AIP | Journal of Applied Physics

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Citation: J. Appl. Phys. **111**, 07D128 (2012); doi: 10.1063/1.3679156
View online: http://dx.doi.org/10.1063/1.3679156
View Table of Contents: http://jap.aip.org/resource/1/JAPIAU/v111/i7
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Cyclical magnetic field flow fractionation

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(Presented 3 November 2011; received 24 September 2011; accepted 6 December 2011; published online 12 March 2012)

In this study, a new magnetic field flow fractionation (FFF) system was designed and modeled by using finite element simulations. Other than current magnetic FFF systems, which use static magnetic fields, our system uses cyclical magnetic fields. Results of the simulations show that our cyclical magnetic FFF system can be used effectively for the separation of magnetic nanoparticles. Cyclical magnetic FFF system is composed of a microfluidic channel (length = 5 cm, height = 30 μm) and 2 coils. Square wave currents of 1 Hz (with 90 deg of phase difference) were applied to the coils. By using Comsol Multiphysics 3.5a, magnetic field profile and corresponding magnetic force exerted on the magnetite nanoparticles were calculated. The magnetic force data were exported from Comsol to Matlab. In Matlab, a parabolic flow profile with maximum flow speed of 0.4 mL/h was defined. Particle trajectories were obtained by the calculation of the particle speeds resulted from both magnetic and hydrodynamic forces. Particle trajectories of the particles with sizes ranging from 10 to 50 nm were simulated and elution times of the particles were calculated. Results show that there is a significant difference between the elution times of the particles so that baseline separation of the particles can be obtained. In this work, it is shown that by the application of cyclical magnetic fields, the separation of magnetic nanoparticles can be done efficiently. © *2012 American Institute of Physics*. [doi:10.1063/1.3679156]

I. INTRODUCTION

In this study, a novel magnetic field flow fractionation (FFF) system was designed and modeled by using finite element simulations. Other than current magnetic FFF systems,[1,2] which use static magnetic fields, our system uses cyclical magnetic fields for the separation of magnetic nanoparticles. In the cyclical magnetic FFF system, in addition to the magnetic field strength, frequency of the magnetic field can also be adjusted to achieve the best separation results. Simulation results show that cyclical magnetic FFF system can effectively be used for the separation of magnetic nanoparticles.

II. THEORY AND METHODS

Cyclical magnetic FFF system is composed of a microfluidic channel and 2 electromagnets, shown in Fig. 1. A pressure driven flow is generated, resulting in a parabolic flow profile in the channel. After the stop flow relaxation of the particles, square wave currents with 90 degrees of phase difference are applied to the top and bottom electromagnets, so that the particles are driven away from the bottom channel wall. The particles with higher magnetophoretic mobilities will move longer distances away from the channel walls. As a result, they stay in the faster fluid regions and elute earlier than the lower mobility particles.

A microfluidic channel (length = 5 cm, height = 30 μm) was modeled in Comsol Multiphysics. Square wave magnetic fields were generated by the electromagnets ($B = 0.8$ T, $f = 1$ Hz). An inlet velocity of 0.4 mL/h was defined, resulting flow profile and magnetic field can be seen in Fig. 2.

By using the magnetic field profile obtained from Comsol Multiphysics simulation, magnetic force acting on the magnetite (Fe_3O_4) nanoparticles was calculated according to Eq. (1), where V_p is the volume of the particle, χ_p is the particle susceptibility, B is the magnetic flux density, and μ_0 is the magnetic permeability of the free space. To obtain the volume magnetic susceptibility for different size magnetite particles at given magnetic fields, equations supplied by Rosensweig[3] were used:

$$F_{\mathrm{mag}x} = \frac{V_p \chi_p}{\mu_0}\left(B_x \frac{\partial B_x}{\partial x} + B_y \frac{\partial B_x}{\partial y}\right)$$
$$F_{\mathrm{mag}y} = \frac{V_p \chi_p}{\mu_0}\left(B_x \frac{\partial B_y}{\partial x} + B_y \frac{\partial B_y}{\partial y}\right). \tag{1}$$

Hydrodynamic force acting on the nanoparticles was calculated by using Stokes drag law:

$$F_{\mathrm{drag}} = 6\pi\eta r_p (v_f - v_p), \tag{2}$$

where, η is the fluid viscosity, r_p is the particle radius, v_f is the velocity of the fluid resulting from the pressure driven flow, and v_p is the velocity of the particle.

By using Eqs. (1) and (2) with Newton's second law, we obtain the following equation, where m_p is the particle mass.

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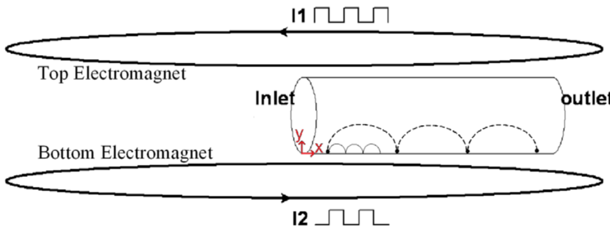

FIG. 1. (Color online) Cyclical magnetic FFF system. Square pulses with pi/2 phase difference were applied to the electromagnets. Dashed line shows the particle trajectory for the particle with high magnetophoretic mobility. Solid line shows the particle trajectory for the low magnetophoretic mobility particle. ($x = 0$ shows the inlet of the channel, $y = 0$ is the bottom wall of the channel).

$$m_p \frac{\partial v_p}{\partial t} = F_{\text{mag}} + F_{\text{drag}}. \tag{3}$$

Due to their very small particle sizes, nanoparticles reach their equilibrium velocity almost instantaneously and as a result we neglect the inertia term in the above equation, and obtain the particle velocity as below:

$$v_p = \frac{F_{\text{mag}}}{6\pi\eta r_p} + v_f. \tag{4}$$

To find the particle trajectories in the channel, a Matlab code was generated which solves the particle velocity Eq. (4).

III. RESULTS

Particle trajectory of a 40 nm magnetite particle inside the channel was calculated and shown in Fig. 3. Figure 3(a) represents the particle motion in the absence of the pressure driven flow, so that only source of motion is the magnetic force. Figure 3(b) shows the motion of the particle, in the presence of the pressure driven flow. As can be seen in the figure, as the particle goes away from the bottom wall of the channel, it gains a higher x velocity and move along the channel.

Particle trajectories of 30 and 50 nm magnetite particles were obtained for the first 3.6 s of fractionation (Fig. 4). As shown in the figure, a 50 nm particle moves much faster throughout the channel.

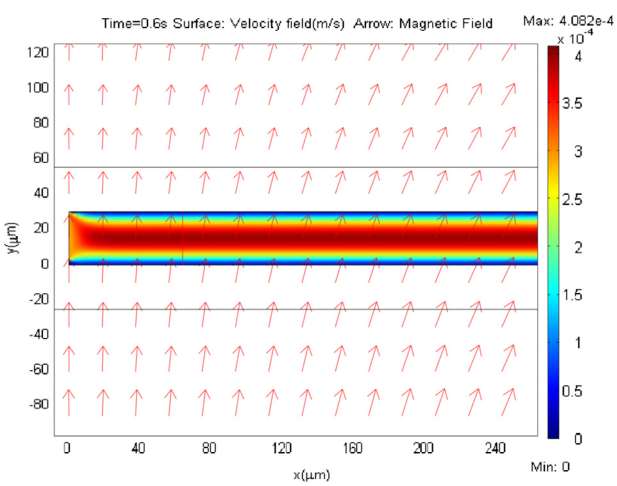

FIG. 2. (Color online) Comsol simulation plot. Surface plot shows the pressure driven fluid velocity. Arrows show the magnetic field vectors when the upper electromagnet is active.

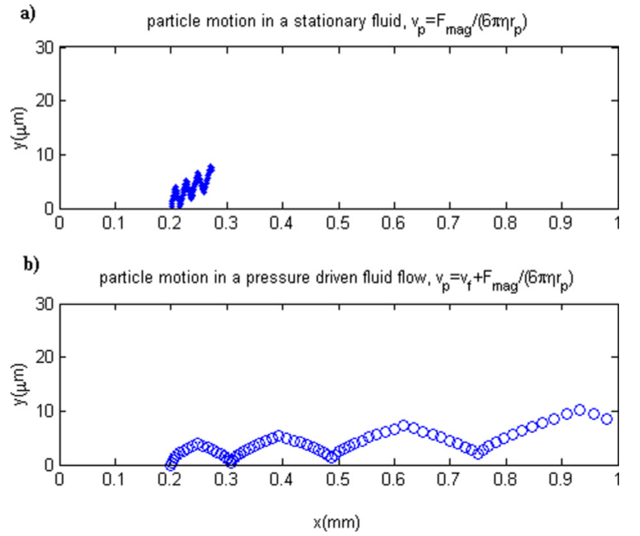

FIG. 3. (Color online) Particle motion of the 40 nm magnetite particle inside the channel. Y-axis shows the channel height, X-axis shows the 1 mm portion of the channel. Initial position of the particle was chosen as $x0 = 0.2$ mm, $y0 = 0$. (a) Particle trajectory in the absence of pressure driven flow. (b) Particle trajectory in the in the presence of pressure driven flow.

The elution times of the particles ranging from 10 to 50 nm were calculated and plotted in Fig. 5. Dots represent the resulting elution times for the applied frequency of 1 Hz, circles represent the result for $f = 5$ Hz. As can be seen, for both of the frequencies there is a significant difference between the elution times of the different sized particles. In addition, for 1 Hz frequency, elution time differences between the particles are slightly larger compared to 5 Hz condition, and we are getting a considerably better separation for 1 Hz field application. The realistic frequencies for this system are in the range of a few tens of Hz.

As observed in the earlier works,[4–6] for a fixed magnetic field amplitude, as we increase the frequency to a much higher value, the distance traveled by the particle in one cycle becomes too low, and this will result in a very poor or no separation. In terms of sychronization of the particle motion with the magnetic field, for low frequencies

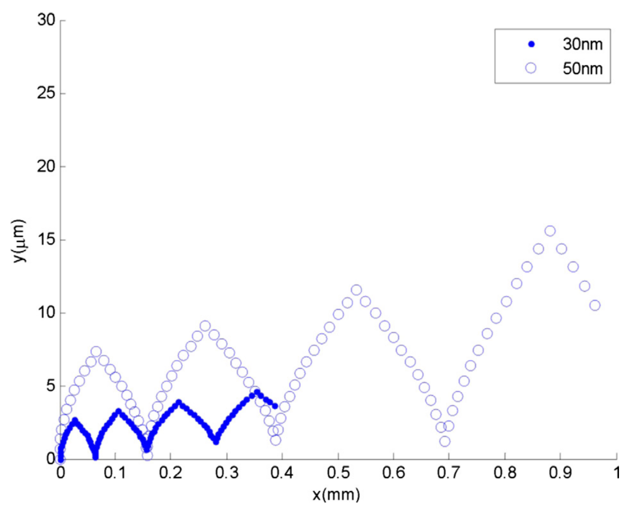

FIG. 4. (Color online) Particle trajectories of 30 and 50 nm particles, between $t = 0 - 3.6$ s. (Y axis shows the channel height and X-axis shows the 1 mm portion of the channel length).

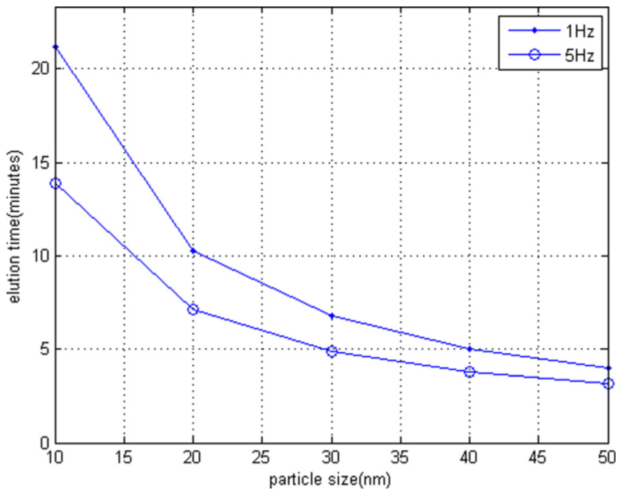

FIG. 5. (Color online) Elution time vs particle size graph for the spherical magnetite particles with sizes between 10 and 50 nm. Dots represent the result for $f = 1$ Hz, circles represent the result for $f = 5$ Hz.

($f < 50$ Hz) the motion of the particles are synchronized with the magnetic field.[4–6]

IV. CONCLUSION

In this work, a cyclical magnetic FFF system was modeled and it was shown that by the application of cyclical magnetic fields, the separation of magnetic nanoparticles can be done efficiently. Compared to the current magnetic FFF systems, this system can be easily adjusted for different types of particle samples, and it is done by just modifying the strength and frequency of the magnetic field. The future work will be the fabrication of the system and the comparison of the experiments with the theoretical data presented here.

ACKNOWLEDGMENTS

This work has been supported by a grant from the National Science Foundation's (NSF) Chemical, Biological and Environmental Transport program (Grant No. 0967037). Any opinions, findings, conclusions, or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of NSF. In addition, this work is supported by TUBITAK (The Scientific and Technical Council of Turkey) International Ph.D. fellowship programme.

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