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The effect of droplet size, channel length and the amount of electromagnetic actuation force on reciprocating movement of mercury droplets in the magneto mercury reciprocating (MMR) micropumps

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ABSTRACT

Micropumps are regarded as one of the devices used in microsystems, which are responsible for pumping working fluid. The magnetic reciprocating micropump is an example of the existing micropumps in which the pumping agent includes three liquid metal droplets placed inside lateral channels and reciprocated by the electromagnetic force inside their channels. The working fluid located inside the main channel is pumped through due to the movement of these three droplets. The time duration in which the droplet traverses the sub-channel length is crucial in the operation of the suggested micropump. The present study aims to evaluate the effect of the length of sub-channels, moving droplet volume and the amount of actuation force on the droplet movement duration by imaging a droplet movement and analyzing the experimental results. Then, it will be shown that all results can be collapsed on one curve by non-dimensionalizing the results and defining an appropriate characteristic time. An empirical equation is presented for prediction of a droplet scrolling time, using the length of sub-channels, moving droplet volume and the amount of actuation force.

1. Introduction

A large number of researchers have focused onsmall-sized equipment called "microsystems" which aims to transfer, mix, or separate fluids. Micropumps are the most commonly used equipment in microsystems, which are responsible for transferring fluids geometrically constrained to a small scale. The micropumps can be divided into two general categories [1]: the dynamics micropumps by which the energy transmitted continuously to the fluid, and the positive displacement micropumps by which the force is applied to the fluid in oscillatory form by the movement of a series of flexible plates (diaphragm). Further, micropumps are classified in terms of the actuation mechanisms. Among the actuators used in reciprocating micropumps are piezoelectric [2], electrostatic, electromagnetic, thermal, pneumatic and thermopneumatic. In addition, the surface-acoustic-wave (SAW), electroosmotic [3], electrohydrodynamic (EHD), electrochemical, hydromagnetic and magnetohydrodynamic (MHD) driving forces [4] have been introduced in the dynamics micropumps.

In this regard, an actuation method is the use of the Lorentz force. A force is applied to the fluid which can move it by passing an electric current through an electric conductive liquid in the presence of a magnetic field. The limitation of this method is that it can only be used for pumping electrically conductive liquids. In 2011, Moghadam [5] drove a Liquid Metal Droplet (LMD), acting as a piston, by Lorentz force in a circular channel, and pumped the air as non-conductive fluid inside. In 2012 [6], the Magneto Mercury Reciprocating (MMR) was developed by using the idea of LMD electromagnetic actuation for pumping non-conductive fluid. In this micropump, LMDs were placed in separate sub-channels and actuated back and forth in these channels, whereby to produce an advancing motion of non-conductive fluid air in the main microchannel. These droplets played the role of pistons and pumped the non-conductive working fluid (air) into a microchannel by their movement. This micropump benefited from the advantages of electromagnetic micropumps, with the superiority of the ability to pump non-conductive fluids, without any need for the valve and magnetic particles in the pumped fluid. While in piezoelectric micropumps, the deformation of piezoelec-

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tric elements become harder as the size reduces, LMDs are still easily actuated in the MMR micropump, even when the dimensions become smaller. Other advantages of the MMR micropump include high performance, the absence of any moving mechanical parts, simple and low cost construction, no limitation in the properties of the pumped fluid, no need for high voltage or high temperature, lack of sensitivity to pH, ambient temperature, and surface loads, and no heat generation. The reason for the high performance of the MMR micropumps is due to their high self-pumping frequency which is defined as the number of times a micropump can pump its whole volume in a second [6]. The MMR micropump is a novel type and few functional studies have been performed in this regard. In order to determine the performance of this micropump, it is necessary to study the LMD movement in the sub-channel as a piston. Haghayegh and Kazemi et al. [7,8], empirically examined the effect of the LMD sub-channels outlet vent shape and the actuation frequency on the motion of the LMD in the MMR micropump. They reported the highest amount of LMD movement for the actuation frequency of 10 Hz and for the angle of 80 degrees between the LMD sub-channel outlet vent and the main microchannel.

On the other hand, the study on the droplet movement in the channel has attracted the researchers' attention for other equipment, in addition to the MMR micropump. So far, many studies have been performed in the field of droplet motion. Washizu et al. [9] presented a microreactor and examined the displacement and the deformation of the droplet by using an electrostatic stimulation of 1 μl water droplets. In 2002, Lattore et al. [10] moved mercury droplets with 10 to 500 μm in diameter through electrostatic actuation and presented an actuation force diagram in droplet diameter. Further, the contact angle residue of the mercury droplet was experimentally obtained to be 6 degrees on an oxidized silicon wafer. In addition, Kim et al. [11] introduced a microswitch which uses LMD electrostatic actuation in such a way that the droplet is actuated in oil, as continues fluid, and an actuation voltage higher than 100 V is required at the switching frequency of 1 Hz due to its high viscosity, which is a very high voltage. In another study, Yadav et al. [12] experimentally examined the motion of the droplet on the slope surface and indicated that the drop retention force resulted from the difference of the advancing and receding contact angles was proportional to the third root of the droplet volume. Furthermore, Shirani et al. [13] modeled the deformation of the droplet inside a continuous fluid for Reynolds numbers between 24 to 1800 and Capillary numbers between 0.014 to 0.219 using the Volume-Of-Fluid (VOF) method in a two-dimensional way. In computational fluid dynamics, the VOF method is a numerical technique for tracking and locating the free surface (or fluid-fluid interface). They calculated the Reynolds and Capillary numbers based on the properties and inlet maximum velocity of the continuous surrounding fluid (ρ, μ, u), and diameter of the liquid droplet (D); $Re=\rho Du/\mu$, $Ca=\mu u/\sigma$. Reynolds number is the ratio of inertial forces to viscous forces within a fluid and Capillary number is a dimensionless group used in the analysis of fluid flow that characterizes the ratio of viscous forces to surface or interfacial tension forces. Based on the results, droplets reach an equilibrium state after about 20 ms. In large Ca numbers, the droplet shape is completely dependent on the Ca. Further, Wang et al. [14] investigated computationally the motion of a droplet in a square microchannel for low Reynolds numbers in a three-dimensional model. They studied the effects of the flow rate, viscosity ratio and droplet size on the motion and developed a periodic boundary implementation for spectral element method. The results showed that large droplets exhibit larger deformation and have smaller velocity.

In the above-mentioned studies [13,14], the droplet was enclosed by another continuous fluid passing the channel and the droplet was transferred through the channel under the influence of this continuous flow. In fact, there was no contact between the droplet and the walls because the droplet was surrounded by the continuous fluid, while in the present work, as in constant contact with the electrodes in the MMR micropump, the force applied to the droplet and its movement cause the continuous fluid to flow. In addition, Mhatre [15] evaluated the dielectrophoretic (DEP) behavior of the suspended water droplet in another fluid in the presence of alternating electric field and provided an analytical model with the assumption of the droplet rigidity. The analytical model for estimating the alternating dielectrophoretic (DEP) motion was able to accurately predict the motion of the droplet.

To the best of our knowledge, no study has been conducted on the LMD reciprocating movement in the MMR micropump. In the MMR micropump, the LMD reciprocates in a square sub-channel by the electromagnetic body force intermittently applied to. The LMD is always in contact with the walls of the channel and the electrodes are connected to the wall, allowing the electrical current to pass through the LMD. The time in which the LMD traverses the sub-channel is considered as the most important factor in the MMR micropump operation. The present study aimed to evaluate the LMD reciprocating movement inside the sum-channel by applying Lorentz body force in the laboratory. The effect of actuation force, sub-channel length, and LMD length on the scrolling time of an LMD in a sub-channel was presented experimentally. Ultimately, a non-dimensionalized correlation was introduced to predict the scrolling time of an LMD for different values of actuation force, sub-channel length, and LMD length.

2. Theory

The proposed MMR micropump is composed of three sub-channels in the vicinity of a main microchannel containing LMDs and each LMD can independently move forward and backward in its sub-channel with a square cross section [16] (Fig. 1a). Through reciprocation movement inside the sub-channel, the second LMD plays the role of a piston in a cylinder and applies a force to the adjacent fluid and moves it into the main microchannel. The first and third LMDs act as the main microchannel's inlet and outlet valves, which can have some pumping effects. If these three LMDs move with a specific pattern, they can pump the fluid through the main microchannel. For effective pumping, the actuation signals of LMDs should have precise and specific frequencies and phases. The flow rate of the MMR micropump is proportional to the volume of fluid displaced by LMD in one cycle multiplied by the frequency of its movement. Fig. 1b illustrates the LMD in a sub-channel of the micropump. The volume displaced by LMD per sub-channel traversing is equal to:

$$v = w^2 L - v' \tag{1}$$

where v represents the displaced volume in a cycle, w indicates the sub-channel width which is equal to the sub-channel depth in this study, L shows the distance which the center of mass of the LMD traverses from the beginning to the end of the sub-channel (scrolling length), and v' is the fluid leakage volume from the gap between the LMD and the channel walls. In fact, the flow rate (displaced volume in one cycle) of the micropump is proportional to the displacement volume divided by the period of one cycle. As a result, an increase in the scroll length, the width or depth of the sub-channel or a decrease in the period leads to an increase in the flow rate. However, increasing the size will increase the size of the micropump, and consequently, the simplest solution is to increase the frequency of LMD motion or decrease its time period. It is worth noting that there is a limitation on this time reduction to provide the LMD with enough time to scroll the entire sub-channel length. This time is called "the scrolling time" and the actuation period should be greater than this amount. On the other hand, an increase