Magnetic Activation of Drug Carriers in Biomedical Engineering by Using Digital Signal Controller

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Abstract
Nowadays, magnetic nanoparticles (MNP) and their combinations have been actively applied in industrial, chemical, medical and similar fields in nanotechnology and micromechanical systems (MEMS). Special pumps are used to transport the MNP aggregates in the required region. Therefore, the development of more effective and economical pump for the transport of MNP's with high toxicological secure in medicine and biotechnology remains one of the important application problems. This study presents the new magnetic pump with high-gradient magnetic field for transport of biomagnetic particles and aggregates (blood, MNP suspensions etc.) and results of examining the pump's pressure characteristics. The magnetization coils of the pump's are fed with an adjustable source to produce increasing or decreasing force in the direction of the suspension flow. These pressure characteristics's evaluation is based on the continuity equation of the flow and the approximate analytical solutions of the Navier-Stokes equation. This magnetic pump has not rotational mechanical parts, for this reason there is not mechanical loses and it gives good output characteristics and an efficient. Therefore, this pump is recommended for biomedical applications. Pump's pressure characteristics are made by digital signal controller circuit that can adjust the external coils's currents over a wide-range with duty ratio of pulse width modulation (PWM) signal. With this approach, it is possible to make such pumps as small size like MEMS or as large size as possible.
Keywords: Blood flow, digital signal controller, MEMS, magnetic nanoparticle, magnetic pump, magnetic suspension.

1. INTRODUCTION

The fluid environments that are used in medical, biology, and also in many industrial fields have magnetic properties (Berkovsky et al., 1993; Hafeli et al.,1997). One of the most important of these fluid environments are the ones that belong to the blood and blood aggregates in medical field. Pumps are used to transport these types fluid environments. However, with regards to toxicology, the use of such pumps for medical and biological environments poses adaptation problem. Also, the presence of mechanical rotating parts in such pumps leads to the formation of mechanical losses in the pumps and the decrease in the efficiency of the pumps. The use of magnetic pumps has been proposed to prevent these problems (Rosensweig, 1997; Mitamura and Okamoto, 2015; Tanveer, 2016). For this reason, unlike other designs, the use of magnetic solenoid pumps allows for a safer and more efficient system. Additionally, magnetic pumps are used effectively in micro/nano fluidic systems and MEMS (Odenbach, 2009). For this reason, the development of magnetic pumps today is very important in many industrial fields.

In this study, a multi-coil solenoid type magnetic pump system was developed as a new magnetic pump system. The magnetic force applied to the magnetic fluid in the H magnetic field is given in equation (1) (Berkovsky et al., 1993; Rosensweig, 1997).

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

In this equation, M is the magnetisation of magnetic fluid. It is necessary to increase the magnetic field gradient (∇H) to increase the magnetic force for pumps operated with these principles. In solenoids magnetic pumps, ∇H can be increased by using finite number of solenoids. Moreover, by changing the electric fields of these solenoids, ∇H can be replaced more effectively. Using PWM technique to change the magnetic field gradient in the pump for each solenoid is easily possible. The implementation of the PWM driven electronic controls which can adjust the current of solenoids used in the proposed magnetic pumps is suggested and the theoretical basis is assessed.

2. MATERIALS AND METHODS

Micron and submicron sized magnetic particles are important in medical field, biology and physics. It is possible to evaluate the $10^{-15}N$ force effects in these systems using these particles. In biotechnological processes, these features of magnetic particles, in magnetic separation (Rosensweig, 1997), magnetic drug targeting (Odenbach, 2009) and in the separation of the immuno-magnetic cell play a dominant role. In many cases, since the mixing ratio of magnetic particles are high, the environment or all suspension carrying these particles may exhibit magnetic magnetization properties. Such suspensions form a special class of fluidics (magnetic fluids) (Berkovsky et al., 1993). One of the fluid types that can be influenced by the magnetic field is blood. Blood consists of blood cells present in blood plasma. By volume, plasma and red blood cells constitutes for about 57% and 43% of whole blood, respectively. Red blood cells contain hemoglobin. Hemoglobin is a protein containing iron that carries oxygen in the body. Since hemoglobin has magnetic properties, the red blood cell is regarded as a magnetic particle, for that reason blood is also considered to be a magnetic fluid. So, it is more advantageous to use magnetic pumps to transport blood and similar biological environments. For this reason, solenoid type magnetic pump can be used. In general, solenoid type magnetic pumps are widely used in magnetohydrodynamic systems and other systems (Odenbach, 2009; Mitamura and Okamoto, 2015). However, in all these systems, an external magnetic field system has a single winding. This causes the magnetic fluid to brake at the center of the solenoid and therefore reduces the performance of the pump. It is possible to increase or decrease the magnetic field of the solenoid system in the direction of the flow of the pumped magnetic fluid suspension to eliminate this disadvantage. The principle diagram of such a magnetic pump system is shown in Figure 1.

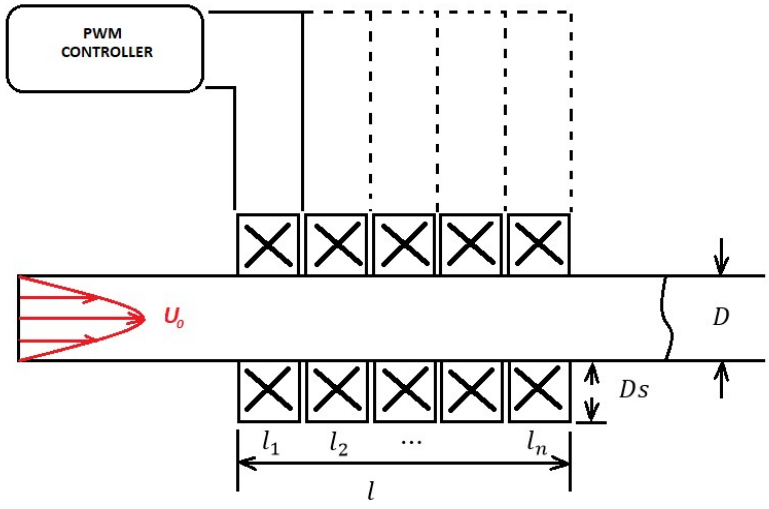

Figure 1. Principle diagram of multi-coil magnetic pump.

The pipe with diameter D is passed through a solenoid group having an inner diameter Ds. The total length of the solenoids is l.

$$l_1 + l_2 + \cdots + l_n = l \tag{2}$$

In above formula, $l_1, l_2, l_3, \ldots, l_n$ are the lengths of the working coils. These coils are fed by an external PWM driver. As the PWM driver independently feeds each coil, the electric current of each coil can be set within a

certain range. Depending on the operating state of the pump, it is possible to create a magnetic field that increases or decreases on the magnetic fluid (blood) in the length of the l magnetic effect. Therefore, the magnetic fluid is affected by acceleration or deceleration (braking) force. Figure 2 shows the signals generated by the PWM driver. These different voltages applied to the coils form magnetic fields having different amplitudes in the coils (Ozguven, 2017).

In Figure 2 shows that the voltage and current signals from the oscilloscope for two PWM signal output channels. The current signal is taken on a 1 Ω resistor connected in series to solenoid. In Figure 2.a and 2.b the duty ratio is 50% and in Figure 2.c and 2.d the duty ratio is 75%. In the digital signal control circuit, the duty ratios of the PWM signals are set by three separate potentiometers and displayed continuously on the LCD as in Figure 2.e.

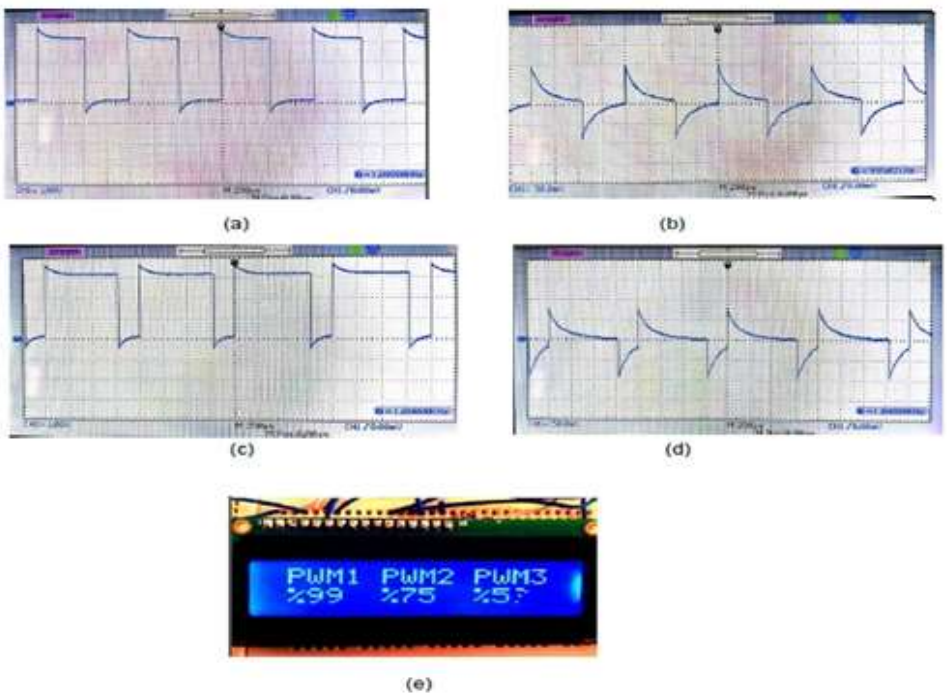

Figure 2. PWM output signals and LCD display, (a,c) solenoid 1 and solenoid 2 voltages, (b,d) solenoid 1 and solenoid 2 currents, (e) LCD.

Numerous experiments with a superconducting solenoid have shown that the magnitude of the magnetic field along the solenoid axis can be determined approximately as in equation (3);

$$H_z(r) = H_0 e^{-\alpha(\frac{z}{l})^2} \tag{3}$$

In this formula, H_0 is the intensity of the magnetic field at the center of the solenoid (A/m), r – is the radial coordinate. The flow of the magnetic fluid (blood) with D diameter pipe in the solenoid can be determined according to the Navier-Stokes equation as shown in equation (4) (Berkovsky et al., 1993; Hafeli et al.,1997).

$$\rho\left(\frac{\partial u}{\partial t} + (u.\nabla)u\right) = -\nabla p + \eta\nabla^2 u + \mu_0\,(M(B).\nabla)H + \rho g \tag{4}$$

In the formula;
ρ: density of blood (kg/m^3).
u: velocity of blood (m/s).

p: pressure *(Pa)*.
η: viscosity of blood *(Pa s)*.
μ_0: magnetic permeability of a free space *(H/m)*
$M(B)$: magnetization of blood *(A/m)*.
H: intensity of magnetic field *(A/m)*.
g: gravitational acceleration *(m/s²)*.

In order to obtain analytical solution for equation (3) following assumptions are taken into consideration;

a) Blood flow in pipe is a flow that is laminar and axial, $\frac{\partial u}{\partial \varphi} = 0$.
b) Blood flow is laminar and $u_r = u_\varphi = 0$ means it has Poiseuille flow profile.

$$u_z(r) = u_0(1 - (\frac{r}{R})^2) \quad (5)$$

In this formula $R = \frac{D}{2}$ is the radius of the blood flowing pipe.

c) Magnetic field inside the solenoid has symmetry in the axial direction.
$\frac{\partial H}{\partial \varphi} = \frac{\partial H}{\partial r} = 0 \quad H_r = H_\varphi = 0$, H_z is determined by the equation (3).

d) The magnetic susceptibility of blood is X_B, and its magnetization properties are linear as it is in paramagnetic material.

$$M = X_B H \quad (6)$$

In all these conditions, the pressure change in the pump from equation (3) is achieved as follows;

$$P = \frac{\mu_0 X_B {H_0}^2}{2} e^{-2\alpha} \left[e^{-2\alpha[(\frac{z}{l})^2 - 1]} - 1\right] - \frac{16\eta u_0}{D^2}(z + l) \quad (7)$$

According to the formula in equation (7), we can evaluate the pressure change of the solenoid type magnetic pump. The data presented in (Mitamura and Okamoto, 2015; Tanveer, 2016) can be used for calculations. Table I gives the operating parameters of the magnetic pump.

Table I. Operating parameters of the magnetic pump.

$u_0, m/s$	$\eta, (Pa\ s)$	l, m	D, m	X_B	$H_0, A/m$
$1{,}65.10^{-5}$	$3{,}5.10^{-3}$	0,1	0,0165	$-7{,}62.10^{-6}$	$(3-8).10^6$

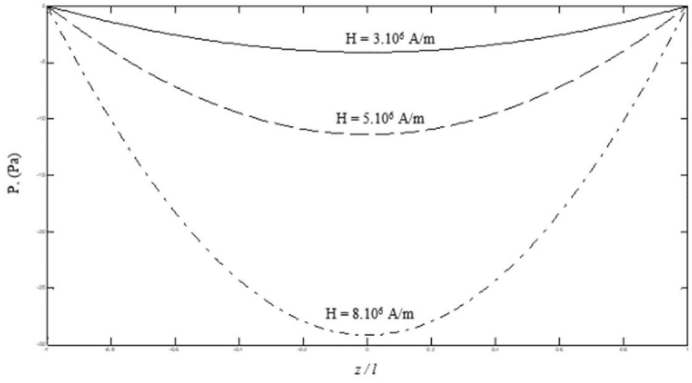

Figure 3. Pressure change of the pump depending on the change intensity of magnetic field of solenoid.

According to equation (7), the pressure change curves for the magnetic pump of the solenoid type are shown in Figure 3. As shown in Figure 3, the pressure values of the magnetic pump can be changed considerably with the changing of the magnetic field strength.

Although μ_0=$4\pi.10^{-7}H/m$, despite P=2,5 Pa, in the intensity of magnetic field $H_0 = 8.10^6$ A/m value, $P = 2{,}8\ Pa$ creates significant increase. This change of the solenoids magnetic field can easily be controlled with digital signal controller included PWM driver. Also, by selecting different number of output channels of PWM controls, we can make different number of solenoids whose magnetic field can be adjusted. We can increase the output performance of the pump by creating a magnetic field that increases or decreases in the direction of the magnetic fluid in the pump.

3. CONCLUSION

Electromagnetic solenoid type pumps can be used for pumping of environments that has magnetic property. Multi-coil solenoids can be made as a cascade group to increase the output performance of the pump. By supplying the electric currents of the solenoid coils from an external source in an adjustable manner, the intensity of magnetic field in the solenoids can also be adjusted. Consequently, the pressure changes in the inlet and outlet of the pump can also be varied over a wide range. The electric currents in the coils can be performed by the PWM controlled electronic control circuit.

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