Magnetic Microbeads

Definition

Magnetic microbeads are spherical particles of a diameter in the micrometer range that have magnetic entities embedded in a latex shell.

Cross-References

► Magnetic Field-Based Lab-on-Chip Devices

Magnetic Pumps

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Synonyms

Electromagnetically actuated pumps; Magnetic pumps; Magnetohydrodynamic pumps

Definition

Magnetic pumps are pumps using electromagnetic or magnetic fields to actuate and control fluid motion in microchannels. The application of electromagnetic or magnetic forces is a flexible way of manipulating fluids in lab-on-a-chip devices.

Overview

Micropumps can be classified into two general categories: mechanical and nonmechanical micropumps (an excellent review on micropumps can be found elsewhere [1]). In a typical mechanical pump, a membrane is used to produce the pumping action. Nonmechanical micropumps on the other hand generally have no moving parts. Common mechanical micropumps fall into three categories based on the mechanical action used: check valve, peristaltic, and rotary pumps. They can also be categorized according to their actuation method: pneumatic, piezoelectric, external electric motor, or magnetic field. Among these actuation techniques, magnetic field actuation has shown promise for research purposes at micro- and nanoscales because of creating smooth fluid flow. Magnetic pumps can be found in both categories, mechanical, and nonmechanical in the literature.

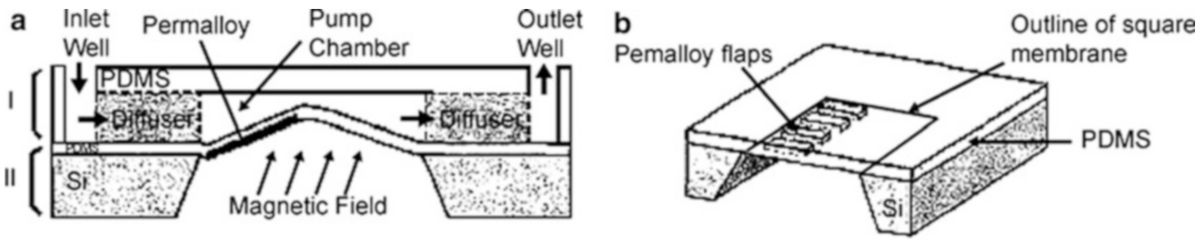
Basic Methodology

The latest developments related to the use of magnetic micropumps in controlling fluid motion in microchannels have focused on creating flexible approaches to fluid actuation. Several configurations have been explored in the literature regarding to magnetic micropumps which can be categorized as below:

- Active-valve magnetic micropumps [2]
- Electromagnetic pumping with hard magnets in annular channel [3]
- Magnetic microactuator based on a thin PDMS membrane [4, 5, 7]
- Centrifugo-magnetically actuated gas micropump [8]
- Applying MHD principle for the development of micropumps by using DC current [10, 11]
- Using AC current in MHD micropump for eliminating bubble generation [13]

Key Research Findings

Shen et al. [2] exploit the peristaltic actuation principle in an active-valve magnetic micropump with advantages as high efficiency and self-priming. The magnetic active-valve micropump consists of three in series chambers in middle layer which the central actuation chamber of this layer acts as a pumping chamber, while the left and right chambers act as valves.



Magnetic Pumps, Fig. 1 (**a**) Cross section of assembled micropump and (**b**) schematic cutout of membrane actuator (Reprinted from [2] with permission from Dr. Liu)

Three cylindrical permanent magnets are embedded in a PDMS sheet on the top of middle layer chambers. In order to generate pulsed flow, peristaltic pump should consist of at least three equivalent pumping chambers that are sequentially operated. To do this, the authors used an assembly of arc-shaped permanent magnets mounted on the rotation axis of a DC minimotor to actuate permanent magnets without requiring any external driving circuit. In addition, their presented magnetic active-valve micropump has key advantages such as low cost (via rapid prototyping), the ability to establish flow rates, and back pressures that are compatible with microfluidic applications and low energy consumption.

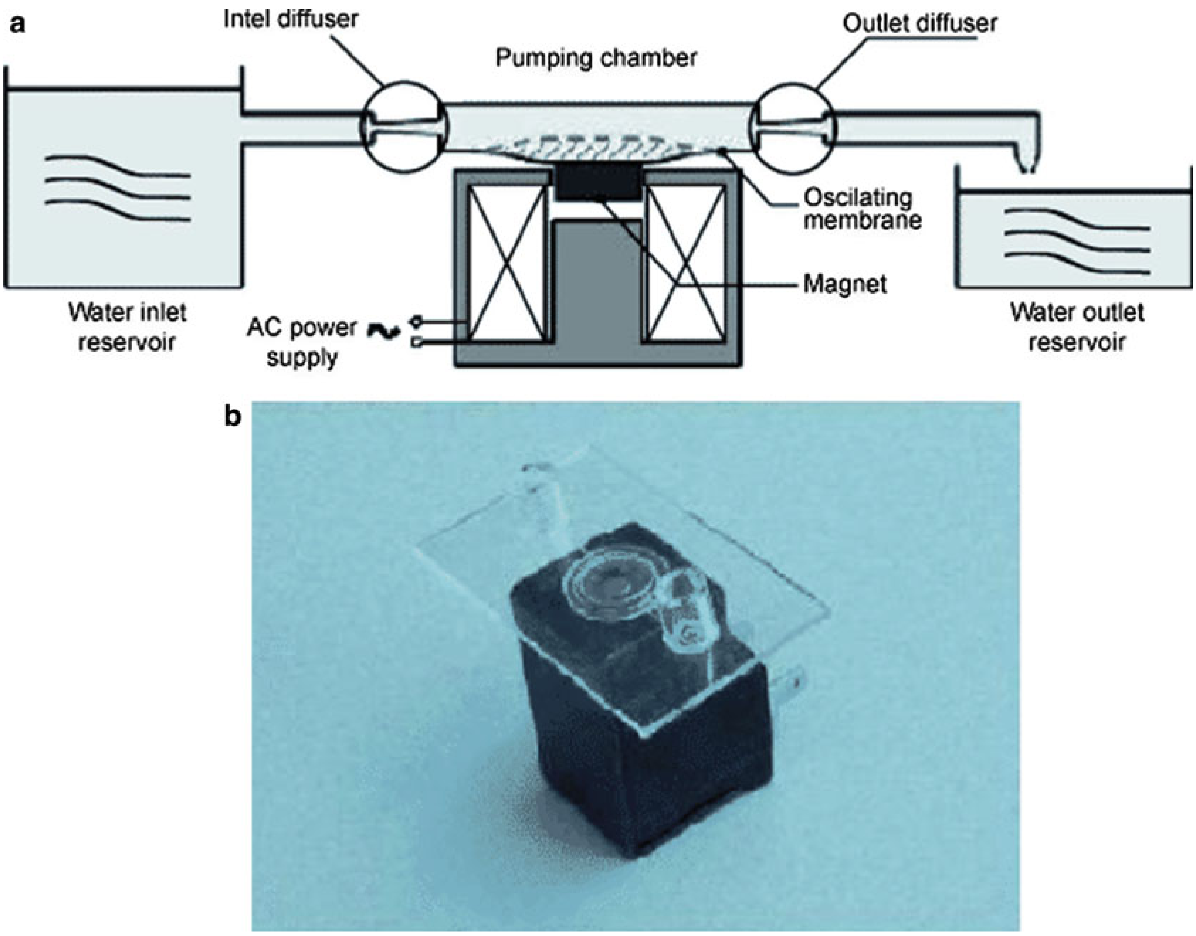
Al-Halhouli et al. [3] described the operation, design, and testing of a new electromagnetic pumping concept that is based on rotating two hard magnets placed in an annular channel in opposing polarity. The electromagnetic pump (EMP) consists of a fluid housing, two pistons (permanent magnets), 12 solenoids, and a cover containing inlet and outlet ports. The energizing operation is controlled by arranged solenoids around the fluid channel (two of them are located between the inlet and the outlet ports and are holding solenoids, while ten remained solenoids are used to create a magnetic field). For described EMP, maximum flow rate of 13.7 ml/min at 200 rpm and a pressure of 785 Pa at 136 rpm were obtained. Researchers highly recommended further investigations on the energizing operation and fluid leakage between the permanent magnets and wall channels.

Khoo and Liu [4] presented results on the design, fabrication, and testing of a novel, micromachined magnetic membrane microfluidic pump. Their pump composed of a magnetic microactuator, which is based on a thin PDMS membrane, and two polymer-based one-way diffuser valves. Membrane displacement was achieved through the interaction of an external magnet field (Fig. 1) with ferromagnetic materials which are embedded within the membrane. It was indicated that flow rate of the micropump can be controlled by controlling the magnetic field strength and the actuation frequency of the membrane.

Yamahata et al. [5] fabricated and characterized a PMMA valveless micropump which was actuated magnetically using an external electromagnet. The pump consisted of two diffuser elements and PDMS membrane with an integrated composite magnet made of magnetic powder. They tested the setup with water and air. They relate the flow rate with the actuation frequency and showed that frequency near to the natural frequency of the membrane generates higher flow rates due to the larger amplitude membrane vibrations. In their following study [6] (Fig. 2), they used glass instead of PMMA and used new designed membrane, improved actuation coil, and a solid magnet rather than a polymer bounded powder magnet. They achieved four times larger pumping pressures compared to the former one.

Pan et al. [7] studied a magnetically driven PDMS-membrane micropump with two ball-check valves (Fig. 3). Two driving mechanisms to generate the external magnetic force for the membrane were used, one is to use a permanent magnet with a small DC motor, and the other one is to use an integrated coil. They obtained higher flow rates with the later mechanism but lower power consumption with the first mechanism.

Haeberle et al. [8] reported for the first time a centrifugo-magnetically actuated gas micropump.



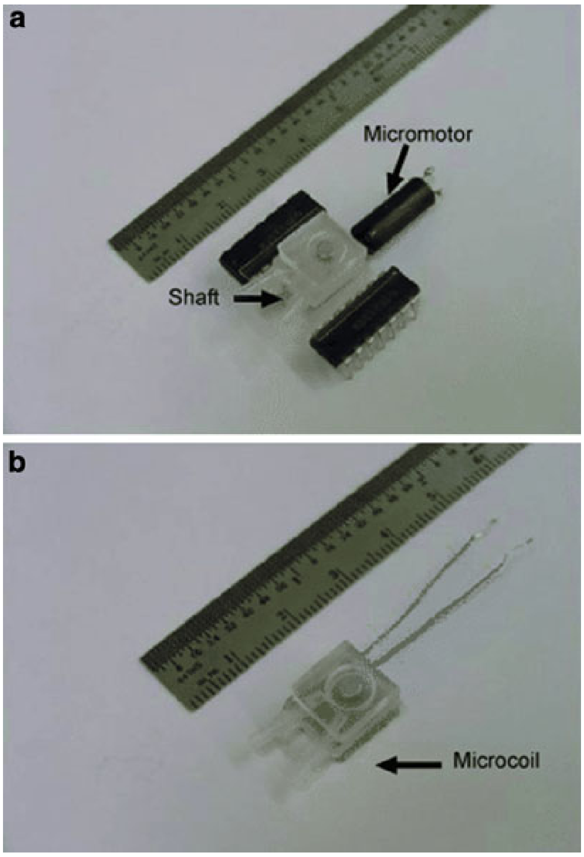
Magnetic Pumps, Fig. 2 (**a**) Schematic and (**b**) photograph of micropump system of [4] (Reprinted from [4] with permission from Dr. Yamahata)

This micropump is integrated on a microstructured polymer disk and is sealed by an elastomer lid. Pumping is done by the phase-shifted displacement of two metal inlays incorporated in the elastic lid of polymer disk. Moreover, the pumping pressure is a function of the frequency of rotation. Rotational motion of this hybrid over a stationary magnet induces a sequence of volume displacements of the elastic lid and results in transportation of gas. The new centrifugo-magnetically actuated micropump adds two important unit operations to centrifugally driven microfluidics as sampling of gas volumes and their introduction to liquid-phase assays on a lab-on-a-disk and the generation of trains of discrete liquid plugs segmented by gas bubbles.

Kurtoglu et al. [14] studied a method to actuate ferrofluids with changing magnetic fields.

In order to obtain a linearly moving magnetic gradient, they used composing a magnetic field with rotating magnetic field sources. Briefly, the studied method in this entry involves positioning magnets around solid rotors in a spiral pattern. When the rotors are rotated in agreement from a starting configuration of a magnet pair facing each other, the magnet pairs face each other periodically and the fluid plug reaches the middle point of a magnet pair, shows that the transitions are smooth enough and magnetic fields are sufficiently strong so the fluid can be smoothly actuated by applying of this technique.

The experimental results show that ferrofluids needs more research efforts in micro pumping, and magnetic actuation can be an appropriate alternative for more common techniques such as electromechanical, electrokinetic, and piezoelectric actuation methods.



Magnetic Pumps, Fig. 3 Test and measurement setup for two micropumps of different driving mechanisms: (**a**) permanent magnet with a small DC motor; (**b**) integrated coil (Reprinted from [5] with permission from Dr. Ziaie)

Nonmechanical micropumps using magnetohydrodynamics (MHD) principle for fluid motion have also been studied in the literature. If an electrical field, $\boldsymbol{E}$, and a magnetic field, $\boldsymbol{B}$, is applied perpendicular each other, they create a Lorenz force in the direction of $\boldsymbol{J} \times \boldsymbol{B}$ where $\boldsymbol{J}$ is the electrical current density. Since the mean free path of the ions in a liquid is extremely small, momentum is transferred from ions to the solvent molecules rapidly by the collisions. Therefore, the sum of the Lorentz forces on all of the ions inside the liquid is just the net driving force causing the bulk liquid motion in MHD pumps. Jang and Lee [9] (Fig. 4), Huang et al. [10], and Zhong et al. [11] successfully applied MHD principle for the development of micropumps by using DC current. The pressure head generated by MHD pumps can be controlled by adjusting the intensity of magnetic field, the magnitude of the applied voltage across the electrodes, and the length of the actuation section which makes the usage of MHD pumps very flexible. Homsy et al. [12] developed a simple method of flow rate measurement inside the bulky nuclear magnetic resonance (NMR) magnet and demonstrated a DC magnetohydrodynamic (MHD) pump as component of a NMR microfluidic chip for first time. According to their results this chip uses only 38 mW of power consumption in a 7 T superconductive magnet for an applied voltage of 19 V and produces a maximum flow rate of 1.5 μL/min in a microchannel.

The working principle of this MHD pump is based on generating a high DC current density without disruption of flow due to bubble formation. Two micromachined frit-like structures connect the pumping channel to side reservoirs. The electrodes are embedded in the side reservoirs and by this way are separated from the main channel. In this way, formed bubbles at the electrodes did not enter the main channel. A high ionic current with a very low volumetric flow rate can be generated over the main channel. Coupling of this ionic current with a perpendicular magnetic field causes generation of a body force in the perpendicular direction, all along the pumping channel.

However, all these micropumps suffered from the bubble generation at certain voltage values at the electrodes which are used to generate the electrical field. Lemoff and Lee [13] used AC current in their MHD micropump and eliminated the bubble generation (Fig. 5). They used electromagnet to generate the magnetic field. They showed that by using electromagnet, multiple pumps can be driven independently by varying the amplitude and phase of the currents of electrodes and electromagnet.

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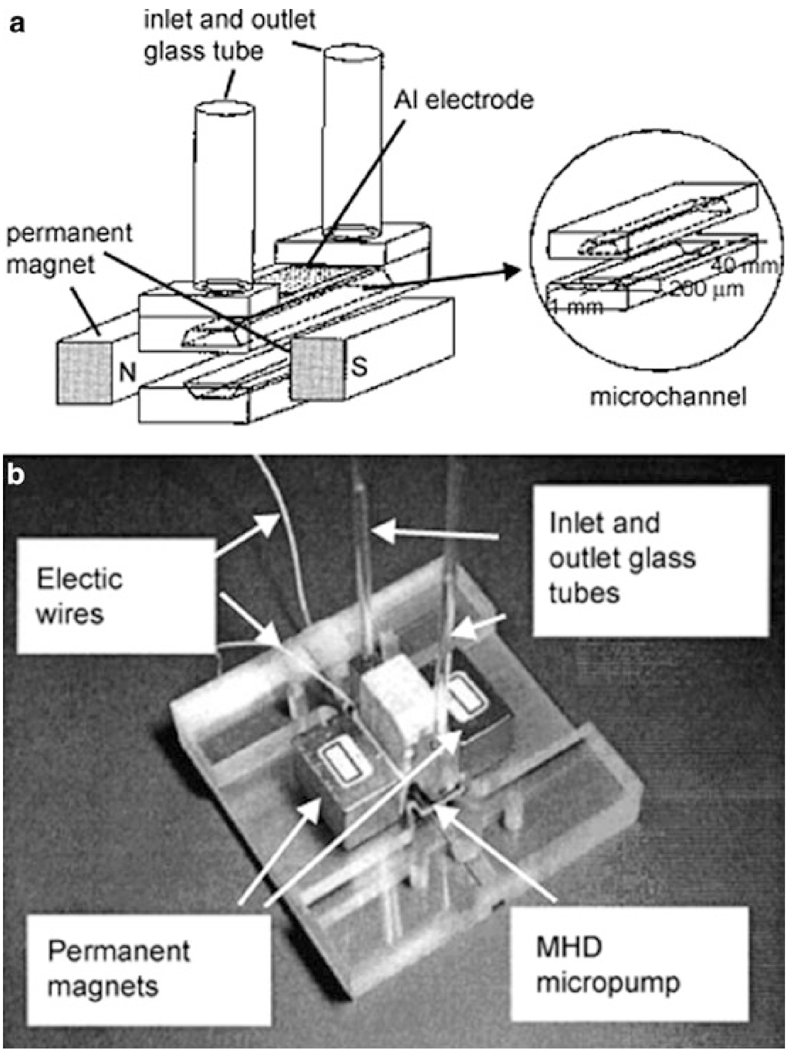
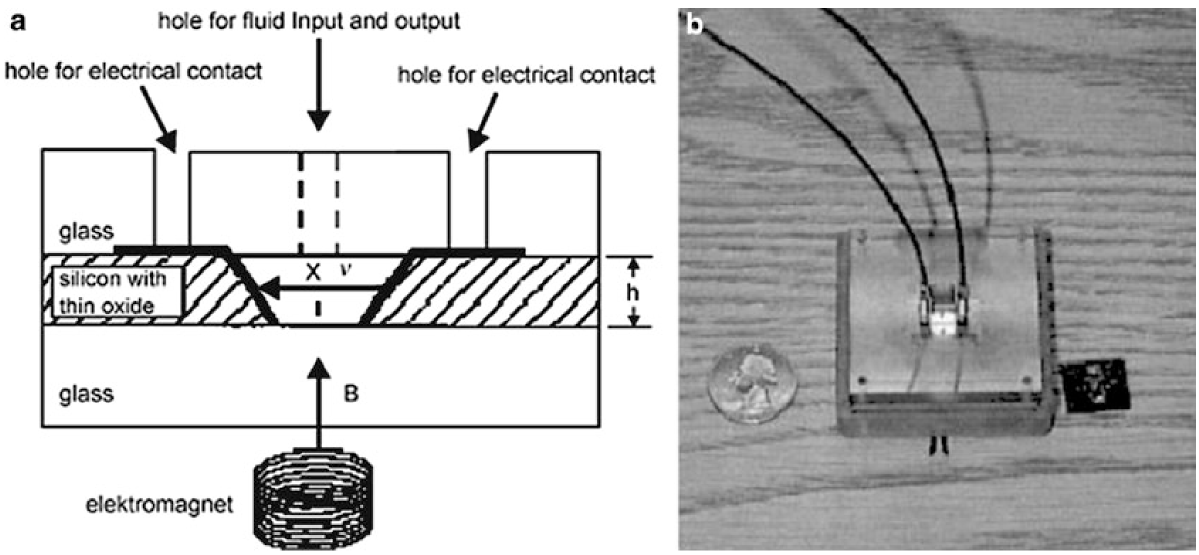


Magnetic Pumps, Fig. 4 (**a**) Schematic and (**b**) photograph of micropump system of [6] (Reprinted from [6] with permission from Dr. Jang)



Magnetic Pumps, Fig. 5 (**a**) Cross section of AC MHD and (**b**) photograph of microsystem of (Reprinted from [9] with permission from Dr. Lee)

When the rotors are rotated in agreement from a starting configuration of a magnate pair facing each other, the magnet pairs face each other periodically and the fluid plug reaches the middle point of magnet pair. This shows that the transitions are smooth enough and magnet field are sufficiently strong so the fluid can be smoothly actuated by applying of this technique.

The experimental results show that ferrofluids needs more research efforts in micro pumping, and magnetic actuation can be an appropriate alternative for more common techniques such as electromechanical, electrokinetic, and piezoelectric actuation methods.

Future Research Directions

Magnetic micropumps are important components within the microfluidic toolbox. Two main factors that should be considered through embedding magnetic micropumps in such systems are providing enough magnetic force and sealing fluidic channel. Because of the importance of mentioned factors, further investigations on the energizing operation and fluid leakage between the permanent magnets and wall channels are highly recommended. Another important factor that should be considered refers to the size of the pumping system. Since the pumping system is going to be designed as part of a lab-on-a-chip device, required optimizations on size should be done to embed the system freely inside the device.

Cross-References

► Microfluidic Rotary Pump
► Thermocapillary Pumping
► Ultrasonic Pumps

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Magnetic Susceptibility

Definition

Magnetic susceptibility represents the amount of magnetization of a material in response to an applied magnetic field.

Cross-References

► Magnetic Field-Based Lab-on-Chip Devices