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Fabrication and development of magnetically actuated PDMS micropump for drug delivery

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Fabrication and development of magnetically actuated PDMS micropump for drug delivery

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Abstract: Micropump is an essential component used in drug delivery systems to dispense small amounts of liquid into human body in a controlled manner over a period of time. Polydimethylsiloxane (PDMS) is an elastomeric polymer with attractive properties such as non-toxicity, biocompatibility and blood compatibility. Further, its bio-inertness inhibits microbial growth, thereby making it more attractive for biomedical applications. This paper presents the fabrication of a simple, dual-chamber, valveless PDMS micropump with an integrated magnetic actuator for drug delivery applications. The micropump developed in the laboratory consisted of two circular reservoirs provided with end nozzle diffusers. The reservoirs were sealed with a thin PDMS layer and a permanent magnet was attached over it to form the actuation membrane. An external magnet fixed to a rotating DC motor shaft is used to excite the actuation membrane. The magnetic force of attraction and repulsion between the rotating magnet and membrane magnet resulted in a vibrating diaphragm and consequently aids in pumping action. The liquid flow rate through the PDMS micropump depends on the rotational speed of the motor, viscosity of the liquid and the geometry of the micropump. Exhaustive experimental results were obtained with different viscous fluids such as water, ethanol and coconut oil. For these fluids, the motor speeds of the developed PDMS micropump worked satisfactorily. The parameter of interest such as flow rate for water was found to be 1.7 mL/min at a motor speed of 3000 rpm. The highest flow rate of the pump corresponded to the resonant frequency of the actuation membrane which is 14.8 Hz.

1. Introduction

Micropumps are devices that can control and manipulate the flow of minute fluids volumes and their typical output flow rate varies in the range µL/min to mL/min [1,2]. Fabrication of such devices is of special interest in microfluidics research for medical application and has offered scope for industrial product integration in recent years. Micropumps are minuscule devices which can sense, propel, merge, monitor and control tiny volumes of microliters (µL) fluids flow [2]. An ideal micropump consists of a pumping chamber with an inlet and outlet valve and a diaphragm. Actuation of the diaphragm can be performed by many types of process such as piezoelectric actuation, thermal actuation, peristaltic actuation, magnetic actuation [3]. Overall improvement in size, production and marketing cost, safety and regulatory issue, improved dosing accuracy compared to existing mini pump fuel has developed an interest to innovate this kind of pump. They find application in biomedical instrumentation, implantable devices, 3D printing, site specific and trans-dermal drug delivery etc [3,4]. In recent times polymeric micropumps have been employed for sustainable release of drugs into a human body in a controlled manner over a period of time. Many researchers have worked on different PDMS micropumps with different actuation process. *Pan et al*, studied PDMS membrane micropump with two one-way balls check valves for micro-fluidic applications where maximum flow rate of 774 μLmin^{-1} for 13 mW was observed and 10-turn planar coil pumping rate was 1 μLmin^{-1} for water [5]. *Ni et al* worked on PDMS with pneumatic actuation [1]. The micropump can generate maximum flow rate of $41\mu Lmin^{-1}$ at 25kPa backpressure [1]. Zhou *et al*., studied the fabrication and process of valve less, single-chamber planar PDMS micropump driven by an external magnetic actuator [6]. Maximum flow rate of $319.6\mu Lmin^{-1}$and a maximum hydrostatic backpressure of 950 Pa (9.5 cm H_2O) were exerted by the micropump. Further *Mamanee et al.,* studied the thermo-pneumatic peristaltic micropump for controlling micro liters of fluid flow [7]. Pump structure consists an inlet and outlet, micro-channel, three thermo-pneumatic actuation chambers and three heaters. Actuation was carried by peristaltic motion, under 14V optimal flow rate of 0.82 µl/min is obtained and under three-phase input voltages at 0.033 Hz operating frequency. With reference to earlier papers, consideration of magnetic actuation force was high, no fluid interaction, operates at room temperature, high bandwidth operation, biocompatible with other physio-chemical samples as to give maximum and suitable flow rate as required. Objective of this study is to develop valve less PDMS micropump using magnetic actuation. Many researchers have reported design and development of micropump with incorporation of valve to establish unidirectional fluid flow. In this study the flow of liquid in the micropump is unidirectional and it is valve less in nature. Liquids such as Water, Ethanol and Coconut oil were used for the experiment. Of these liquids the viscosity of water is comparable with that of insulin. Hence, performance of developed micropump can be extrapolated for drug delivery applications as well.

This paper reports the design, fabrication and controlled magnetic actuation of a valve less PDMS micropump. To address the issue of unidirectional fluid flow, a nozzle diffuser configuration was adopted. In this design magnetic actuation was employed for controlling the fluid pumping rate through the micropump. A thin, strong magnet integrated with the actuation membrane provides the required force/pressure required for pumping fluid. Periodic attraction and repulsion of this magnet results in continuous positive fluid displacement and easy flow of the fluids.

2. Design of Micropump

The micropump design consists of a two circular fluid chambers (20 mm diameter) with inlet and outlet ports as seen in figure 1 (a). The unidirectional fluid flow is achieved by planar nozzle diffuser configuration which is a small opening at the outlet of fluid chamber with tapering end. This, design ensures unidirectional fluid flow without additional mechanical valves. The fluid chamber is encapsulated with a thin PDMS membrane about 200 µm in thickness as seen in figure 1 (b). Circular neodymium magnet of 10 mm diameter and 1mm thickness was embedded onto the PDMS membrane. Magnetic actuation was performed by bringing an external magnet close the membrane magnet. By moving or rotating the external magnet the force of attraction/repulsion between these two magnets can be changed.

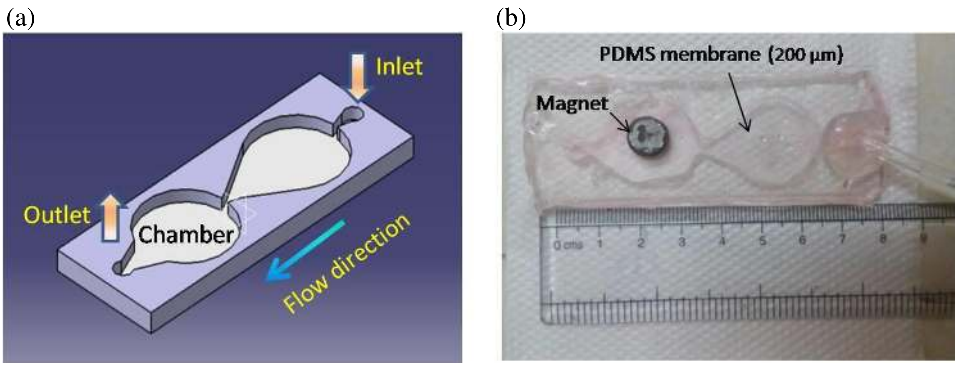

Figure 1. (a) CAD model of the dual chamber PDMS micropump with nozzle diffuser (b) Fabricated PDMS micropump with actuation magnet attached to its membrane

The membrane magnet moves close to or away from the external magnet, this in-turn moves the actuation membrane increasing the chamber volume and decreasing the chamber pressure which draws fluid into it. As the membrane magnet moves away from the external magnet, it pushes the actuation membrane downward. Thus, exerting pressure on the chamber fluid and causing it to be expelled from the fluid volume. Due to the nozzle diffuser configuration the volume displacement is greater at the chamber outlet and minimal at the inlet ensuring unidirectional fluid flow. The speed at which the polarity of the external magnet changes determines the frequency of membrane actuation and hence the fluid flow rate.

3. Experimental Procedure

3.1. Fabrication of PDMS micropump

Polydimethylsiloxane (PDMS) is an organic silicone polymer is used as a structural material to fabricate the fluid chamber and actuation membrane for micropump. Its unique properties such as biocompatibility, low cost production and flexibility make it suitable for application in microfluidics, lab-on-chip devices and BioMEMS. Table 1 shows the specifications of PDMS polymer used in fabrication of micropumps in this paper [8]. Commercially available PDMS Slygard 184 elastomer kit was obtained from Dow Corning Corp, Mumbai. The PDMS pre-polymer is a transparent, viscous liquid which is mixed with the hardener solution in ratio 10:1.

Table 1. Specification of PDMS polymer

Property	Value
Density	0.97 kg/m^3
Young’s Modulus	0.57 MPa
Poisson’s Ratio	0.5
Thermal Conductivity	0.15 W/m.K
Specific Heat	1.46 kJ/kg.K
Viscosity (Base)	5.1 Pa.s
Refractive index	1.4
Dielectric constant	2.3-2.8
Resistivity	4x10^{13} Ω.m

The fabrication of PDMS micropumps reported in this paper doesn’t require lithography facility. This method is both simple and cost effective. The solid molds for making PDMS fluid chamber was made by cutting sticky tapes in desired patterns and stacking them above the other till a depth of 2 mm was attained. This pattern was then stuck onto acetate sheet. It was experimentally observed that the adhesion of PDMS over acetate sheets was lesser than its adhesion to glass. The use of acetate sheets made processing and peeling of PDMS easier. Later, the prepared PDMS pre-polymer with hardener (10:1) was then poured over the patterned mold and again degassed in vacuum for 10 minutes to remove excess air bubbles from PDMS. Then it was heated to 80°C for 20 minutes till the entire PDMS liquid completely solidifies due to polymer cross-linking. PDMS membrane (200 µm) was made by mixing PDMS pre-polymer and hardener in volume ratio 10:1 and the mixture was degassed in vacuum for about 10 minutes and spin coated over acetate sheets at 500 rpm for 60 seconds with an acceleration of 5 ms^{-2}. These PDMS sheets were then heated at 80°C for 10 min and peeled off from the acetate sheet. By applying a thin layer of PDMS pre-polymer between the fabricated fluid chamber and PDMS membrane and further curing at 80°C, these layers can be completely sealed. Later, two flexible tubes were connected to the inlet and outlet ports through which fluid was drawn into and out of the fluid chamber. The edges of these tubes were again sealed using hot glue to avoid any leakage of fluid. Finally, a thin circular magnet was attached to one of the fluid chambers using a drop of PDMS so that it firmly fixed with the actuation membrane.

3.2 Evaluation of magnetic field strength

Magnetic actuation of the PDMS membrane was achieved using the force of attraction and repulsion between magnetic poles. Two circular, flat permanent magnets made of neodymium were used for this purpose. One magnet was embedded onto the surface of the PDMS membrane, while the other magnet was attached to the rotating shaft of the DC motor (see figure 3). The magnetic field strength of individual magnets varies inversely with respect to the distance between them as seen in figure 2. The variation of magnetic field between two magnets was measured using a gauss meter and it may be observed that higher field strength can be obtained by keeping the distance between magnets as small as possible. This is however, limited by the radius of the rotating circular magnet which is 5 mm. Hence, distance was between the magnets for all flow rate measurement in this paper was maintained >5mm. The magnetic field strength corresponding to this distance is about 100 gauss.

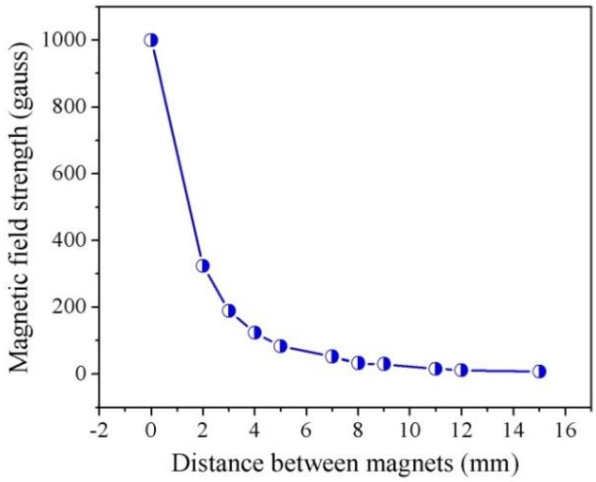

Figure 2. Magnetic field with a varying distance

3.3 DC motor Speed control using Arduino interface

The fabricated PDMS micropump was driven by magnetic actuation of the membrane. The force of attraction/repulsion between membrane magnet and external magnet attached to the rotating shaft of the DC motor controls the rate of membrane actuation and fluid pumping rate. By precisely controlling the driving voltage of the DC motor, the shaft rotation speed can be controlled. In this paper, a small DC motor of 10 mm diameter and 20 mm length with low power ratings was considered and a permanent magnet was attached to its rotating shaft. Figure 3 shows the schematic diagram of the electrical circuit used for speed control of the DC motor. Arduino Uno R3 was used for driving the DC motor and measuring its speed of rotation. 9V battery was used as power supply for motor and a 10 kΩ potentiometer connected to the Arduino board was used for voltage control to the DC motor. Varying the knob position on the potentiometer different motor speed can be obtained and the instantaneous speed of the motor is displayed in the computer connected with the Arduino board. Using this arrangement, the motor rotation speed could be controlled from 500 rpm to 4500 rpm.

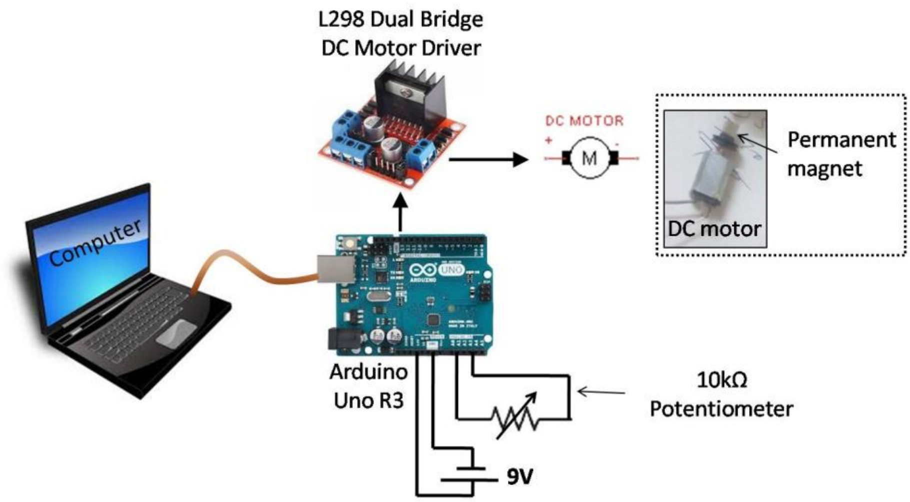

Figure 3. Schematic diagram showing the electrical circuit used to control DC motor speed

3.4 Flow rate measurement

Figure 4 shows the photograph of the flow measurement set-up used in this paper. The DC motor speed was controlled by potentiometer and the corresponding motor speed is displayed on the computer. The external magnet is brought in close proximity to the membrane magnet such that it experiences maximum membrane actuation. This figure 4 also shows saffranin stained water being pumped. The water dispelled out of the pump is collected using a glass Petridish and its volume is measured using a graded clinical syringe. Flow rate at a particular motor speed is measured as fluid volume displaced for one minute. For water, the PDMS membrane was actuated from 500 - 4000 rpm in steps of 1000 rpm and the corresponding fluid flow rate was recorded for 60 seconds. The same procedure was repeated for ethanol and the coconut oil.

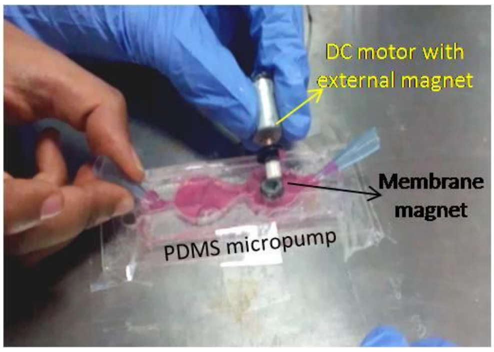

Figure 4. Photograph of flow rate measurement for water using fabricated PDMS micropump

4. Results and discussion

The performance of the fabricated PDMS micropump was evaluated for three fluids with different viscosities such as water, alcohol and oil as seen in Table below. The flow rates of these liquids through the PDMS channel is significantly influenced by the frictional forces provided by the channel walls to different fluid viscosities. Figure 5 illustrates the flow rate for water, ethanol and coconut oil at various rotation speed of the DC motor. The process of attraction and repulsion of the membrane magnet and the external magnet excites the circular PDMS membrane. At a certain rotation speed when the membrane is excited to its resonant frequency it experiences maximum mechanical displacement and the corresponding flow rate through the micropump is maximum for all the liquids. For a circular diaphragm, the resonant frequency of the actuating PDMS membrane can be expressed as [9]

$$f_0 = \frac{1}{4\pi}\sqrt{\frac{k}{m}} \quad ...(1)$$

Where, k is the stiffness of the circular diaphragm of PDMS with radius (r) 20 mm and thickness (h) 200 µm. Further, the stiffness of a circular membrane is given by

$$k = \frac{16\pi E h^3}{r^2(1-\nu^2)} \quad ...(2)$$

Where, E is the Young's modulus of PDMS (0.57 MPa) and ν is its Poisson's ratio (0.5). Substituting these values in equation (2), we get the stiffness of the circular PDMS membrane to be 3.056 $Nm^{-1}$and its resonant frequency was calculated from equation (1) to be about 14.8 Hz. At this frequency the flow rate was observed to be maximum which corresponds to motor rotation speed of 3000 rpm. This is the operating frequency at which the reported micropump produces optimum pumping rates for any fluid. For the fabricated PDMS micropump, the flow rate is highest for water (1.7 mL/min) which possesses least viscosity and minimum for oil. Also, for all the three liquids, maximum flow rate was observed at a rotation speed of 3000 rpm. For water, ethanol and oil, the maximum flow rate at 3000 rpm was measured to be 1.7 mL/min, 1.2 mL/min and 0.8 mL/min respectively. It is clear from these experiments that the flow rate reduces for high viscosity fluids. As mentioned in the introduction, the viscosity of water is comparable with drugs such as insulin. Hence, this fabricated PDMS micropump can be used for controlled dispensation of insulin drug. Future work aims at fabricating a mechanical fixture for the micropump and DC motor. Also, the flow control will be completely automated.

Table 2. Viscosities of various fluids at 20°C

Fluids	Viscosity (mPa.s)
Water	0.89
Ethanol	1.2
Coconut Oil	80

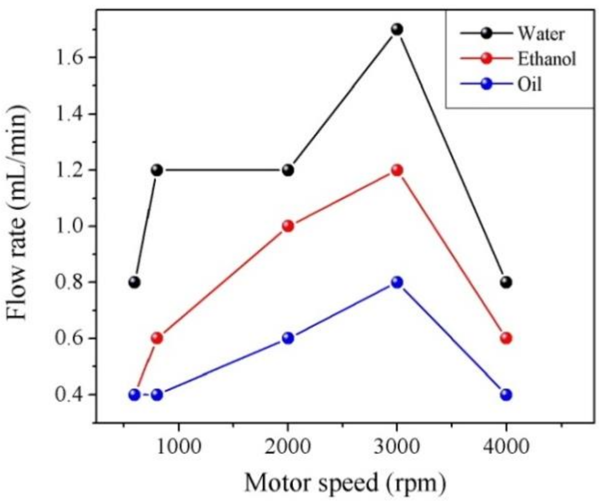

Figure 5. Flow rate of water, ethanol and coconut oil through the fabricated micropump Viscosities of water, ethanol and oil

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5. Conclusion

A dual-chamber valveless PDMS micropump was fabricated and actuated using external strong magnets. Unidirectional fluid flow was achieved with nozzle-diffusers at the outlet of each fluid chamber. The micropump was driven by magnetic force of attraction and repulsion between membrane magnet and external magnet attached to a rotating shaft. By controlling the speed of DC motor shaft rotation, the fluid pumping rate was precisely controlled. The performance and flow rate of the fabricated PDMS micropump was evaluated for three liquids with different viscosities. It was observed that maximum flow rate corresponding to the lowest viscosity fluid. In this study, water had the least viscosity and hence maximum flow rate. The measured flow rate was about 1.7 mL/min, 1.2 mL/min and 0.8 mL/min respectively for water, ethanol and coconut oil for a motor speed of 3000 rpm. This corresponded to the resonant frequency of the actuation membrane which is 14.8 Hz.

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