High-Performance Microchannel Emulsification Device with Microfabricated Asymmetric Through-Holes

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INTRODUCTION

Microchannel (MC) emulsification, proposed in the late 1990s, enables producing monodisperse emulsions via MCs with a slit-like terrace [1]. However, originally designed MC emulsification devices had a very low droplet productivity due to their limited linear arrangement of microgrooves [1,2]. Kobayashi *et al*. have recently developed MC emulsification devices with numerous through-holes (e.g., 10^4 cm^{-2}) for mass production of monodisperse emulsions [3,4]. In addition, novel MC emulsification devices with asymmetric through-holes enable the highly robust generation of uniform droplets [4], whereas investigations on emulsification using the MC emulsification devices are still lacking. This paper presents the production of monodisperse emulsions using a high-performance MC emulsification device with microfabricated asymmetric through-holes. This study also analyzed droplet generation via an asymmetric through-hole using experimental and CFD methods.

MATERIALS AND METHODS

This study used a 24×24-mm silicon MC emulsification device (WMS2-2) with 11,558 asymmetric through-holes within a 10 × 10-mm central area. Asymmetric through-holes were microfabricated via two steps of deep reactive ion etching. Each of the microfabricated asymmetric through-holes (Fig. 1a) consisted of a microslot (10×70-μm size and 40-μm depth) and a circular MC (10-μm diameter and 110-μm depth). Refined soybean oil was used as the dispersed phase, and a Milli-Q water solution of 1.0 wt% sodium dodecyl sulfate (SDS) was used as the continuous phase. MC emulsification experiments were conducted by injecting the dispersed phase via asymmetric through-holes into the upper channel filled with the continuous phase.

A CFD code (CFD-ACE+) with a finite volume method was used to simulate oil droplet generation via an asymmetric through-hole. All the walls in the computational domain were set to be not wetted by the dispersed phase. The other properties of the two phases were input using experimentally measured values.

RESULTS AND DISCUSSION

As depicted in Fig. 1b, a monodisperse O/W emulsion with an average droplet diameter of 32.0 μm was produced using the WMS2-2 device at a high droplet productivity of 10.0 mL/h, which corresponds to a droplet production rate of $\sim 2.4 \times 10^5$ s^{-1}. The WMS2-2 device improved the droplet productivity of previous MC emulsification devices with microgrooves by typically two orders of magnitude. The

CFD simulation results demonstrate that an emulsion droplet is stably generated via an asymmetric through-hole in the absence of a cross-flowing continuous phase (Fig. 2). The droplet size and droplet generation rate obtained from the CFD simulations also quantitatively agreed well with those found experimentally. MC emulsification devices presented here are also capable of generating uniform droplets of low viscosity at their large production scale (>100 mL/h).

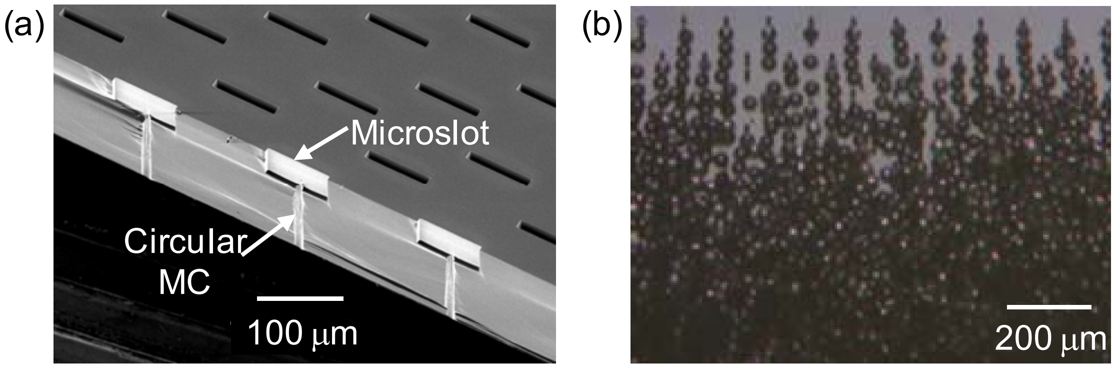

Figure 1. (a) Scanning electron micrograph of the microfabricated asymmetric through-holes. (b) Optical micrograph of the mass production of uniform oil droplets via asymmetric through-holes.

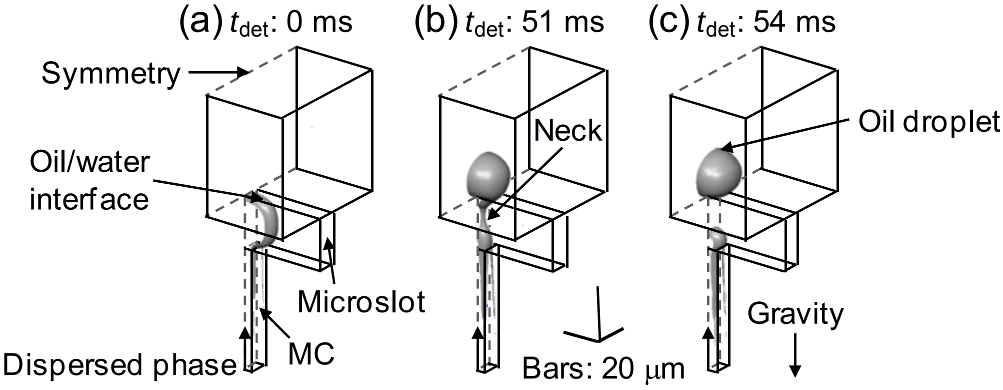

Figure 2. Oil droplet generation via an asymmetric through-hole with a 10 μm-diameter MC obtained from CFD simulation using the volume of fluid method. The dispersed-phase velocity inside the MC was 1.0 mm/s. t_{det} is the detachment time.

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