A Two-Phase Coupled Computational Flow Model Describing the Magnetic Separation of Microspheres

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Purpose

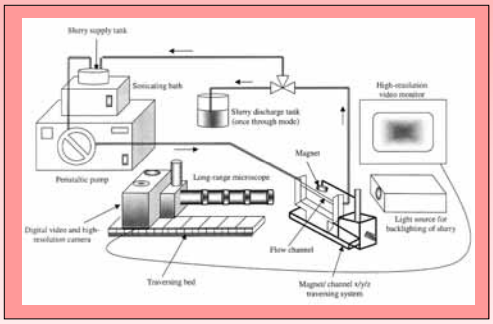
We present studies conducted at Argonne National Laboratory to develop a coupled computational code to describe the magnetic targeting of magnetic carriers under controlled laboratory conditions.

Background

Magnetic targeting of magnetic carriers will require sophisticated modeling programs that describe the arrangement of magnetic fields to optimize delivery to specific organ targets. Such models will require communication between computational magnetic field codes and computational two-phase fluid dynamics codes to accurately describe the trajectory of magnetic carriers under the influence of the externally applied magnetic fields and transient blood flow patterns. These models may eventually couple to dosimetry models, for example, to describe the dosimetry map for concentration of radioactive magnetic carriers to solid tumors. Another example is the concentration of clot-lysis-loaded magnetic carriers in arterial beds within the brain to dissolve fresh blood clots in stroke patients. Furthermore, such codes can aid in the design of magnetic filtration units being studied at Argonne and The University of Chicago to cleanse the blood of toxins using functionalized magnetic carriers.

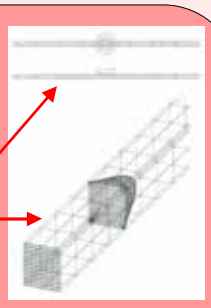
Approach

Using high resolution digital photography, we track the buildup of magnetic carriers in 2x2mm tubes carrying the blood volume equivalent of large breeder rats.



Model Development

A permanent NdFeB magnet (0.4 T surface) is placed against the flow cell to produce well characterized magnetic fields. The 3-D mesh is constructed of the flow cell and magnet orientation.



Photographs of the pile collected under the magnet are used to benchmark the model output.

Modeling Assumptions

- Particle-particle interaction can be neglected.
- Particles in suspension do not influence the fluid dynamics.
- Particle buildup and subsequent channel blockage are neglected.
- Particles are uniformly (randomly) distributed in space when entering the flow cell.
- Stokes drag law is appropriate.
- The flow field is steady, spatially fully developed, and laminar.
- Radial B-field gradients are neglected.
- The particle magnetism is in a fully saturated state.
- The particle diameter is D_p = 7µm, although, in fact, the particle diameters are known to have a Gaussian-like distribution centered roughly at 7µm.

Particle positions are computed using $F = m_e a$, where a is the particle acceleration, m_e, is the effective mass (accounting for fluid-inertia effects), and F is the net force on the particle computed as -- $F = F_f + F_m$.

Governing Equations

Magnetic forces: $F_m = V_m M_{S_w} \frac{dB}{dy}$ $\quad F_m = C_m \left|\frac{dB}{dy}\right| \hat{j} = 1.72\text{x}10^{-11} \frac{dB}{dy}$ Nm/T

Stokes drag force: $F_f = 3\pi\mu D_p (V_f - V_p)$

Reynolds number for laminar flow: $Re_H = \frac{H\bar{V}}{\nu} = \frac{(0.002m)(0.833m/s)}{(1\text{x}10^{-6} m^2/s)} = 1667.$

Trajectory matrix equation in x-direction:

$$\frac{d}{dt}\begin{pmatrix} X_p \\ V_p \end{pmatrix} = \begin{pmatrix} 0 & 1 \\ 0 & -C_f \end{pmatrix}\begin{pmatrix} X_p \\ V_p \end{pmatrix} + \begin{pmatrix} 0 \\ C_M \frac{dB}{dy}\hat{j} + C_f V_f \end{pmatrix}$$

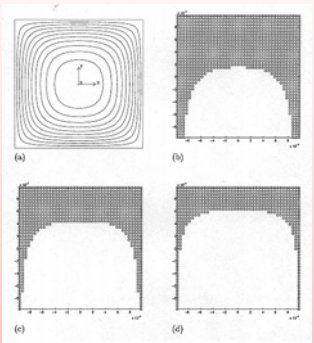
where $C_f = 3p\mu D_p/m_e$

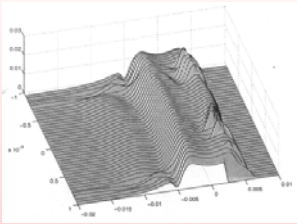
Trajectory matrix equation in y-direction:

$$\frac{d}{dt}\begin{pmatrix} y_p \\ v_p \end{pmatrix} = \begin{pmatrix} 0 & 1 \\ 0 & -C_f \end{pmatrix}\begin{pmatrix} y_p \\ v_p \end{pmatrix} + \begin{pmatrix} 0 \\ C_M \frac{dB}{dy} \end{pmatrix}$$

Model Results

The particles were tracked using the Crank-Nicolson/Adams-Bashforth scheme and were deemed to be "trapped" if they came within one particle radii of the upper wall. (a) Contours of axial velocity at intervals corresponding to 0.1kUmax, where k = 1, 2, 3, ..., 9. (b)-(d) Region (identified by circles) corresponding to particles that are trapped by the magnet at flow rates of 42, 83, and 167 cm/s, respectively.





Remaining particle fraction after 4 minutes of simulated rat blood flow

Flow Rate, mL/min	Fully Mixed	No Axial Mixing
41	0.605	0.502
83	0.578	0.527
167	0.554	0.517

Summary

- We confirmed that Argonne and commercial code produce identical results under identical modeling assumptions.
- Based on limited comparisons with experiment the model yields realistic results.
- We can model the traditional "scalar" magnetic field as well as the effects of the full 3-dimensional B-field, including the effects of magnetization strength (i.e., not just the saturated magnetization level). The influence of full modeling vs. the standard assumptions yields only a 3-4 % change in particle capture rate.
- At 50 mL/min, a 1-mm variation in particle size yields a 10 % change in capture rate.
- At 100 mL/min, a 1-mm variation yields a 7 % change in capture rate.
- At 200 mL/min, a 1-mm variation yields a 4 % change in capture rate.
- The influence of the trapped particle pile shape on the flow conditions and magnetic field strength (due to increased distance from the magnet) was simulated with pile heights of 0, 0.05, 0.1, 0.2 and 0.4mm extending into the flow field for the 2-mm channel. Pile buildup to this extent does not significantly alter particle capture rate.
- For limited simulations of pile shape with 7-mm mean diameter particles and the current magnets, there is reasonable agreement with the experimental data.

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