^{-3} is attained.

1.6 Code Validation and Values of Thermophysical properties of Base fluid and magnetic/non- magnetic particles

To ensure the authenticity of the applied numerical code, we check our obtained computational results with the existing results of [13] for $\theta'(0)$ when $B = \varphi = 0$ and this results captured in Table1 and shows a better agreement.

Table 1. Comparison of $\theta'(0)$ with Hayat et al. [13] for various values of Pr and η.

Pr	η	$\theta'(0)$	
		Hayat et al. [13]	Present results
1	0	-0.5825	-0.5804
	1	-1.0000	-1.001
3	0	-1.1654	-1.164
	1	-1.92368	-1.929

Additionally, the thermo-physical values of blood and $CoFe_2O_4$ and Al_2O_3 are shown in Table2 [10-11, 16-17].

Table 2. Values of base fluid (blood) and magnetic particles ($CoFe_2O_4$) and non-magnetic particles (Al_2O_3).

Properties	Blood	$CoFe_2O_4$	Al_2O_3
C_p	3.9×10^3	700	765
ρ	1050	4907	3970
κ	0.5	3.7	25
β	4×10^{-4}	1.3×10^{-5}	0.85×10^{-5}

1.7 Results and Discussion

In this section, the influence of appearing physical parameters such that ferromagnetic number, mixed convection, particles volume fraction, Prandtl number for blood-$CoFe_2O_4$ and blood-Al_2O_3 on the velocity and temperature distributions are studied due to understand the current mathematical model. Additionally, the variation of skin friction coefficient and the rate of heat transfer also studied in this model. All the figures are plotted with considering the following values as well as those considered in Table2. Where, $B = 0, 5, 10$ as in [11, 16]; $\lambda = 0.5, 1, 1.5$ as in [13]; $\varphi = , 0.1, 0.15, 0.2$ as in [11-16]; $D = 0.5, 1$ as in [11, 12]; $\varepsilon = 0.1, 0.3, 1, 2, 3$ as in [11, 13]; $\Pr = 21, 23, 25$ as in [12]. It is also assumed that, the human body temperature $T_w = 310\ k$ [12]

while body Curie temperature is $T_c = 314\,k$ .Using these values, dimensionless temperature $\varepsilon_1 = \frac{T_c}{T_c - T_w} = \frac{314}{314-310} = 78.5$ [11], viscous dissipation number $\lambda_1 = 6.4 \times 10^{-14}$ [11] and dimensionless distance $\alpha = 1$ [11].

Figure2 and Figure3 have been plotted to show the influence of ferromagnetic interaction parameter (B) on velocity and temperature profile for blood-$CoFe_2O_4$ and blood-Al_2O_3. It is observed that as the values of $_B$ increases, velocity decreases whereas temperature profile enhanced. This is due to the fact that the applied strong field introduces a retarding body force which known as Kelvin force. Because in transport phenomena, this applied magnetic field and electrically non-conducting fluid such as blood are creates stronger Kelvin force which act as a resistance force. For that blood motion gets much slower consequently heat is produced much higher. It is also noticed that major blood flow is attained for Al_2O_3 compare than Co-Fe_2O_4; whereas major heat is obtained for Co-Fe_2O_4.

The behaviors of blood-$CoFe_2O_4$ and blood-Al_2O_3 on velocity and temperature profiles for various values of particles volume fraction is depicted in Figure4 and Figure5. Here, the values of magnetic/non-magnetic particles volume fraction (φ) used up to 20%. From these figures it is evident that for enlarging values of φ , the blood flow gets weaken and this leads to rise the momentum boundary layer thickness. Major reduction is observed for $CoFe_2O_4$. On the other hand, it is also observed that temperature profile are decreased as the values of φ increased. This is due to the fact that the thermal conductivity of blood which is temperature dependent, as a result when more particles suspension with blood temperature gets slower. However, the major heat of blood is attained for $CoFe_2O_4$.

Figure6 show the influence of mixed convection parameter on velocity profile. Since the ratio of buoyancy to inertial forces known as mixed convection parameter. So it is expected that for larger values of mixed convection parameter, velocity profile is enhanced. Note that, heat is convected from cylindrical surface to the blood flow when the values of mixed convection parameter is greater than zero.

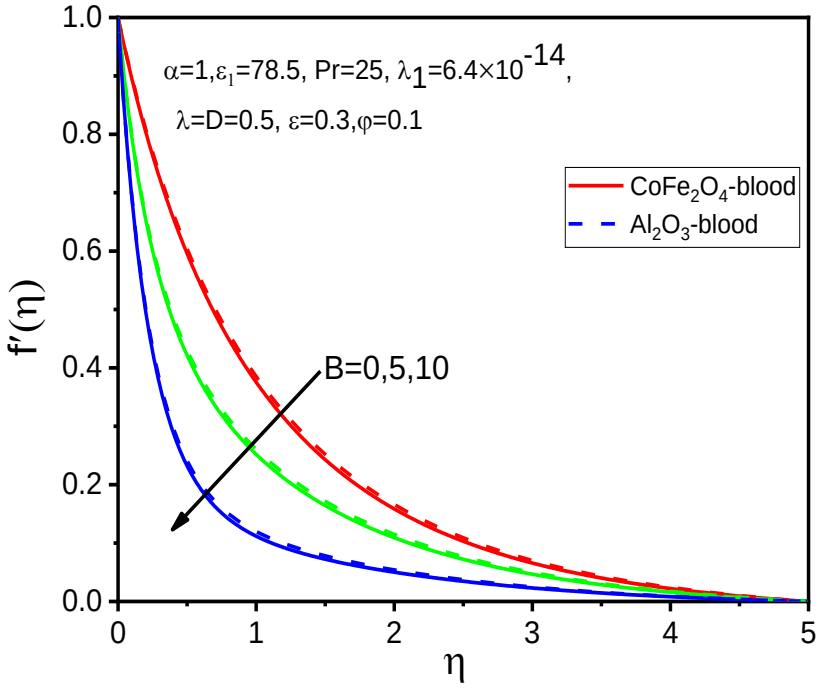


Figure2. Profile of $f'(\eta)$ for various values of B

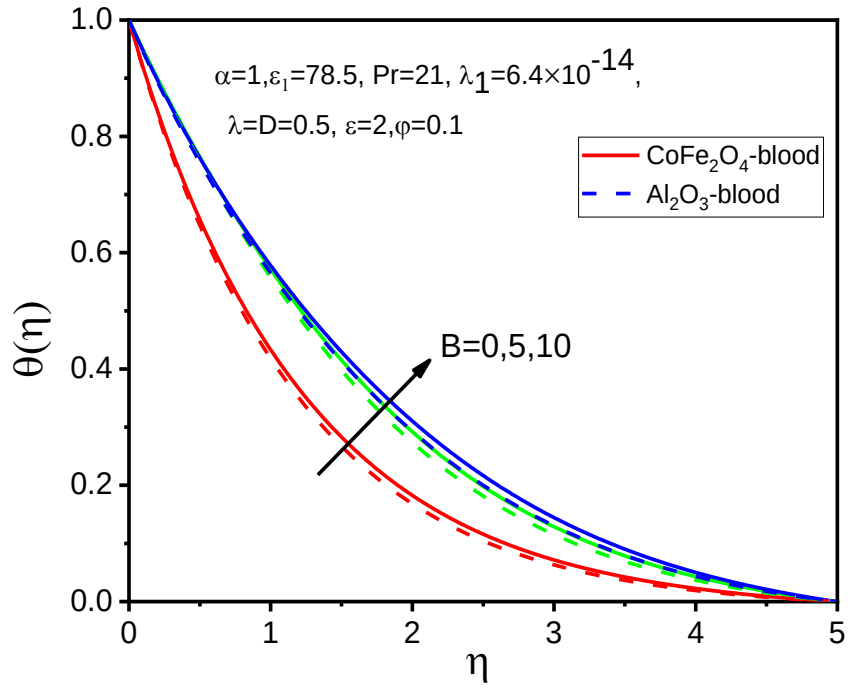


Figure3. Profile of $\theta(\eta)$ for various values of B

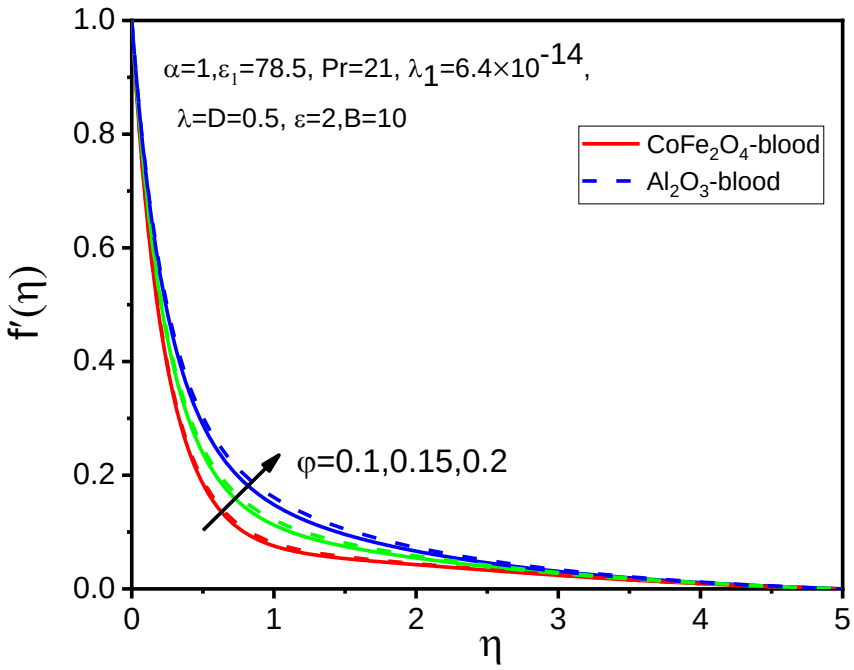


Figure4. Profile of $f'(\eta)$ for various values of φ

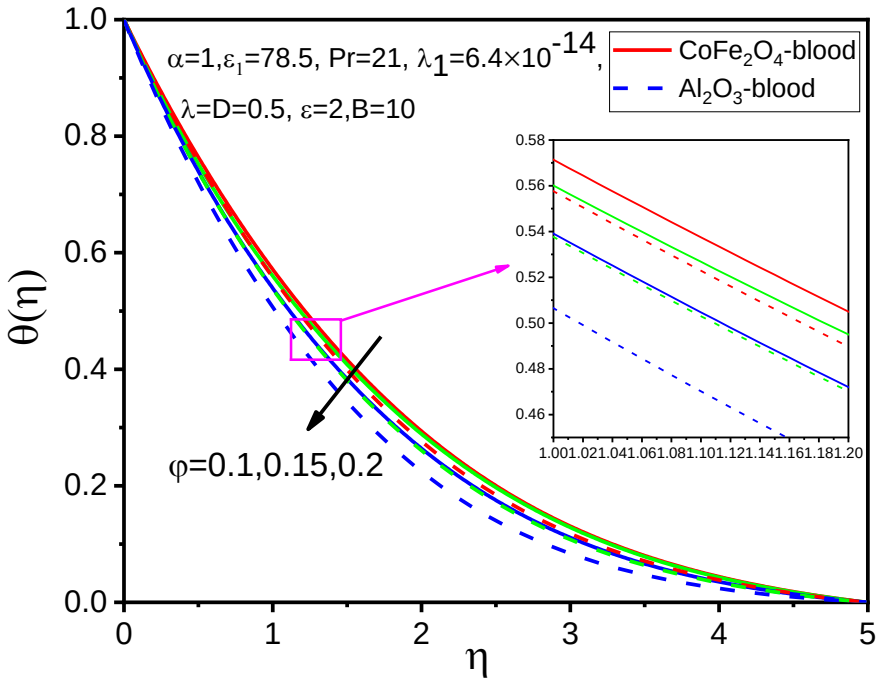


Figure5. Profile of $\theta(\eta)$ for various values of φ

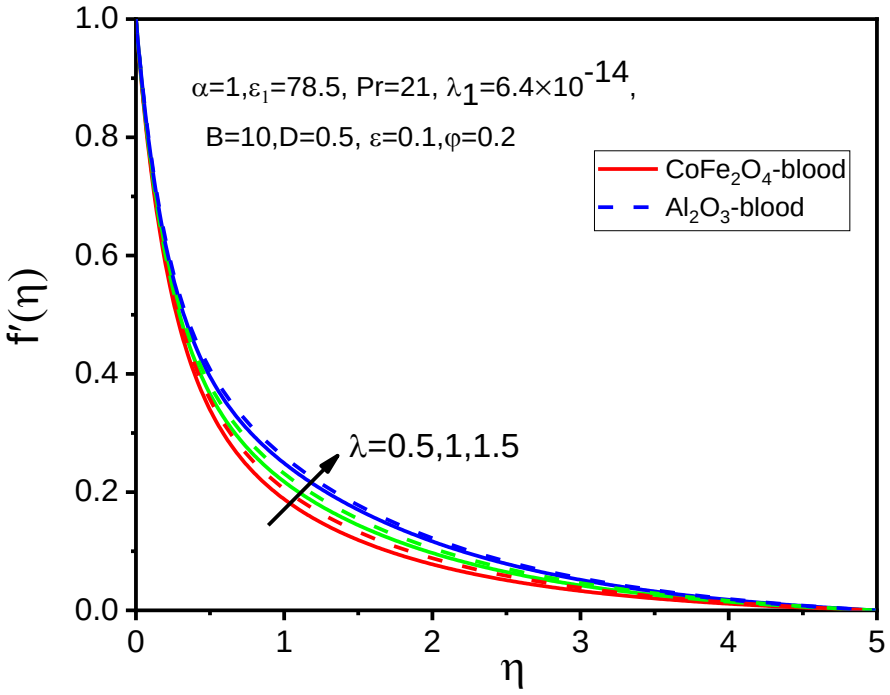


Figure6. Profile of $f'(\eta)$ for various values of λ

Figure7 demonstrate the characteristics of thermal conductivity parameter on the temperature profile for blood-$CoFe_2O_4$ and blood-Al_2O_3. It is evident from this figure that temperature profile enhanced for the larger values of thermal conductivity parameter, while the major heat is attained for $CoFe_2O_4$ magnetic particles compare than Al_2O_3 non-magnetic particles. Since thermal conductivity depends on temperature, as a result when higher thermal property is suspend with electrically no-conducting fluid such as blood, its produce much heat in boundary layer. As a result thickness of the thermal boundary layer also enhanced.

Figure8 to Figure10 show the variations of skin friction coefficient and the rate of heat transfer for blood-$CoFe_2O_4$ and blood-Al_2O_3 for various values of particles volume fraction and ferromagnetic interaction parameter. It is observed that skin friction coefficient increased and rate of heat transfer decreased for increasing values of volume fraction. Where, major increment of $f''(0)$ is found for Al_2O_3 while major increment of $\theta'(0)$ is attained for $CoFe_2O4$. The increment of $f''(0)$ is attained for increasing values of ferromagnetic number.

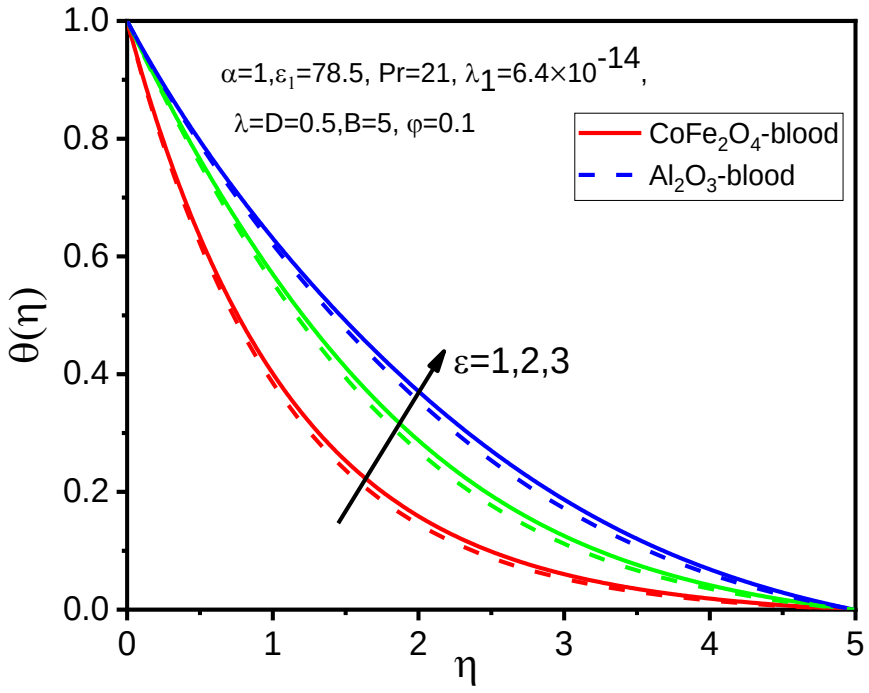


Figure7. Profile of $\theta(\eta)$ for various values of ε

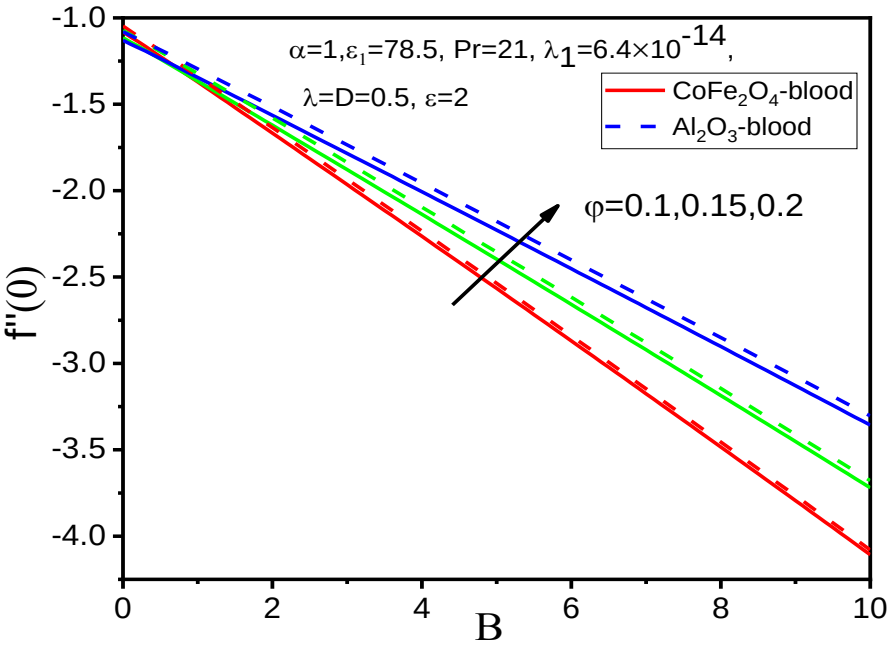


Figure8. Profile of $f''(0)$ for various values of φ with regard to B

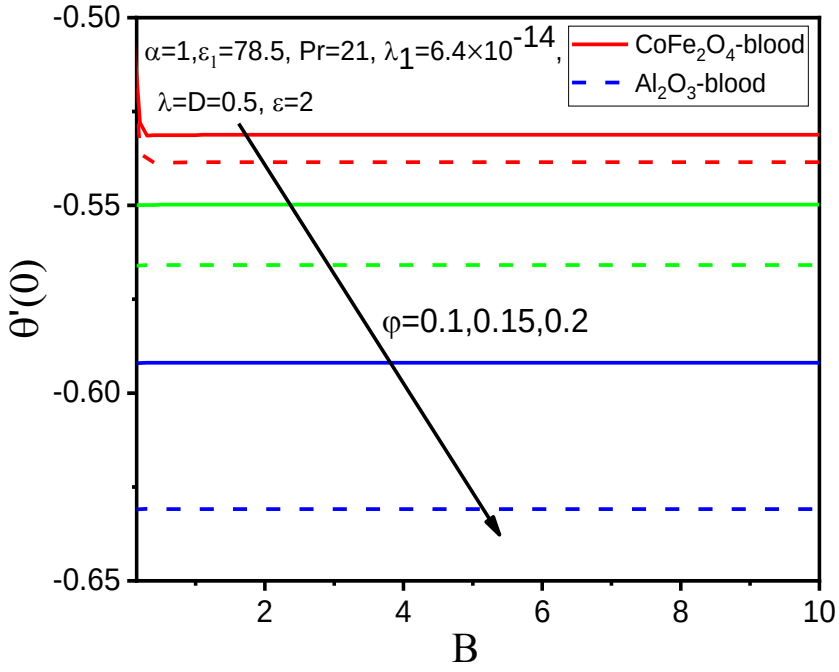


Figure9. Profile of $\theta'(0)$ for various values of φ with regard to B

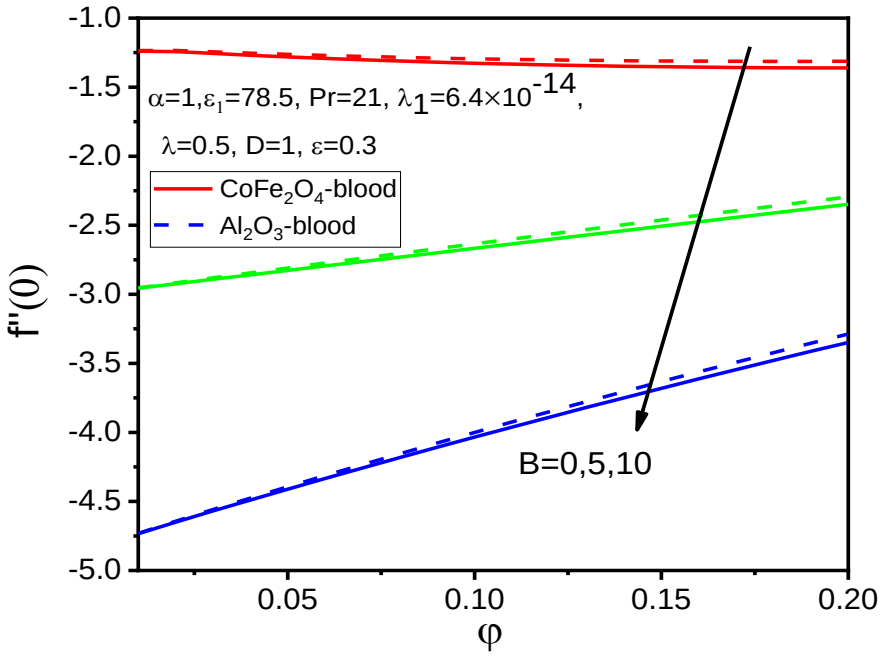


Figure10. Profile of $f''(0)$ for various values of $_B$ with regard to φ

1.8 Conclusions

In this paper, we present a mixed convection boundary layer flow of biomagnetic fluid with magnetic/non-magnetic particles through a stretched cylinder under the influence of ferroHydrodynamics (FHD) principle. Where, blood is considered as base fluid and $CoFe_2O_4$ and Al_2O_3 considered as magnetic and non-magnetic particles, respectively. However, from the present investigations we can draw the following statements:

(1) The blood flow and heat transfer have been significantly influenced when different types particles mixed with blood. The major decrement of blood flow and major enhancement of blood temperature is attained for magnetic particles ($CoFe_2O_4$) than non-magnetic particles (Al_2O_3).
(2) Velocity of blood decreases when ferromagnetic number, particles volume fraction increases; whereas reverse trend is observed for mixed convection parameter.
(3) Temperature of blood enhanced when the values of ferromagnetic number, particles volume fraction and thermal conductivity are increased, respectively.
(4) Skin friction coefficient increases with particles volume fraction but decreased with ferromagnetic number. The major increment on both cases attained for Al_2O_3.
(5) With increasing values of volume fraction, the rate of heat transfer of blood decreased.

1.9 Acknowledgement

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