Feasibility Study of MEMS Technique for Characterizing Magnetic Susceptibility of Subcellular Organelles

John Korkko\textsuperscript{a}, Emily Paukert\textsuperscript{b}, Susan Mantell\textsuperscript{b}, Bruce Hammer\textsuperscript{b}, Phil Williams\textsuperscript{b}

\textsuperscript{a}Department of Mechanical Engineering, \textsuperscript{b}Department of Diagnostic Radiology University of Minnesota, Minneapolis, MN, USA

INTRODUCTION

What is magnetic susceptibility, \( x (m^3/kg)? \)

The degree of magnetization of a material in response to an applied magnetic field. Magnetic force acting on material is a function of magnetic susceptibility, vacuum permeability \( \mu_0 \), the magnetic field \( B(T) \) and magnetic field gradient \( \frac{dB}{dz}(T/m) \).

Susceptibilities are known for various elements such as water \((9.051\times10^{-8} m^3/kg)\) and bismuth \((1.704\times10^{-8} m^3/kg)\).

Why do we want to identify \( y \) for subcellular organelles?

It is reasonable to assume that there is a 10\% variance between magnetic susceptibilities for different types of subcellular organelles. If individual susceptibilities are identified, it could be possible to target an individual organelle type for magnetic therapy.

OBJECTIVE

The objective of the present study is to determine if magnetic susceptibilities of subcellular organelles can be sensed with sufficient accuracy using magnetophoresis in combination with a CCD imaging approach.

MAGNETOPHORESIS

Approach

When particles with magnetic susceptibility are sent through a flowing channel with an applied magnetic field, they will straitly and separate. The amount of \( y \)-displacement is proportional to \( y/m \)

Previous research used a 6mm x 6mm x 20 \( \mu \)m channel with an average flow velocity of 3mm/sec and observed greater displacement when using a paramagnetic fluid.

Create a model of the particle movement

Assumptions:

- \( x \) has a constant \( x \)-direction velocity
- \( x \) is 2-dimensional and laminar
- \( x \) drifts along the \( x \)-axis
- \( x \) is uniform magnetic field and \( x \)
- \( x \) is paramagnetic \((x_0 \) different sign than \( x_0)\), thereby increasing the magnetic force.

Resulting in the following system of equations:

\[ F_x = \frac{2x_0 B V B}{\mu_0} \]

\[ F_y = 0 \]

\[ F_z = 0 \]

Fig. 1. Subcellular organelles refers to the organelles contained within a cell. Mitochondria, ribosomes, and nuclei are of particular interest here. These organelles vary in size from 20 nm to 22 \( \mu \)m and are dependent on the cell type.

Fig. 2. A general pictorial depiction of the magnetophoresis technique implemented through a simple flow channel oriented vertically (parallel to gravity) and perpendicular to the magnetic force.

Fig. 3. Free body diagram of particle forces.

Fig. 4. Flow channel orientation with respect to the magnet bore.

Fig. 5. Magnetic Velocity as a function of the particle size and magnetic field.

The magnetic velocity will increase with the cube of the particle diameter. Thus, the organelles can be clustered to improve the accuracy and resolution of measuring the magnetic susceptibility.

OBJECTIVE

The objective of the present study is to determine if magnetic susceptibilities of subcellular organelles can be sensed with sufficient accuracy using magnetophoresis in combination with a CCD imaging approach.

MAGNETOPHORESIS

Approach

When particles with magnetic susceptibility are sent through a flowing channel with an applied magnetic field, they will straitly and separate. The amount of \( y \)-displacement is proportional to \( y/m \)

Previous research used a 6mm x 6mm x 20 \( \mu \)m channel with an average flow velocity of 3mm/sec and observed greater displacement when using a paramagnetic fluid.

Create a model of the particle movement

Assumptions:

- \( x \) has a constant \( x \)-direction velocity
- \( x \) is 2-dimensional and laminar
- \( x \) drifts along the \( x \)-axis
- \( x \) is uniform magnetic field and \( x \)
- \( x \) is paramagnetic \((x_0 \) different sign than \( x_0)\), thereby increasing the magnetic force.

Resulting in the following system of equations:

\[ F_x = \frac{2x_0 B V B}{\mu_0} \]

\[ F_y = 0 \]

\[ F_z = 0 \]

Fig. 1. Subcellular organelles refers to the organelles contained within a cell. Mitochondria, ribosomes, and nuclei are of particular interest here. These organelles vary in size from 20 nm to 22 \( \mu \)m and are dependent on the cell type.

Fig. 2. A general pictorial depiction of the magnetophoresis technique implemented through a simple flow channel oriented vertically (parallel to gravity) and perpendicular to the magnetic force.

Fig. 3. Free body diagram of particle forces.

Fig. 4. Flow channel orientation with respect to the magnet bore.

Fig. 5. Magnetic Velocity as a function of the particle size and magnetic field.

The magnetic velocity will increase with the cube of the particle diameter. Thus, the organelles can be clustered to improve the accuracy and resolution of measuring the magnetic susceptibility.

Example:

- Particle size: 10 micron
- Camera: 200 p/mm (4 MP camera)
- View Length: 20 mm
- \( U_{mag} = 3.2 \) microns/second
- \( U_{mag}/U_{flow} = 0.1, 20 p/mm \)
- Particle would displace 400 pixels in given view length
- If 10\% increase in \( U_{mag} \), \( U_{mag} = 3.5 \) microns/second
- \( U_{mag}/U_{flow} = 0.11, 22 p/mm \)
- Particle would displace 440 pixels in given view length

Fig. 6. An image of light emission intensity from a particle, collected using a CCD and processed using a MATLAB program for position detection.

Fig. 7. Displacement due to magnetic susceptibility as a function of the flow ratios.

Fig. 8. Displacement of particle on 4 MP camera using magnetophoretic position detection method.

The capability of magnetophoresis to accurately detect a magnetic velocity is limited by: - Camera field of view - Local intensity of the magnetic field - Particle density \((p_i, pixels per unit length)\)

Future plans involve utilizing fluorescently tagged particles and a photodetector with pixel density on the order of 200 Mipixels/mm for evaluation.

ACKNOWLEDGMENTS

Funding provided by the Nanofabrication Center at the University of Minnesota