A study on the novel type of ferrofluid magnetic pipette

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ABSTRACT

This study was performed to design the novel type of ferrofluid magnetic pipette on a micro scale for the purpose of applications to delivery systems, which is the core device of Lab on a chip in medicine and biology. The proposed ferrofluid magnetic pipette in this paper has been designed for precisely actuating and fast pipetting in submicronliter range. The magnetic dipole in ferrofluids line up with the applied field due to the permanent magnet with surface gauss 3400. The device was fabricated by MEMS technology with silicon wafer. The stepping motor with 20 steps was used as a control of pipetting. One step makes the permanent magnet move 18° in the circumferential direction and samples the liquid in nanoliter level. Of all things, it is a significant point that the possibility that a pipette for sampling the liquid can be integrated in lab on a chip is presented.

Keywords: ferrofluid, magnetic pipette, microfluidics, microchannel, MEMS.

1 INTRODUCTION

Recently, the field of microfuidics is growing very rapidly in both basic research and device development. A variety of microfluidic devices are developed for applications ranging from chemical analysis systems to actuating systems such as micro pump and micropipette of Lab on a chip (LOC) in medicine and biology [1]. Many researchers have tried to control the actuating and pumping components in the micron or submicron unit range in microfluidic devices [2]. Many methods and materials were used to realize the above problems. Those pumping and pipetting device had some disadvantages of combining a Lab on a chip in the reason of complex structure and fabrication process. The pumping and pipetting system using ferrofluid were studied in the previous researches [3], [4].

In this study, a new and very simple liquid delivery system is presented at the goals to control and pipette a tiny quantity of fluid in microchannels and show the possibility of integration of delivery system with the biochemical analytic systems in Lab on a chip. The sampling liquid can flow through the microscale channels by the ferrofluid magnetic pressure in a rounded microchannel. Also the sampling volume and flow rates are controlled by stepping motor.

2 FERROFLUID AND THEORY

Ferrofluids or Magnetic fluids are stable and colloidal dispersion of sub-micron sized single domain magnetic particle in carrier liquids [5]. The carrier liquid can be an organic solvent, water, or a variety of oil bases. The particles, which have an average size of about 100Å, are coated with a stabilizing dispersant which prevents particle agglomeration even when a strong magnetic field gradient is applied to the ferrofluid. These suspensions are stable and preserve their properties at extreme temperatures and over long period of time[6]. In this study, we chose a synthetic iso-paraffinic magnetite ferrofluid (EMG-901) with a saturation magnetization of 600G made by Ferrotech.company. The physical and magnetic properties of the fluid are shown in Table 1. This ferrofluid is composed of base liquid, ferromagnetic particles and chemically adsorbed surfactant. The vigorous thermal-movement makes particles avoid settling, and the repulsion caused by surfactant prevent aggregation between particles. As a result, it is so stable that no separation occurs.

The pressure due to the ferrofluid under the applied magnetic field is able to be predicted considering the ferrohydrodynamics[5].

For the irrotational flow of an incompressible ferrofluid, the equation of motion is given by

$$\rho adsv\frac{dv}{ds} = -a\frac{dp}{ds} = -a\frac{dp}{ds}ds - \rho adsg\sin\alpha + \mu_0 M\frac{dH}{ds}ads \quad (1)$$

where v, ρ, and M are the velocity, density and magnetization of the ferrofluid, respectively. p is pressure, g is the acceleration due to gravity, μ_0 is the free space magnetic permeability and H is the intensity of magnetic force density. The magnetic pressure can be obtained from equation (1).

$$P_{mag} = \mu_0 \int M dh + \frac{1}{2}\mu_0 M_n^2 \quad (2)$$

Equation (2) is composed of the body force and surface force terms of ferrofluids in the external magnetic field.

Table 1. EMG901 ferrofluid physical properties

Property	value	units
Density @ room temperature	1.53	g/cm^3
Viscosity @ 27°C	10	dyne-sec/cm^2
Magnetic Saturation	600	Gauss
Particle Size	100	Angstroms = 10^{-10}m

The constant frictionless pressure drop in the length of channel with a rectangular cross section area is calculated using the Hagen-Poiseulle equation that express the flow in a duct by the pressure difference[7].

$$\frac{\Delta P}{L} = \frac{Q(12\mu)}{wh^3} \qquad (3)$$

where w is the width of channel, h is the height of channel, Q is flow rate, μ is viscosity of the working fluid, L is the length of channel, ΔP is pressure drop.

The pressure drop in equation (3) also can be expressed by equation (2) in the case the working fluid is ferrofluids.

Therefore the pressure gradient from the Hagen-Poiseulle equation when the flow rate is known can be compared to the magnetic pressure. However it is reported that the calculated magnetic pressures with an appropriate demagnetization factor have higher values than measured pressures. Hence we believed in experimental values only.

3 DESIGN AND FABRICATION

The schematic of structure of ferrofluid magnetic pipette is shown in the figure 1. The device is composed of the microchannel in silicon wafer, permanent magnet and stepping motor.

The microchannel is divided of three parts, the rounded channel that is filled with ferrofluid, the linear channel that is passage of the sampling liquid and the reservoir. The dimension of diced silicon microchannel is $15 \times 28 \times 0.8\,\mathrm{mm}^3$. The permanent magnet is attached to the stepping motor (SP-15RF), which has the dimension of 15.7mm height and 15mm diameter respectively. The permanent magnet should have the so high magnetic field that was selected the neodymium composite (3mm diameter, 2mm thick, surface Gauss=3400).

The intensity value of magnetic field from the center of permanent magnet to the edge of that is measured with Gauss meter (F.W.BELL,Model 5080)and shown in the figure 2. The intensity of magnetic field was sharply decreased from the edge of permanent magnet to the outside. Therefore, the edges of ferrofluid in a rounded channel should be near in the range of the diameter of the permanent magnet. The actuated principle of ferrofluid magnetic pipette is illustrated in figure 3. The ferrofluid is injected into the rounded channel and the sampled liquid is filled in the straight channel. The air is in the space between the ferrofluid and the pipetted liquid.

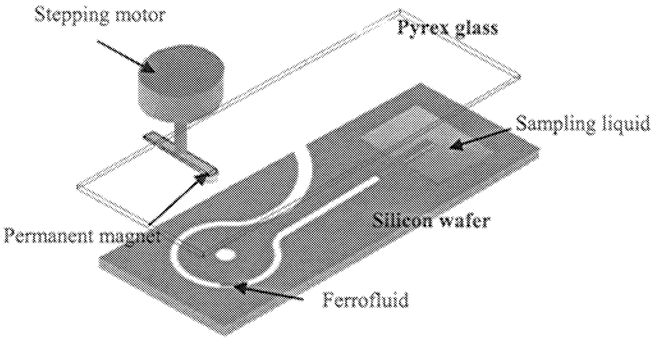

Figure 1. The schematic of the ferrofluid magnetic pipette

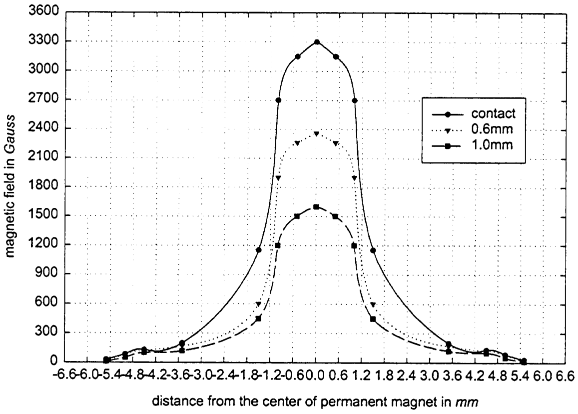

Fig 2. The gradient magnetic field in permanent magnet

The ferrofluid is flowing through the rounded channel under the gradient magnetic field resulted from the movement of permanent magnet controlled by stepping motor.

Then the sample liquid exactly flows through the straight channel as much as the distance at which ferrofluid move by magnetic pressure gradient arisen from the movement of permanent magnet in the rounded channel. So the core point of pipetting control is the step angle of the motor. The step angle used in the device is 18^0. Therefore, step angles and the microchannel dimensions determine the volume of sampling liquids.

The device was fabricated in simple way used MEMS technology. A prime-grade-4 in (100) silicon wafer was oxidized thermally and patterned.

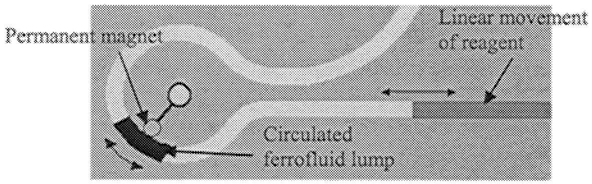

Figure 3. The schematic of the principle of ferrofluid magnetic pipette

Table 2. The dimension of the fabricated microchannels

Channel No.	Width(μm)	Depth(μm)	D_h(μm)
1	1000	100	181
2	500	100	167
3	100	100	100

The rounded channel, the straight channel and the reservoir were formed.

Finally, both wafers were anodically bonded. Because the fabrication process is very simple and the traditional photolithography methods as well as other materials are able to be used in stead of the silicon wafer, the proposed ferrofluid magnetic pipette is easily fabricated with the other microfluidic systems in Lab on a chip (LOC). The dimension and hydraulic diameter of the microchannel were shown in the table 2.

4 EXPERIMENTS AND RESULTS

The intensity of magnetic field was measured according to the distance deviation from the surface of the permanent magnet. The results were shown in figure 4. The magnetic field was sharply decreased until the probe of gauss meter (F.W.BELL, Model 5080) reached up to 2mm from the surface of the permanent magnet. Also, in the region above 2mm, the intensity of magnetic field was below 600G which intensity can be saturated the ferrofluid, EMG901.

The quantitative procedure was used in order to measure the magnetic pressure of ferrofluid. In 1976, Perry and Jones used this method. The figure 5 shows the schematic of experimental setup. In Teflon tube (1.4mm inner diameter, 0.7mm tube thickness) with hydrophobic character the water and the ferrofluid was filled like figure 5. Then permanent magnet attached to the micrometer moved away from the Teflon tube gradually. Then the magnetic pressure was estimated inclining the experimental setup in similar to the principle of an inclined manometer.

The maximum value of magnetic pressure gradient according to the distance from the surface of permanent magnet is plotted in figure 6. The maximum pressure gradient at the surface was 91.4Pa/mm.

The sampling volume per a step in each microchannel was shown in table 3. Namely, the step angle of a stepping motor determines the pipetting volume and also the flow rates depend on the stepping motor speed. In this study, the stepping motor with 20 steps was used. The microscope image of a sampling flow in 1000 μm width channel was shown in figure 7. The distance of a flow can be checked using the ruler pattered beside the channel.

The experiment on ferrofluid flows in a rounded channel was conducted as stepping motor speed changes. The stepping motor speed was increased from 10rpm to 30rpm. The results were shown in the figure 9. In each speed, the distance was controlled between a permanent magnet

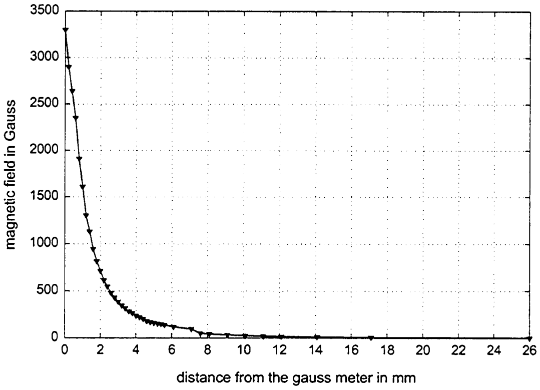

Figure 4. The magnetic field of permanent magnet due to the distance variation

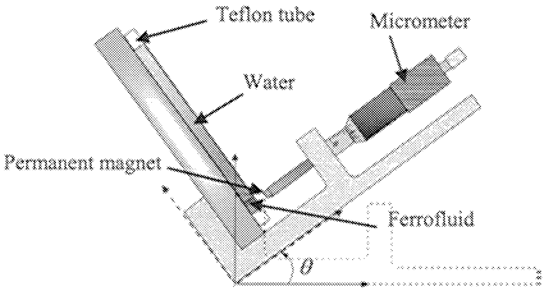

Figure 5. The schematic of experimental setup of the magnetic pressure

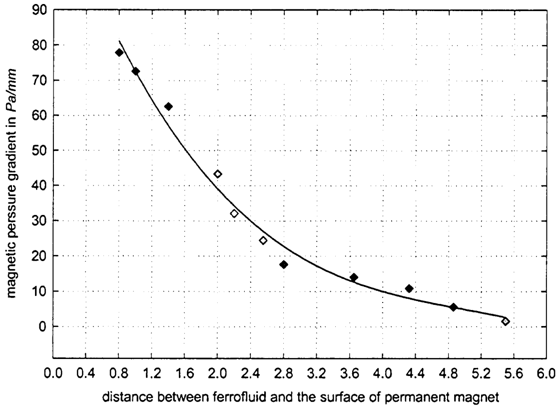

Figure 6. The magnetic pressure gradient due to the distance variation

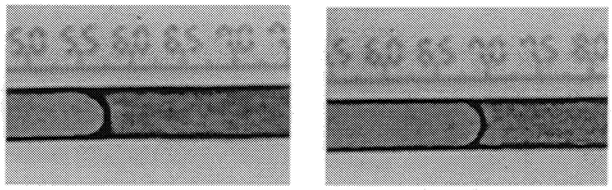
(a)
(b)

Figure 7. The microscope image of the sampling liquid flows per a step

Table 3. The sampling volumes per a step of the stepping motor

Microchannel width (μm)	Microchannel depth (μm)	D_h (μm)	Vol/step (nl)
1000	100	181	62.5
500	100	167	33.4
100	100	100	7

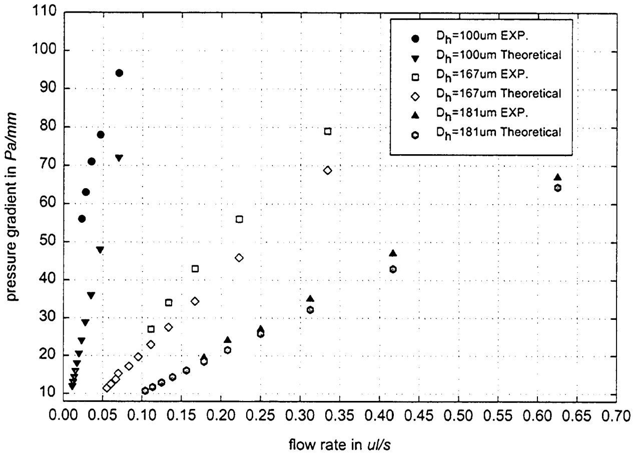

Figure 8. The comparison of pressure gradients in microchannels

attached to the motor and ferrofluid in the rounded channel. The values of magnetic pressure gradient were read in the figure 6 after measuring the distance between the ferrofluid and the surface of permanent magnet.

The measured minimum values are a little higher than the computed ones. The reason is that the apparent viscosity of the fluid becomes the sum of the fluid viscosity and the roughness viscosity [8]. The roughness in the wall of the microchannel increases as the hydraulic diameter is smaller and then the effect of roughness viscosity becomes more significantly.

5 CONCLUSION

In this paper the novel type of ferrofluid magnetic pipette was presented. The device was fabricated using the conventional MEMS technology based on the silicon wafer for an application of the integration of the microfluidic system in Lab on a chip (LOC). The magnetic pressure was measured and compared with the computed one. The maximum magnetic pressure gradient is 91.4Pa/mm. And we found so smooth flows of ferrofluid and sampling liquid in microchannel even at the speed of 30rpm without leakages.

As compared with the previous ferrofluid magnetic pipette, this device has no heat generation so that there is no harmfulness of biological liquid and no denaturalization of reagents and the response time is so fast because the permanent magnet is used instead of the electromagnet.

The stepping motor size we used was a little big. However, because the permanent magnet can be moved using the very small torque of motor, we can use the smaller motor. Then the dimension of the device could be downsized.

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