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Effect of non-uniform magnetic field on biomagnetic fluid flow in a 3D channel

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ABSTRACT

In this study, the influence of the magnetic field due to a wire carrying electric current on the biomagnetic fluid flow in a three dimensional channel was simulated numerically. A new method for finding appropriate computational grid to achieve grid independency has been introduced. Appropriate computational grid is a grid that almost covers the magnetic force accurately. Individual effect of the Lorentz force and the magnetic force arising from the magnetization of the magnetic field on the fluid flow has been investigated. Study carried out for the range of magnetic number (Mn) and Stuart number (N) that are consistent with the biomagnetic fluid properties. Results indicate that the Lorentz force does not have a significant effect on the fluid flow, and the fluid flow is affected by the magnetic force arising from the magnetization. This magnetic field causes a secondary flow creation which is considerable in the velocity profile. Also results show that existence of the secondary flow increases non-axial shear stress on the channel walls.

1. Introduction

Biomagnetic fluids are biological fluids that are affected in the presence of the magnetic field. Recognition of biomagnetic fluids behavior in the presence of magnetic fields has much attention by researchers. Many applications in the medical and biomedical engineering, such as cell separation, targeted drug delivery, wound healing due to the effects of magnetic fields and cancer treatment with magnetic hyperthermia have been presented in this field [1–10]. The most characteristic biomagnetic fluid is blood. Hemoglobin is a protein-based component of red blood cells which is primarily responsible for transportation of oxygen within the human body. Oxygen binds to iron atoms existing in the hemoglobin structure. Investigations [11–15] showed red blood cells orient under influence of the magnetic field. Binding oxygen to hemoglobin causes change in the magnetic susceptibility of hemoglobin, so that oxyhemoglobin behaves as a diamagnetic material and deoxyhemoglobin behaves as a paramagnetic material [16,17]. In general, biological elements have weak magnetic susceptibility in the order of 10^{-6} [18]. In order to do some mechanical work on the biological fluids, the magnetic susceptibility of the fluid should be increased at first. For example, in the separation of cellular components, by labeling the biological cells with magnetic materials, the magnetic susceptibility of the biological cells can be increased [1,2].

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Nomenclature

Symbols

x	axis in Cartesian coordinates
y	axis in Cartesian coordinates
z	axis in Cartesian coordinates
h	side of channel x-y cross section (m)
L	channel length (m)
(a, b)	place of the wire in x-y plan (a = 0.5 h and b = −0.2 h) (m)
$\mathbf{V} = (u, v, w)$	velocity field (m/s)
$\overline{W}_0$	average inlet velocity (m/s)
p	pressure (Pa)
$\mathbf{J}$	electric current density (A/m^2)
I	electric current intensity (A)
$\mathbf{M}$	magnetization (A/m)
$\mathbf{H}$	magnetic field intensity (A/m)
H_x	magnetic field intensity component in x direction (A/m)
H_y	magnetic field intensity component in y direction (A/m)
H_0	magnetic field intensity at the point $(a, 0)$ (A/m)
$\mathbf{B}$	magnetic field induction (T)
B_x	magnetic field induction component in x direction (T)
B_y	magnetic field induction component in y direction (T)
B_0	magnetic field induction at the point $(a, 0)$ (T)
Re	Reynolds number $(\rho \overline{W}_0 h/\mu)$
Mn	Magnetic number $(\chi {B_0}^2/\mu_0 \rho {\overline{W}_0}^2)$
Ha	Hartmann number $(B_0 h\sqrt{\sigma/\mu})$
N	Stuart number $({B_0}^2 h\sigma/\rho\overline{W}_0 = Ha^2/\mathrm{Re})$

Greek Letters

ρ	density (kg/m^3)
μ	dynamic viscosity (kg/m s)
μ_0	magnetic permeability of vacuum ($=4\pi \times 10^{-7}$Tm/A)
σ	electrical conductivity (s/m)
χ	magnetic susceptibility
τ	shear stress (N/m^2)

Superscripts

$*$	dimensionless symbol

Biomagnetic fluid dynamics (BFD) is biological fluid dynamics in the presence of magnetic field. Haik et al. [19] presented a mathematical model of the BFD. The BFD model is based on ferrohydrodynamics (FHD) [20]. In the model proposed by Haik et al. [19] the magnetic force due to magnetization that depends on the gradient of the magnetic field is only considered. Tzirtzilakis [21] developed the BFD model. In his study, the Lorentz force was considered based on the principles of Magnetohydrodynamics (MHD) [22] as the magnetic force due to magnetization was.

In order to investigate the biomagnetic behavior subject to magnetic field, numerous numerical simulations have been performed. In these investigations the fluid flow is under influence of uniform and non-uniform magnetic fields [21,23–34]. One of the non-uniform magnetic fields is the magnetic field created by the wire carrying electric current. So far some efforts to investigate the effect of this magnetic field on the magnetic fluid have been done [21,26–31]. To investigate the effect of the magnetic field on the fluid flow, this is very important that the results be independent of computational grid. Tzirtzilakis et al. [27] studied the blood flow in a three-dimensional channel under the influence of the magnetic field. They have expressed that the results in different grids show oscillatory behavior. Some other investigations were carried out for mention magnetic field but none of them considered the grid independency in the presence of the magnetic field [28,31]. In the previous studies solution was carried out in a particular grid. Authors believe that changing of the density or type of grid has a sensible effect on results. Tzirtzilakis [21] investigated biomagnetic fluid flow (blood) in a channel under the influence of this magnetic field. In his study the grid 75×75 in perpendicular cross section to the wire has been chosen, which by increasing the grid points the results change.

Therefore, this study is tried to describe an achievement of appropriate computational grid to simulate biomagnetic fluid flow under influence of magnetic field due to wire carrying electric current. Furthermore, after achieving an appropriate grid for predicting the behavior of biomagnetic fluid flow in the presence of the magnetic field, the effect of magnetic field on the fluid flow in a three-dimensional channel is investigated.