AN INTEGRATED, HIGH FLOW RATE MEMS FERROFLUID PUMP

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ABSTRACT

We present the design, numerical analysis, fabrication and experimental investigation of an integrated, high flow rate ferrofluid micropump. The dynamics of ferrofluids in spatially-traveling, sinusoidally time-varying magnetic fields is simulated. A prototype ferrofluid micropump is designed and fabricated based on the numerical simulations. Preliminary results show good agreement between theory and experiment.

Keywords: Ferrofluid, Micropump

1. INTRODUCTION

Ferrofluids are stable colloidal suspensions of nanosize ferromagnetic particles in either aqueous or oil-based media. A magnetic field gradient, combined with liquid viscous forces, allows continuous actuation and precise positioning of a ferrofluid segment in a flow channel [1]. Ferrofluids have found their way into a variety of applications, such as sealing, damping and blood separation [2]; in dilute, functionalized forms, they have also been used as drug delivery and MRI contrast agents [3]. Ferrofluids offer attractive alternatives to moving mechanical components in miniaturized cooling, pumping and integrated microTAS devices for chip-scale chemistry and biology. Water-based ferrofluids can be made bio-compatible, rendering them useful in novel cell manipulation and sorting schemes. Here, we present a new, integrated ferrofluid micropump design that achieves high flow rates. This device requires no external moving mechanical parts for actuation, and is suitable for fully-integrated microfluidic circuits.

2. THEORY

Ferrofluid pumping in spatially uniform, sinusoidally time-varying magnetic fields has been studied extensively in the past [4]. Our design is based on spatially travelling sinusoidal magnetic fields, which offer the advantage of utilizing both magnetic force and magnetic torque pumping to achieve high flow rates [5]. Our approach involves solving the magnetization constitutive equation with coupled linear and angular momentum conservation equations to model the behavior of ferrofluids in microchannels in the presence of spatially traveling magnetic fields [1]. Flow velocity for a given ferrofluid depends partly on the spatial period of the traveling wave and the channel dimensions; the frequency of the input excitation precisely controls the flow speed. Flow can be reversed by changing the traveling magnetic field direction. As shown in Figure 1, maximum flow velocity is achieved when the product of the excitation wavenumber and height of the ferrofluid channel approaches unity, and the excitation frequency is close to the reciprocal of the Brownian relaxation time constant of the magnetic nanoparticles.

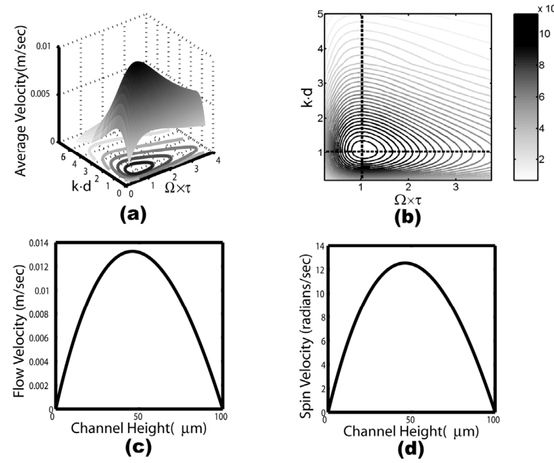

Figure 1. 3-D (a) and contour (b) plot of average flow velocity of ferrofluid versus the product of wave number and the height of the channel ($k \times d$) for various applied magnetic field frequencies. The Brownian relaxation time constant for the nanoparticles (τ), as well as the geometry determine the pumping peak. The flow velocity (c) and particle spin velocity (d) profiles across the height of the microchannel are also shown. Here, K_s = 10000 A/m, height of channel d = 100 µm, traveling wave period $\lambda = 2\pi/k$ = 1.26 mm, χ_0 = 1.17, τ = 3.75 μs, η = 0.0045 Kg/m.s, ζ = 0.00039 Kg/m.s, η' = 10^{-9} Kg/m.s (refer to [5] for symbol meanings). Relevant material properties correspond to the EMG 700 series ferrofluid (from FerroTec) used in actual experiments. The excitation frequency is 42 kHz, chosen to correspond to maximum pumping given τ.

3. FABRICATION

Figure 2 depicts the process flow and an initial prototype of the ferrofluid micropump designed based on previous numerical analysis. Initial devices are constructed on metal insulated substrates using standard wet etching of the top copper layer and subsequent soft lithography to define the microfluidic channels. SU-8 negative photoresist is used as an etching mask. The copper electrodes are connected by wire bonds to form a two-phase traveling magnetic field. Next generation devices will feature thick electrodes embedded in soft magnetic materials for optimal flux transfer to the ferrofluid [6]. A pair of external pressure sensors

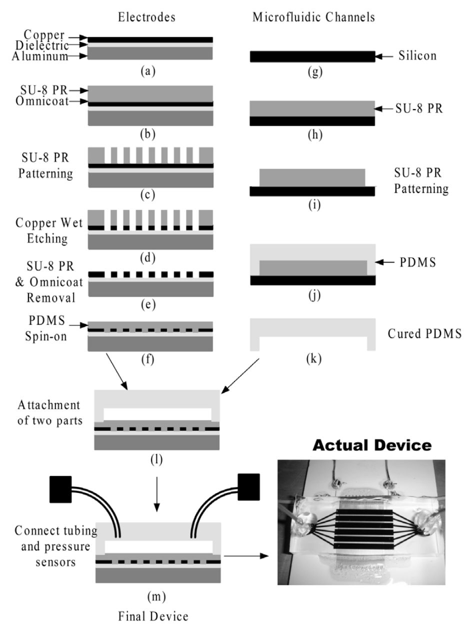

Figure 2. Fabrication process steps for the ferrofluid micropump and a picture of the completed device.

are currently utilized to measure the pumping pressure of the water-based ferrofluid.

4. EXPERIMENTAL RESULTS AND DISCUSSION

Figure 3 shows a sample TEM image and overall particle size distribution of the EMG 700 ferrofluid. The Brownian relaxation time constant (τ) of a ferrofluid is given by $4\pi r^3\eta_0/kT$, where r is the overall effective radius of the nanoparticles (a mode of 6.5 nm for EMG 700); η_0 is the viscosity of liquid (4.5 cp); k is the Boltzmann constant and T is the temperature (300 K). Based on the discussion in the theory section above, the ferrofluid pumping peak frequency is therefore expected to be around 42 kHz. Figure 4 compares the experimental ferrofluid pumping characteristics of the micropump to the predictions of the theory. Since static pumping pressure, and not fluid velocity, is measured, the numerical models are run iteratively to determine the pressure differential that results in stopped flow. The only fit parameter in the simulation is the magnitude scaling of the signal, which cannot not be eliminated owing to the difficulty of absolute pressure calibration of the sensors. Notice, however, that the pumping peak location is where it is expected.

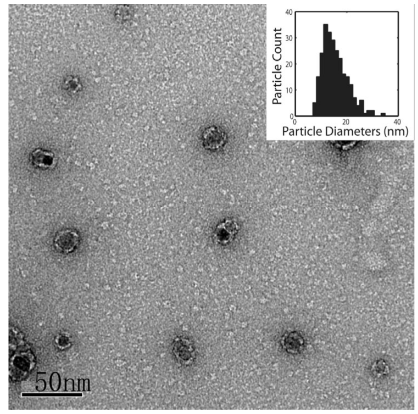

Figure 3. A sample TEM image of EMG 700 series water-based ferrofluid and the overall particle size distribution.

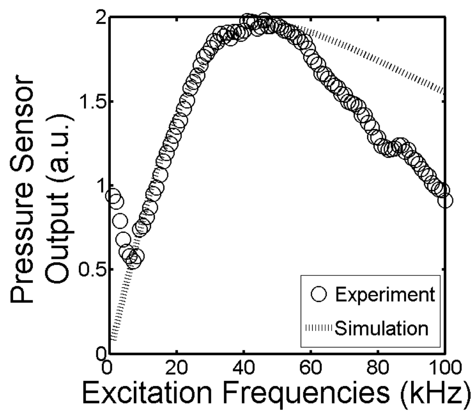

Figure 4. Experimental results and theoretical fit for the pumping characteristics of an EMG 700 series ferrofluid in the micropump.

The experimental pumping curve depicted in Figure 4 deviates in at least two ways from the simple theory that assumes a monodisperse suspension of particles and constant environmental conditions. First, at relatively very low frequencies, there is a minor pumping peak associated with a certain fraction of particles forming small agglomerates in the presence of the applied fields. The frequency of that minor pumping peak (around 1 kHz) indicates an effective hydrodynamic radius about three times that of the median. Secondly, there is a clear discrepancy between experiment and simple theory as the excitation frequency is increased beyond the main pumping peak. We believe this discrepancy is due to eddy-current heating of the aluminum substrate just under the electrodes and the dielectric layer, and gets worse with increasing frequency. Increasing ferrofluid temperature lowers the Brownian relaxation time constant and reduces pumping at high frequencies. Next generation devices will feature fully insulating, thermally high conductive substrates to alleviate this phenomenon.

5. CONCLUSIONS

We have presented the numerical modeling and experimental results of a ferrofluid micropump. Our theory successfully predicts the peak location of ferrofluid pumping based on Brownian relaxation dynamics of the magnetic nanoparticles inside the carrier liquid. The next step in the device development will involve measuring the ferrofluid pumping flow speed in closed-loop geometries directly using tiny fluorescently-tagged particles under a microscope.

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