Implementation of a Simplified Method for Actuation of Ferrofluids

Evrim KURTOĞLU[1], Alp BİLGİN[1], Muhsincan ŞEŞEN[1], Havva F. YAĞCI ACAR[2], and Ali KOŞAR[1, *]

[*]Corresponding Author: Tel: +902164839621; Fax: +902164839550; Email: kosara@sabanciuniv.edu
1: Faculty of Engineering and Natural Sciences, Mechatronics Engineering Program, Sabancı University, Istanbul, Turkey
2: Faculty of Engineering and Natural Sciences, Department of Chemical Engineering, Koç University, Istanbul, Turkey

Abstract Magnetic actuation of ferrofluids is an emergent field that will open up new possibilities in various fields of engineering. The quality and topology of the magnetic field that is being utilized in such systems is determinant in terms of flow properties, flow rates and overall efficiency. Determining the optimal magnetic field topology to achieve the desired results, and determining the methods by which these magnetic fields are to be generated are central problems of obtaining the desired flow. A healthy comparison of various magnetic field topologies requires a varied set of examples from the most simplified to most sophisticated. Such comparisons are necessary to have a well grounded starting point. This study focuses on a particular pump design that employs a simplified magnetic field topology to obtain ferrofluid flow. The results of this paper such as flow and pressure difference are intended to form a baseline for future reference.

Keywords: Continuous Flow, Micropumps, Ferrofluids, Magnetic Actuation

1. Introduction

Many research efforts have been focused on micropumps for more than three decades, the number of studies on this field still increasing so that an impressive variance of micropump designs and concepts have emerged during that time such as microdiaphragm pumps, peristaltic, electrohydrodynamic, electromagnetic, magnetohydrodynamic, electroosmotic and thermopneumatic micropumps. Almost every MEMS (Microelectromechanical Systems) based actuation principle was combined with micropumps based on nonconventional materials such as ferrofluids, which implement pumping operations via magnetic field gradient [1][2]. The use of ferrofluid was an innovative actuation method for fluid handling since magnetic particles offer additional functional advantages since a magnetic force could be easily applied on a magnetic particle by inducing a magnetic field gradient [3]. Moreover, the pumping strategy implemented by using ferrofluids is free of mechanical moving parts thereby avoiding stress and increasing the life time of the device [4]. Because of the above mentioned diversity of the micropumps, it is possible to divide them into two groups: reciprocating micropumps and continuous flow micropumps. The oscillatory movement of mechanical parts is used to convert mechanical energy to fluid movement by reciprocating pumps. The working fluid is delivered in a series of plugs, which results in a fluctuating flow. On the other hand, continuous flow micropumps directly transfer a nonmechanical or mechanical energy into the fluid movement. Electrohydrodynamic, electroosmotic, magnetohydrodynamic and ultrasonic micropumps are some examples of the continuous flow micropumps [1][5]. The previous studies of SU (SabanciUniversity) Microfluidics Research group were on reciprocationg micropumps. As a result of these studies, it was observed that to be able to obtain laminar continuous flow, it is crucial to determine the optimal magnetic field topology and methods to generate this magnetic field [6][7]. In this study, under the light of the mentioned previous studies, a magnetomechanical micropump is presented as an implementation of a simplified method for actuation of ferrofluids in mini and microscale.

2. Theory

The magnetic force on a magnetized particle is dependent on a non-zero magnetic field strength and a non-zero field gradient, as expressed in Equation 1 [8]. Where x_p and x_c are magnetic permissivities of composite medium, μ_o is the magnetic susceptibility of free space, V is magnetisable volume,B is the magnetic field strength and ∇ is the gradient operator.

$$F_{mag} = \frac{(x_p - x_c)VB\nabla B}{\mu_o} \quad (1)$$

Using a magnetic field of homogenous field strength to move magnetic materials is still possible, if the field is in motion and only a fraction of the fluid is inside the field's boundaries. The moving field boundaries act as the gradient that is necessary for this force. The components of the motion, which are parallel to the tube, generate the motion. Theoretically, manually sliding a magnet over a tube filled with ferrofluid is sufficient for inducing a flow. The proposed mechanism is intended to formalize this method and provides a repeatable experiment that yields promising results. In simpler terms, the mechanism will drag magnets along a finite length of a micro tube to propel the working fluid along the microtube.

The basic principle in this proposed design is putting simplicity above all else. Rare earth magnets are attached to a timing belt that is stretched parallel to the tube that contains the ferrofluid as shown in Figure 1. The magnetic material is expected to flow through the tube when the timing belt drags the magnets parallel to the tube. The magnet rotates towards the tube in the beginning and magnetizes a fluid plug, which is pulled along by the moving magnet. At the end of the pump is released. Rare earth magnets that are 1cm in diameter, and have a near surface magnetic field strength of 0.3 T are used. Magnets are placed 4 cm apart from each other, or the closest approximation depending on the limitations of length of the stock timing belts available. The magnets that are in the tube's close proximity will simultaneously drag multiple magnetized fluid plugs along the same direction at the same speed to increase the transmitted power.

The magnetic field boundary is prone to magnetize the next available magnetizeable particle instead of moving the currently magnetized particle. Additional care must be taken to ensure that the speed of the magnetic field is sufficiently slow that no such skipping of particles occurs.

In this experiment the pressure difference forced by the pump is correlated with the current drawn by the motor. Considering the constraint mentioned above the pump is expected to have an optimum pumping speed above which the efficiency will be constant.

The input will be the current drawn by the motor of the pump and the output will be the pressure difference calculated from the observed height differences of fluid containers as shown in Figure 1.

The pressure drop is calculated from the hydrostatic pressure equation [9] where ρ is the fluid density, g is gravitational acceleration constant, h_o is the height of fluid in output container and hi is the height of the fluid in input container:

$$\Delta P = \rho g(h_o - h_i) \quad (2)$$

The flow velocity is determined as an approximate average by dividing the total volume by the transient time during which the fluid flows. Equation 3 is a formal representation, where $\dot{Q}$ is volumetric flow rate, $\sum V$ is total volume transferred, t is total time:

$$\dot{Q} = \frac{\sum V}{t} \quad (3)$$

3. Experimental Setup and Procedure

3.1 Ferrofluid Preparation

The nanofluid used in this experiment was prepared by mixing two aqueous Fe^{+2} and Fe^{+3} solutions of appropriate molar concentrations.

The surfactant molecules are introduced during titration to prevent aggregation and precipitation. Nanoscale superparamagnetic particles that are soluble in water due to attached surfactants are the end result of this process.
$FeCl_2$ and $FeCl_3$ are preferred ion sources for the indicated process, and lauric acid is the surfactant molecule particular to the SPIO-LA specimen. The particle size is 25 nm on average. Considerably small and uniform particle sizes are generally achieved through controlling the rate of addition of the base to the reaction environment.

Table 1.Ferrofluid Properties

ID	[Fe] (M)	Si/Fe (mole %)	Base/Fe (mole %)	Dh-I (nm)	Dh-I washed (nm)	Dh-N (nm)	Dh-N washed (nm)
SPIO-LA	0,17	1,25	1,5	23-100	23	32-100	28

3.2 Experimental Setup

The experimental setup design was constructed as a platform for testing of a fundamental idea that is taken for granted in magnetic actuation so that the effectiveness of a moving homogenous magnetic field strength distribution, as a means of ferrofluid actuation, could be tested. See Figure 1 for a representation of distributed magnetic plugs and their positions relative to the magnets.

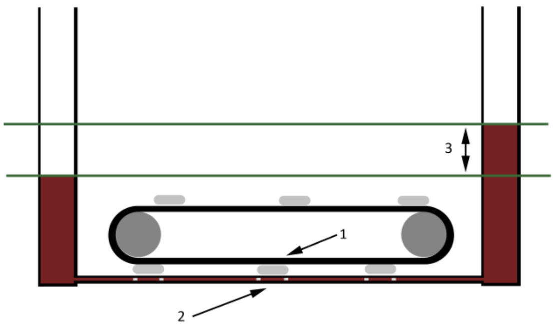

Figure 1. A schematic of the experimental setup. 1 indicates light grey colored magnets and black colored timing belt. 2 indicates the brown colored inert ferrofuid and white colored ferrofluid plugs that are dragged along the channel by magnetic forces. 3 indicates the steady state height difference induced by the pump.

The promising results will potentially serve as a ground value for reference charts in future.
The pump was manufactured by fitting two ball bearings on the grooves of a stock part. Two pulleys reside on two individual shafts that fit into individual ball bearings. A timing belt is stretched across the pulleys and rare earth magnets are placed on the timing belt with cyanoacrylate adhesive. A gear is affixed to one of the shafts, while another gear is affixed to a DC torque motor. When the gears are connected and the motor is supplied with current, the timing belt rotates the magnets. The path of each individual magnet is parallel to the tube for half of the rotation period as shown in Figure 2 second division.

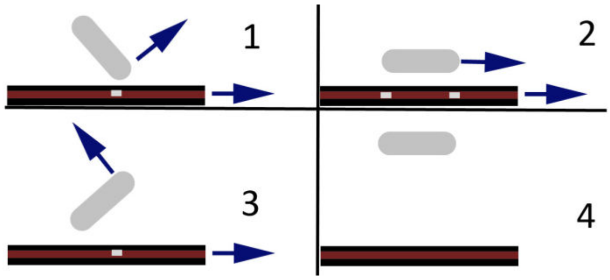

Figure 2. Diagram, showing the interaction of fluid and magnets around the pulleys. 1 shows the approach of the magnet. 2 shows the parallel movement of the magnet. 3 shows the magnet as it moves away. 4 shows the magnet as it returns to the beginning away from the channel. The belt is omitted to reduce cluttering.

During this time the magnets affect the fluid. The pressure drop of the pump is expected to vary almost linearly in the operative region, which is between zero difference and the eventual upper limit**.** Opposing ends of the tube are connected to graduated containers with waterproof sealing. The flow of fluid causes a height difference of fluid levels in the containers. Eventually the flow and the pressure equalize and height difference settles to a fixed amount. Assuming that both containers are open to atmospheric pressure in sufficiently close proximities, the height difference of fluids can be measured to calculate the exact pressure drop forced by the pump.

4. Results and Discussions

The generated pressure differences are displayed in Figure 3. Only the results that fall between zero pressure difference and the maximum pressure difference are plotted for convenience, because this region shows an almost linear relationship between current and pressure difference. This region is defined as the linear region of this particular pump design. Additional data points that correspond to higher current values establish the limit.

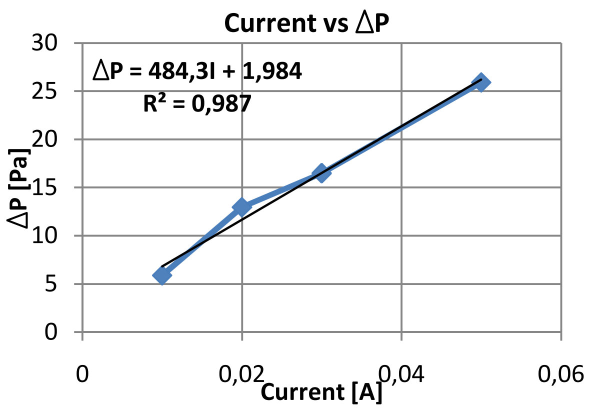

Figure 3. Current vs Pressure Drop Linear Correlation

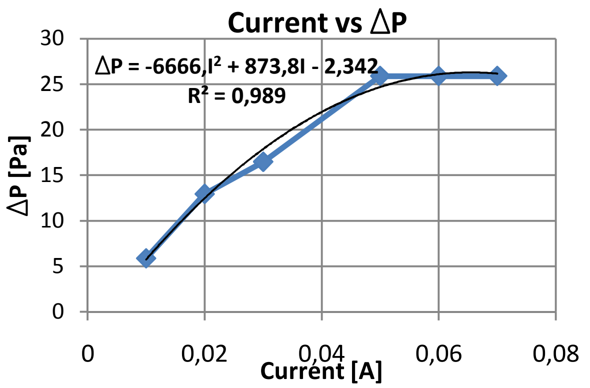

Figure 4. Current vs Pressure Drop Upper Limit

Figure 4 shows the omitted data points from the setup, imposed on to Figure 3. The previously omitted points clearly designate the upper limit of the pressure that is enforceable by the pump. When the Figures 3 and 4 are compared to interpret the significance of the previously omitted data points, it can be seen that the additional points convey no further information regarding to the performance characterization of the pump. The previous decision to omit these points in characterization of the pump is thus justified.

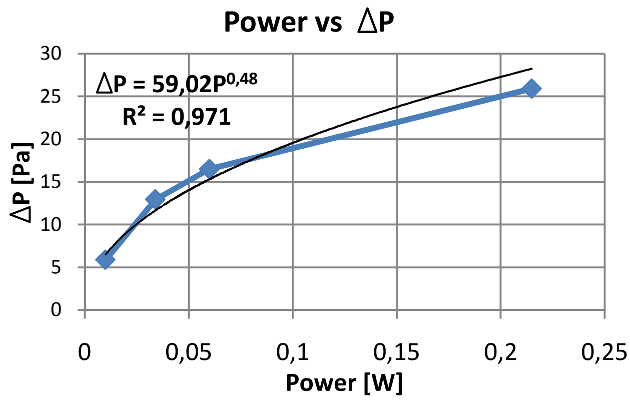

Figure 5. Power vs Pressure Drop

Figure 5 displays a clear relationship of diminishing returns in between the power fed to the system and the resultant pressure difference. It should be noted that this relation is not expected to be linear in the first place.

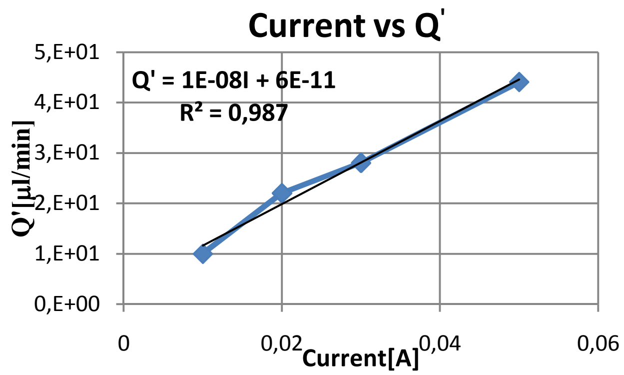

Figure 6. Current vs Flow Rate

Figure 6 shows the correlation of volumetric flow rate and current fed to the system. The fluid flows through a microtube of 254 micron inner diameter. The functional relationship is trivial as pressure drop and volumetric flow rate are codependent quantities, and both depend on current in this particular case. The results in Figure 6 show that significant flow rates could be attained with modest power consumption, assuming that the magnetic field that is interacting with the fluid is not sustained through electrically induced magnetism. In absence of resistive power losses of inductors, power consumption is mostly tied to overcoming the viscous drag forces in the fluid and various other mechanical inefficiencies related to the experimental setup. When compared to its predecessors, this design has a lower maximum practical flow rate, but this is compensated by the comparably lower power consumption. [6][7]

5. Conclusion

This study proves that steep magnetic field gradients are capable of actuating ferrofluids in micro scale. There was a well defined maximum pressure difference that cannot be surpassed with increased power in the system. The linear region that is defined in results is also the operational region with applicable functionality.

A continuous micro flow was observed in the transient time band, before the final pressure value is reached. Since the flow rate values obtained are strictly average values, the flow rate can be potentially higher for low pressure difference settings.

6. Acknowledgements

This work was supported by the Sabancı University Internal Research Grant, no: IACF09-00642. Graduate student support provided by the Faculty of Engineering and Natural Sciences of Sabancı University is greatly appreciated. The authors would like to thank to Dr. Burcu Özel and Prof. Yusuf Menceloğlu from Materials Engineering Program of Sabancı University for their valuable help in the viscosity measurements of the nanofluid samples.

Nomenclature

B	Magnetic Field Strength [T]
F_{mag}	Magnetic Force [N]
h_i	Height of the fluid in input container [m]
h_o	Height of the fluid in input container [m]
I	Current [A]
P	Power [W]
$\dot{Q}$	Volumetric Flow Rate [m^3/s]
t	Time [s]
V	Magnetizable Volume [m^3]
x_c	Magnetic Susceptibility of H_2O
x_p	Magnetic Susceptibility of Fe_3O_4
Greek	
ΔP	Pressure Drop[Pa]
μ_0	Permeability of Free Space [N/A^2]
ρ	Fluid Density [kg/m^3]

References

[1] Woias, P., “Micropumps-summarizing the first two decades”, *Microfluidics and BioMEMS*, Proceeding of SPIE, Vol. 4560, 2001, pp.39-52.

[2] Andò, B., Ascia, A., Baglio, S., Pitrone, N., “Ferrofluidic Pumps: A Valuable Implementation Without Moving Parts”, Proceeding of IEEE Transactions on Instrumentation and Measurement, Vol. 58, No. 9, September 2009.

[3] Wirix-Speetjens, R., Fyen, W., Xu, K., Boeck, J., D., Borghs, G., “A Force Study of On-Chip Magnetic Particle Transport Based on Tapered Conductors”, Proceeding of IEEE Transactions on Magnetics, Vol. 41, No. 10, October 2005.

[4] Andò, B., Ascia, A., Baglio, S., Pitrone, N., “A novel architecture to implement low-cost ferrofluidic pumps”, Proceeding of IMTC 2007 - Instrumentation and Measurement Technology Conference Warsaw, Poland, May 1-3, 2007.

[5] Woias, P., “Micropumps—past, progress and future prospects”, Proceeding of Sensors and Actuators B 105, 2005, p. 28–38

[6] Bilgin, A., Kurtoglu, E., Erk, H. C., Sesen, M., Acar, Y. H. F., Kosar, A., “Magnetic Nanoparticle Based Nanofluid Actuation with Dynamic Magnetic Fields”, ASME 2011 9th *International Conference on Nanochannels, Microchannels, and Minichannels*, ICNMM 9, Edmonton, Canada, June 19-22, ICNMM2011-58222, 2011.

[7] Bilgin, A., Kurtoglu, E., Erk, H. C., Sesen, M., Acar, Y. H. F., Kosar, A., “A Novel Magnetomechanical Pump To Actuate Ferrofluids In Minichannels”, *International Symposium on Thermal and Materials Nanoscience and Nanotechnology*, TMNN 2011, Antalya, Turkey, May 29-June 3,

TMNN-2011/054, 2011.
[8] Veeramachaneni, U. K., Carroll, R. L., "Magnetic Particle Motion in a Gradient Field", Proceedings of the COMSOL Conference, Boston, 2007.
[9] Okiishi, T., H., Munson, B., R., Young, D., F., "Fundamentals of Fluid Mechanics 5th ed.", John Wiley & Sons, Inc., 2006, p.43.