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A stepper micropump for ferrofluid driven microfluidic systems

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Abstract

We demonstrate a novel stepper micropump for ferrofluid driven microfluidic systems. The rotor is a ferrofluid plug that works as a piston pushing another liquid in a circular microchannel. The actuation concept is similar to that of a stepper motor, where the angular velocity can be precisely controlled by a series of actuating solenoids. The actuation force is adjusted by the driving voltage or current. Thus fluids with different viscosities can be handled in the pump. The pump can be used for a circular ferrofluid driven microchip for rapid polymerase chain reaction (PCR), where the sample is continuously pumped in a closed loop over three temperature zones to realize thermal cycling.

Keywords: micropump, ferro fluid, electromagnetic actuation, PCR, microfluidics

1. Introduction

The rapid development in life sciences leads to a growing demand for new microfluidic devices and systems such as labs on a chip (LOC). The key components in a LOC are micropumps and micromixers. Many LOC devices still need to rely on external pumping systems such as syringe pump and vacuum pump, while existing micropumps vary in complexity and effectiveness [1]. Mechanical micropump actuated by a membrane such as check-valve pump [2], peristaltic pump [3], and diffuser/nozzle pump [4] have the drawbacks of pulsatile flow and sensitivity to trapped bubbles. Even in micropumps without moving parts such as the ultrasonic micropump [5] and other non-mechanical concepts, the sample fluid is often exposed to intense ultrasonic field, high temperature and high voltage. All reported micropumps are relatively complex and require expensive micromachining technologies.

Pumping based on magnetic force is one of the gentle methods without high temperature and shear forces. The fact that magnetic force is a body force is the main drawback of magnetic actuation. However, magnetic actuators for pumping applications can be miniaturized due to the possible high magnetic field gradient and flux in microscale. West et al. [6] utilized the magnetohydrodynamic (MHD) effect of an electrolyte between two ring electrodes to pump it in a closed loop. In the MHD concept, the sample liquid is in direct contact with the electric field leading to high temperature due to Joule heating as well as electrolysis. Ferrofluids can also offer a gentle actuation concept. A ferrofluid is a stable colloidal suspension of magnetic particles in a liquid carrier. The magnetic particles have a size on the order of 10 nm. At this size, the Brownian motion is dominant and the particles are well dispersed even in a strong magnetic field. A ferrofluid plug acts as a liquid magnet and can be used to drive another immiscible liquid in microchannels. Hatch et al.[7] used a ferrofluid plug as a piston in a micropump. The ferrofluid plug was driven by an external magnet. A similar magnetic actuator was also reported later by Yamahata et al. [8]. Liu et al. used a circular channels and peristaltic micropumps to realize polymerase chain reaction (PCR) of DNA [9]. Recently, we reported a ferrofluid driven microchip for rapid PCR [10]. In this device, PCR sample was driven by a

ferrofluid plug a circular closed loop over three different temperature zones. The ferrofluid plug was pushed by a permanent magnet attached to a stepper motor. The angular speed of the stepper motor was a key parameter for optimizing the cycling time of the PCR. In this technical note, we report a further development of this pumping system. Instead of using a stepper motor and an external permanent magnet, we realize a stepper micropump where the ferrofluid acts as the rotor. Controlling the external stator allows precise positioning of the ferrofluid plug and consequently its angular velocity. The positioning capability of this stepper micropump would allow a more flexible PCR protocol.

2. Design and fabrication

The stepper micropump consists of two parts: the microchip and the external stator. The design and fabrication of the microchip with the ferrofluid plug was described before by Sun et al. [10] The chip was fabricated in two polymethyl methacrylate (PMMA) sheets. CO₂ laser was used for machining the circular microchannels, the inlet as well as the outlet ports. The channel was sealed by thermal bonding. The chip measures 30 mm×30 mm. The circular channel has a diameter of 20 mm, a width of 800 μ m and a depth of 430 μ m. For testing purpose, the microchannel was filled with silicone oil purchased from Sigma Aldrich (USA) ($[-\text{Si}(\text{CH}_3)_2\text{O}-]_n$). The silicone oil has a density of $\rho = 960 \text{ kg/m}^3$ and a kinematic viscosity of $\nu = 5 \times 10^{-5} \text{ m}^2/\text{s}$. A ferrofluid plug was used as the rotor and driving piston in our pumping concept. The ferrofluid (APG S10n) was purchased from Ferrotec, USA. The carrier liquid of this ferrofluid is synthetic ester oil, which can be considered as immiscible to silicone oil and water. The viscosity, the density, and the surface tension of the ferrofluid at 25°C are $\mu_{\text{ff}} = 0.406 \text{ kg/ms}$, $\rho_{\text{ff}} = 1330 \text{ kg/m}^3$, and $\sigma_{\text{ff}} = 32 \times 10^{-3} \text{ N/m}$, respectively. The saturation magnetization and the initial susceptibility of this ferrofluid are 44 mT and $\chi = 1.6$, respectively [11, 12]. Figure 1(a) depicts the main components of the microchip.

The stator is an array of eight solenoids arranged circularly around the channel loop. Figure 1(b) shows the arrangement of these solenoids. The solenoids were modified from

commercially available coils which have a resistance of 17.8 ± 0.2 Ohms. The original core of the solenoid was replaced by a steel core of 6-mm diameter. The tip of the core was tapered to an angle of 20° to maximise the magnetic flux at the tip. The tapered cores were permanently attached to the solenoid using epoxy. The solenoid with the tapered core was then attached permanently to a aluminium holder by epoxy adhesive, Figure 1(b). The holder was made of a 2-mm thick aluminium bar that was bent 90° and 45° at its two ends. The holder with the solenoid was subsequently attached to a chassis made of PMMA using screws. The aluminium holders offer a rigid support to the solenoids and do not interfere with the magnetic field. Furthermore, the holder works as a heat spreader for the solenoid. The position of the core tip can be fine tuned by the screw connection at the chassis, which firmly holds the microchip with the circular channel. The total dimension of the setup measures 100 mm×100 mm×50 mm.

Similar to a stepper motor, the solenoid was controlled in a half-step mode due to the relatively large gap of $\pi/8$ rad between two core tips. The ferrofluid plug acting as a rotor should be at least longer than the gap between two neighbouring core tips. Figure 1(c) show the control scheme of the eight solenoids. The activation sequences are A, A-B, B, B-C, C, C-D,..., H, H-A. An activation period p_1 of a single solenoid is followed by an activation period p_2 of the same solenoid and its next neighbour. Thus, the time needed for all 16 steps or a complete loop is $T = 8(p_1 + p_2)$. The corresponding average angular velocity of the pump is then $2\pi/T$ (rad/sec). Figure 2 depicts the fabricated system.

3. Results and discussions

The magnetic flux at the core tip was measured with a gaussmeter (GM05, Hirst Magnetic Instruments Ltd, UK) Figure 3 shows the magnetic flux at different voltages. At a voltage of 20 V, the solenoid can induce a magnetic flux of approximately 250 mT. The trend shows that the magnetic flux at the core tip reaches its saturation value at about 20 V or 0.9 A. The control scheme depicted in Fig. 1(c) was implemented with a micro controller (BasicX-24p, NetMedia Inc, USA). The micro controller provides 8 digital outputs for

the 8 solenoids. The driving signals were conditioned by bipolar transistors (2SD882, NEC, Japan). All solenoids were connected to the same power supply.

The stepper micropump was characterized using a video setup. Images of the pump were captured by a CCD camera and transferred to a personal computer. The frame rate of the CCD camera can be adjusted so that precise time sequences can be recorded. A customized image processing programme evaluates the motion of the ferrofluid. Figure 4 shows the typical responses of the ferrofluid plug to the driving sequence depicted in Fig. 1(c). In our experiments, the ferrofluid plug spans over three core tips or $\pi/4$ rad. Figure 5 shows the measured angular displacement and the angular velocity of the advancing meniscus of the ferrofluid plug at activation periods of $p_1 = p_2 = 25$ sec and a driving voltage of 20 V. The pumping steps represented by the velocity peaks caused by the activation of the solenoid can be clearly observed, Fig. 4(b).

The two key parameters for the behaviour of the stepper micropump are the activation periods and the driving voltage (the current and the magnetic flux) of the solenoids. Since magnetic force and inertial force are both body forces, in the case of the stepper micropump they have the same order of magnitude. The optimal activation time should be long enough for the ferrofluid plug to follow and short enough to not waste the idle time. A model can be formulated for the dynamic behaviour of the ferrofluid plug as well as the liquid inside the circular channel based on the balance between the driving magnetic force, the inertial force and the friction force. Previously, we have formulated and investigated a similar model for a ferrofluid droplet suspended in silicone oil [12]. According to this model, the response time of the ferrofluid plug depends on its size, the strength of the magnetic field and the viscosity of the surrounding fluid. To ensure that the ferrofluid plug can reach its final position, the activation period should be longer than the response time. Figure 4(b) shows that with an activation periods of $p_1 = p_2 = 25$ sec, the plug velocity almost approaches zero at the end of each step and the ferrofluid plug reaches its final position. A shorter activation period would bring the position of the ferrofluid plug out of synchronization with the position of the solenoid's core tips.

The next key parameter for the stepper micropump is the applied voltage or current. If the driving voltage is too low and the activation period is not long enough, the ferrofluid plug is not able to reach its final position before the next step is activated. Thus, a low driving voltage may lead to dissynchronization between the plug and the core tip position. Figure 5 shows the angular displacement of the ferrofluid plug at different driving voltages above 10 V. Figure 3 already shows that the higher the voltage or driving current the higher is the magnetic flux at the core tip of the driving solenoid. From 15 V to 20 V, the magnetic flux reaches its saturation and does not change significantly with increasing voltage. This fact reflects well in the angular displacement depicted in Fig. 6. The behaviours of the ferrofluid plug are almost identical for driving voltages of 15 V and 20 V. In Figure 6, the straight line is the ideal displacement predicted based on a continuous motion with an angular velocity of $2\pi/T$, where $T = 16 \times 25 \text{ sec} = 400 \text{ sec}$. The results show that the relatively low driving voltage of 10V is able to keep the actual angular displacement on the ideal line. The activation time of 25 sec is not long enough for higher voltages of 15 V and 20 V. Since the ferrofluid plug velocity does not come to zero [Fig. 5(b)], it is slowly brought out of course, Fig. 6. Since the ferrofluid plug is $\pi/4$ rad long, the deviation shown in Fig. 6 is still acceptable for a single full loop. The ferrofluid will be out of synchronization in the subsequent loops.

4. Conclusions

In conclusion, we have demonstrated a stepper micropump for ferrofluid driven microfluidic systems. The pump is a circular channel with a ferrofluid plug as the rotor or the driving piston. The stator consists of eight solenoids with tapered cores. Similar to a stepper motor, the solenoid was controlled in a half-step mode. The pump needs 16 steps to complete a loop. The experimental results show that the activation period of each step and the driving voltage need to be optimized to synchronize the plug position with the positions of the actuating core tips. The shape of the core tip can be further improved. A sharp tip may bring high magnetic flux but also a high field gradient. We observed that at a high driving voltage and a short activation time the ferrofluid tends to move faster on the channel wall, enclosing and forming silicone oil droplets inside it. This phenomenon

may lead to the rupture of the original ferrofluid plug. Surface treatment of the microchannel could further reduce the friction force allowing the system to respond faster to the actuating field. The stepper micropump presented here can work with the ferrofluid driven microchip for rapid polymerase chain reaction (PCR) reported previously by our group [10]. The positioning capability of this micropump would allow a more flexible PCR protocol.

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