

Ferrofluid actuation with varying magnetic fields for micropumping applications

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Abstract Magnetic nanoparticle suspensions and their manipulation are becoming an alternative research line. They have vital applications in the field of microfluidics such as microscale flow control in microfluidic circuits, actuation of fluids in microscale, and drug delivery mechanisms. In microscale, it is possible and beneficial to use magnetic fields as actuators of such ferrofluids, where these fluids could move along a dynamic gradient of magnetic field so that a micropump could be generated with this technique. Thus, magnetically actuated ferrofluids could have the potential to be used as an alternative micro pumping system. Magnetic actuation of nanofluids is becoming an emergent field that will open up new possibilities in various fields of engineering. Different families of devices actuating ferrofluids were designed and developed in this study to reveal this potential. A family of these devices actuates discrete plugs, whereas a second family of devices generates continuous flows in tubes of inner diameters ranging from 254 μm to 1.56 mm. The devices were first tested with minitubes to prove the effectiveness of the proposed actuation method. The setups were then adjusted to conduct experiments on microtubes. Promising results were obtained from the experiments. Flow rates up

to 120 and 0.135 $\mu\text{l/s}$ were achieved in minitubes and microtubes with modest maximum magnetic field magnitudes of 300 mT for discontinuous and continuous actuation, respectively. The proposed magnetic actuation method was proven to work as intended and is expected to be a strong alternative to the existing micropumping methods such as electromechanical, electrokinetic, and piezoelectric actuation. The results suggest that ferrofluids with magnetic nanoparticles merit more research efforts in micro pumping.

Keywords Microfluidics · Microchannel · Magnetic actuation · Ferrofluids · Nanofluids · Pumps · Magneto hydrodynamics

1 Introduction

Fabrication of the first literal micropumps has been enabled by the emergence of Microelectromechanical Systems (MEMS) fabrication in the 1980s (Van Lintel et al. 1988; Yamahata et al. 2005; Woias 2004; Anton et al. 1980) and was followed by the innovatory advances of the actuation methods such as the magnetically actuated ferrofluids. As a result of these developments, the first ferrofluidic piston pump was first offered in 1991 (Leland 1991). The realization continued with new developments on the actuation methods such as the electromagnetically actuated ferrofluidic micropipette (Greivell and Hannaford 1997), magnetic actuation, and valving application of ferrofluidic plugs (Pérez-Castillejos et al. 2000; Hartshorne et al. 2004). With the developing MEMS technology, existing micropumps vary in complexity and effectiveness, but the most important aim in micropump designs is to achieve simple yet effective micropumps that could be easily

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combined with other microfluidic elements to have portability (Hatch et al. 2001).

Magnetic actuation of ferrofluids is becoming a very popular research area with its wide and differing application areas such as biomedical (Al-Halhouli et al. 2010; Kong et al. 2011), microelectronics (Jin and Aluru 2011), microelectromechanical systems (MEMS) (Zhang et al. 2011), and biological microelectromechanical systems (bioMEMS) applications (Sanders and Manz 2000; Chen et al. 2011a). In micropumping applications, it is necessary to use magnetic actuation with non-uniform magnetic field strength gradients since significant flow rates can be achieved with this method (Martsenyuk 1980) without tactile interference with the fluid flow. Nanofluids for this task are colloidal compounds, where the solid-phase material is composed of nano-sized particles, while the liquid phase can potentially be any fluid, but aqueous media are common. The solid particles are held in suspension by weak intermolecular forces. The particles may be synthesized from materials with different magnetic properties (Kakaç and Pramanjaroenkij 2009). Magnetite (Fe_3O_4) is one of the well-known materials used for its natural ferrimagnetic properties. It has a spinel structure where oxygen ions sit on the corners of a cube and there appear tetrahedral and octahedral sites available for Fe ions. Fe has two oxidation states at tetrahedral and octahedral sites: Fe^{2+} at tetrahedral sites and Fe^{3+} at octahedral sites. The sign of the exchange interaction between the two Fe sites is a negative and therefore spin alignment is antiparallel. However, the spin moments are not equal and a net moment from the Fe^{2+} sites remains uncanceled, creating the net permanent magnetic moment density in the crystal. Magnetite has a significant susceptibility to external magnetic fields and is easy to synthesize, making it one of the favored materials for magnetic fluids. A magnetite-based ferrofluid could be moved with magnetic fields, which makes magnetic manipulation a possibility.

For magnetite-based nanofluids, each particle is desired to be sufficiently small so that it will exist in the superparamagnetic limit, where each particle consists of a single magnetic domain. Depending on the extent of the anisotropy energy in such systems and the surface area-to-volume ratio, magnetic polydomains can significantly reduce the response of the particles to external applied fields. Synthesizing these particles with sizes comparable or smaller than the domain wall widths (at the order of 50–100 nm) stabilizes a material that is in the superparamagnetic limit and can have a strong linear response to external fields without any undesired hysteresis effects. Such magnetic particles in the superparamagnetic limit can be suspended in the fluid and can be magnetized through an external magnetic field's influence (Acar et al. 2005). The magnetized particles move to saturate the magnetic field,

and thus, a ferrofluid plug is formed. The existence of a magnetic field is also expected to change the viscous properties of the composite fluid. (Martsenyuk 1980).

Ferrofluids retain their fluid characteristics even under strong magnetic forces. Carefully engineered ferrofluids return to initial diffusion state at the moment of demagnetization without any irreversibilities for many magnetization cycles (Pamme 2006). Surfactants are an integral part of the nanofluids, which provide the longevity and stability of the fluids. Particles must be covered with surfactants to prevent agglomeration of particles and to help retain the colloid state (Zhu et al. 2011). The function and amount of surfactants in fluids can be engineered according to their application (Dababneh and Ayoub 1995).

The emergence of ferrofluids brought up the possibility of implementing magnetic actuation in fluidic and hydraulic systems. The novel advantage of non-tactile actuation is open to exploitation (Ando et al. 2009). Microscale application of magnetic fields in fluidic applications requires the efficient generation of magnetic fields to improve power management and to prevent undesirable interactions (Derec et al. 2010). Optimization of magnetic field topologies in theoretical realm is trivial, yet realizing some of the most optimal designs in real world can be considered as unusual feats of engineering.

While magnetic actuation of ferrofluids in microchannels has not received significant attention in the microfluidics community yet during the past decade, the advantages offered by this intelligent magnetic actuation are various. Magnetic actuation allows fine control of magnetic particles in a non-magnetic medium and mostly ignores the charges, pH values, and moderate temperature variations (Pamme 2006; Tsai et al. 2009). Currently, magnetic actuation is an expanding research field that offers different approaches and solutions and is implemented in the microfluidics context. Fine magnetic manipulation of particles and specimens labeled with magnetic indicators was proven to be possible (Afshar et al. 2009; Wang et al. 2007). Through the use of ferrofluid plugs, non-ferrous fluids were also indirectly actuated with magnetic manipulation (Pamme 2006; Song et al. 2007). Although magnetic actuation is freely scalable, smaller physical scales allow better efficiencies. Objects ranging from nano-scale magnetite crystals to micron-scale biological specimens can be treated with magnetic actuation methods. This kind of actuation is being continuously articulated, and the achievable finesse is being continuously improved (Wang et al. 2007).

Advances in microfluidics significantly improved biotechnological and medical processes. Sample volumes, costs, and consumption of hazardous materials are decreased, whereas portability and integrability are improved. Delicate manipulation of bio-matter of

micro-nano scales is a prerequisite of improving biological application of microfluidics (Derec et al. 2010). Development of new pumping methods directly improves technologies related to biomedical applications such as diagnostics, drug delivery, and lab-on-chip (Lien et al. 2009, Lacharme et al. 2009, Chen et al. 2011b). Reliability, device compatibility, and biocompatibility are improved via engineered materials and novel actuation methods (Tsai et al. 2009).

Samples that are frequently used as materials for nano particles, such as iron oxides, are mostly bioresorbable (Acar et al. 2005). Their usage in biomedical applications and chemical analysis systems is therefore not restrained. Since very high-power permanent magnets and very small-scale inductors are readily available, development of systems that utilize these materials is not expected to be as prohibitively expensive (Ando et al. 2011).

Microfluidic control structures that employ magnetic forces as the primary mode of actuation can realistically be designed and implemented. Magnetizable fluids can be pumped or held in place with varying magnetic fields. Processing of magnetic or non-magnetic objects traveling in the fluid is possible with this technique (Tierno et al. 2008; Sing et al. 2010; Karle et al. 2010).

Plug magnetization of fluids is one viable method of realizing pumping systems. These systems are driven by externally generated magnetic fields. This idea simplifies the device designs and decreases production costs. Magnetized fluid plugs can actuate other non-magnetic fluids, given that the two fluids do not mix (Pamme 2006; Song et al. 2007).

Our previous research proposed magnetomechanical micro pumps to actuate ferrofluids using varying magnetic fields, and promising results were obtained (Bilgin et al. 2011a, b; Kurtoglu et al. 2011). Our experimental results showed that considerable flow rates (more than to 50 $\mu\text{l/s}$), which can also be precisely controlled, could be achieved with the proposed micro pumping technique.

Motivated by the aforementioned studies and findings, to deepen our previous research on this area, and to provide more insight into magnetic actuation of ferrofluids in mini/micro scale, this study focuses on the development of pumping devices that operate with the principle of ferrofluid actuation with varying magnetic fields. The objective is designing a compact device that utilizes permanent magnets to actuate ferrofluids. Ideally, the pumping method is exploited in such a way that it would be applicable to discrete and continuous actuations. Two groups of devices were utilized for this purpose. A family of devices actuates discrete ferrofluid plugs, whereas a second family of devices generates continuous ferrofluid flows. The devices are first tested with 1.56 mm inner diameter minitubes to prove the effectiveness of the proposed actuation

method. The setups are then adjusted to test with 254 μm inner diameter microtubes.

2 Operation principle

The presence of a non-uniform magnetic field induces a force on magnetized particles. The particles migrate to the point where the field is the strongest (Veeramachaneni and Carroll 2007). Static magnetic fields are capable of agitating ferrofluids, but the fluid quickly falls to equilibrium (Choi et al. 2008). Disturbing the equilibrium state by changing the magnetic field is vital if a useful actuation method is to be developed (Song et al. 2007).

To realize a dynamic magnetic field, either stationary sources of variable magnetic power, or moving sources of constant magnetic power can be utilized (Anton et al. 1980; Love et al. 2005; Song et al. 2007). Magnetic fields generated by solenoid inductors can be adjusted through electrical systems so that Helmholtz coils placed along the sides of the channel can be used to actuate the fluid. Another approach is mechanically actuating permanent magnets to vary the magnetic field strength.

It was experimentally determined that miniscale inductors fail to generate magnetic fields that are sufficiently strong to compete with extant devices.

A magnetic field, sustained by a permanent magnet, forces the surrounding particles to move towards the magnet surface. When such a field performs a translational motion, it causes a net displacement of particles along the motion direction. In the case of a ferrofluid, the particles are suspended in a viscous fluid medium. If the magnetic force is strong enough, the displaced particles would drag the fluid along the magnetic field's motion direction. If fluid is placed in a channel and magnetic field gradient is placed in parallel or coincident to the channel, the fluid can be forced to move along the channel.

The magnetic field magnetizing the sample fluid must be generated to perform a translation motion parallel to the channel. Constructing a mechanism to perform this task is possible, but the prospects they present towards miniaturization are weak. Mimicking the translational motion of magnets with rotating magnets is a viable solution to this problem. Thus, the problem changes to finding a method of mimicking the resultant magnetic field of a translating magnet with rotating magnets.

The proposed methods in this paper consist of placing magnets around solid rotors in a spiral pattern. When the rotors are rotated in unison from a starting configuration of a magnet pair facing each other, the magnet pairs periodically face each other. Then the fluid plug reaches the middle point of a magnet pair. They must be disengaged and another pair of magnets is brought in position just in

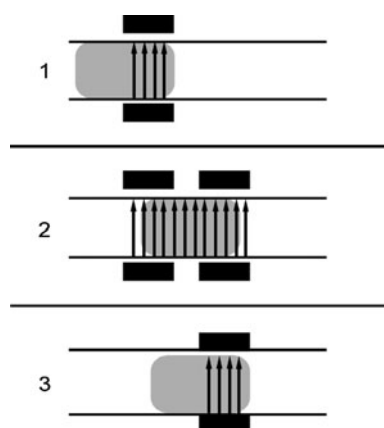


Fig. 1 1 The magnetized plug is held by two magnets. 2 The rotors rotate slightly to expose the plug to next set of magnets along with the first pair. 3 Rotors fully rotate to move the previous set of magnets away and the magnetized plug. This cycle can be repeated to move the plug in either direction

front of the plug so that the plug will move forward. Given that the transitions are smooth and magnetic field is sufficiently strong, the fluid can be smoothly actuated with this technique.

The dynamic behavior of the magnetic field generated by the rotating magnets is inspired by a natural phenomenon. The motion and the shape change of our proposed magnetic field topology resemble the motion of an inchworm. Initially, the magnetic field strength distribution constitutes a single wave, as depicted in Fig. 1. The axial coverage of the magnetic field expands by one wavelength towards the intended flow direction, and the peak magnetic field strength simultaneously decreases. Meanwhile, the magnetized plug moves half the field expansion distance. In one continuous motion, the magnetic field begins to contract in the same direction as the expansion, and the field strength increases in a reversal of the previous change, which pushes the fluid yet again for a distance equal to half of the contraction length being also equal to one wavelength. The magnetic field reverts to its initial state only one wavelength away from the initial position. In this paper this peculiar dynamic behavior will be called “creep dynamics”.

There are two approaches for the actuation of ferrofluids using magnetic fields. The direct methods that depend on the influence of field over fluid either utilize the discrete magnetization of a plug or produce a homogenous flow induced by the magnetized volume.

The characteristics of the described creep dynamics are beneficial to the actuation of discrete plugs. The semi-discrete magnetization methods employ the non-Newtonian properties of the subject fluid with respect to changing magnetic field strength around the fluid (Menz et al. 2000). The ferrofluid plug can be pinned to a specific location in

the channel by the proposed mechanisms. Implementations of devices that exaggerate the inchworm motion are straightforward, but their practicality is limited to low power applications. This approach yields a discontinuous actuation that is used for microfluidic valves (Menz et al. 2000), liquid pistons for pumps (Yamahata et al. 2005), and precision actuators for other fluids (Greivell and Hannaford 1997).

The semi-homogenous force methods focus on the design of the magnetic field to induce sufficiently equal forces on multiple plugs. The implementation is tricky but the flow can be continuous (Mao and Koser 2011). This yields a continuous actuation that is useful when the ferrofluid needs to be pumped as bulk or when it needs to be circulated. The creep dynamics hinders the continuous actuation if the variations of magnetic field are too great. The field variations decrease the efficiency of the pump as the difference gets greater. The characteristics of the creep dynamics must be minimized to achieve a more stable magnetic field.

For both cases the mechanical behavior of the magnetized plug resembles a first-order linear differential system. The movement induced by the magnetic force is dampened by the drag forces, and in theory, it reaches a steady-state velocity. However, the magnetic force is not constant, shifts in space, and changes in magnitude. As a result, the velocity of the fluid is not constant. With continuous actuation, this simply results in a loss of efficiency and maybe degradation of a subjective flow quality. Depending on the application, both could be. In discontinuous actuation when the fluid fails to track the shifts in the magnetic field, it simply remains in the last position until the magnetic field peak comes close again, when the plug moves slightly backwards before moving forwards. This phenomenon is referred as “skipping” in this study as shown in Fig. 2.

Skipping error is more noticeable if the plug is used in positioning or valving applications, while skipping appears as a loss of pumping power in continuous flow applications.

3 Experimental setups and procedures

3.1 Ferrofluid preparation

A lab-made sample of Lauric acid-coated super paramagnetic Iron oxide (SPIO-LA) was used as the ferrofluid species in this study. SPIO-LA has magnetic nano particles, which have 25 nm average diameter. The fluid is prepared by co-precipitation of aqueous solutions of FeCl_2 and FeCl_3 in a basic environment. Through fine control of the addition rate of the reactants to the reaction vessel;

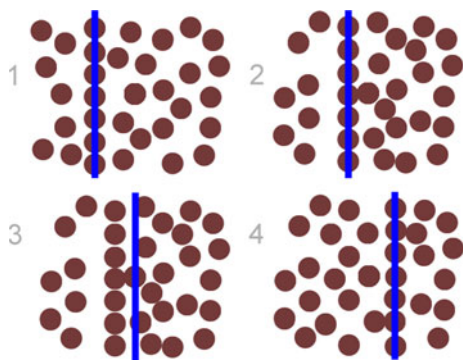


Fig. 2 This schematic visualizes an overly simplified example of skipping. 1 Some of the particles in the fluid are held by a very thin planar magnetic field shown as a line. 2 The moving magnetic field drags the particles, which in turn push the particles in front of them. 3 The magnetic field keeps on moving, but the magnetic force is not enough to force the particles to move through the congestion. The magnetized particles are left behind as the field magnetizes and attracts the closest particles. 4 A new set of particles are fully magnetized, and the magnetic field drags them forward

considerably small and uniform particle sizes are easily achieved. To prevent aggregation and to facilitate their motion inside the liquid, nanoparticles of SPIO were coated with lauric acid, which also contributes to the long-term stability of the nanofluid.

The sizes of the ferromagnetic nanoparticles in the sample SPIO-LA are 20–30 nm. This refers to the hydrodynamic size in water measured by dynamic light scattering (DLS) and reported as number average. No significant aggregation was observed in 18 months.

Forty-five milliliter of distilled water was put into a 100-ml three-necked round-bottom flask fitted with a mechanical stirrer and a condenser and deoxygenated for 30 min. 2.162 g $\text{FeCl}_3 \cdot 6\text{H}_2\text{O}$ and 0.795 g $\text{FeCl}_2 \cdot 4\text{H}_2\text{O}$, lauric acid (LA) were added to the flask and stirred at 400 rpm under nitrogen for about 15 min. Reaction flask was placed in an oil bath at 85 °C. After 10 min of mixing, 7 ml ammonium hydroxide was injected into the flask with vigorous stirring at 600 rpm. Reaction was allowed to continue for 30 min to produce a stable colloidal solution, then cooled to room temperature, and placed atop a magnet (0.3 Tesla) for few hours. Any precipitate was removed with magnetic decantation. Usually, there are no precipitates. Final ferrofluid has 29 mg Fe/l.

3.2 Discontinuous actuation

Moving a magnetic field without distorting its shape is trivial if the source of magnetic field can be moved in the same direction. It was decided that such a mechanism would be cumbersome at best. Instead, the linear movement of the magnet was mimicked with magnets rotating around a common axis.

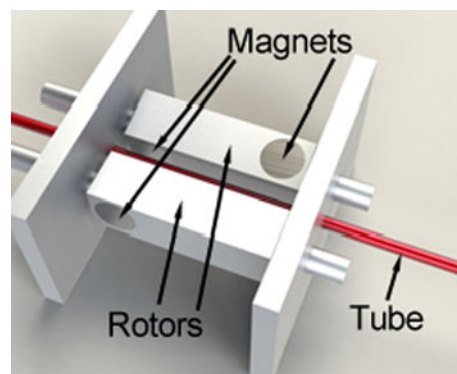


Fig. 3 Rectangular rotor—minitube setup

3.2.1 Minitube setups

3.2.1.1 Rectangular rotor—minitube The idea behind this design is using the synchronous rotation of symmetric and opposing magnets to generate a magnetic field, which peaks when the magnets are at the closest position and which diminishes while the magnets are at the farthest position. Rare earth magnets with 300 mT magnetic field strength are placed on to the each face of the square profile rotors with the $(i-1) \times a$ mm distance from the reference edge, where i is the magnet number and a is the magnet diameter. The rotors are placed in such a way that the tube, which has 3 mm outer diameter, stays in between the rotors, which are actuated by a simple DC motor. The flow rate is obtained by visualizing the motion of plugs using a CCD camera with time. A digital rendering for the setup can be seen in Fig. 3.

Angular velocities are calculated from the position data, which are obtained from the encoder of the motor.

3.2.1.2 Hexagonal rotor—minitube The previously mentioned pump design could actuate ferrofluid plugs, but irregularities were observed on the generated magnetic field, which affected the maximum performance of the pump. Thus, the first design has been improved by reducing the angular separation of rare earth magnet pairs to obtain higher flow rates, fewer discontinuities on the magnetic field, and better position tracking. This was achieved by changing rectangular rotors into hexagonal rotors. The improved second setup can be seen in Fig. 4.

The improvement mentioned above increases the flow rate values of this pump architecture. A comparison of results will be included in the following sections.

3.2.2 Microtube setups

3.2.2.1 Rectangular rotor—microtube Since the ultimate aim is to produce microfluidic devices that can actuate ferrofluids, the next step is to use microtubes.

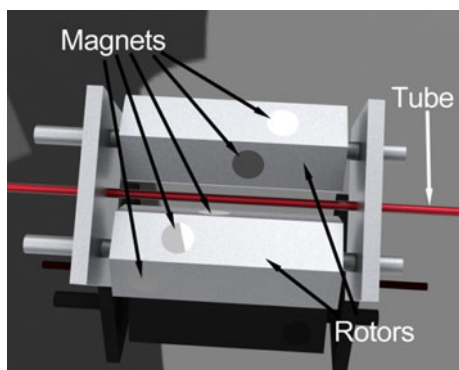


Fig. 4 Hexagonal rotor—minitube setup

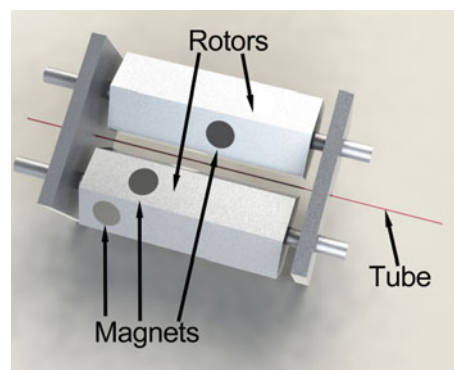


Fig. 6 Hexagonal rotor—microtube setup

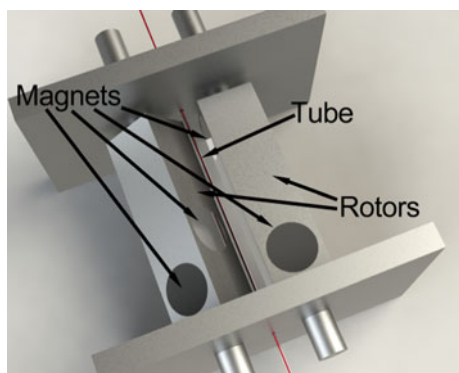


Fig. 5 Rectangular rotor—microtube setup

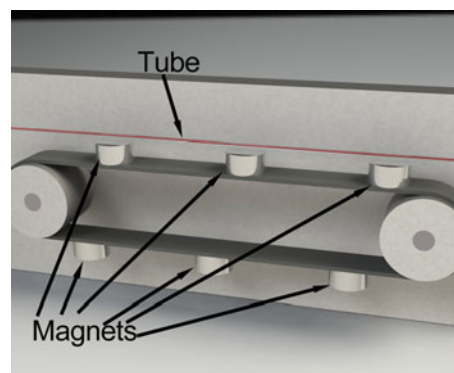


Fig. 7 Conveyor belt—microtube setup

The microtubes used in experiments have 254 μm inner diameter and 762 μm outer diameter. Rectangular rotor setup was modified accordingly for microtube experiments. A digital rendering of the setup can be seen in Fig. 5.

3.2.2.2 Hexagonal rotor—microtube The experiments of inducing flow in microtubes were repeated in the hexagonal rotor setup. A digital rendering of the hexagonal setup with microchannel can be seen in Fig. 6.

It was seen that contrary to the results seen in mini scale, flow rate values deteriorate for the same angular velocity values in microscale due to size effects of smaller size. The idea of changing the angle between two magnets to improve rectangular rotors is not applicable when it comes to microtubes. The particulars of this will be explained in Sect. 4.

3.3 Continuous actuation

After plug actuation methods are studied, the next step is the generation of continuous flows with ferrofluid.

3.3.1 Conveyor belt—microtube

This design is constructed from a conveyor belt, on which rare earth magnets are attached, and two pulleys, which are

fixed to two individual shafts that fit into bearings. A gear is affixed to one of the shafts, while another gear is affixed to a DC torque motor. The gears are placed to stay in mesh and the motor is switched on to actuate the mechanism. A simplified digital rendering can be seen in Fig. 7.

When current is supplied to the motor, the conveyor belt rotates the magnets so that the ferrofluid could be actuated, and a continuous flow is induced.

The pressure drop of the pump is expected to vary almost linearly between zero difference and the eventual upper limit. Both ends of the microchannel are sealed into graded containers. The fluid flow causes a height difference between the fluid levels in the containers until the flow and the pressure equalize and height difference settles. The height difference between containers can be measured to calculate the exact pressure drop created by the pump.

3.4 Uncertainty in data

The uncertainties in the measured values are given in Table 1. They were provided by the manufacturer's specification sheet, whereas the uncertainties on volumetric flow rate and angular velocity were obtained using the propagation of uncertainty method included in Kline and McClintock (1953) and ISO Guide to the expression of

Table 1 Uncertainty data

Parameter	Uncertainty (\pm)
Area	0.94 %
Length	0.1 %
Volumetric flow rate	2 %
Angular velocity	8 %
Current	0.1 %
Magnetic field strength	2 %

uncertainty (GUM 1995). Moreover, each measurement of each setup was repeated for ten times and the results were averaged.

4 Results and discussion

4.1 Rectangular rotor—minitube

The results of this first setup show a linear relationship between the angular velocity of the rectangular rotors and the volumetric flow rate as shown in Fig. 8. The ferrofluid is subjected to a field that reaches a maximum magnetic field strength of 300 mT. Figure 8 shows the relationship between the angular velocity and the volumetric flow rate.

The results show that achieving flow rates up to 60 $\mu\text{l/s}$ is possible with this design. If the angular velocity increases more than the maximum value, the average velocity of the nanofluid flow decreases because of the natural limitations of this design. More specifically, the magnetic field moves faster than the maximum steady-state linear velocity of the fluid, and therefore, the fluid needs more than one cycle to move along a single length L . In addition to the above-mentioned observations, when the rare earth magnet pair on the rotor moves faster than the limit velocity and is unable to drag the magnetized

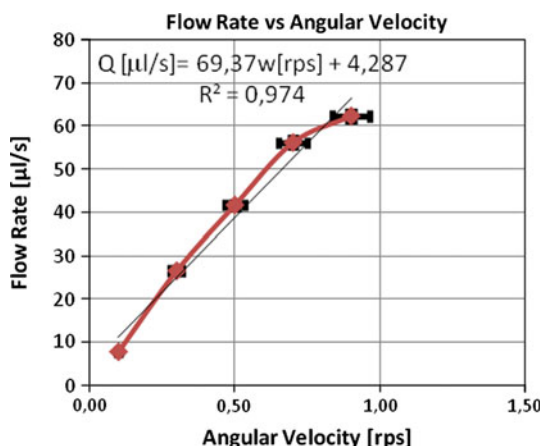


Fig. 8 Flow rate versus angular velocity graph for rectangular rotor—minitube setup

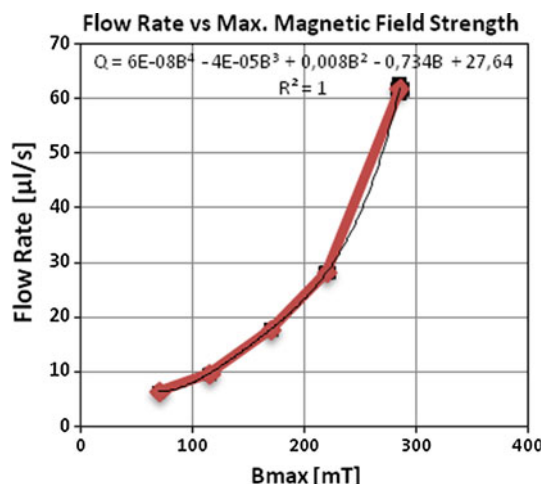


Fig. 9 Maximum flow rate versus maximum magnetic field strength graph for rectangular rotor—minitube setup

ferrofluid plug, the plug is reverted to the original position in the next cycle by the same pair of magnet. Thus, the model is expected to break down at high angular velocities, and the flow rate will be zero under such conditions. The limit for system to breakdown is 1.1 rps for minitube setups and 0.066 rps for microtube setups (both for rectangular and hexagonal setups).

Maximum volumetric flow rates that are achievable with the maximum applied magnetic field strengths are plotted in Fig. 9. Since there is an absolute upper limit to the applicable magnetic field force, the distance between the magnet holders are adjusted to generate lower maximum magnetic field strengths.

The maximum flow rate values are obtained using a fixed angular velocity of 1 rps to ensure that the plotted curve only emphasizes on the relationship between magnetic field strength and flow rate.

The results from this setup suggest that the limit velocity for rotors can be increased by reducing the angle between the magnets. The skipping that causes the plug to revert could be prevented using this approach. This fact leads to the hexagonal rotor—minitube design, which will be discussed in the following section.

4.2 Hexagonal rotor—minitube

Decreasing the angle between the magnets reduces the severity of the sudden shifts in magnetic field, which creates magnetic dead zones and causes the limitation in terms of the flow rate values as mentioned earlier. The increased maximum achievable speed significantly improved the design and doubled the obtained flow rate values as shown in Fig. 10.

The relationship between the flow rate and angular velocity is again linear as expected, and flow rate values up to 120 $\mu\text{l/s}$ can be obtained with this setup.

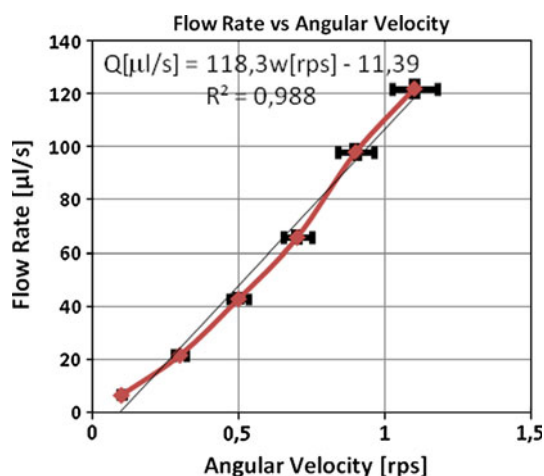


Fig. 10 Flow rate versus angular velocity graph for hexagonal rotor—minitube setup

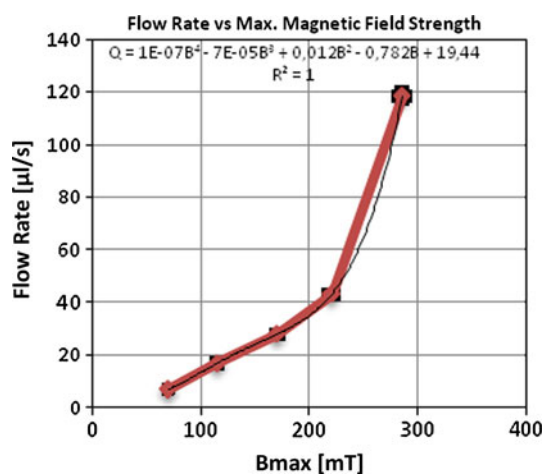


Fig. 11 Maximum flow rate versus maximum magnetic field strength graph for hexagonal rotor setup

Figure 11 shows the relationship between the maximum magnetic field strength and maximum achievable flow rate. Accordingly, a flow rate of 120 $\mu\text{l/s}$ can be achieved with a maximum magnetic field strength of 300 mT.

A commercial compact pump of similar size scale, which can also achieve the same flow rates as in the proposed design, was selected as an example. This pump constitutes the benchmark for comparison (Single-Channel Variable-Speed Compact Commercial Pumps, http://www.masterflex.com/catalog/product_view.asp?sku=7712020). The commercial product, which is a single channel, variable speed compact pump, has the dimensions of 19 cm (length) \times 8.9 cm (width) \times 8.9 cm (height) and 1.42 mm inner diameter of channel, whereas the proposed setups have the dimensions of 8 cm (length) \times 8 cm (width) \times 4 cm (height), and 6 cm (length) \times 5 cm (width) \times 4 cm (height), which are significantly smaller than the commercial

pump in terms of its volume and has a 1.56 mm inner diameter channel (very close to the one in the commercial pump). It can be claimed that this proposed design is promising since it is more compact than the commercial pumps in terms of the size but generates the same flow rates compared with the compact commercial pumps. It should also be noted that the pumps in this study can withstand backpressures up to 3 and 0.2 atm under discontinuous and continuous actuation conditions, respectively. In addition, another commercial micro pump, which is an Electroosmotic (EO) micropump (model 3000128 on datasheet) (http://www.dolomitmicrofluidics.com/images/PDFs/micro_elctro_osmotic_pump.pdf) with dimensions of 8 mm (diameter) and 17.9 mm (length), needs at least 460 V of potential difference to generate the flow rate of the proposed design. This estimation was calculated by taking the referenced datasheet as it is. The proposed design requires voltage values (few Volts) that are far below than this commercial micropump.

4.3 Rectangular rotor—microtube

After successfully actuating ferrofluid plugs in minitubes, the next step was conducting experiments with microtubes using the previously mentioned setups. First, the rectangular rotor setup was tested. It was seen that the design can also successfully actuate ferrofluid plugs in microtubes, but with proportionately lower flow rates. Figure 12 shows flow rates as a function of angular velocity, and the linear relationship between them is present similar to the minitube results.

Flow rates up to 0.135 $\mu\text{l/s}$ of are obtained with this design.

4.4 Hexagonal rotor—microtube

Higher flow rates than the aforementioned setup was expected from this setup based on the improved results obtained from the first two setups that acted on minitubes. However, no significant improvement was recorded between results of this device and the previous device (Fig. 13).

This shows that the previous device was fully capable of actuating the fluid at the maximum speed possible for the given tube size and magnetic field strength. To prevent skipping, the rotors rotate too slowly for the angle variation to have any significant effect. Any possible improvement is thus undetectable for this setup.

4.5 Conveyor belt—microtube

The purpose of this design was to induce a continuous flow in addition to plug actuation. The proposed setup was successful in accomplishing this aim. Figure 14 shows the

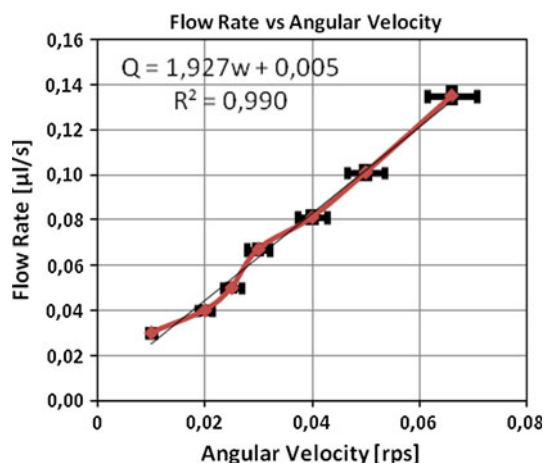


Fig. 12 Flow rate versus angular velocity graph for rectangular rotor—microtube setup

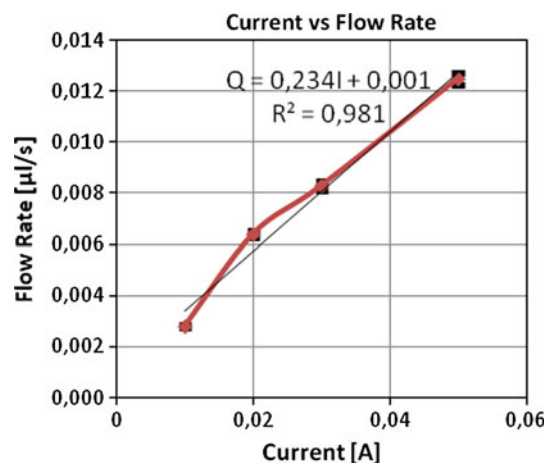


Fig. 14 Current versus flow rate graph for conveyor belt setup

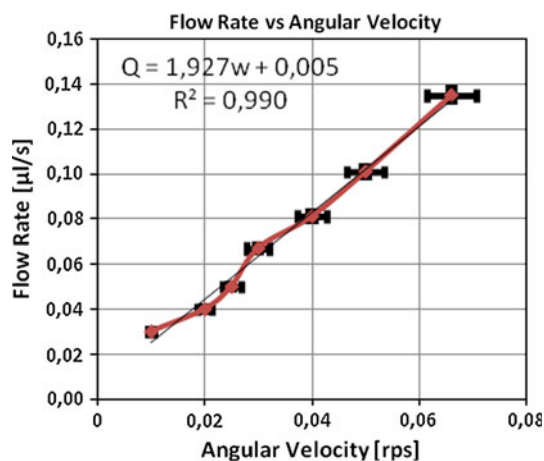


Fig. 13 Flow rate versus angular velocity graph hexagonal rotor—microtube setup

volumetric flow rate as a function of current fed to the system.

Flow rates up to 0.0125 µl/s through a microtube with 254 µm inner diameter can be obtained with this design. The flow is always expected to be fully laminar due to the length scale. The surface interactions have an improved effect with regard to body forces. This result shows that notable flow rates are achieved with modest power consumption especially since the magnetic field, which is interacting with the fluid, is not obtained through electrically induced magnetism. Instead of power losses due to the resistance of inductors, power consumption mostly occurs due to the viscous drag forces in the fluid, manipulation of magnetic interactions, and various other mechanical inefficiencies related to the experimental setup. When compared with previous setups, this design has lower flow rate values, but this is compensated by the comparably lower power consumption and improvement of

the flow by allowing continuous flow instead of plug actuation.

4.6 Theory and discussion

Particle-based approach can be implemented to explain the theory behind magnetic actuation. For this, a unit cell can be constructed as a single particle and an appropriate fraction of the carrier fluid. The forces acting on the magnetic nanoparticle are the magnetic force, F_{mag} , and drag force, F_d , so that Newton's Second Law could be expressed as

$$ma + F_d = F_{mag} \tag{1}$$

The magnetic force is calculated through the subtraction of the total forces exerted to environment and forces exerted on the particle, where x_c and x_p stand for the magnetic susceptibility of the base and particle. Their difference is multiplied with magnetizable volume, V , and the gradient of the applied magnetic field squared, ∇B^2 , and divided to permeability of free space, μ_0 , to give the magnetic force on a single particle:

$$F_{mag} = \frac{(x_p - x_c)V\nabla B^2}{2\mu_0} \tag{2}$$

The drag force is found using a generalized drag force acting on a small particle for a low Reynolds number flow due to the small particle size, where μ is the viscosity of the base fluid, v and d_i are velocity and diameter of the particle, respectively:

$$F_d = 3\pi\mu v d \tag{3}$$

The local velocity of the magnetic nanoparticle is deduced from Eq. 1 by integrating the acceleration over time. An analytical solution for the local velocity is

possible under uniform magnetic field gradient assumption and is expressed as

$$v = v_0 e^{-c_1 t} + \frac{c_2}{c_1} (1 - e^{-c_1 t}) \quad (4)$$

where v_0 is the initial particle velocity,

$$c_1 = \frac{3\pi\mu d}{m}, \text{ and } c_2 = \frac{(x_p - x_c)V\nabla B^2}{2m\mu_0}$$

Since moving nanoparticles having high concentration in the base fluid could push the molecules of the base fluid, a bulk fluid flow could be generated. The corresponding volumetric flow rate could be approximated as the product of the average linear velocity of the nanoparticle, v_{av} , and cross-sectional area, A :

$$\dot{Q} = v_{av} \times A \quad (5)$$

The aforementioned equations provide a basis for explaining the experimental results. Same magnets are utilized along both micro and mini tubes, while they would produce similar local magnetic fields and gradients along the channel for the discontinuous actuation configuration. Based on the performed magnetic field measurements by using Teslometer and due to the smaller spacing between the magnets, magnetic field gradients in discontinuous actuation are measured to be around 2.5 times greater than the continuous actuation, while the magnetic susceptibilities are fixed for all the configurations due to the use of the same fluid sample. As a result of greater magnetic field gradients, the magnetic forces are expected to be greater in discontinuous actuation compared with continuous actuation according to Eqs. (2), (4), and (5). As a result, considerably lower flow rates are apparent for continuous fluid actuation compared with discontinuous actuation in microtubes of the same dimension (Figs. 12, 13, 14).

When the flow rates of discontinuous actuation are considered, a significant increase in flow rates can be observed when the tube diameter is increased. Since similar magnetic fields and gradients are expected for both minitubes and microtubes similar average velocities will be also obtained for nanoparticles. According to Eq. 5, the volumetric flow rates should be much larger in minitubes because of the larger inner diameters of minitubes compared with microtubes tested in this study (more than 5 times), which bolsters the experimental findings. In addition to this effect, wall shear stress on the wall also increases for bulk fluid flow with the reduction of the tube diameter leading to a further decrease in the flow rate. As a result, a reduction of more than 100 times in flow rates occurs when switching from minitubes to microtubes (Figs. 8, 9, 10, 11, 12, 13).

The position of magnets is adjusted in such a way that plugs could be propelled one by one by placing the first set

of two magnets sufficiently close to each other while positioning the other set of two magnets further to the first set. However, for the continuous actuation, it was made sure that each magnet is placed close to each other and is moved completely horizontally along the entire microtube so that each piece of the working fluid could be continuously driven along the microtube thereby assuring a continuous actuation.

5 Conclusion

In this study, a method to actuate ferrofluids with varying magnetic fields was tested. The method of composing a magnetic field with rotating magnetic field sources to obtain a linearly moving magnetic gradient was successful. The generated magnetic fields actuated the ferrofluid plugs in mini and microtubes. Flow rates up to 120 and 0.135 $\mu\text{l/s}$ were achieved in the experiments in minitubes and microtubes with modest maximum magnetic field magnitudes of 300 mT for discontinuous and continuous actuation, respectively. A simple comparison of results shows that the ratios of flow rates are consistent with the physical scale ratio of minitubes and microtubes.

It was proven that actuation of ferrofluid plugs in microtubes with very modest power rates is possible if permanent magnets with high magnetic moment density are employed as the field sources. These devices do not produce waste heat like electrically generated fields, and they always remain “on” in the last functioning state if the power is cut. The lack of generated heat reduces the unwanted interference with the fluid and tubing.

It was previously seen that when a series of rotating magnets are employed to simulate a translating magnet, reducing the angular difference of consequent magnets improves the quality of the resultant magnetic field. The said improvement was significant in actuation of ferrofluids in minitubes. The errors in the magnetic field were dampened and the average velocity of the plug was increased. However, the results obtained from modified devices that operate in microtubes showed that the aforementioned adjustment to the angular displacement between magnets is irrelevant in microscale. For this reason, results for hexagonal rotor and rectangular rotor designs were almost identical in micro scale.

Continuous flows of ferrofluids could be also generated with a conveyor belt system. Flow rates up to 0.0125 $\mu\text{l/s}$ through microtubes could be obtained with the proposed approach.

The promising results suggest that ferrofluids merit more research efforts in micro pumping, and magnetic actuation could have a high potential for being a significant alternative for more common techniques such as electro-mechanical, electrokinetic, and piezoelectric actuation.

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