Journal of Magnetism and Magnetic Materials 380 (2015) 54–60

Contents lists available at ScienceDirect

Journal of Magnetism and Magnetic Materials

journal homepage: www.elsevier.com/locate/jmmm

Numerical analysis of the effects of a high gradient magnetic field on flowing erythrocytes in a membrane oxygenator

Yoshinori Mitamura*, Eiji Okamoto

Department of Human Science and Informatics, School of Biological Science and Engineering, Tokai University, Sapporo 005-0825, Japan

ARTICLE INFO

Article history:
Received 19 June 2014
Received in revised form 13 October 2014
Accepted 18 October 2014
Available online 22 October 2014

Keywords:
Biomagnetics
Blood
High gradient magnetic field
Magnetic properties

ABSTRACT

This study was carried out to clarify the effect of a high gradient magnetic field on pressure characteristics of blood in a hollow fiber membrane oxygenator in a solenoid coil by means of numerical analysis. Deoxygenated erythrocytes are paramagnetic, and oxygenated erythrocytes are diamagnetic. Blood changes its magnetic susceptibility depending on whether it is carrying oxygen or not. Motion of blood was analyzed by solving the continuous equation and the Navier–Stokes equation. It was confirmed that oxygenation of deoxygenated blood in the downstream side of the applied magnetic field was effective for pressure rise in a non-uniform magnetic field. The pressure rise was enhanced greatly by an increase in magnetic field intensity. The results suggest that a membrane oxygenator works as an actuator and there is a possibility of self-circulation of blood through an oxygenator in a non-uniform magnetic field.

1. Introduction

Extracorporeal circulation and artificial hearts are routinely used in medical treatments. In open heart surgery, extracorporeal circulation is used to maintain the blood circulation of a patient instead of his/her heart and lung. During blood dialysis, extracorporeal circulation is also used to circulate blood through a dialyzer. A roller or a centrifugal pump is used for extracorporeal circulation. In patients with severe heart diseases, an artificial heart is used to assist or to replace the damaged heart. An implantable centrifugal or axial pump is used as an artificial heart. Centrifugal and axial blood pumps, however, have several problems. The most important problem is blood compatibility. The pumps are made of foreign materials such metals, ceramics and polymers. Contact of blood with foreign materials increases the risk of thrombus formation or hemolysis. Therefore, blood circulation without using a mechanical pump is ideal.

1.1. Self-circulation of magnetic fluid

Direct drive of a magnetic fluid utilizing its magnetic properties has been reported [1–6]. A magnetic fluid in a pipe is exposed to an axially non-uniform magnetic field induced by a solenoid coil (Fig. 1). The magnetic field is symmetrical with respect to the center of the coil. Magnetic force (F) applied to the magnetic fluid is given by

$$F = \mu_0 M(MF) \nabla H \tag{1}$$

where F is force/volume (N/m^3) and $M(MF)$ is magnetization of a magnetic fluid.

Since the magnetic force applied to a magnetic fluid is proportional to the magnetic field gradient, outlet-ward force is applied to the magnetic fluid in the inlet region ($z<0$). On the other hand, inlet-ward force is applied to the magnetic fluid in the outlet region ($z>0$). Since magnetic susceptibility of the magnetic fluid in the inlet region χ_L is generally equal to that of the magnetic fluid in the outlet region χ_R, the inlet-ward force and the outlet-ward force are in equilibrium and the magnetic fluid does not move in either direction.

However, if a low boiling point magnetic fluid is heated and boiled in the downstream side of the magnetic field, a gas–liquid two-phase flow is induced and χ_R becomes smaller than χ_L (Fig. 2). The outlet-ward force exceeds the inlet-ward force and the driving force is enhanced, and then the magnetic fluid moves outlet-ward [1–3]. Temperature-sensitive magnetic fluid (TSMF) is also used [4–6]. TSMF has a temperature-dependent magnetization. When TSMF is heated in the outlet region, χ_R becomes smaller than χ_L and the magnetic fluid moves outlet-ward. Self-circulation of a magnetic fluid is possible without using a mechanical pump.

* Corresponding author. Present address: Hokkaido University, 5-5-1-2 Sumikawa, Minami-ku, Sapporo 005-0005, Japan.
E-mail addresses: ymitamura@par.odn.ne.jp (Y. Mitamura), okamoto@tspirit.tokai-u.jp (E. Okamoto).

http://dx.doi.org/10.1016/j.jmmm.2014.10.081
0304-8853/

Nomenclature

B: flux density (T).
D_s: inner diameter of a solenoid coil (m).
D_F: inner diameter of a hollow fiber (m).
g: gravitational acceleration (m/s^2).
H: intensity of magnetic field (A/m).
H^*: dimensionless magnetic field ($=H/nI$).
I: current to a coil (A).
L: length of a solenoid coil (m).
$M(MF)$: magnetization of a magnetic fluid (A/m).
$M(B)$: magnetization of blood (A/m).
n: number of turns of a coil per unit length (turns/m).
p: pressure (Pa).
R: radius of a hollow fiber (m).
T: temperature (K).
u: velocity of blood (m/s).
u_0: velocity of blood at the center of a hollow fiber (m/s).
z: longitudinal axis (m).
z^*: dimensionless length ($=z/L$).

Greek symbols

α: aspect ratio of a coil ($=D_S/L$).
χ_B: magnetic susceptibility of blood.
χ_{MF}: magnetic susceptibility of a magnetic fluid.
η: viscosity of blood (Pa s).
μ_0: magnetic permeability of a free space (H/m).
ρ: density of blood (kg/m^3).

Suffix

r: polar axis.
z: longitudinal axis.
φ: angular coordinate.

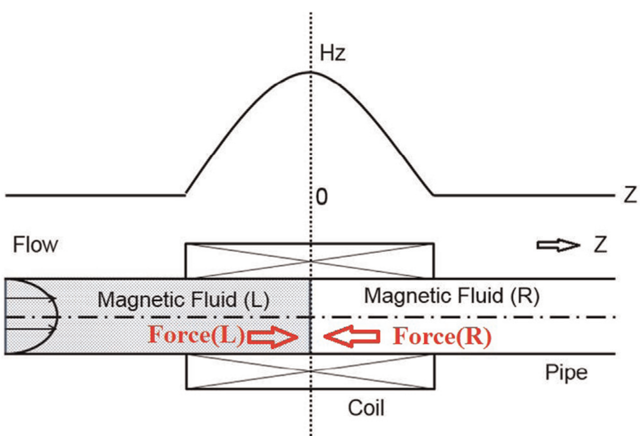

Fig. 1. Force applied to the magnetic fluid in a non-uniform magnetic field.

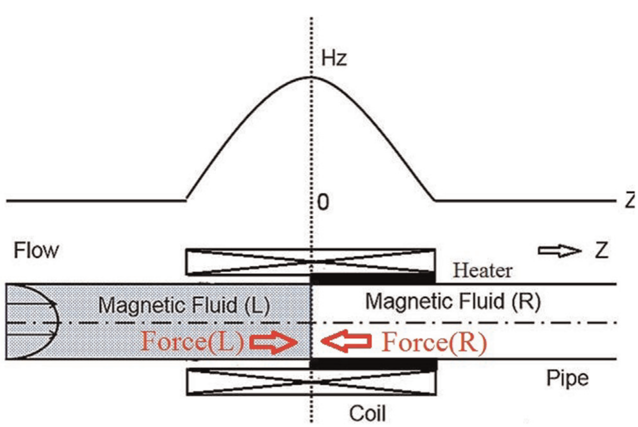

Fig. 2. Working principle of the self-circulate device.

1.2. Magnetic characteristics of blood

Blood is composed of blood cells suspended in blood plasma. By volume, red blood cells constitute about 43% of whole blood and plasma constitutes about 57%. A red blood cell contains hemoglobin. Hemoglobin is an iron-containing protein that transports oxygen around the body. The structure of the hemoglobin molecule changes slightly depending on whether it is carrying oxygen or not. Hemoglobin has magnetic properties that are different depending on whether it is carrying oxygen or not. Deoxygenated erythrocytes are paramagnetic, and oxygenated erythrocytes are diamagnetic.

In this study, a red blood cell was considered as a magnetic particle and blood was considered a magnetic fluid. Therefore, blood changes its magnetic susceptibility depending on whether it is carrying oxygen or not.

1.3. Hollow fiber membrane oxygenator

A hollow fiber membrane oxygenator is used as a lung machine. Deoxygenated blood circulates through the hollow fibers with oxygen gas outside. Deoxygenated blood enters the membrane lung, receives oxygen through the membrane, and is oxygenated in the membrane lung. The oxygenated blood exits the membrane lung. Therefore, outlet blood from a membrane oxygenator is more diamagnetic than is inlet blood to the oxygenator.

1.4. Objective

Self-circulation of magnetic fluids (low boiling point magnetic fluid and temperature-sensitive magnetic fluid) and change in the magnetic susceptibility of blood in a membrane lung have led us to study the effect of a high gradient magnetic field on flowing erythrocytes in a membrane oxygenator. Magnetic force applied to the inlet blood in the oxygenator is in an inlet direction and that of the outlet blood is in outlet direction. The magnitude of the outletward force is greater than that of the inlet-ward force. Therefore, there is a possibility of self-circulation of blood through a membrane oxygenator in a non-uniform magnetic field. The objective of this study was to clarify the effect of a high gradient magnetic field on pressure characteristics of blood in the hollow fiber membrane oxygenator by means of numerical analysis.

2. Methods

The model used for analysis is shown in Fig. 3. An endocapillary blood flow oxygenator is placed inside a superconductive solenoid coil (D_S: 0.0165 m and L: 0.1 m). Electric current to the coil is I (A) and the number of turns of the coil per unit length is n (turns/m). Blood in the membrane oxygenator is exposed to an axially non-uniform magnetic field. Deoxygenated blood circulates through the hollow

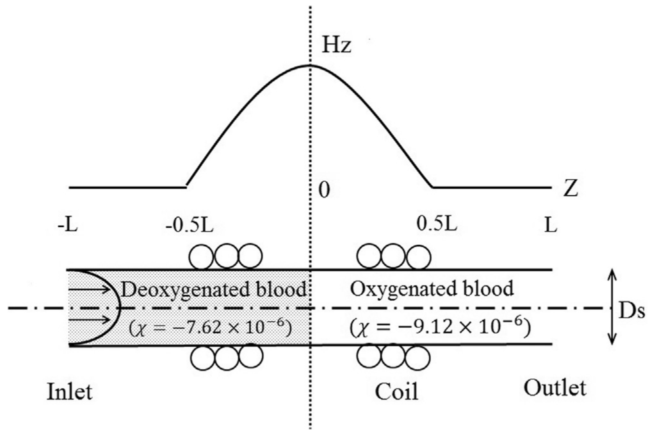

Fig. 3. Proposed model for analysis.

fibers (number: 2269, outer diameter: 300 μm, D_F: 200 μm, length: 0.2 m) with oxygen gas outside and is oxygenated at the center of the coil. A cross section of the membrane oxygenator is shown in Fig. 4. Each hollow fiber is surrounded by six fibers. In this structure, 2269 hollow fibers are packed in a pipe of 0.0165 m in inner diameter. The total cross-sectional area of the 2269 hollow fibers is 7.12×10^{-5} m^2.

Motion of the blood through a hollow fiber is governed by the continuous equation and the Navier–Stokes equation [7].

Continuous equation

$$\nabla \cdot u = 0. \tag{2}$$

Navier–Stokes equation

$$\rho(\partial u/\partial t + (u \cdot \nabla)u) = -\nabla p + \eta \nabla^2 u + \mu_0 (M(B) \cdot \nabla)H + \rho g. \tag{3}$$

The equations were solved on the basis of the following assumptions:

a. Steady-state conditions were assumed.
b. Blood flow in the hollow fibers is axially symmetric, $\partial u/\partial \varphi = 0$.
c. Blood flow is laminar and is a Poiseuille flow, $u_r = u_\varphi = 0$.
d. The magnetic field inside the coil is axially symmetric and radially uniform, $\partial H/\partial \varphi = \partial H/\partial r = 0$.
e. Only the axial component of the magnetic field (Hz) is considered.

$$Hr = H\varphi = 0, \quad M(B)r = M(B)\varphi = 0.$$

In a cylindrical coordinate system, Eq. (2) is expressed by

$$\nabla \cdot u = 1/r \cdot 1/\partial r \cdot (r \cdot u_r) + 1/r \cdot (\partial u_\varphi/\partial \varphi) + \partial u_z/\partial z = 0. \tag{4}$$

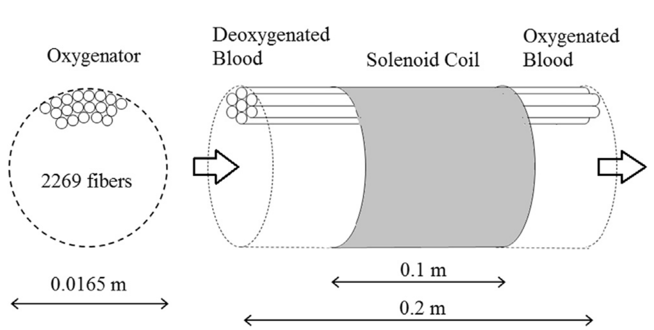

Fig. 4. Hollow fiber membrane oxygenator model.

Due to the assumptions (a) and (b), Eq. (4) becomes

$$\nabla \cdot u = \partial u_z/\partial z = 0. \tag{5}$$

Assuming that gravitational force is ignored, an axial component of the Navier–Stokes equation in a steady state is given by

$$\rho(u_r \cdot (\partial u_z/\partial r) + u_z \cdot (\partial u_z/\partial z)) = -\partial p/\partial z + \eta(1/r \cdot \partial/\partial r \cdot (r \cdot (\partial u_z/\partial r)) + \partial^2 u_z/\partial z^2) + \mu_0 (M(B) r (\partial Hz/\partial r) + M(B) z \cdot (\partial Hz/\partial z)). \tag{6}$$

Due to the assumptions (b) and (c) and Eq. (5), Eq. (6) becomes

$$0 = -\partial p/\partial z + \eta \cdot 1/r \cdot 1/\partial r \cdot (r \cdot \partial u_z/\partial r) + \mu_0 M(Bz \cdot (\partial Hz/\partial z). \tag{7}$$

We assume that the Poiseuille flow is expressed by

$$u_z(r) = u_0(1 - r^2/R^2). \tag{8}$$

Therefore

$$\partial/\partial r \cdot (r \cdot (\partial u_z/\partial r)) = -(4u_0 r)/R^2$$
$$1/r \cdot \partial/\partial r \cdot (r(\partial u_z/\partial r)) = -(4u_0)/R^2 = -16u_0/D_F^2 \tag{9}$$

Substituting Eq. (9) into Eq. (7), we obtain

$$\partial p/\partial z = \mu_0 M(B) z (\partial Hz/\partial z) - 16\eta u_0/D_F^2. \tag{10}$$

Let χ_B be the magnetic susceptibility of blood, then

$$M(B)z = \chi_B Hz. \tag{11}$$

Substituting Eq. (11) into Eq. (10), we obtain

$$\partial p/\partial z = \mu_0 \chi_B Hz \cdot (\partial Hz/\partial z) - 16\eta u_0/D_F^2. \tag{12}$$

By integrating Eq. (12), we obtain pressure increase by magnetic force:

$$p = \int_{-L}^{z} \mu_0 \chi_B Hz(\partial Hz/\partial z) dz - 16\eta u_0 (z + L)/D_F^2. \tag{13}$$

We assumed that pressure is zero at the inlet of the oxygenator. We also assumed that:

f. Deoxygenated blood is fully oxygenated at the center of a membrane lung.

Magnetic characteristics of the red blood cell and whole blood have been reported in many articles [8–10], but the values do not coincide with each other. Magnetic susceptibility of oxygenated blood and that of deoxygenated blood were calculated on the basis of Zborowski's values (magnetic susceptibility of deoxygenated red cell: -5.72×10^{-6}, χ of oxygenated red cell: -9.24×10^{-6}, χ of plasma: -9.05×10^{-6}) as follows:

χ of deoxygenated blood:

$$-9.05 \times 10^{-6} \times 0.57 - 5.72 \times 10^{-6} \times 0.43 = -7.62 \times 10^{-6}$$

χ of oxygenated blood:

$$-9.05 \times 10^{-6} \times 0.57 - 9.24 \times 10^{-6} \times 0.43 = -9.12 \times 10^{-6}$$

where the magnetic susceptibility of whole blood was calculated by averaging χRBC and $\chi plasma$ by the volumes. Hematocrit was assumed to be 43%.

In order to calculate Eq. (13), we calculated Hz and $\partial Hz/\partial z$ induced by the solenoid coil (Fig. 5). According to the Biot–

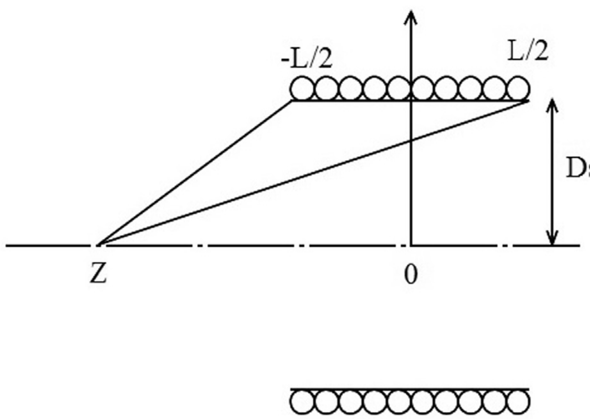

Fig. 5. Magnetic field induced by a solenoid coil.

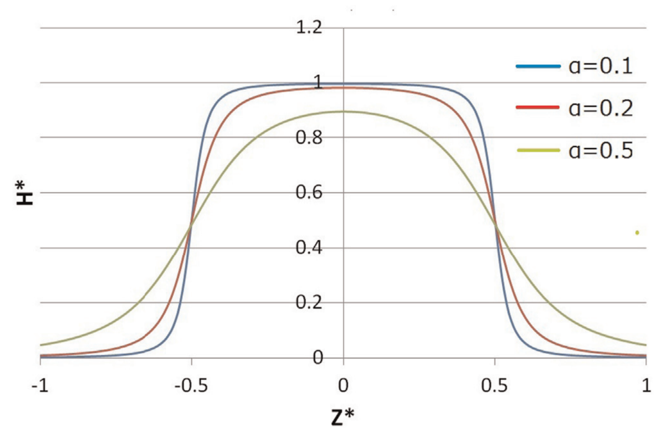

Fig. 6. Dimensionless magnetic fields induced by a solenoid coil with various aspect ratios.

Savart law, flux density in the axial direction at point z on the central axis of the solenoid coil is given by

$$H(z) = nI/2\cdot\left((L/2 - z)/\left((L/2 - z)^2 + D_S{}^2/4\right)^{1/2} + (z + L/2)/\left((z + L/2)^2 + D_S{}^2/4\right)^{1/2}\right) \quad (14)$$

The thickness of the wire windings in the solenoid was assumed to be small compared to the diameter D_s.

We introduce the following dimensionless variables z^*, α and H^*

$$z^* = z/L$$

$$\alpha = D_s/L (= \text{ aspect ratio of the coil})$$

$$H^* = H/nI.$$

Then the dimensionless magnetic field is given by

$$H^*(z^*) = 1/2\cdot((0.5 - z^*)/((0.5 - z^*)^2 + 0.25\alpha^2)^{1/2} + (z^* + 0.5)/((z^* + 0.5)^2 + 0.25\alpha^2)^{1/2}) \quad (15)$$

and the dimensionless magnetic field gradient is given by

$$dH^*/dz^* = 1/2\cdot(-0.25\alpha^2/((0.5 - z^*)^2 + 0.25\alpha^2)^{3/2} + 0.25\alpha^2/((z^* + 0.5)^2 + 0.25\alpha^2)^{3/2}). \quad (16)$$

3. Results and discussion

Dimensionless magnetic fields were calculated using Eq. (15) for aspect ratios of 0.1, 0.2 and 0.5 (Fig. 6). With a decrease in the aspect ratio α, the magnetic field inside the coil becomes more uniform and greater. With α of 0.165 (D_s: 0.0165 m, L: 0.1 m), the dimensionless magnetic field and magnetic field gradient were calculated using Eqs. (15) and (16), respectively (Fig. 7). The magnetic field gradient changes greatly at z^*=0.5, i.e., end of the coil.

Magnetic fields induced by a coil with D_S=0.0165 m and L=0.1 m (α=0.165) were calculated using Eq. (15) for nI of 3×10^6, 5×10^6 and 8×10^6 A/m (Fig. 8). The maximum magnetic fields were Hz_{max} =2.96×10^6 A/m (Bz_{max}=3.72 T) for nI=3×10^6 A/m, Hz_{max}=4.93×10^6 A/m (Bz_{max}=6.19 T) for nI=5×10^6 A/m, and Hz_{max}=7.89×10^6 A/m (Bz_{max}=9.91 T) for nI=8×10^6 A/m.

Magnetic field gradients were calculated using Eq. (16) (Fig. 9). Maximum magnetic field gradients were $(dHz/dz)_{max}$=1.82×10^8 A/m^2 ($(dBz/dz)_{max}$=229 T/m) for nI=3×10^6 A/m, $(dHz/dz)_{max}$=

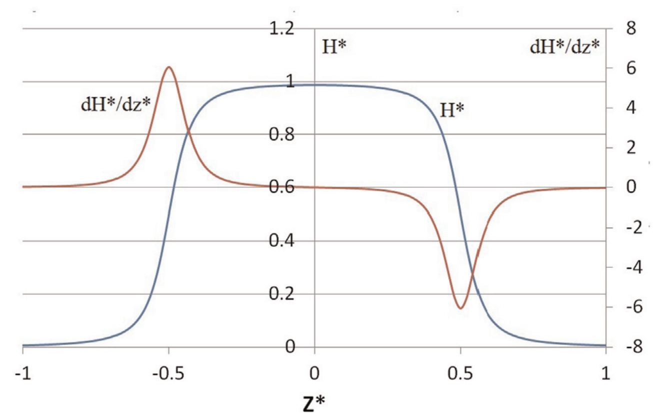

Fig. 7. Dimensionless magnetic field and magnetic field gradient for an aspect ratio of 0.165.

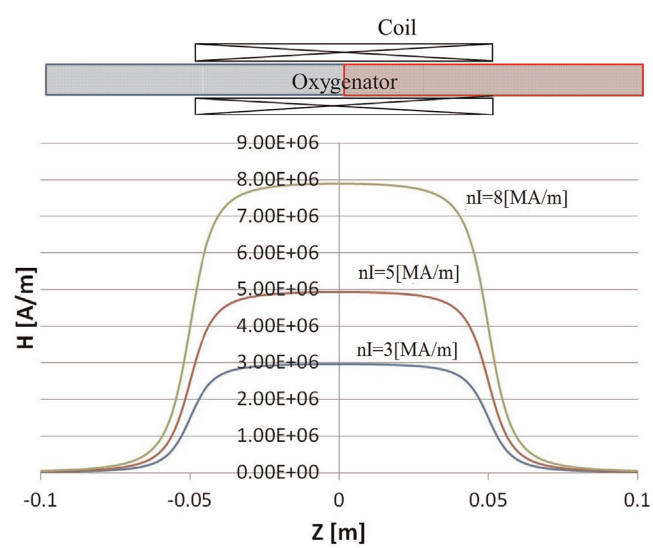

Fig. 8. Magnetic fields induced by a solenoid coil with an aspect ratio of 0.165 for various ampere-turns.

3.03×10^8 A/m^2 ($(dBz/dz)_{max}$=381 T/m) for nI=5×10^6 A/m and $(dHz/dz)_{max}$=4.85×10^8 A/m^2 ($(dBz/dz)_{max}$=609 T/m) for nI=8×10^6 A/m.

Changes in magnetic force were calculated on the basis of Eq. (1) using $M(B)$ instead of $M(MF)$ (Fig. 10). The magnetic force changes greatly at the inlet and outlet of the coil. The magnetic

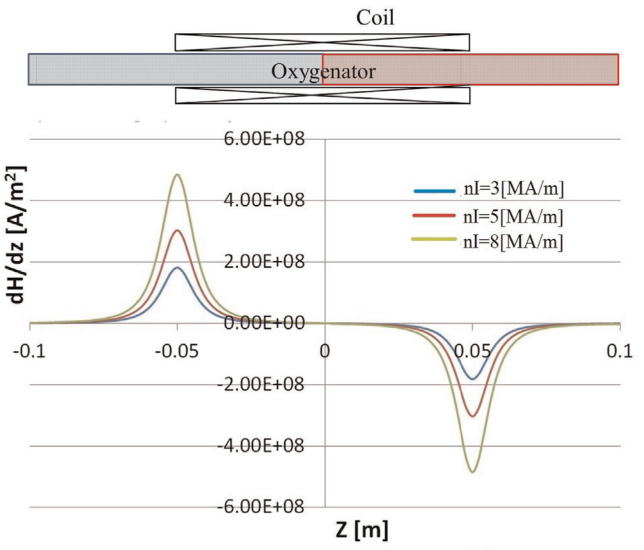

Fig. 9. Magnetic field gradients induced by a solenoid coil with an aspect ratio of 0.165 for various ampere-turns.

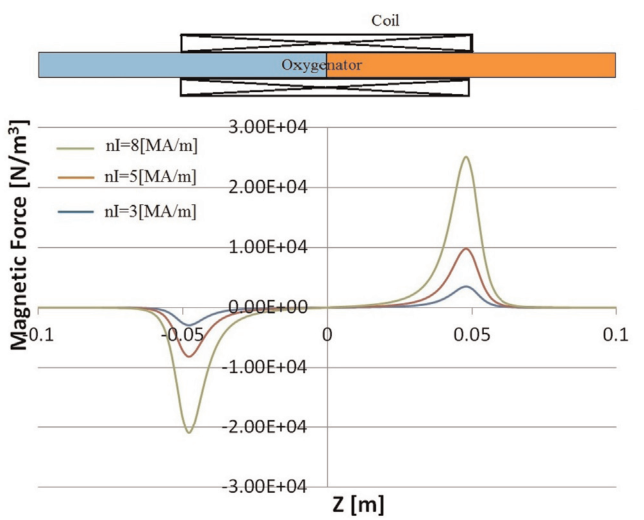

Fig. 10. Changes in magnetic force for various ampere-turns.

force is negative in the inlet region of the coil because the blood is diamagnetic and the magnetic field gradient is positive ($\nabla H > 0$). The magnetic force becomes positive in the outlet region because the blood is diamagnetic and the magnetic field gradient is negative ($\nabla H < 0$). Magnitude of the positive magnetic force is greater than that of the negative magnetic force because oxygenated blood is more diamagnetic than is deoxygenated blood ($\chi_{oxygenated\ blood} < \chi_{deoxygenated\ blood}$).

Magnetic pressure due to magnetic force was calculated by

$$\int_{-L}^{z} \mu_0 \chi_B Hz \cdot \partial Hz / \partial z \cdot dz$$

Change in magnetic pressure is shown in Fig. 11. Negative pressure is induced in the inlet region, but the pressure changes to positive pressure in the outlet region because the magnitude of the outlet-ward magnetic force is greater than that of the inlet-ward force.

Pressure distribution in the hollow fiber membrane oxygenator considering the viscous loss of blood was calculated by Eq. (13). Values of ρ and η were assumed to be 1.06×10^3 kg/m^3 and 3.5×10^{-3} Pa s, respectively. The pressure distribution for a

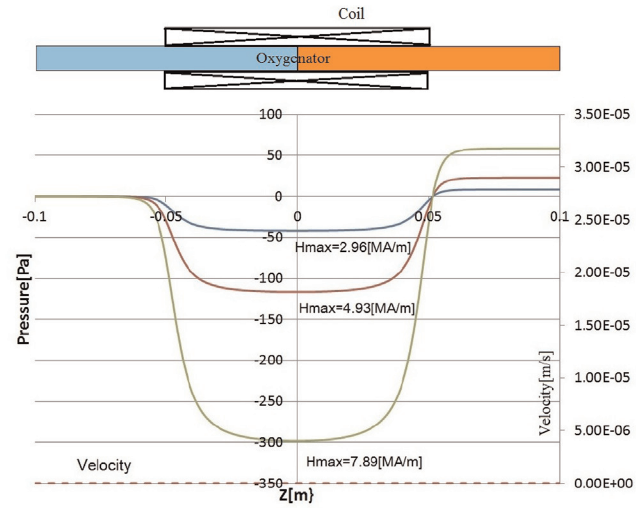

Fig. 11. Changes in magnetic pressure for various ampere-turns.

Reynolds number $Re = 0.001$ ($u = 1.65 \times 10^{-5}$ m/s, $Q = 70.5$ μL/min) is shown in Fig. 12. Blood pressure increased in the downstream direction, but due to the viscous loss, the outlet pressure decreased to -0.98 Pa for $H_{max} = 2.96 \times 10^6$ A/m, 13.7 Pa for $H_{max} = 4.93 \times 10^6$ A/m, and 49.5 Pa for $H_{max} = 7.89 \times 10^6$ A/m from the magnetic pressure in Fig. 11.

In the condition of $Re = 0.002$ ($u = 3.3 \times 10^{-5}$ m/s, $Q = 141$ μL/min), pressure distribution in the hollow fiber membrane oxygenator is shown in Fig. 13. Due to viscous loss, the outlet pressure decreased to 4.46 Pa for $H_{max} = 4.93 \times 10^6$ A/m and 40.2 Pa for $H_{max} = 7.89 \times 10^6$ A/m.

The relationship between pressure increase in the hollow fiber membrane oxygenator and maximum magnetic field is shown in Fig. 14 for various blood flow rates (Reynolds numbers of 0.001–0.003). With an increase in the magnetic field, the pressure rise in the membrane oxygenator increased. With an increase in blood flow rate, the pressure rise decreased.

It was confirmed that oxygenation of deoxygenated blood in the downstream side of the applied magnetic field is effective for pressure rise in a non-uniform magnetic field. The pressure rise is enhanced greatly by an increase in magnetic field intensity. The results of calculation suggest that a membrane oxygenator works

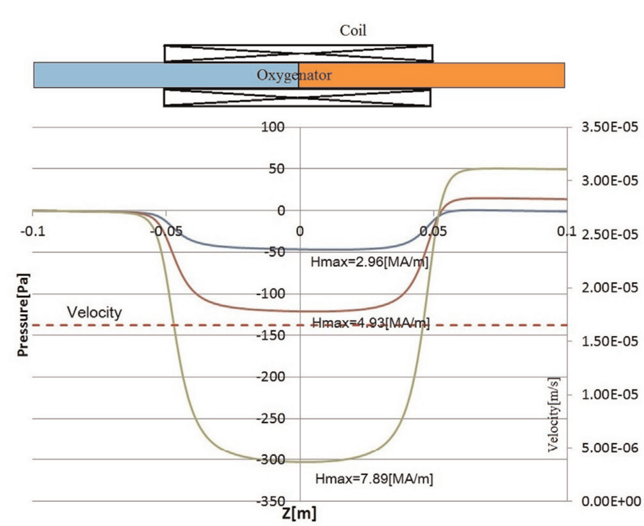

Fig. 12. Pressure distribution in a hollow fiber membrane oxygenator (Re=0.001) for various ampere-turns.

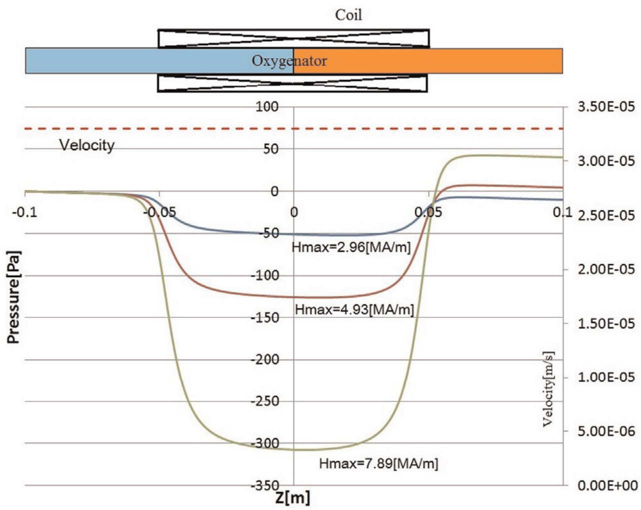

Fig. 13. Pressure distribution in a hollow fiber membrane oxygenator (Re=0.002) for various ampere-turns.

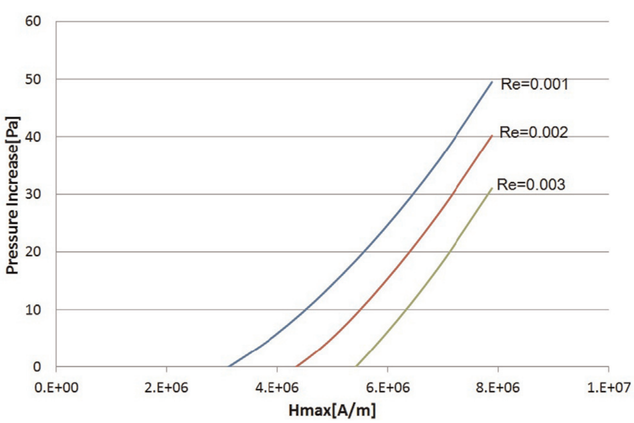

Fig. 14. Relationship between maximum magnetic field and pressure increase in a hollow fiber membrane oxygenator for various flow conditions.

as an actuator and that magnetic driving force is produced. Therefore, there is a possibility of self-circulation of blood through an oxygenator by a non-uniform magnetic field, although flow rate is very low. In this study, an endocapillary blood flow oxygenator was assumed. Pressure drop in the oxygenator can be decreased if an extracapillary blood flow oxygenator is used. This enhances the magnetic driving force.

To the best of our knowledge, there has been no report about the interaction between blood with a variable magnetic property and a non-uniform magnet field from the standpoint of blood as a magnetic fluid. Although the magnetic susceptibility of blood is very low, the interaction between blood and a high gradient magnetic field has been studied. Paramagnetic deoxygenated red blood cells are attracted towards an increasing magnetic field in a high gradient magnetic field. Red blood cell magnetophoresis has been reported [9,11]. This method is based on the hypothesis that differential migration velocity is possible if hemoglobins with different magnetic properties (paramagnetic or diamagnetic character) are exposed to a high magnetic field. The equation of motion of a single red blood cell in a blood suspension of a very low hematocrit of 0.02% was solved by balancing the magnetic force with viscous resistance determined by the Stokes law. Analysis of the interaction between a single red blood cell and a high gradient magnetic field is reasonable because the objective was cell separation and the hematocrit was very low.

Shiga et al. [12,13] studied the interaction between a blood solution with a low hematocrit (0.5–13.4%) and a high gradient magnetic field. They calculated displacement of the flow of blood solution containing paramagnetic hemoglobins (Hct of 5%) toward a magnetic field gradient. In one calculation, magnetic force was assumed to be applied to the single red blood cell. However, the observed and calculated displacements of the blood stream did not coincide. In another calculation, magnetic force was assumed to be applied to a volume of erythrocyte suspension with equivalent magnetic susceptibility to a mixture of red blood cells and plasma by volume. The calculated displacement was almost the same as the observed displacement. These results support the hypothesis that blood is attracted as a whole by the magnetic field.

The interaction between a diamagnetic fluid and a non-uniform magnetic field, as shown in Fig. 1, has been reported. Ueno et al. studied the properties of a diamagnetic fluid (distilled water) in static magnetic fields up to 8 T with a gradient of 50 T/m [14]. When magnetic fields were changed from 0 to 8 T, the flow velocity of distilled water decreased and the flow stopped at 8 T. The mechanism of these phenomena was explained on the basis of results of a stress analysis of a diamagnetic fluid. The hydrodynamics of a diamagnetic fluid in $\sim$400 T^2/m can be compared with that of a ferromagnetic fluid in weak magnetic fields. This result suggests that hydrodynamics of diamagnetic blood in a non-uniform magnetic field, as shown in Fig. 1, can be analyzed using the Navier–Stokes equation.

Considering the above-described studies, the analytical method used in this study is reasonable because blood with a normal hematocrit is treated as a continuum and the Navier–Stokes equation including the magnetic force term is used to analyze blood flow.

There is, however, limitation of the analytical method used in this study. In this study blood (hematocrit=43%) was treated as a continuum with volume-weighted mean magnetic susceptibility and the Navier–Stokes equation was used to analyze motion of blood. However, blood is a two-phase system comprising cells (mostly red blood cells) and plasma. Therefore in the analysis of a two-phase system (blood) two equations of motion are used: one is for red blood cells and the other is for plasma including interaction forces. Therefore there is probably a difference between the results of this study (one-phase system) and the results of the two-phase system. The difference depends on two factors. One factor is velocity difference between red blood cells and plasma. When the velocity difference is large, the model of the one-phase system becomes a poor approximation of the two-phase system. In a rectangular microfluidic channel model the velocity difference between red blood cells and plasma is reported to be small [15]. Another factor is magnetic force. In this study the magnetic force was applied to the whole blood with volume-weighted mean magnetic susceptibility. In the two-phase the magnetic force is applied to red blood cells with their own magnetic susceptibility. There is probably a difference between the two forces. Further studies are required to obtain more accurate results.

In this study deoxygenated blood is fully oxygenated at the center of a membrane oxygenator (assumption (f)). This is a simplified assumption. Oxygen and carbon dioxide transfers in a membrane oxygenator are a complex process. The oxygen transfer depends on several factors such as blood flow rate and oxygen gas flow rate. Oxygen saturation of blood gradually increases with the distance from the inlet of a membrane oxygenator and saturates [16]. Therefore the assumption (f) gives a greater pressure increase in the oxygenator model than in a real oxygenator. Further studies are also required to obtain more accurate results.

4. Conclusions

Oxygenation of deoxygenated blood in the downstream side of the applied magnetic field is effective for pressure rise in a non-uniform magnetic field. The pressure rise is enhanced greatly by an increase in magnetic field intensity. A membrane oxygenator works as an actuator and there is a possibility of self-circulation of blood through an oxygenator in a non-uniform magnetic field.

Acknowledgments

The authors would like to thank Prof. H. Yamaguchi (Doshisha University), Dr. Iwamoto (Doshisha University) and Emeritus Professor S. Ueno (University of Tokyo) for their useful discussion.

References

[1] S. Kamiyama, S. Inoue, A study on the two-phase flow characteristics of a magnetic fluid, Trans. JSME Ser. B 54 (1988) 80–86 (in Japanese).
[2] S. Kamiyama, T. Kamiya, H. Izu, Boiling two-phase flow characteristics of a magnetic fluid in a nonuniform magnetic field, Trans. JSME Ser. B 57 (1991) 1617–1622 (in Japanese).
[3] H. Yamaguchi, S. Shuchi, K. Sakatani, M. Enomoto, Research on driving force characterisitics of low boiling point solution mixture of temperature sensitive magnetic fluid, Trans. JSME Ser. B 70 (2004) 2591–2597 (in Japanese).
[4] T. Kuwahara, M. Ohnishi, H. Yamaguchi, S. Shuchi, Heat transport and driving force characteristics of heat transport device using magnetic fluid in various magnetic fields, Trans. JSME Ser. B 73 (2007) 2085–2091 (in Japanese).
[5] Y. Iwamoto, H. Yamaguchi, X.D. Niu, Self-circulate heat transport using temperature sensitive magnetic fluid, Jpn. J. Multiphase Flow 24 (2010) 641–648 (in Japanese).
[6] Y. Iwamoto, Y. Fuji, K. Takeda, X.-D. Niu, H. Yamaguchi, Driving characteristics of a mini magnetically-driven heat transport devices using magnetic fluids, in: Proceedings of the 22nd International Workshop on Rare-Earth Permanent Magnets and Their Application, 2012.
[7] R.E. Rosensweig, Ferrohydrodynamics, Cambridge University Press, Cambridge, 1985.
[8] M.E. Cano, R. Casta~neda-Priego, A. Barrera, J.C. Estrada, P. Knauth, M.A. Sosa, Magnetisation of red blood cells: a Brownian dynamics simulation, Rev. Mex. F ́ıs. 58 (2012) 391–396.
[9] M. Zborowski, G.R. Ostera, L.R. Moore, S. Milliron, J.J. Chalmers, A.N. Schechter, Red blood cell magnetophoresis, Biophys. J. 84 (2003) 2638–2645.
[10] W.M. Spees, D.A. Yablonskiy, M.C. Oswood, J.J.H. Ackerman, Water proton MR properties of human blood at 1.5 T: magnetic susceptibility, T1, T2, T⁎2, and non-Lorentzian signal behavior, Magn. Reson. Med. 45 (2001) 533–542.
[11] M. Zborowski, L.R. Moore, P.S. Williams, J.J. Chalmers, Separations based on magnetophoretic mobility, Sep. Sci. Technol. 37 (2002) 3611–3633.
[12] M. Okazaki, N. Maeda, T. Shiga, Effects of an inhomogeneous magnetic field on flowing erythrocytes, Eur. Biophys. J. 14 (1987) 139–145.
[13] T. Shiga, M. Okazaki, A. Seiyama, N. Maeda, Paramagnetic attraction of erythrocyte flow due to an inhomogeneous magnetic field, Bioelectrochem. Bioenerg. 30 (1993) 181–188.
[14] S. Ueno, M. Iwasaka, Properties of diamagnetic fluid in high gradient magnetic fields, J. Appl. Phys. 75 (1994) 7177–7179.
[15] Wei-Tao Wu, N. Aubry, M. Massoudi, J. Kim, J. Antaki, A numerical study of blood flow using mixture theory, Int. J. Eng. Sci. 76 (2014) 56–72.
[16] G. Jayaraman, A. Lautier, Hung Bui-Mong, G. Jarry, D. Laurent, Numerical scheme for modelling oxygen transfer in tubular oxygenators, Med. Biol. Eng. Comput. 19 (1981) 524–534.