Sensors and Actuators A 243 (2016) 59–65

Contents lists available at ScienceDirect

Sensors and Actuators A: Physical

journal homepage: www.elsevier.com/locate/sna

Magnetic droplet microfluidic system incorporated with acoustic excitation for mixing enhancement

Kang Yong Lee[1], Seungeun Park[1], Young Rang Lee, Sang Kug Chung*

Department of Mechanical Engineering, Myongji University, Yongin, South Korea

ARTICLE INFO

Article history:
Received 25 September 2015
Received in revised form 3 March 2016
Accepted 8 March 2016
Available online 11 March 2016

Keywords:
Droplet microfluidic system
Micromixer
Magnetic droplet
Droplet oscillation
Acoustic excitation

ABSTRACT

This paper describes a new type of magnetic droplet microfluidic system incorporated with acoustic excitation for the enhancement of mixing performance. The oscillation amplitudes of acoustically oscillating droplets with different volumes (6 μl and 8 μl) in different frequencies are measured by high-speed images. When a droplet is acoustically excited, it only strongly responds to the droplet's natural frequency. Internal flow inside an acoustically oscillating droplet is visualized using fluorescent particles (15 μm diameter). Mixing performance is investigated using a methylene blue and glycerol (5 wt%) mixture droplet. The mixture droplet (6 μl) is completely mixed within 60 s with acoustic excitation; whereas, the mixture droplet remains unmixed without the excitation. The mixing efficiency is quantitatively evaluated through mixing indexes obtained by image analysis. The transportation of a magnetic droplet (6 μl) containing magnetic particles (500 nm dia.) is separately demonstrated using a neodymium magnet beneath a chip. The maximum manipulation speeds of magnetic droplets (approximately 25 mm/s for 6 μl droplet and 20 mm/s for 8 μl droplet) are measured by the magnetic droplet rotation test. As proof of concept, the manipulation of four magnetic droplets with two different volumes (3 μl and 4 μl) and colors (red and blue) is experimentally achieved by incorporating magnetic actuation for the transportation of droplets and acoustic excitation for the oscillation of droplets. This result shows the highly reliable manipulation of magnetic droplets with high mixing performance.

1. Introduction

Micro total analysis systems (μTAS) based on microfluidic technology have greatly impacted on chemical and biomedical applications [1–4]. μTAS consist of tiny channels, pumps, and sensors, and provide fast and reliable measurements of biochemical samples through various microfluidic operations [5–7]. These include pumping, transporting, mixing, and separating, of which mixing is especially important [8]. It is inevitable for multiple microfluidic processes such as sample dilution and chemical reaction, but is also a time-consuming process. As the size of a fluidic system decreases, the Reynolds number, the ratio of inertia forces to viscous forces, linearly decreases, while the viscous force becomes more dominant [9,10]. As a result, the mixing process in microfluidic systems relies primarily on slow diffusion without turbulence.

A variety of microfluidic techniques have been developed to improve the speed and efficiency of fluid mixing in microfluidic systems [11,12]. The developed mixing techniques can be characterized as passive and active depending on the existence of external disturbances [13,14]. Passive mixing techniques do not require external actuators and energy sources [15,16]. The Whitesides research group demonstrated passive chaotic mixing in microchannels with staggered herringbone surface patterns to increase the interfacial area between fluids [17]. On the other hand, active mixing techniques require external actuators and energy sources for the enhancement of fluid mixing. Various types of actuators and energy sources, such as acoustics [18], pressure [19], thermal actuation [20], electrohydrodynamics [21], dielectrophoretics [8], electrokinetics [22,23], and magneto-hydrodynamics [24] have been applied to the active mixing techniques. Active mixing techniques typically provide higher mixing efficiency than the passive techniques.

More recently, interest has emerged in droplet microfluidic systems based on the manipulation of discrete tiny droplets on an open surface [25,26]. These systems do not require complex microfabricated three-dimensional (3D) channel structures, but offer fast sample reaction times, lower sample consumption, and higher system flexibility than the continuous-flow systems [27–29]. Several mixing methods for the droplet microfluidic systems have been

* Corresponding author.
E-mail address: skchung@mju.ac.kr (S.K. Chung).

[1] These authors contributed equally to this work.

http://dx.doi.org/10.1016/j.sna.2016.03.009
0924-4247/

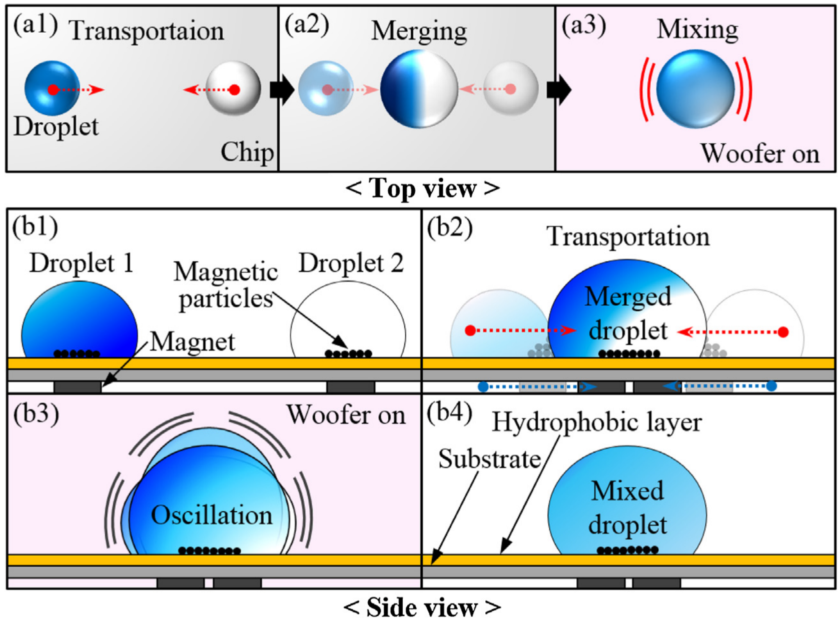

Fig. 1. Schematic diagram of a proposed magnetic droplet manipulation system actuated by magnetic actuation and acoustic excitation: (a) top view; (b) side view.

developed by using different actuation schemes. Some research groups have utilized an electrowetting-on-dielectric (EWOD) principle, which controls wettability of a droplet on a solid substrate using an applied electric field [30–32], for the enhancement of mixing droplets based on two different approaches: stationary droplet oscillation using alternating current (AC)-EWOD actuation [33–35] and sequential droplet transportation using the array of patterned EWOD electrodes [7,36]. On the other hand, others have applied a surface acoustic wave (SAW) method using a piezoelectric substrate upon which a droplet is placed to oscillate and simultaneously mix the droplet [37–39]. Magnetic actuation has been also used for the droplet mixing enhancement using magnetic nanoparticles or microstructures with an applied magnetic field [40–42].

This paper presents a new type of magnetic droplet manipulation method incorporated with acoustic excitation, which will allow not only the enhancement of mixing performance, but also remote and selective droplet oscillation. Wang research group has developed magnetically driven droplet microfluidic systems where liquid droplets containing magnetic particles are manipulated by permanent magnets or electromagnets for fundamental microfluidic operations on a single chip [42–44]. Most of the magnetic droplet manipulation systems have frequently used the transportation of droplets for mixing of constituents in the droplets.

In contrast to the previous magnetically driven droplet systems, our proposed system firstly applies remote acoustic excitation to improve the droplet mixing performance. This system provides selective droplet oscillation based on the droplet properties such as size, density, and surface tension, increasing the efficiency of diagnostic systems. The schematic diagram of the proposed magnetic droplet manipulation system is shown in Fig. 1. For the manipulation of chemical droplets containing biocompatible magnetic particles, two different actuation schemes are applied: magnetic actuation using neodymium magnets for droplet transportations, and acoustic excitation using a woofer for droplet oscillation. Two different chemical droplets, each actuated by magnet beneath a chip, are transported to the central region and merged, as shown in Fig. 1(a1–a2, b1–b2). When the merged droplet is acoustically excited by a woofer at its natural frequency, it oscillates and simultaneously induces internal flow, improving the chemical mixing in the merged droplet, as shown in Fig. 1(a3, b3–b4). A preliminary report on this work was presented at the 18th International

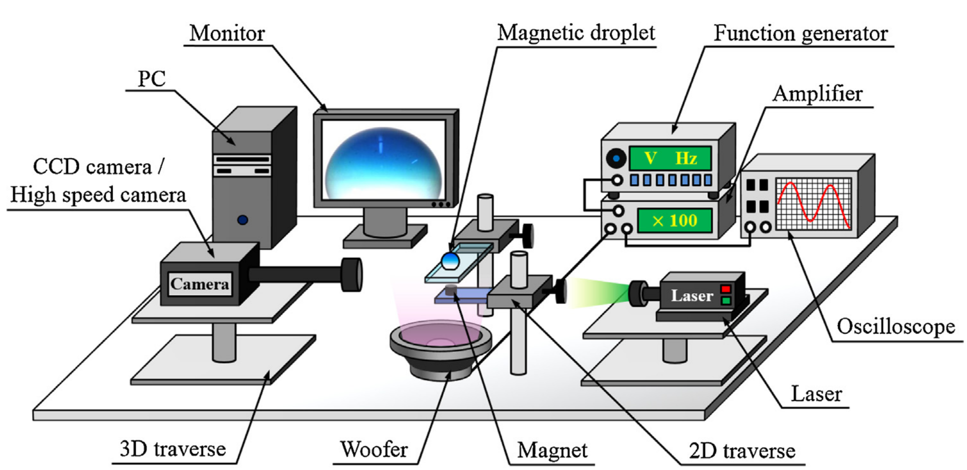

Fig. 2. Experimental setup.