Development of a Novel Meso-Scale Electromagnetic pump for Biomedical Applications

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Abstract

This work introduces a novel electromagnetic pump (EMP) that depends on rotating two hard magnets placed in an annular channel in opposing polarity through simultaneous energization of a set of solenoids. The magnetic field in each winding is energized to move one magnet (pumping) while the other is attracted between the inlet and the outlet ports (valving). At the end of each pumping cycle, magnets change their function between pumping and valving. The pump concept was tested for pumping water, where a flow rate of 13.7 ml/min at 200 rpm and a pressure of 785 Pa at 136 rpm are obtained.

\textit{keywords:} electromagnetic pump, biomedical fluids, circular channel;

1. Introduction

The rapid developments in miniaturization toward efficient biomedical and lab-on-a-chip applications encourage continuous efforts in developing fluidic devices\textsuperscript{1,2,3} (i.e. pumps, and separators). Pumps are key components in these systems, where gentle handling of fluids carrying particles sensitive to shear stresses is highly important. Recently, ferrofluidic plugs were used to create gentle pumping based on a magnetic force\textsuperscript{4,5}. The ferrofluidic plug was driven in an annular channel by an external magnet\textsuperscript{4} or by a series of actuating solenoids\textsuperscript{5}. However, degradation of the ferrofluid in the annular channel is disadvantage of such pumps. In this work, permanent magnets placed in opposite polarities in an annular channel are used to create pumping effect. The actuation of the magnets is controlled through a set of solenoids distributed around the channel.

2. EMP Operation

The EMP is comprised of a fluid housing, two pistons of permanent magnets, solenoids, and a flat cover that includes the inlet and outlet ports (Fig. 1a). The pumping concept depends on synchronization of the motion of the two pistons electronically through an annular channel as shown in Fig. 1b. The permanent magnet pistons placed in
opposing polarities inside the channel to prevent any sticking between the pistons during the pumping cycle. The energization scheme is controlled through a set of solenoids (twelve solenoids) arranged around the fluid channel. Two of them are holding solenoids and located between the inlet and the outlet ports, while ten are used to create a magnetic field on the free magnet to create actuation on the fluid. The pumping cycle begins through holding one of the magnets at the left solenoid located between the inlet and the outlet ports, so that it acts as a valve separates the inlet flow from the pumped one and forced the flow out of the channel. The second magnet is rotating clockwise along the channel through successive activation of the solenoids that attract it due to their magnetic force in steps. Due to magnet movement, the fluid is pushed out through the outlet and withdrawn into the channel from the inlet. As the moving piston is reaching the outlet and while one solenoid is separating between the pistons, they begin to exchange their roles and move together, where the stationary one is accelerated and attracted along the channel to act as a moving piston while the moving one is decelerated until stops between the inlet and outlet ports and acts as a valve. This movement was found as the best solution to avoid that the inlet and outlet ports to be open in the same time. This exchange in roles continues and a continuous pumping action is obtained.

![Diagram](image1)

![Diagram](image2)

**Fig. 1.** (a) 3D plot of the EMP; (b) Pump concept.

### 3. Design, Fabrication and Testing

The EMP includes a fluid channel of \((2 \times 2 \text{ mm}^2 + 0.1 \text{ mm tolerance})\) at an inner diameter of 16 mm, and an outer diameter of 18 mm. The solenoids grooves were created using precision machining techniques (CNC milling machine) in Plexiglass. The same is done for the pump cover but holes for the inlet and the outlet ports are drilled. Using plexiglass allows the visualization of the fluid flow and the movement of the magnets through the channel. The solenoids grooves are constructed so that the gap between the solenoid first turn and the inner channel wall is of 1 mm. This is important for the attracting magnetic force between the solenoids and the magnet. Block permanent magnets (material grade N38, \(2 \times 2 \times 3 \text{ mm}^3\) dimensions) were set in the channel in opposing polarity and the cover is then fixed to the pump housing. For the solenoids, 250 µm copper wires were wrapped of 98 turns around the fluidic channel with a \(1.45 \pm 0.1 \Omega\) resistance, and the inlet and outlet ports is connected to the cover holes.

The activation of the solenoids is controlled through a digital electronic circuit using AVR STK 500 microcontroller. The energization scheme is written in C-program considering the following parameters: activation time step, number of activated coils, switching scheme between the stationary and moving magnets, and the current direction. This program allows flexible changes on the active magnet rotational speed and magnetic force. As shown in Fig 2, the holding solenoids are located between the inlet and outlet ports to hold the stationary magnet and ten solenoids are along the channel to create a synchronized motion of the active magnet.
The range of rotational speeds investigated in this work is between 30 and 200 rpm. The inlet and outlet tubes are 24 cm long and have an inner diameter of 1.5 mm. The inlet tube is connected to the fluid reservoir, which is large enough to avoid level changes during operation, and the outlet tube is connected to the collection reservoir. Digital balance was used to read the mass of the pumped fluid during fixed intervals of time.

The pump is firstly connected with the electronic circuit, the inlet and outlet tubes are connected to the reservoirs and the pump is filled with water. Before applying voltage on the solenoids and to ensure steady state flow measurements, the air is bled from the test loop, and the pump is activated to the desired speed. The readings are taken after ensuring steady state flow conditions, where the pumped fluid is collected for fixed interval of times and the flow rate is estimated. For maximum pressure difference values, the outlet tube is mounted vertically and the pressure difference values are measured through the distance between the fluid reservoir level and the maximum stable distance marked on the outlet tube.

4. Results and Discussion

The flow performance in the EMP depends on two main parameters: the solenoids activation period and their driving voltage (the current and the magnetic flux). The activation period determines the rotational speed of the pump and the magnetic flux overcomes the friction and inertia forces to move the active magnet along the channel. Pump rotational speed is proportional to the driving voltage (magnetic flux) which should be adjusted to employ simultaneous attraction force on the piston.
As shown in Fig. 3, the flow rate for simultaneous energization of one and two solenoids changes nearly linearly with the rotational speed. The flow rate of the one moving solenoid case is higher than that of the two moving solenoids case since the displaced volume within one revolution is larger than that of two solenoids. However, energizing two solenoids simultaneously enables reaching higher rotational speeds up to 200 rpm with maximum flow rate of 13.7 ml/min.

Measurements of the maximum pressure difference the pump can work against is predicted in Fig. 4. A maximum pressure difference of 785 Pa was obtained at rotational speed of 136 rpm for one moving solenoid.

![Graph showing maximum pressure difference at different rotational speeds](image)

**5. Conclusions and Recommendations**

As a conclusion, a new electromagnetic pump that works through simultaneous energization of two permanent magnets placed in an annular channel in opposing polarity has been realized and tested. A maximum flow rate of 13.7 ml/min at 200 rpm and a pressure of 785 Pa at 136 rpm were obtained. Pump components and their fabrication are easy to be realized in microscales. Further investigations on the energization schemes and fluid leakage between the permanent magnets and wall channels are highly recommended.

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**References**