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MAGNETIC ACTUATION OF NANOFLUIDS WITH FERROMAGNETIC PARTICLES

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ABSTRACT

Electromagnetically actuated microflows are generated by using ferromagnetic nanofluids containing Fe_2O_3 based nanoparticles. Because of their magnetic properties these nanoparticles are able to response to a magnetic field imposed along a microchannel so that a microflow could be driven. Nanofluid samples were located inside a minichannel and were directed with a magnetic field, which was induced by a solenoid wrapped around the minichannel, to drive the flow inside the minichannel, where its flow rate was also recorded.

The flow rate was measured as a function of the imposed magnetic field. The corresponding pressure drop to deliver the same flow rate with an ordinary pump along the same minichannel was estimated so that the potential of this system for acting as a micropump in microfluidic applications was revealed.

1.0 INTRODUCTION

Nanofluids are fluids having suspended nanoparticles of nanometer-size and chemistry (metals, oxides, carbides, nitrides, or nanotubes). If they contain ferromagnetic nanoparticles, they are generally called ferrofluids. Ferrofluids get strongly magnetized when subjected to a magnetic field. Thermal agitation drives the nanoparticles back to a homogenous low energy state as soon as the magnetic field is removed. Thus, ferrofluids can be thought more as ‘superparamagnetic’ in nature than ferromagnetic [1].

Nanofluids are widely used in applications where necessary samples should be treated in small quantities just as microfluidic systems are used in analytical separations [2]. Much attention has been focused recently on miniature systems for chemical and biological analysis [3-10]. Nanofluids offer enhanced performance in microfluidics such as thermal management in microfluidic systems and micropumping [3]. Valveless micropumps have been considered as 'long runners' in science [11] and magnetic actuation of nanofluids could be a strong candidate for this.

Microfluidic devices are required to dispense tiny amounts of fluids which turns the control of these devices into an immense challange. These devices are widely used in drug delivery. A typical drug delivery system includes microsensors, microchannels and micropumps along with their related circuitry [12]. Flow control is an important aspect for such microfluidic devices. In order to release required amount of drugs in a specific amount of time, microfluidic devices are in urgent need for precise flow rate control. Traditionally, electrokinetic effects (electroosmosis and electrophoresis) and mechanical gear pumps have been used to achieve flow control and delay [1]. As technology evolves, new micropumps are required more for compactness and lightness compared to the existing methods. In order to meet this demand nanofluid actuation is considered in this study. Electromagnetic actuation of nanofluids requires less energy consumption, occupies less space and does not generate excess heat. Thus, nanofluid actuation is proposed as an alternative to traditional pumps.

Pumps can be divided into two major categories: displacement pumps, which generally depend on moving or deforming walls exerting pressure forces on the fluid and dynamic pumps, which continuously add energy to the fluid in a manner that increases either its momentum (e.g centrifugal pumps) or its pressure directly (e.g electroosmotic and electrohydrodynamic pumps) [3]. Displacement pumps generally work by oscillations in the fluid boundaries and thus producing a steady flow. A good example would be piezo-electric pumps. Gear pumps are also examples of displacement pumps since they rotate continuosly pushing the fluid on one side and creating suction on the other. Dynamic pumps, on the other hand, include centrifugal pumps but these pumps have not yet been miniaturized considerably. Other examples of dynamic pumps would be electrohydrodynamic, magnetohydrodynamic and electroosmotic pumps in which an electromagnetic field attracts the fluid, as in our case, to produce flow. These kinds of pumps can be miniaturized to a great extent and operated with low power consumption which is a great advantage compared to its counterparts. This study addresses to this potential and explores the applicability of magnetic actuation of nanofluids to micropumping applications.

NOMENCLATURE

Symbol	Description
B	Magnetic Field
μ_0	Permeability of free space
N	Number of turns
I	Current
F	Force
u	Velocity in x direction
v	Velocity in y direction
p	Pressure
ρ	Density of the Fluid
L	Length of the Solenoid
F_b	Body force acting on the fluid due to magnetic field
$\dot{Q}$	Volumetric Flow Rate
A	Cross sectional area
Δx	Displacement
Δt	Time
D	Inside diameter of the minichannel
f	Friction Factor
Δp	Pressure Drop
Re	Reynolds Number
μ	Viscosity of the Fluid

2.0 OVERVIEW ON NANOFLUIDS AND THEIR PREPARATION TECHNIQUES

Nanofluid Properties

Nanofluids are fluids having suspended nanoparticles of nanometer-size and chemistry (metals, oxides, carbides, nitrides, or nanotubes). In this study, samples of nanofluid containing ferromagnetic particles have been used. These kinds of nanofluids can be actuated by the application of a magnetic field. The actuation of these ferromagnetic nanoparticles should further drive its base liquid's molecules along so that a flow could be generated. For this purpose, a nanofluid sample was prepared, namely AKY028. To decrease their viscosities and thus to facilitate their motion inside the liquid, nanoparticles of AKY028 were coated with NH_2. The sizes of the ferromagnetic nanoparticles in the sample AKY028 were measured as 23 nm. Table 1 shows some properties of the nanofluid sample used in this study. Dh-I refers to hydrodynamic diameter measured with Dynamic Light Scattering (DLS) using scattered light intensity and Dh-N uses DLS with numerical averaging.

Nanofluids Preparation

$FeCl_2$ and $FeCl_3$ salts (Fe^{+3}/Fe^{+2} mole fraction) were dissolved in deoxygenated water. Mixture was heated under nitrogen at 85°C and ammonium hidroxide was added to the mixture. In AKY028 sample, coating solution was added to the mixture after the addition of iron salts. All fractions are given in Table 1. The mixture was blended for 30 minutes and cooled down to room temperature. Mixture was then placed above a magnet which generates a magnetic field of 0.3 T(tesla) and was left for a night. Precipitated particles are removed from the mixture. Excessive coating materials were removed with pure water from ultrafiltration tubes. The entire volume was replaced with pure water three times.

Fluid Property	AKY028
Fe [M]	0,175
Si/Fe [mole %]	1,25
Base/Fe [mole %]	1,5
Dh-I [nm]	23-100
Dh-I washed [nm]	23
Dh-N [nm]	32-100
Dh-N washed [nm]	28
Density (Assumption) [kg/m3]	1500
Viscosity (Assumption) [Ns/m-2]	0,0025

Table 1. Nanofluid Properties

3.0 EXPERIMENTAL SETUP AND PROCEDURE

Electromagnetic field is generated by a solenoid wrapped around a plastic tube of length of 9 cm. Inside and outside diameters of tube are 1.95 mm and 3.15mm respectively. Copper wire is wrapped around the tube and has a total of 200 windings. The experimental setup is demonstrated in Fig. 1. The solenoid is directly connected to a power supply from both ends. Voltage is applied through the wire and the current flowing through the wire is measured. The current induces a magnetic field within the minichannel (Fig. 2). The induced magnetic field creates a magnetic body force on the nanoparticles inside the nanofluid which in turn drives the nanofluid and causes the fluid flow. Fluid displacement is observed in the horizontal tube at varying voltages and flow rate is measured accordingly with the input of fluid displacement with time.

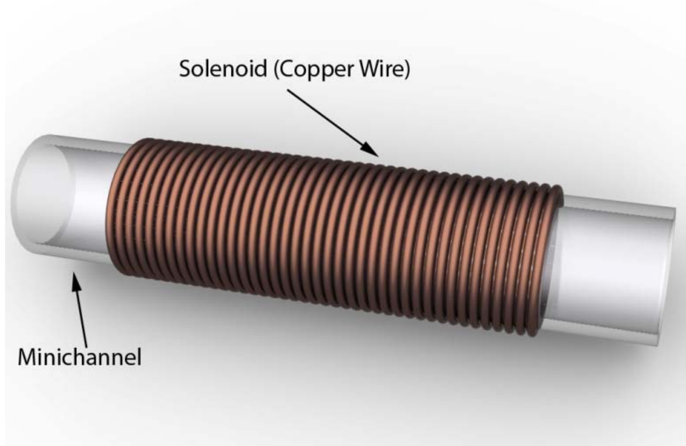

Figure 1. Experimental setup

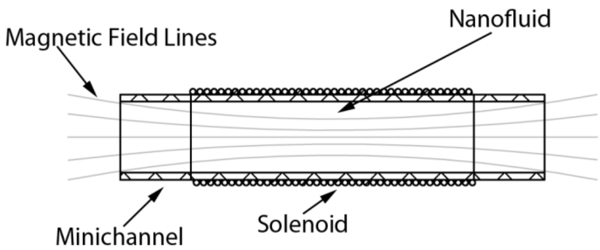

Figure 2. Section view of the setup showing magnetic field lines

4.0 THEORY & DATA REDUCTION

The magnetic field induced within the minichannel was generated by a solenoid formed by wrapping thin wire around the minichannel and the resulting magnetic field can be expressed as:

$$B = \frac{\mu_0 NI}{L} \quad (1)$$

where

$$\mu_0 = 4\pi \times 10^{-7}\ [Hm^{-1}] \quad (2)$$

In this equation μ_0 is the permeability of free space, B is the induced magnetic field in Henries, N is the number of turns, L is the length of the solenoid in meters and I is the current passing through the system in amperes. The magnetization of the ferrofluid by external magnetic field generates a magnetic volume force which drives the flow within the minichannel [1]. This force is denoted as F_b. As a result, the flow could be modeled with Navier-Stokes equations:

$$\rho\left(u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y}\right) = -\frac{\partial p}{\partial x} + \mu\left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2}\right) + F_b \quad (3)$$

The flow rate across the minichannel generated by the magnetic field is measured as a function of both the magnetic field and the wattage drained by the micropump. Magnetic field is calculated analytically whereas the wattage is directly read from power supply display. The displacement of the fluid is recorded as a function of time and used to deduce the flow rate using the channel cross sectional area and the displacement:

$$\dot{Q} = \frac{A\Delta x}{\Delta t} \quad (4)$$

where $\dot{Q}$ is the volumetric flow rate given in ml/min, Δx is the displacement measured experimentally and Δt is the elapsed time. To obtain the same flow rate with conventional means, a definite pressure drop should exist between the inlet and the exit of the minichannel. Under the laminar flow conditions the necessary pressure drop is given as:

$$\Delta p = \frac{f}{2}\frac{L}{D}\rho\frac{\dot{Q}^2}{A^2} \quad (5)$$

where Δp is the pressure drop across a channel of length L, diameter D and cross sectional area A containing a fluid of density ρ which flows with a flow rate of $\dot{Q}$. The friction factor, f, is then given by:

$$f = \frac{64}{\rho\dot{Q}D}A\mu \quad (6)$$

where μ is the viscosity of the fluid. Finally, Reynolds number is expressed as:

$$Re = \frac{\rho u D}{\mu} \quad (7)$$

where u is the velocity of the moving fluid calculated as:

$$u = \frac{\dot{Q}}{A} \quad (8)$$

Uncertainty Analysis

The uncertainties of the measured values are given in Table 2 and are derived from the manufacturer's specification sheet while the uncertainties of the derived parameters are obtained using the *propagation of uncertainty* method developed by Kline and McClintock [13].

Uncertainty	Error
Voltage	±0.1 V
Current	±0.1 A
Resistance	±0.01 Ω
Area	±0.01 mm^2
Displacement	±0.1 mm
Time	±2 sec
Length	±0.1 mm
Power	4.6%
Magnetic Field	1.13%
Volumetric Flow Rate	1.02%

Table 2. Uncertainty Figures in Data

5.0 RESULTS & DISCUSSION

The results gathered from the experiments show that a locally linear profile can be achieved with the experimental setup. The power consumption of the proposed micropump is graphed against the corresponding volumetric flow rates given in milliliters per minute in Fig. 2. The flow rate can easily be controlled with the linear correlation for the provided data. The correlated R^2 value, which quantifies the error in a mean squared manner, is calculated as 0.9969 which is very promising.

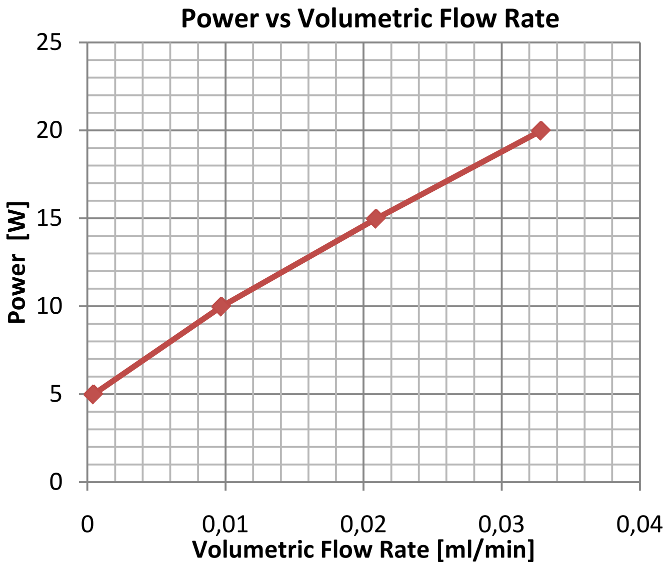

Figure 3. Power vs. Volumetric Flow Rate

Same results are also correlated according to calculated magnetic field induced within the minichannel and can be seen in Fig. 3. The flow rate profile is again linear when it is plotted against magnetic field given in Teslas. The linear approximations can be used to further deduce F_b which is the body force acting on the volume of the fluid. The R^2 value is calculated as 0.9761 in this case.

The relationship between input voltage and the flowrate is shown in Fig. 4. As seen from this figure relatively low voltages are required to obtain considerable flowrates with magnetic actuation compared to electroosmotic flow, where typically high voltages should be applied to drive the fluid. This proves the advantage of the proposed method over electrokinetic micropumping methods and also its practical nature.

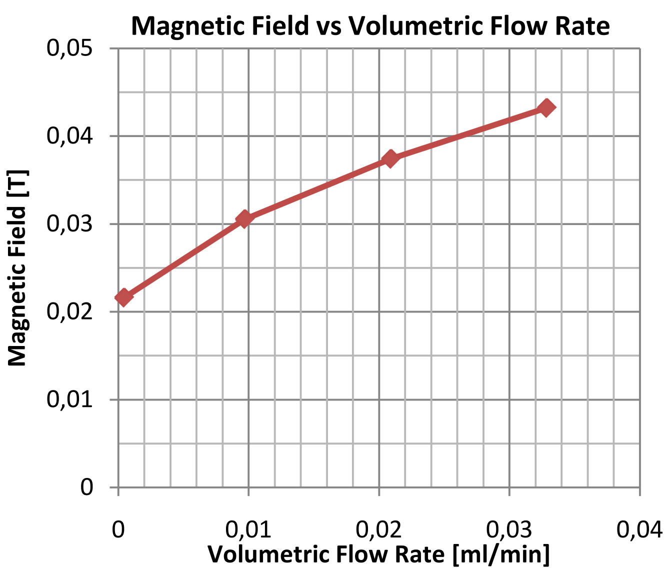

Figure 4. Magnetic Field vs Volumetric Flow Rate

The pressure drop across the minichannel is calculated analytically (Fig. 6) using the results from the experiments and implementing them into Equations (5) and (6). The pressure drops are found to be on the order of magnitude of 100mPa.

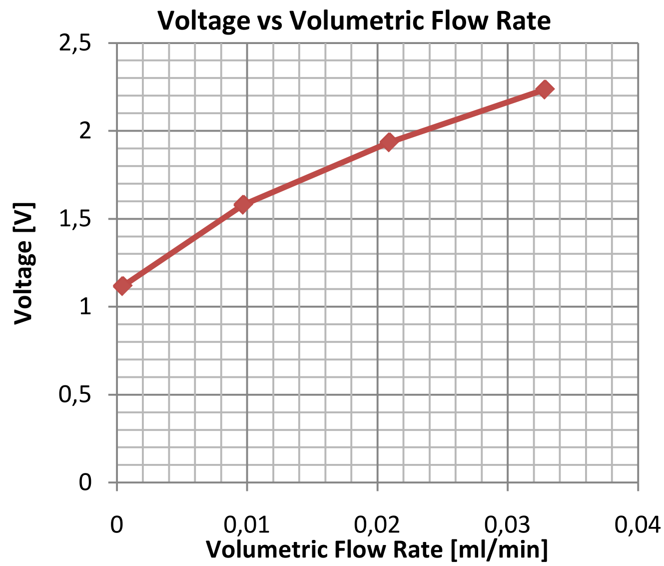

Figure 5. Input Voltage vs Volumetric Flow Rate

The Reynolds number, which quantifies the inertial forces to viscous forces ratio, is also important for characterization of flows. Thus, it was calculated theoretically and plotted against volumetric flow rate (Fig. 7). The calculated Reynolds number values are smaller than 1 which indicates that the flow is creeping under the experimental conditions of this study so that we can neglect the inertial terms in the Navier-Stokes equations.

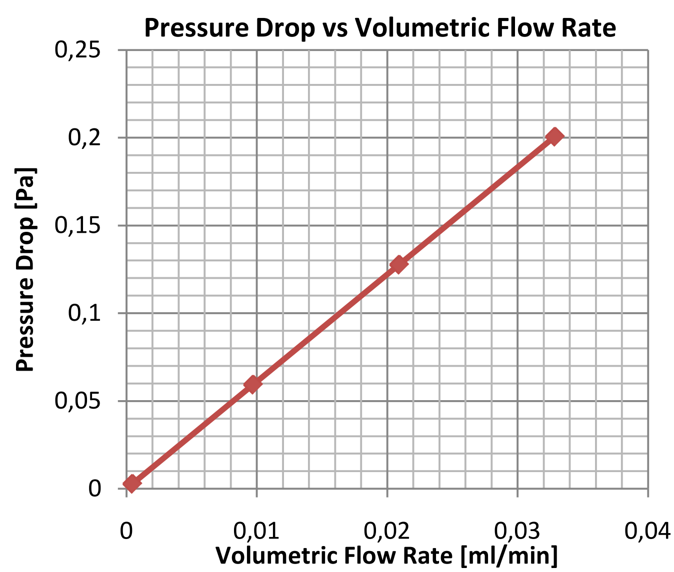

Figure 6. Theoretical Pressure Drop vs Volumetric Flow Rate

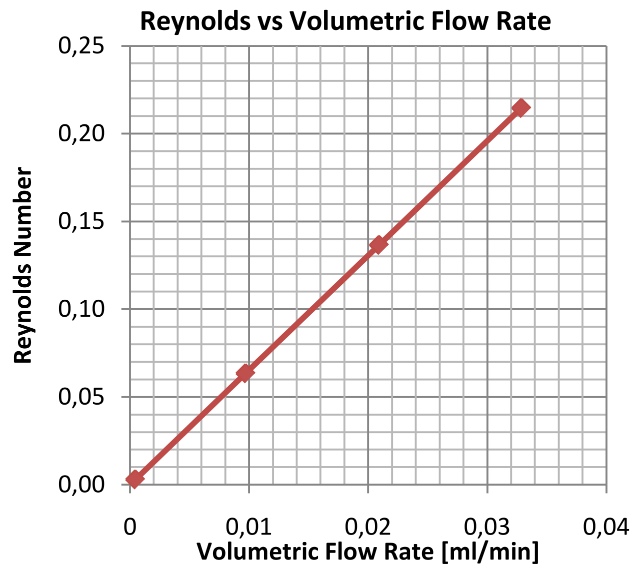

Figure 7. Theoretical Reynolds Number vs Volumetric Flow Rate

6.0 CONCLUSION

This paper reports a magnetically actuated pump in which nanofluid samples containing ferromagnetic nanoparticles are driven with an induced magnetic field generated by a solenoid wrapped around a minichannel. The results show that flow rates as high as ~30 µl/min can be achieved with 20 Watts of power consumption with the proposed micropumping technique. The flow can be controlled precisely down to ~5µL/min with the pumping device. Such precise flow control devices are required in drug delivery systems. Further studies include correlating the proposed body force F_b acting on the volume of the nanofluid with the induced magnetic field, B, extending the pumping capabilities through usage of various nanofluids with varying physical properties and implementing this technique to smaller channels (micro/nanochannels).

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