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Periodic flow patterns of the magnetic fluid in microchannel

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Abstract

In this study, of interests are the periodic flow patterns of the oil-based magnetic fluid in microchannels. A microfluidic chip is made of poly-dimethylsiloxane (PDMS) and contains cross-shape microchannels. The microchannels are 1000 μm in width and 200 μm in depth. A syringe pump was used to drive the fluids. Periodic flow patterns were seen and the slugs of magnetic fluid and DI water were generated. The operating factors discussed in the present work are the flow rates and the magnetic field. The frequency of generation of the slugs increases with increase in the flow rates. Besides, by settling the permanent magnet around the microchannel, the periods of the slug generation are changed. Different positions of the magnet lead to different periods for generating the slugs. By adjusting operating conditions, to control the frequency and the volume of the slugs is practical.

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Keywords: Periodic flow patterns; Magnetic fluid; Microchannel

1. Introduction

In recent years, there has been a growing interest in developing microfluidic devices to facilitate timely chemical reactions and biological interactions. Among the microfluidic researches, multiphase flow in microfludic devices has been used for mixing [1] that is a critical requirement in microfluidic systems. Two immiscible fluids are needed to form droplets or slugs in microchannels. The flow rates and the fractions of the two fluids have shown the dependence on the flow patterns, lengths of the slugs and the frequency of slug generation [1]. Magnetic fluids [2] are fluids containing suspended magnetic particles, which can be attracted by the magnetic field. Such a characteristic provides a way to drive or control the fluids in microfluidic systems.

This paper aims at investigating the characteristics of a multiphase flow (water and oil-based magnetic fluid) under the influence of an external magnetic field. Two factors, including flow rates of the fluids and the positions of the permanent magnet are discussed.

2. Experimental apparatus

The magnetic fluid used in the present work was synthesized by a co-precipitation method. Nano-sized Fe_3O_4 coated by oleic acid are uniformly suspended in diesel oil. The concentration of nanoparticles in the magnetic fluid is 0.156 M. Due to the coating of the surfactants, the magnetic particles are in well suspension without aggregation. The viscosity and density of the magnetic fluid is $4.89\times10^{-3}\,\mathrm{s\,Pa}$ and $833\,\mathrm{kg/m^3}$, respectively. The Reynolds numbers for the magnetic fluid range from 0.024 to 0.096.

The microfluidic chips were fabricated by soft lithography using poly-dimethylsiloxane (PDMS). The chip was made by casting PDMS against a silicon mold that contained structures complementary to microchannels. After de-molding, the PDMS-based part was bonded with a glass slice to generate microchannels. The microchannels were in cross-shape, with 1000 μm in width and 200 μm in depth.

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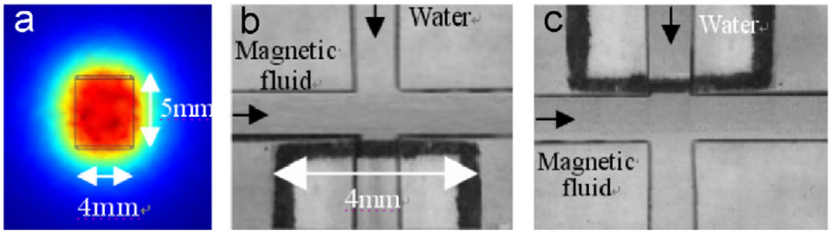

Fig. 1. The magnetic field and setup of the magnet. (a) The magnetic field simulated by FEMLAB: (b) Case 1, (c) Case 2. Edges of the magnet are marked by dark lines for clarity.

A syringe pump (KDS-101) was used to drive the fluids. The flow rates of each fluid were set the same and the total flow rates range from 10 to 40 × $10^{-9}\,\mathrm{m}^3$/min. In order to test the magnetic effect on the flow field, a permanent magnet (5 mm × 4 mm × 2 mm in size and 0.1 T in field strength, shown in Fig. 1(a)) was set under the macrofluidic chip. Two positions of the magnet were set, as shown in Figs. 1(b) and (c). The images of the flow field were captured by a CCD camera. The time intervals between two periodic patterns were then recorded to calculate the frequency.

3. Results and discussions

The flow pattern for the case without the magnet is shown in Fig. 2, which is incompressible laminar viscous flow dominated by the inertial force, the viscous force, the surface tension. The two momenta toward down (water) and toward right (magnetic fluid) interact around the junction of the channel. The water slug is pushed toward the two outlets and finally cut into two small slugs. It is observed that the magnetic fluid separates each water slug and forms a bridge-like layer between them.

As the magnet was set, the magnetic force exerts and the flow patterns changes. The periodic characteristics were still observed. The patterns of case 1 and case 2 are shown in Figs. 3 and 4, respectively. For case 1, the magnet attracts the magnetic fluid that part of the momentum of the magnetic fluid turns toward down. Since the momentum toward right is reduced, the slug tends to flow down rather than right and they are cut into a long slug (downside) and a short slug (right side) (as shown in Fig. 3(a)). Slugs are cut into two pieces at low-flow rate (total flow rate less than 20 × $10^{-9}\,\mathrm{m}^3$/min). But once the portion of the slug toward right is small, that part of slug would be pulled back towards down rather than being cut. Under such a condition, the cutting appeared every two slugs (total flow rate more than 30 × $10^{-9}\,\mathrm{m}^3$/min) and the time interval between two cuttings is only taken as one period. Thus, the frequency is highly reduced for this case.

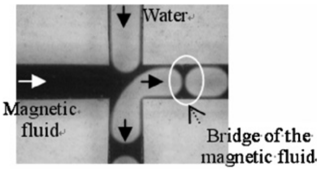

Fig. 2. Flow patterns of the case without the magnet, total flow rate = 10 × $10^{-9}\,\mathrm{m}^3$/min.

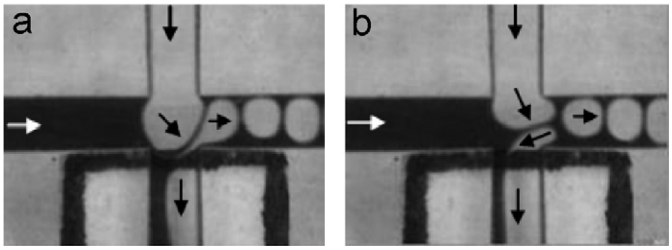

Fig. 3. Flow pattern of case 1, total flow rate = 30 × $10^{-9}\,\mathrm{m}^3$/min.

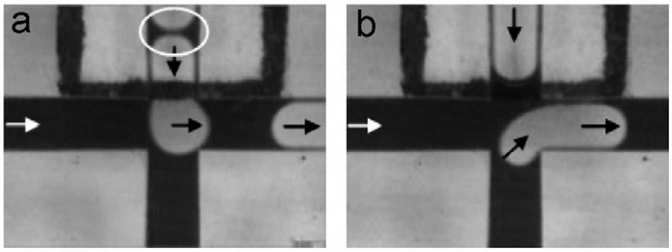

Fig. 4. Flow pattern of case 2, total flow rate = 10 × $10^{-9}\,\mathrm{m}^3$/min.

Slugs were also observed in case 2 but with shorter lengths compared with those of the case without the magnet. The bridge-like patterns appear even before the water slugs reach the junction of the channel (as shown in Fig. 4(a)). Part of the magnetic fluid is attracted by the magnet to form a layer along the side wall of the channel of water. This layer is pushed back by the water and forms the bridge-like structure once the amount is sufficient. Such a development makes the water slugs cut earlier than that in Fig. 2 and thus leads to shorter slugs. The water slugs are firstly pushed down and then pulled back toward right (as shown in Fig. 4(b)), such a push-and-pull process makes a delay of the period between two slugs and thus, a lower frequency appears.

The frequency of the periodic patterns is shown in Fig. 5. The frequency of the case without the magnet increases linearly with increase in the flow rates. After setting the magnet, the frequency is highly changed. There are two reasons for the decrease of the frequency: One is that the

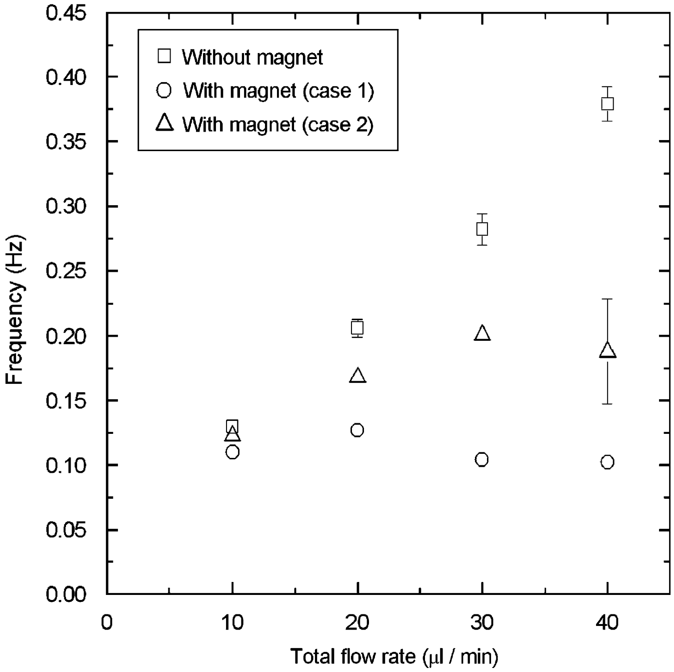

Fig. 5. Flow rate dependence of frequency of the periodic patterns.

patterns may change (e.g. Fig. 3); the other is that the slugs may sustain longer period around the corner (e.g. Fig. 4). For some conditions, the above reasons may appear both and thus nonlinear relations are seen. Further works are needed to study the interaction of the several forces within the microchannel.

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