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A novel revolving piston minipump

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ABSTRACT

In this study, a novel prototype high-efficiency miniature pump that uses magnetic properties of a ferrofluid in both pumping and valving mechanisms is presented. The minichannel consisting of a cylindrical pumping chamber, a check valve, an inlet and an outlet, comprises six bonded layers of PMMA. A cylindrical permanent magnet that is placed inside the chamber and is externally actuated by a motorized off-center permanent magnet, functions as a revolving piston which sweeps the perimeter of the cylinder. Ferrofluid is used to cover the gaps between the magnetic piston and the channel walls, also serves as a separating plug between the inlet and the outlet of the chamber preventing recirculation of the pumped fluid inside the chamber. This novel revolving piston design eliminates the need for an inlet valve. Pressure head is maintained using one ball check valve at the outlet of the pump. Water has been successfully pumped at flow rates of up to 934 μL/min, backpressures of up to 994 Pa, and maximum achieved volumetric efficiency of 79 percent while working at 80, 52, and 9 rpm rates, respectively.

1. Introduction

With a growing interest in the development of microfluidic systems over the past two decades, there have been numerous reports on the fabrication of microfluidic devices for use in a wide range of applications, such as chemical analysis, biological and chemical sensing, drug delivery, molecular separation such as DNA analysis, amplification, sequencing or synthesis of nucleic acids, environmental monitoring, and also in precision control systems for automotive, aerospace and machine tool industries. Several micropumps have been developed for the purpose of microscale pumping of fluidic samples. Various pumping principles with different actuation mechanisms have been investigated including electrostatic, piezoelectric, thermal, pneumatic, shape memory alloy, bimetallic, ion conductive polymer film, electromagnetic, magnetic, phase change, magnetohydrodynamic, electrohydrodynamic, electroosmotic, electrowetting, bubble type, flexural planar wave, electrochemical, and evaporation based; reviewed in [1–4].

Micropumps made of polymeric materials with contactless external actuations are of particular interest for disposable applications with the reusability of the costly parts of the device. In particular, magnetic actuation has the advantages of rapid time response with low actuation voltage as well as large displacement with the ability of self-priming. Several magnetically driven micropumps were presented based on deflection of elastic membranes with embedded permanent magnet using external electromagnets [5–9] or external permanent magnets with controllable movement [9–11]. The former actuation method has an issue of heating whereas the latter one has the advantage of lower input power.

On the other hand, most of the investigated pumping and valving devices are relatively complex and need expensive precision micromachining technologies. Among the microfabricated systems, ferrofluidic devices have the advantage of obviating the required tolerance of the micromachined channels or the allowances needed for the microfabricated moving parts; thereby reducing the cost as well as improving the reliability; because ferrofluids (colloidal liquid made of nanosize ferromagnetic particles suspended in a carrier fluid) have the benefit of conforming to different channel shapes and providing self-sealing capability with low friction in motion responding to imposed magnetic fields. The use of magnetism for controlling fluidic functions such as pumping, mixing, magnetowetting, and magnetic manipulation of particles are reviewed in [12]. A review of the recent advances in mechanical applications of ferrofluids is provided by Torres-Díaz and Rinaldi [13].

Many researchers used the self-sealing property of ferrofluid plugs actuated by permanent magnets or electromagnetic coils for pumping and valving functions in microchannels. The ferrofluidic micropumps usually withstand the low pressure in the order of 1 kPa which can be increased with decreasing the dimensions of

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the microchannel or increasing the strength of the applied magnetic field. With the advantages of low complexity and low cost while reducing total pump volume, for example, these pumps can be employed to circulate the cooling liquid through micro heat exchangers [4]. Wagner et al. [14] demonstrated the displacement of ferrofluids activated by the linear movement of an external motorized permanent magnet inside a minichannel. Greivell and Hannaford [15] proposed an electromagnetic micropipette using a ferrofluid. Pérez-Castillejos et al. [16] reported the capability of the use of ferrofluids in microactuators due to pressure generation in the presence of magnetic field. Hatch et al. [17] designed a ferrofluidic micropump using rotating motion of ferrofluid in a ring channel where magnetically actuated plugs of ferrofluid served both for pumping and valving. Based on the foresaid idea, Kim et al. [18] proposed a peristaltic micropump using magnetic fluid without any contamination of the working fluid. In Ref. [19], an actuation mechanism similar to that of a stepper motor has been used to demonstrate a circular micropump with a ferrofluid plug as the rotor or the driving piston and eight solenoids as the stator. The authors stated that the developed stepper micropump with the capability of precise positioning of the ferrofluid plug would allow a more flexible polymerase chain reaction (PCR) protocol and can work with the ferrofluid driven microchip for rapid PCR reported previously by their group [20]. Yamahata et al. [21] used a ferrofluidic plug as a piston in a micropump with two check valves. Hartshorne et al. [22] demonstrated the use of ferrofluid in two types of microvalves as Y-valve and well-valve and also presented a ferrofluidic piston micropump with a ferrofluid plug as a piston and two ferrofluidic “well” valves controlled by the movements of external permanent magnets. Ando et al. [23] introduced a pump that consisted of a single volume of ferrofluid held flattened at the bottom of a pipe by a fixed permanent magnet. An array of five electromagnets allowed for the formation and the movement of a ferrofluidic cap acting simultaneously like a valve and a plunger. They also controlled and synchronized the actuation of three ferrofluid plugs in a tube using external electromagnets to pump an immiscible fluid [24].

In this study, design, fabrication and characterization of a novel magnetically actuated miniature pump is presented. It consists of a polymethyl methacrylate (PMMA) casing of circular cross-section, a revolving disk inside it, and a check valve at the outlet. The pumping is based on the peripheral displacement of the disk piston inside the cylindrical chamber. The disk is a permanent magnet which is externally actuated using another cylindrical permanent magnet driven by a motor. Ferrofluid is employed to maintain sealing by filling the gaps between the magnetic disk and the chamber walls. Also, a combination of ferrofluid and an external stationary permanent magnet is used to form a physical barrier between the inlet and the outlet ports. Continuous high performance pumping, working at relatively low voltages, simple design, easy fabrication, and low cost manufacturing are the main advantages of this miniature pump. With the avail of non-contact external actuation, this pump can be used in many applications when microfluidic systems need to be disposable and low cost.

2. Working principle

The pumping mechanism is based on the peripheral sliding motion of a disk inside a cylinder. A schematic of the pump is given in Fig. 1a. The pump consists of a cylindrical chamber with one inlet port and one outlet port, one passive valve at the outlet, and a revolving disk piston inside the chamber. The disk piston is a permanent magnet which is externally actuated using another cylindrical permanent magnet driven by a motor. The rotating shaft of the motor has its axis of rotation that matches with the centerline of the chamber; however, it is eccentric with respect to the revolving piston. The magnetic piston is fully covered with ferrofluid which is held to the surface of the disk by its magnetic force. The ferrofluid fills the gaps between the cylindrical magnet and the chamber walls to maintain sealing. Serving as the sliding vane in a “roller compressor”, a narrow plug of ferrofluid which is held by an external stationary permanent magnet is always present in the upper section of the chamber between the inlet and the outlet ports.

As demonstrated in Fig. 1, the pump does not require an inlet valve but requires an outlet valve. The sealing between the high and low pressure sides has to be provided along the line of contact between the piston and the cylinder block, that is along a line staring from the small sector between the inlet and the outlet ports to the piston as well as the piston and the end pates of the chamber. The effectiveness of the ferrofluidic sealing depends mainly on the strength of the magnetic fields and the piston speed and partly on the clearance, surface finish and ferrofluid viscosity.

As long as the force imposed by the pressure gradient does not exceed the force generated by the external stationary permanent magnet, the ferrofluid will block the section between the inlet and the outlet ports. On the other hand, the rpm of the motor rotating the external actuator of the revolving piston should be low enough to impose the required force to the piston to follow the path of the moving external magnetic field.

The ferrofluid is always exposed to the magnetic fields of all the magnets. Therefore, as illustrated in Fig. 1, a contiguous ferrofluidic plug will be established between the piston and the stationary magnet in the chamber as it revolves. When the magnetic piston moves away from the region around the stationary magnet, a portion of the ferrofluid is more strongly affected by the field of the magnetic piston and sticks to its surface. Therefore, a plug of ferrofluid goes along with the translating magnetic piston while another plug is always held in the small sector below the stationary permanent magnet. The dimensions of the system and the employed magnetic fields should be compatible as to never let the two plugs of ferrofluid separate from each other as well as staying as thick as the height of the chamber.

The functional principle of the pump is schematically described in Fig. 1. In this figure, there are two distinct situations for the pumping phases based on the location of the revolving piston: the case when the revolving piston is sweeping the larger sector between the inlet and the outlet ports (Fig. 1a–c) and the case when it is confined to the small sector between the inlet and the outlet ports (Fig. 1d). In the first case, the revolving piston sweeps the chamber counterclockwise from the inlet to the outlet as shown in Fig. 1a–c. As the result, the displaced volume of the working fluid will be pushed into the outlet port. In the second case, as it is shown in Fig. 1d, by approaching the revolving piston to the region between the inlet and the outlet of the chamber, they become accessible to each other through the part of the chamber at opposite side of the stationary permanent magnet. In this situation, the check valve located after the outlet will resist the fluid from flowing reversely from the outlet port to the inlet port. So, during the second situation, there is no significant reverse flow of fluid through the pump. Therefore, in a complete cycle, a net positive fluid flow from the inlet into the outlet will be established which is in the order of the volume of the chamber excluding the spaces occupied by the piston and the ferrofluid.

The geometry of the piston movement inside the cylinder is shown in Fig. 2. The instantaneous volumetric flow rate of the pump can be roughly estimated by the differential sweeping volume of the piston. This can be expressed by the rate of change in the shaded area in Fig. 2 which is approximately given by Eq. (1). Also, an estimation of the theoretical average volumetric flow rate of working fluid through the pump which is expressed by the free volume inside the cylinder is given by Eq. (2).