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Water flow patterns induced by bridge oscillation of magnetic fluid between two permanent magnets subjected to alternating magnetic field

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ABSTRACT

This paper describes the characteristics of water flow induced by the bridge oscillation of magnetic fluid between two permanent magnets subject to an external alternating magnetic field. The magnetic fluid bridge is formed in the space between a pair of identical coaxial cylindrical permanent magnets submerged in water. The direction of alternating magnetic field is parallel /antiparallel to the magnetic field produced by two permanent magnets. The magnetic fluid bridge responds to the external alternating magnetic field with harmonic oscillation. The oscillation of magnetic fluid bridge generates water flow around the bridge. Water flow is visualized using a thin milk film at the container bottom. Water flows are observed with a high-speed video camera analysis system. The experimental results show that the flow pattern induced by the bridge oscillation depends on the Keulegan–Carpenter number.

1. Introduction

Recently, the importance of the study on sinusoidally oscillating flow induced by periodic forcing in a fluid is well recognized due to the massive development of microfluidics [1]. Therefore, extensive investigations on oscillating flows have been conducted by a number of researchers. For example, development of vortex patterns around a circular cylinder oscillating in quiescent water was investigated using time-resolved particle image velocimetry [2]. Two-dimensional and three-dimensional instabilities of the two-dimensional symmetric flow generated by a circular cylindrical oscillating with simple harmonic motion in quiescent fluid were investigated via Floquet analysis and direct numerical simulation [3]. Time-averaged laser doppler velocimetry measurements and time-resolved numerical flow predictions were performed to investigate the laminar flow induced by harmonic in-line oscillation of a circular cylinder in water at rest [4]. The flow around a circular cylinder undergoing sinusoidal oscillating movement in still water was investigated by phase-locked particle image velocimetry measurements [5]. In these studies, however, the flow fields were produced by the mechanical vibration of the ridged object. However, non-contact and wireless energy supply methods are needed in the microfluidic applications.

In this paper,a non-contact energy supply system in order to generate micro water flow was proposed. Micro water flow was produced by the bridge oscillation of magnetic fluid between two small permanent magnets. The bridge oscillation of the magnetic fluid was driven by the external alternating magnetic field. The water flow was visualized by a thin milk film on the container bottom. The characteristics of water flow were revealed with the high-speed video camera analysis system.

2. Experimental apparatus and procedures

A schematic diagram of the experimental apparatus is shown in Fig. 1. The experimental apparatus is composed of the magnetic fluid bridge system, water container system, external magnetic field generation system, and high-speed video camera analysis system. The magnetic fluid bridge system is composed of two circular cylindrical permanent magnets and magnetic fluid as shown in Fig. 2. The magnetic fluid bridge is formed between two NdFeB magnets fixed on a glass plate with adhesive. The letters N and S in Fig. 2 show the poles of the magnet, and d_{fm} is the neck diameter of the bridge. The diameter of the cylindrical magnets is 1.5 mm and the gap between two magnets is $\varepsilon = 3.6$ mm in Fig. 2. In the experiment, the gap ε was changed to study the effect of the Keulegan–Carpenter number. The magnetic flux density of the permanent magnet is $B = 220$ mT. The sample magnetic fluid is synthetic hydrocarbon-based magnetic fluid MSG P50 (FerroTec).

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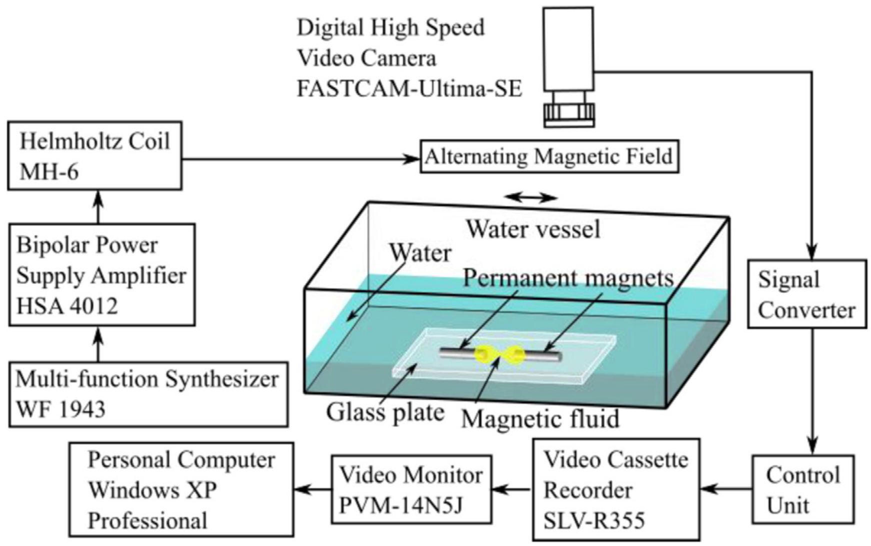

Fig. 1. Schematic diagram of experimental apparatus.

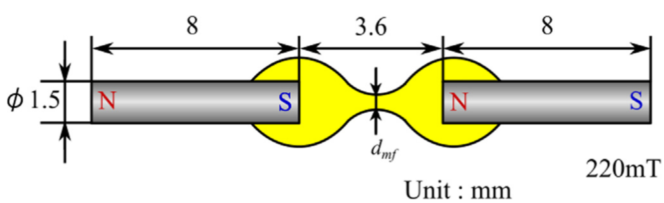

Fig. 2. Formation of magnetic fluid bridge and size of permanent magnets.

The bridge system is subjected to the alternating magnetic field. The external magnetic field generation system and high-speed video camera analysis system are the same as our previous paper [6]. The alternating magnetic field is generated by applying the sinusoidal voltage to the Helmholtz coil. The applied voltage is given as follows:

$$E = \frac{E_0}{2}\cos(2\pi f_0 t), \quad (1)$$

where $E_0/2$ is the amplitude of the alternating voltage, f_0 is the frequency, and t is the time. The experiment was performed at room temperature.

3. Experimental results and discussion

3.1. Water flow by bridge oscillation

Water flow around the oscillating magnetic fluid was studied with the high-speed video camera analysis system. Fig. 3 shows a series of photographs of the water flow growth at the frequency f_0=90 Hz. In this experiment, the gap between the two magnets is ε=3.6 mm, and the volume of magnetic fluid is $V_m = 10\times10^{-9}$ m^3. The time interval between each frame is δ_t=0.08 s in Fig. 3. The flow growth starts from the neck part of the bridge. When the magnetic fluid bridge was subjected to alternating magnetic field, the bridge diameter responded with alternating extension and

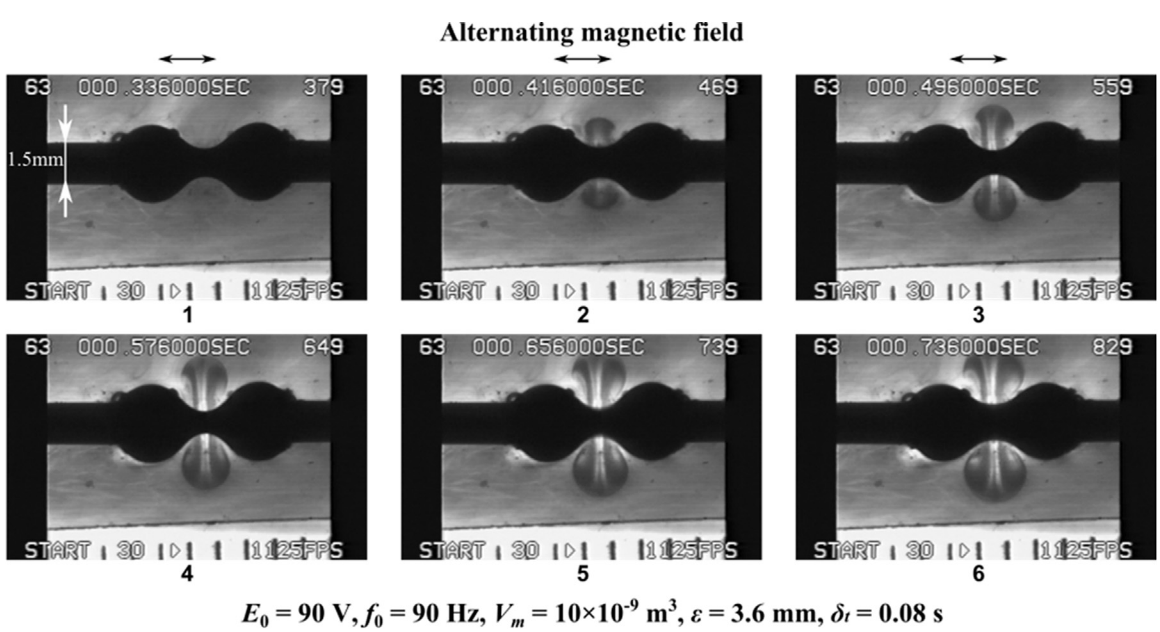

Fig. 3. Photographs of the growth of water flow induced by the bridge oscillation of magnetic fluid.