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Numerical Simulation of Blood Flow Mixed with Magnetic Nanoparticles under the Influence of AC and DC Magnetic Field

Nanoparticles combined with magnetic fields are one of the most important research areas in the field of biomedical engineering. Direct Current (DC) magnetic and Alternative Current (AC) magnetic fields are often used for controlling nanoparticles. It is also used for hyperthermia treatment. The purpose of the current study is to investigate the effect of DC and AC magnetic field on nanoparticles mixed with biofluid (non-Newtonian blood).The coupled nonlinear equations continuity, momentum, concentration and energy are solved with finite volume code. Results show that increase in blood temperature doesn't influence the nanoparticles concentration as well as the velocities and pressure distribution of bloodinside the channel. In addition results show that the DC magnetic field absorbs magnetic nanoparticles and the AC magnetic field induces energy into nanoparticles. Also the eddy current, as the only source of energy in this study, doesn't change the blood flow temperature. Finally it is shown that magnetic nanoparticles mixed with magnetic fields are a good tool for medical applications.

Keywords: magnetic nanoparticle; blood flow; magnetic field; temperature; simulation

1   Introduction

In recent years magnetic nanoparticles (MNPs) are widely used in different scientific field. In magnetic resonance imaging (MRI), MNPs increase the contrast and quality of the images. In addition, magnetic nanoparticles, as separator, can break up some pathogenesis from human body. On the other hand, under DC magnetic field, MNPs can carry and release drug into the target tissue. In this approach not only the dose of drug may be increased but also the side effect on the body may be decreased. Drug delivery with MNPs has created high hopes among researches for cancer treatment [1]. Farokhzad and et.al investigated the effect of nano

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drug on mouse tumor. They showed that animals treated with nano drug survived for 109-day [2]. Li and et.al investigated the effect magnetic field on the Newtonian biofluid mixed with nanoparticles [3].Habibi and et.al numerically studied the concentration of magnetic nanoparticles used in non-Newtonian biofluid under the influence of magnetic field. They showed that the flow and pressure field were changed. Moreover, the optimum diameter of nanoparticle and distance of channel from magnetic field were reported as two important parameter [4]. Habibi and et.al also studied the distribution of nanoparticles in pulsatile blood stream near a magnetic field [5]. They reported that during the systole, magnetic nanoparticles were washed by blood flow. They also showed that blood flow velocity is a very important parameter in nanoparticles absorption.

The magnetic nanoparticles mixed with blood inside the human body under the influence of AC magnetic field may increase the human tissue temperature. Temperature Enhancement is one of the methods used for release of the drug at a targeted location. It is also used for hyperthermia treatment. Rosensweig and et.al developed analytical relationships of power dissipation in magnetic fluid. They reported the effect of frequency and size of nanoparticles on heat absorption [7]. Zhangand et.al investigated the effect of frequency and intensity of magnetic field on heat inducing in nanoparticles [8]. Ivkovand et.al experimentally studied the effect of different magnetic field on a mouse and proposed a proper magnetic intensity [9]. Cervadoro and et.al numerically studied the superparamagnetic iron oxide and human tissue energy absorptions, under the radio frequency magnetic field [10].

To date most researches focused on the nanoparticles in Newtonian fluid under the influence of DC or AC magnetic field. The purpose of the current study is to examine the behavior of magnetic nanoparticles dispersed in a non-Newtonian blood under the influence of a combined DC and AC magnetic field. The DC magnetic field absorbs nanoparticles and the AC magnetic field induces energy into the nanoparticles. In this study the energy equation is solved and effect of temperature on magnetic nanoparticles concentration is considered.

2   Proposed Model

The schematic of the flux density distribution acting on a blood channel is shown in Figure (1). The width (W) and length (L) of the channel are considered to be 0.001 and 0.02m, respectively. The susceptibility of superparamagnetic nanoparticles is lower than ferromagnetic. Therefore, we can ignore the effect of superparamagnetic nano-paricles on external magnetic field [4].
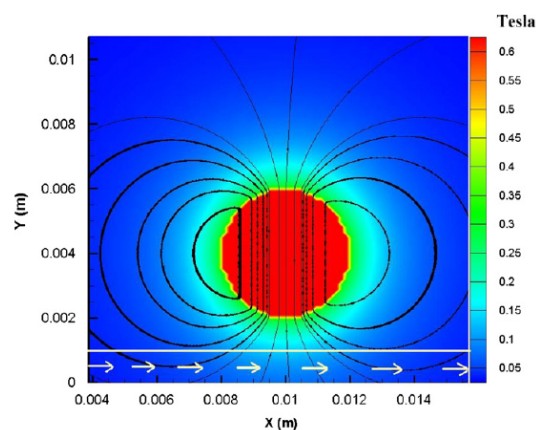

Figure 1 Magnetic flux density

Table 1 The blood and iron oxide nanoparticles properties [5,11]

Property of blood	Unit	Value
Density	kg/m3	1055
m	(N·s)/m2	0.012
n		0.8
Viscosity – Newtonian	(N·s)/m2	0.0032
Thermal conductivity	W/(m·K)	0.52
r_P	m	$0.01*10^{-6}$
Specific heat capacity	J/kg K	4200

The Intensity and frequency of the AC magnetic field is constant and equal to 20 Oe and 5.85 MHz. As known the blood behaves as non-Newtonian fluid in small vessel [3].The relation between the shear stress τ and the shear rate $\dot{\gamma}$ for non-Newtonian fluid is as follows:

$$\tau = \mu\dot{\gamma} \tag{1}$$

Where the shear rate is:

$$\dot{\gamma} = \left[\nabla V + \nabla V^{tr}\right] \tag{2}$$

And the power law model for the viscosity is as [5]:

$$\mu = m\dot{\gamma}^{n-1} \tag{3}$$

Blood and magnetic nanoparticles properties are shown in table1.Also the MNPs electrical conductivity is assumed 0.001 S/m.

3 Governing equation

The governing equations for 2-D blood channel with constant properties are as follow:

Continuity:

$$\frac{\partial \vec{u}}{\partial x} + \frac{\partial \vec{v}}{\partial y} = 0 \tag{4}$$

Momentum equations:

$$\rho(u\frac{\partial \vec{u}}{\partial x} + v\frac{\partial \vec{u}}{\partial y}) = -\frac{\partial p}{\partial x} + \mu(\frac{\partial^2 \vec{u}}{\partial x^2} + \frac{\partial^2 \vec{u}}{\partial y^2}) + \vec{F}_x$$

$$\rho(\vec{u}\frac{\partial \vec{v}}{\partial x} + \vec{v}\frac{\partial \vec{v}}{\partial y}) = -\frac{\partial p}{\partial y} + \mu(\frac{\partial^2 \vec{v}}{\partial x^2} + \frac{\partial^2 \vec{v}}{\partial y^2}) + \vec{F}_y \tag{5}$$

Where F_x and F_y are as follows:

$$\vec{F}_x = n_P \vec{F}_{Mag-x}$$
$$\vec{F}_y = n_P \vec{F}_{Mag-y}$$
(6)

n_p is the number of particles per unit volume and the magnetic force on single particle in x and y directions is given by [3]:

$$\vec{F}_{mag} = \frac{1}{2}(Volume)_p \, \mu_0 \chi \nabla H^2$$
(7)

By substituting Eq. (7) into Eq. (6) F_x and F_y are as follows, respectively:

$$\vec{F}_x = \left[\frac{1}{2} \mu_0 \chi \frac{\partial}{\partial x} \left(\vec{H}\vec{H} \right) \right] C_V$$

$$\vec{F}_y = \left[\frac{1}{2} \mu_0 \chi \frac{\partial}{\partial y} \left(\vec{H}\vec{H} \right) \right] C_V$$
(8)

Volume concentration (C_V) and concentration equation are given by:

$$C_V = C_{V0} C$$
(9)

The initial volume of particles per unit volume $C_{V\,0}$ is equal to 0.03.

$$\vec{\nabla} \cdot (C\vec{v}_p) = \vec{\nabla} \cdot \left(D\vec{\nabla} C \right)$$
(10)

The particle velocity is determined by balancing the hydrodynamic and magnetic forces [4].

Diffusion coefficient (D_B) is obtained from Einstein equation [5]:

$$D_B = \frac{k_B T}{6\pi \mu r_P}$$
(11)

Energy equation:

$$\rho C_B \left(u \frac{\partial T}{\partial x} + v \frac{\partial T}{\partial y} \right) = k \left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} \right) + \dot{q}$$
(12)

Applying alternative magnetic field on the blood vessel for hyperthermia treatment induces energy in magnetic nanoparticles ($\dot{q}$). The source term ($\dot{q}$) in the energy equation is calculated as:

$$\dot{q} = C \left(\dot{q}_{hysteresis} + \dot{q}_{eddy \; current} + \dot{q}_{residual} \right)$$
(13)

Where $\dot{q}_{hysteresis}$ is the hysteresis loss, $\dot{q}_{eddy \; current}$ is the eddy current loss and $\dot{q}_{residual}$ loss is residual loss. For DC magnetic fields (without frequency) the hysteresis, eddy current and residual loss are ignored.

For AC magnetic field the hysteresis loss is ignored for superparamagnetic iron oxide nanoparticles [10].

The residual loss is due to different relaxation effect of magnetization in AC field. Neel and Brownian relaxation are two parts of residual loss [8]. Neel relaxation τ_N is due to domain rotation in nanoparticles under AC magnetic field. It is defined by [8]:

$$\tau_N = \tau_0 \exp\left(\frac{KV}{kT}\right) \tag{14}$$

Friction between particles and fluid causes energy loss (τ_B). This parameter is given by [8]:

$$\tau_B = \frac{3\eta V_H}{k_B T} \tag{15}$$

The hydrodynamic volume V_H is related to magnetic field characteristic [7].

The effective relaxation time τ_{eff} and total relaxation loss (P) are defined as follows, respectively [9]:

$$\tau_{eff} = \frac{\tau_B \tau_N}{\tau_B + \tau_N} \tag{16}$$

$$P = \frac{\left(mH\,\omega\tau_{eff}\right)^2}{\left[2\tau_{eff}\,kTV\,\left(1+\omega^2\tau_{eff}{}^2\right)\right]} \tag{17}$$

The DC magnetic field flux density is higher than the AC magnetic field intensity. Thus, the DC magnetic field is dominated, and magnetic nanoparticles are fixed in a one direction. In this condition, they don't rotate under AC magnetic field. So the relaxation loss due to AC magnetic field is enough small to be ignored.

The eddy current as the only energy source in this study is calculated by [12]:

$$\dot{q} = \frac{\pi}{20}B_m{}^2 d^2 \sigma f^2 \times 10^{-16} \tag{18}$$

4   Numerical Scheme

A finite volume base code is developed and utilized. The code is based on the SIMPLE algorithm. The governing nonlinear mass, momentum and concentration equation which coupled with energy equation are utilized. The flowchart of solution algorithm is given in Figure (2).

4.1 Code Verification

In order to verify the results, the Nusselt number for blood flow inside a channel is obtained, and it is compared with that of Shah and London [13].
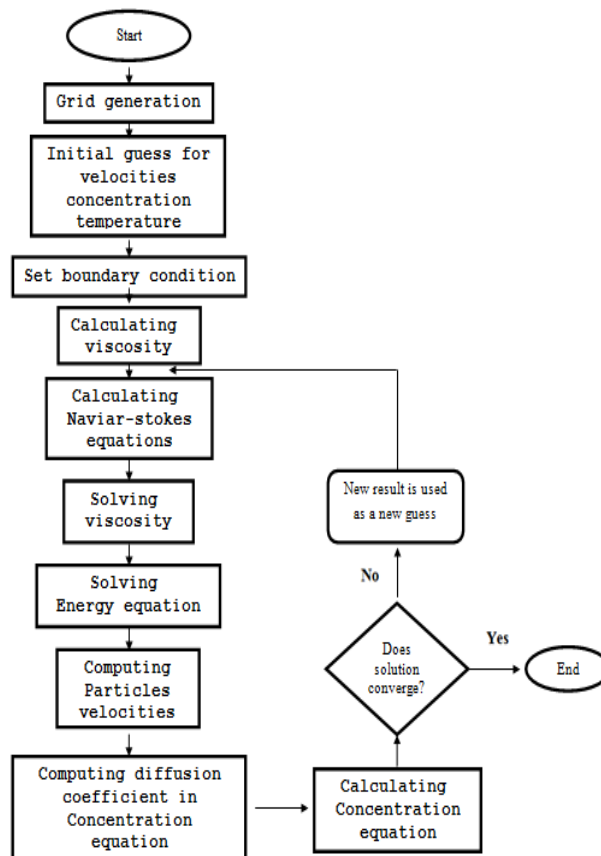
$$Nu_x = \frac{hD}{k} \tag{19}$$

Figure 2 Flowchart for the numerical simulation

$$h_x = \frac{-k \left.\dfrac{\partial T}{\partial y}\right|_{wall}}{T_{wall} - T_b} \tag{20}$$

$$T_b = \frac{1}{U_{mean} A_c} \int_{A_c} uT dA_c \tag{21}$$

Analytical value of the Nusselt number is calculated by Shah and London for constant wall temperature as follow [13]:

$$\begin{aligned} Nu_x &= 1.077 x_*^{-1/3} - 0.7 & x_* \leq 0.01 \\ Nu_x &= 3.657 + 6.874\left(10^3 x_*\right)^{-0.488} e^{-57.2} & x_* \succ 0.01 \end{aligned} \tag{22}$$

Figure (2) depicts the comparison between the numerical result with the Shah and London model.
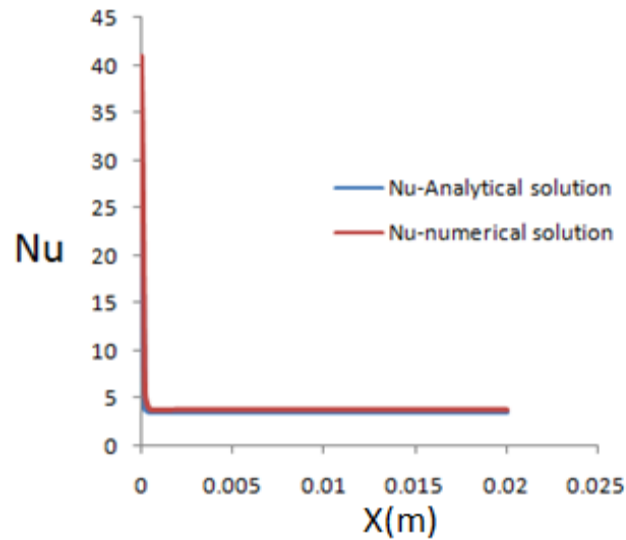
Figure 3 Numerical and analytical Nusselt numbers

4. 2 Grid Independency

Figure (3) depict the grid independency of the results for constant temperature boundary condition. As shown by the Figure (4), increasing the number of grid from 200*40 to 200*60 has no effect on the result. Therefore 200*40 grid is used.

4. 3 Boundary Condition

$U_{upper\ wall} = 0$

$U_{lower\ wall} = 0$

$C_{inlet} = 1$

$T_{walls} = 315.14K$

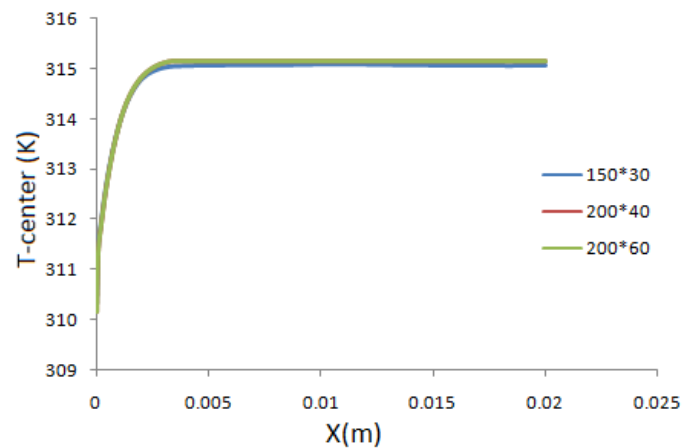$T_{blood\ inlet} = 310.15K$

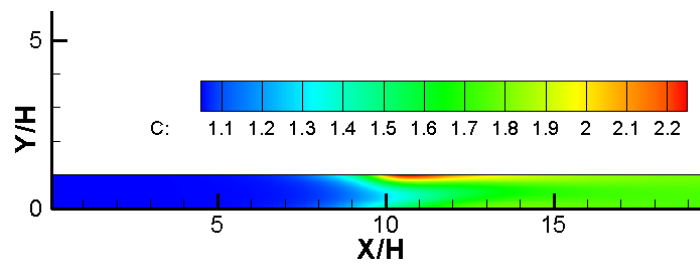**Figure 4** Grid study for temperature at center line of vessel

Figure 5 Concentration distribution of nanoparticles inside the channel under the influence of magnetic field

For the temperature, velocity and concentration the Neumann boundary condition is applied at exit $\left(\partial/\partial x = 0 \text{ x=L,y}\right)$. Moreover, the concentration of the upper and lower walls is considered isolated.

5   Results and Discussion

The effect of magnetic field on flow and temperature field is investigated and results are discussed in the following sections.

5. 1 Flow field results

Figure (5) depicts the distribution of magnetic nanoparticles under the influence of the magnetic field when the blood inlet velocity is assumed to be 1 mm/s.

As shown the nanoparticles are absorbed with DC magnetic field near the upper wall. Velocity contour of the blood flow inside the channel under the influence magnetic field is shown in Figure (6). As shown in the Figure (6) the magnetic nanoparticles shift toward the magnetic field. It causes the channel diameter to decrease. So the blood velocity is increased underneath the particles concentration.

Figure (7) depicts Pressure distribution of blood inside the channel under the influence of magnetic field. As shown, near the magnetic source the pressure increases due to the restriction that particles create in front of the blood flow.
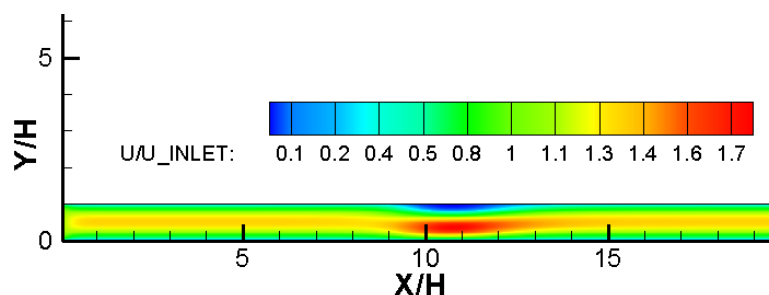

Figure 6 Velocity contour of the blood flow inside the channel under the influence of magnetic field
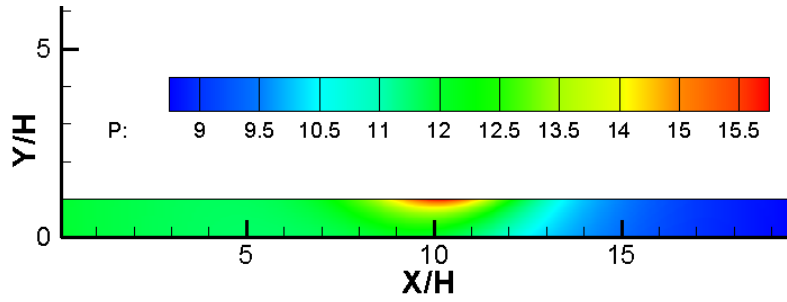
Figure 7 Pressure distribution of blood inside the channel under the influence of magnetic field

Figure (8) shows the blood velocity in the center line of channel for constant and variable temperature distribution.
Results show that changing temperature does not change the blood velocity and blood has a same behavior in these two case studies.($T_{constant}$ means $T_{i,j}= 300K$ and $T_{variable}$ means $T_{walls} = 315.14K$ and $T_{blood\ inlet} = 310.15K$)

5. 2 Temperature field results

Figure (9) shows the blood temperature distribution in channel without magnetic field.
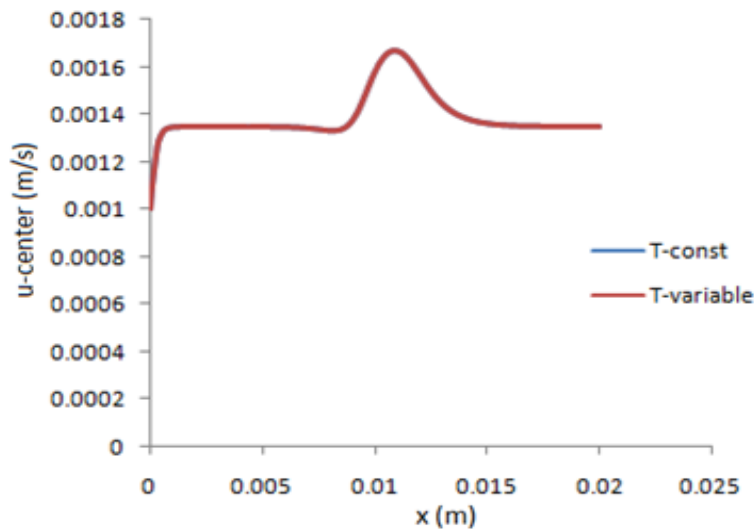

Figure 8 Blood velocity in the central line of channel for constant and variable temperature distribution
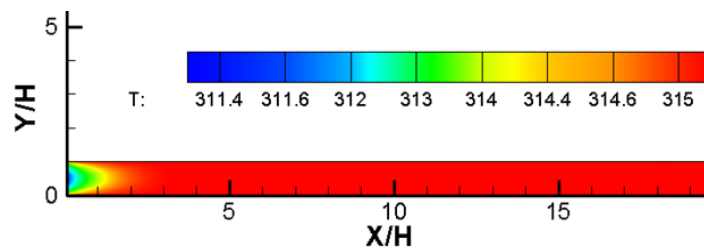

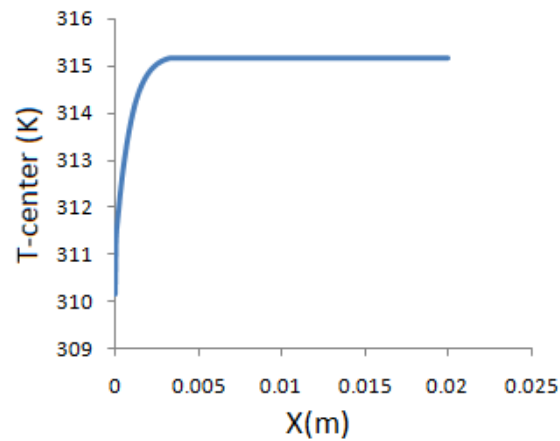**Figure 9** Temperature contour without magnetic field

Figure 10 Temperature of blood at center line of channel

The blood temperature in center of channel without magnetic field is shown in Figure (10).

Figure (11) depicts the blood temperature contour in channel under the influence of magnetic field. The induced energy with magnetic field is depended on magnetic nanoparticle concentration.

Also Figure (12) depicts the blood temperature in center line of channel under the influence of magnetic field.
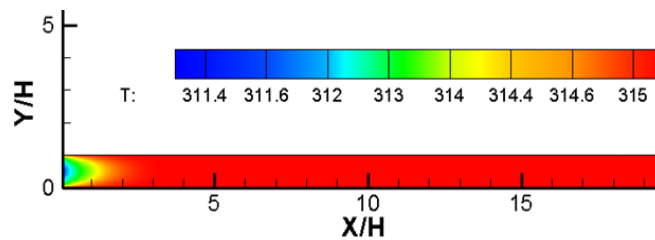

Figure 11 Blood temperature contour under influence of magnetic field
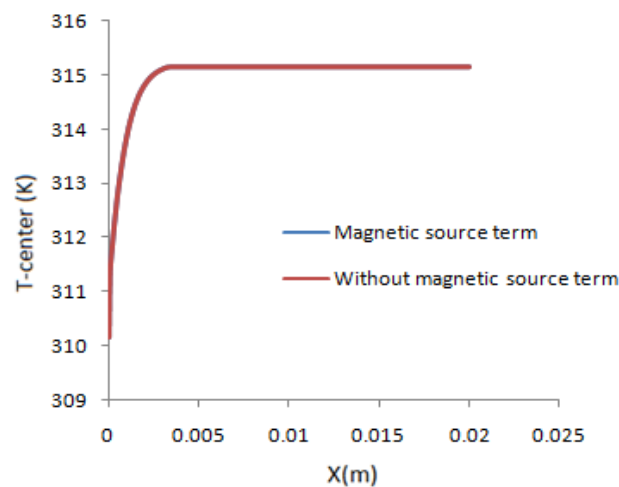

Figure 12 Comparison the blood temperature in central line of channel with magnetic field and without magnetic field

According to Figure (12) magnetic field has no effect on blood temperature.

The electrical conductivity of nanoparticle superparamagnetic iron oxide is very smaller than the bulk iron oxide. Moreover size of superparamagnetic iron oxide is so small. According to these reasons eddy current cannot change the blood temperature in channel under influence of magnetic field.

6 Conclusion

A finite volume code is developed and utilized. The nonlinear and coupled continuity, momentum, concentration and energy equations are utilized and solved for blood inside the channel. Results show that increase in blood temperature doesn't influence the nanoparticles concentration as well as the velocities and pressure distribution of blood inside the channel. Because of type of nanoparticles and using DC and AC magnetic fields simultaneously, the AC magnetic field do not effect on temperature distribution. The residual loss is neutralized by DC magnetic field on the other hand super paramagnetic iron oxide has single domain, thus hysteresis loss is ignored. Eddy current is only source term that can induce energy in magnetic nanoparticles. Also after solving energy equation with eddy current source, the temperature distribution changing isn't seen. So the magnetic nanoparticles mixed with magnetic fields are a good tool for medical applications.

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Nomenclature

Re	Reynolds number
K_B	Boltzmann constant
T	absolute temperature
V_H	hydrodynamic volume of particle
k	anisotropy constant of magnetic nanoparticles
u	velocity in x direction
v	velocity in y direction
$\dot{q}$	energy source
r_p	particle radius
P	pressure
D	diffusion coefficient
H	magnetic field
C_v	volume concentration
C_{v_0}	Initial volume concentration per unit volume
v_P	particle velocity
C_P	specific heat
k	thermal conductivity
P	residual loss
T_{wall}	wall temperature
U_{mean}	mean velocity
h_x	local convection coefficient
F_x	magnetic force in x direction
F_y	magnetic force in y direction
Pr	Prantle
Nu	nusselt number

B_m amplitude of magnetic induction

n_P number of particles per unit volume

T_b bulk temperature

Greek Symbols

χ magnetic susceptibility

μ_0 magnetic permeability of vacuum

τ stress

μ viscosity

ρ density

σ electrical conductivity

f frequency

$\dot{\gamma}$ share rate

τ_N neel relaxation

τ_B brownian relaxation

τ_{eff} effective relaxation

چکیده

یکی از زمینه های جدید تحقیقات بکارگیری نانوذرات در میدان های مغناطیسی جهت کاربردهای مهندسی پزشکی می‌باشد. اغلب از میدانهای جریان مستقیم یا جریان متناوب برای کنترل نانوذرات استفاده می‌شود.

هدف از این مطالعه، بررسی اثر میدان‌های جریان مستقیم و متناوب بر نانو ذرات مخلوط در سیال زیستی (خون) است. معادلات غیر خطی پیوستگی، مومنتوم، غلظت و انرژی به روش حجم محدود حل شده‌اند. نتایج نشان می‌دهند که افزایش دمای خون تاثیری بر غلظت، سرعت و همچنین توزیع فشار خون ندارد. همچنین نتایج نشان می‌دهند که میدان‌های جریان مستقیم نانوذرات مغناطیسی را جذب و میدان‌های جریان متناوب در داخل نانوذرات ایجاد انرژی می‌کنند. ضمنا تنها منبع انرژی یعنی جریان های گردابی، دمای جریان خون را تغییر نمی‌دهند. در انتها نشان داده شده است که استفاده از نانوذرات مغناطیسی در حضور میدان‌های الکترومغناطیس می‌تواند یکی از ابزارهای خوب در پزشکی باشد.