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Fabrication of micro-spinbars with controllable aspect ratios using a simple fluidic device for fluid mixing

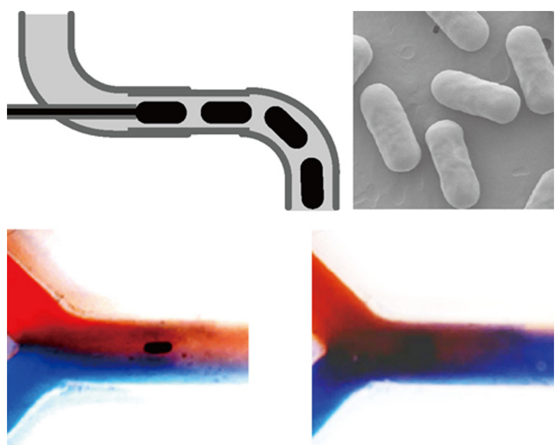
Ji Sun Lee [a], Seok-Joon Hwang [a], In Woo Cheong [b], Sung-Wook Choi [a,*]

[a] Department of Biotechnology, The Catholic University of Korea, 43 Jibong-ro, Wonmi-gu, Bucheon-si, Gyeonggi-do 420-743, Republic of Korea
[b] Department of Applied Chemistry, Kyungpook National University, 80 Daehakro, Bukgu, Daegu 702-701, Republic of Korea

HIGHLIGHTS

- Gelatin micro-spinbars with uniform aspect ratios were fabricated using a simple fluidic device for fluid mixing.
- The aspect ratios of the micro-spinbars were controlled from 1 to 5.
- Active fluid mixing using the micro-spinbar was demonstrated in a glass slide and Y-shaped small device.

GRAPHICAL ABSTRACT



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ABSTRACT

Micro-spinbars with uniform aspect ratios were fabricated from gelatin using a simple fluidic device based on water-in-oil emulsion for fluid mixing. Aqueous gelatin solution containing magnetic nanoparticles and toluene solution were used as the discontinuous and continuous phases, respectively. The gelatin droplets with uniform aspect ratios formed within the glass capillary tube of the fluidic device and flew into the cold collection phase (toluene). Due to the feature of sol–gel transition of the gelatin solution with respect to temperature, the gelatin droplets maintained their original shape in the cold collection phase during water evaporation. The aspect ratios of the micro-spinbars were finely controlled from 1 to 5 by simply changing the flow rate of the continuous phase. Their potential applications for active fluid mixing were demonstrated in a glass slide and Y-shaped small device.

1. Introduction

Microfluidic systems based on polydimethylsiloxane (PDMS) are an emerging technology in a variety of chemical, biological, and analytical applications [1–10]. For example, synthesis of gold nanoparticles has been demonstrated in a microfluidic reaction

* Corresponding author at: Department of Biotechnology, The Catholic University of Korea, 43-1 Yeokgok 2-dong, Wonmi-gu, Bucheon-Si, Gyeonggi-do 420-743, Republic of Korea. Tel.: +82 2 2164 4449; fax: +82 2 2164 4865.
E-mail address: choisw@catholic.ac.kr (S.-W. Choi).

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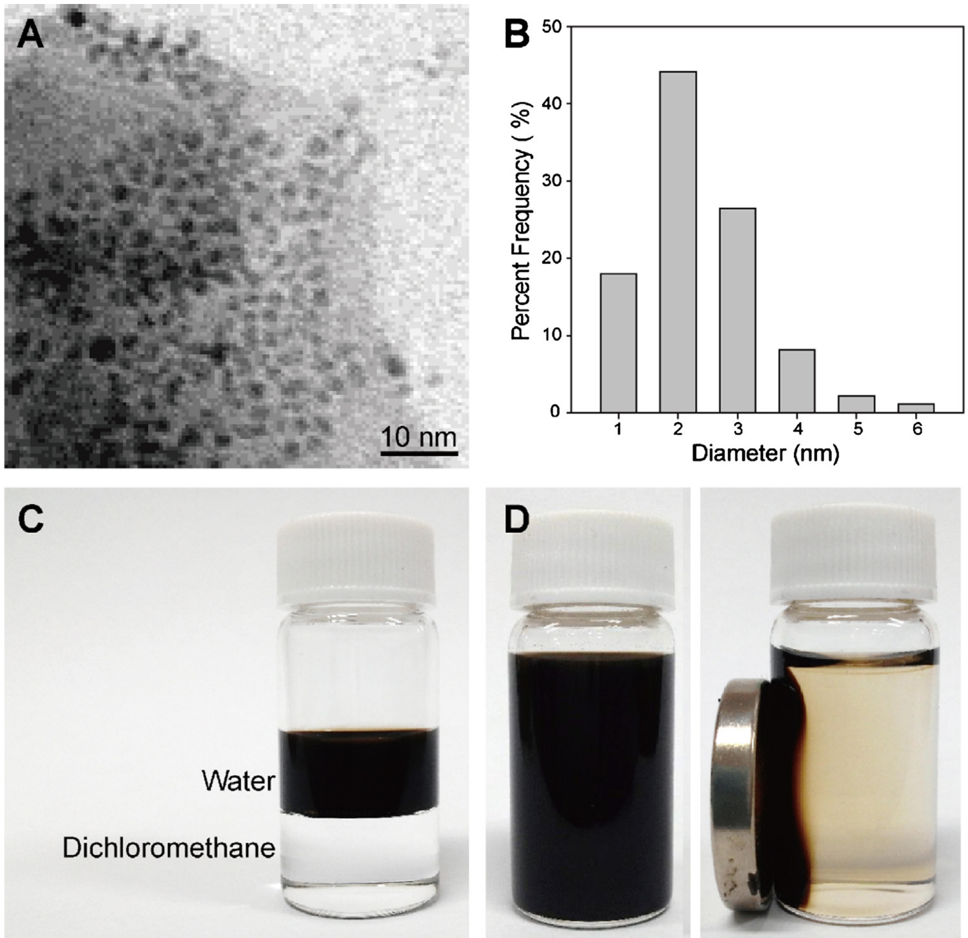

Fig. 1. (A) TEM images and (B) size distribution of the magnetic nanoparticles. (C and D) Photographs showing (C) the water-dispersibility and (D) the magnetism of the magnetic nanoparticles.

systems [11]. Biological applications of microfluidic systems include micro arrays, DNA sequencing/hybridization, cell separation and detection, drug screening, as well as environmental monitoring [12–16]. In addition, micro total analysis system (μTAS) was developed to continuously conduct all lab operations such as synthesis, process, purification, and analysis within one small fluidic device in an efficient and economical way [14,17–19]. The advantages of a microfluidic system include portability, small amount of reactant and sample, relatively low cost, fast, and high-throughout analysis. Rapid and complete mixing of the liquid streams containing reactants and samples is essential for reliable and fast reaction and analysis in most microfluidic systems.

Micro-scale fluid mixing remains a challenge in microfluidic systems because fluid flow is typically in a laminar regime with a low Reynolds number (*Re*) less than 100. Therefore, much effort has been focused on the development of strategies to achieve rapid and complete mixing of laminar flow in a microfluidic device. The strategies of micro-scale fluid mixing can be classified into two categories depending on the external source for mixing: passive and active mixers.

Passive mixers rely on the approach of repeated inter-layering of multiple patterns in order to maximize interfacial area and diffusive mass transfer. Usually, the multi-patterned PDMS geometry improves mixing efficiency and thus reduces channel length for complete mixing. Despite the unique advantages of no input of external energy and easy integration, passive mixing systems have intrinsic shortcomings as follows. The patterned geometry in a small device is more complex even in three-dimensional fashion for more efficient micro-scale fluidic mixing, which leads to a problem on device fabrication. In addition, insufficient mixing is also pointed out as an obstacle, particularly at an extremely low Reynolds number less than 1 [20,21], because diffusion is the only mechanism in a microfluidic device [22]. This low mixing efficiency might lead to the production of unexpected side products and long reaction/analysis times.

Active mixers have been characterized by the employment of the external forces such as electro-osmosis, magnetic stirring, acoustic actuation, and ultrasonic force [22–25]. These external forces produce chaos in microfluid. Although it requires external energy and is often difficult to integrate into a microfluidic system, an active mixing system can produce excellent mixing even at a low *Re* number in a short mixing length. Therefore, our work is focused on active mixing. Lu et al. [26] demonstrated micro-scale fluid mixing in a small PDMS device by incorporating a magnetic microstirrer. However, fabrication of the microfluidic device may have been a bit tricky and complex to assemble.

To overcome these issues, micro-spinbars were fabricated from gelatin and magnetic nanoparticles using a simple fluidic device based on a water-in-oil emulsion by adjusting the flow rate of the continuous phases. The aspect ratio of the micro-spinbar can be finely tuned by simply changing the flow rate of the continuous phase. We have demonstrated the mixing of dye solution in a water droplet on a slide glass by rotating a micro-spinbar driven by a conventional magnetic stirrer. The advantages of an active mixing