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

$$F = \mu_0 M(MF) \nabla H \quad (1)$$

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.

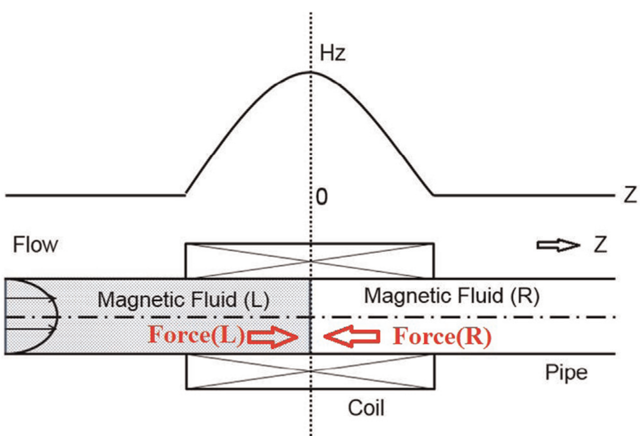

Fig. 1. Force applied to the magnetic fluid in a non-uniform magnetic field.

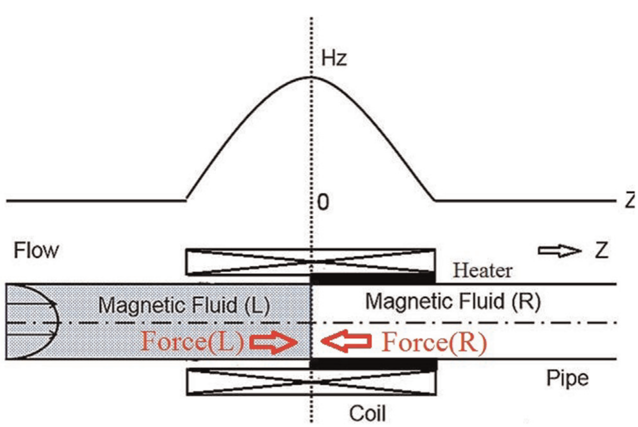

Fig. 2. Working principle of the self-circulate device.

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