Simulation of the particle trajectory under laminar flow for MDDS application

Jyun-Kong Huang 1, Chia-Ming Yang 1, Wei-Hsuan Chang 1, In-Gann Chen 1

1. Department of Materials Science and Engineering, National Cheng-Kung University, Tainan, Taiwan

Abstract:
Magnetic drug delivery systems (MDDS) can gather magnetic drugs to specific areas through an external magnetic field, increase drug concentration and improve efficiency, while reducing side effects on healthy tissues. To understand the motion of the magnetic drugs under magnetic field, this study established a multiphysics simulation model (including: magnetic force, drag force, and buoyancy-gravity), and verified with the trajectory of magnetic particles in the microfluidic channel. Nd-Fe-B permanent magnets and Y-Ba-Cu-O superconductors were placed under the microfluidic channels as magnetic sources, and their maximum magnetic field strengths are 0.247 T and 0.66 T, respectively. In the microfluidic validation experiment, the flow rate (1.5-7.1 cm/sec), channel width (0.8-1.8 mm), and viscosity (3.2 ρPa) referred to the vein conditions were considered. The results show that in the validation experiment under external magnetic field, the particle trajectory error is less than 1.72 mm for every 1mm of flow distance, which means that our model has a high degree of reliability. In addition, we also studied the influence of different magnetic field sources on different particle sizes in the vein environment. The simulation results show that when the magnetic source is placed at z = 11 mm and the flow rate was 1 mm/s, the attracting particle size range of permanent magnets is 1-7 μm, and the attracting size range of Y-Ba-Cu-O superconductors is 0.5-7 μm, showing that the stronger magnetic field-strength and gradient can attract smaller magnetic particles.

Introduction:

Fig. 1. Diagram depicting the mode of action of Magnetic Drug delivery system [1].

The Magnetic Drug Delivery System (MDDS) has been proposed in cancer and gene therapy since its development in 1980. The main mechanism is to attract magnetic drugs (carriers) injected into the human body through an external magnetic field. Compared with traditional treatment, MDDS can concentrate the drug to the target affected area, minimize the side effects on other tissues, and increase the dose concentration in the target area. Thereby, the dosage of the drug can be reduced, and better therapeutic effect can be obtained with the traditional method.

Fig. 2. Schematic diagram of the force of magnetic particles attracted by the magnet in the fluid [2]. (a) Three sets of parameters (magnetic particle, fluid in vessel, magnetic source) were mainly concerned to describe the motion behavior of magnetic particle. (b) The force acting on magnetic particles can be divided into two directions (X and Z axis) in the mathematical model.

This study explore the influence of the magnetic field on the motion of magnetic particles in the fluid at laminar state. To be noticed, the boundary condition and parameter in using this study referred to the real situation of magnetic particles in a vein, e.g. the blood flow rate (1.5-7.1 cm/sec), the vein diameter (0.8-1.8 mm), and the blood viscosity (3.2 ρPa) [3].

Fig. 3. Laminar flow velocity distribution diagram shows that the farther away from the center, the lower the velocity will be. The flow rate of the laminar flow in the cylindrical channel is given by:

\[ v = \frac{Q}{r} \]  

Where \( v \) is the flow rate of laminar flow, \( r \) is the average flow rate, \( P_{f} \) and \( P_{z} \) are distances between particle and center of channel in the y and z axis.

Experiment:

(a) syringe pump Digital OM Flow direction Magnetic field line

(b) Digital OM detection area

(c) MDDS image

Fig. 4. (a) The schematic diagram of the validation experiment includes a syringe pump, the microfluidic channel, and a digital microscope. The solution is extracted from the syringe through the syringe pump, flows through the catheter to the microfluidic channel on top of a magnetic source. (b) A digital microscope is used to record images on the specific XZ plane from the Y-axis. (c) The image of the magnetic particles (iron particles with size range from 1.7 μm) used in the validation experiment.

TABLE 1. parameters used in this article [PM = Permanent Magnet, HTS = High Temperature Superconductor]

<table>
<thead>
<tr>
<th>No.</th>
<th>Type</th>
<th>Diameter (μm)</th>
<th>Mass (g/m²)</th>
<th>Saturation Magnetic Strength (A/m)</th>
<th>Liquid Density (g/cm³)</th>
<th>Viscosity (cP)</th>
<th>Flow rate (mm/s)</th>
<th>Channel width (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PM</td>
<td>NdFeB</td>
<td>0.5</td>
<td>5</td>
<td>300</td>
<td>80%</td>
<td>9</td>
<td>5</td>
<td>1</td>
</tr>
<tr>
<td>HTS</td>
<td>YBCO</td>
<td>0.6</td>
<td>5</td>
<td>30</td>
<td>80%</td>
<td>9</td>
<td>5</td>
<td>1</td>
</tr>
</tbody>
</table>

The velocities of the magnetic particles in a fluid along the flow direction can be described by the BBO equation, which can be simplified as follows:

\[ a = \frac{d(v - v_0)}{dt} = \frac{1}{(1 + r)} \mu \frac{d}(2B2r_0) \mu_0 (v - v_0)^2 \int \frac{d^2a}{dt^2} \]

Where \( a \) is the particle velocities (μm/s), \( m \) is mass of particle (kg), \( v_0 \) is the mean of mass particle, \( g \) is acceleration of gravity, \( t \) is time, \( R \) is the radius of the particle, \( c \) is a constant.

Result and discussion:

A. Validation of particle trajectory under magnetic field

\[ t = \frac{1}{2} (v_0 + v) \]

\[ t = \frac{1}{2} \frac{v_0 + v}{v} \]

\[ t = \frac{1}{2} \frac{v_0 + v}{2v} \]

Flow rate (mm/sec)

Position_Z (mm)

Flow rate (mm/sec)

Position_X (mm)

Conclusion:

- In validation experiment under external magnetic field, the theoretical particle size of 1-2 μm can be obtained by model fitting and the average error is 1.72 mm (z axis)/mm (x axis).
- The parameters: magnetic source (PM), iron particles (size is less than 10 μm), liquid (glycine Solution), and channel width (1.8 mm).
- Validation of particle trajectory under different conditions

Fig. 5. A set of laminar flow experiment photos modified by the technical Weka Segmentation processing of image J, showing the trajectory of magnetic particles on the XZ plane observed with a digital microscope.

Fig. 6. The trajectories of particles under different flow rate and permanent magnet. The particle size is fitted by the BBO equation, and the calculated particle size is consistent with the size observed by SEM in Fig. 4.

Comparing with experiment data and simulation result, the average error is 1.72 mm (z axis)/mm (x axis).

The parameters: magnetic source (PM), iron particles (size is less than 10 μm), liquid (glycine Solution), and channel width (1.8 mm).

B. Simulation of particle trajectory under different condition

Fig. 7. The simulation results of different magnetic sources attracting particles of different sizes. (a) When the magnetic source at the position z = -11 mm, the attracting particle size of Y-Ba-Cu-O superconductor and permanent magnet is larger than 0.5 μm and 1 μm, respectively. (b) When the magnetic source at the position z = -6 mm, the particle size attracted by the superconductor and permanent magnet is larger than 0.3 μm and 0.5 μm, respectively. The parameters: magnetic source (HTS), liquid (blood), flow rate (1 mm/s), and channel width (2 mm).

Reference: