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High-performance production of monodisperse emulsions using microfabricated asymmetric through-hole array

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HIGH-PERFORMANCE PRODUCTION OF MONODISPERSE EMULSIONS USING MICROFABRICATED ASYMMETRIC THROUGH-HOLE ARRAY

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ABSTRACT

This paper reports high-performance production of monodisperse emulsions using numerous asymmetric through holes microfabricated on a silicon chip. Monodisperse oil-in-water (O/W) emulsions with droplet sizes of approximately 30 μm were stably produced via asymmetric through holes at high droplet generation rates up to several hundreds of thousands per second. This paper also reports three-dimensional simulation of emulsion droplet generation via an asymmetric through hole using a computational fluid dynamics (CFD) method. The calculation results showed an excellent agreement with the experimental results and provided a better understanding of the droplet generation process.

Keywords: Asymmetric through holes, droplet generation, CFD, microchannel emulsification

1. INTRODUCTION

A microchannel (MC) emulsification method, introduced by Kawakatsu et al. [1] in the late 1990s, is capable of producing monodisperse emulsions via MC arrays with a slit-like terrace. Microfluidic emulsification methods for generating monodisperse emulsion droplets using e.g. T-junction devices [2] and flow focusing devices [3,4] have been introduced, beginning in the early 2000s, whereas the microfluidic devices usually consisting of a single MC for a to-be-dispersed phase have very low droplet productivity. We recently developed a new MC emulsification device consisting of numerous microfabricated asymmetric through holes for large-scale production of monodisperse emulsion droplets [5]. However, the droplet productivity of monodisperse emulsions via an asymmetric through-hole array has not yet been investigated. Here we present the production of monodisperse emulsions using a microfabricated asymmetric through-hole array device at high droplet production rates. We also simulated emulsion droplet generation via an asymmetric through hole using a CFD method.

2. EXPERIMENTAL

Figure 1(a) is a schematic of a silicon chip consisting of 11,558 asymmetric through holes, microfabricated via three steps of silicon dry etching. Each asymmetric through hole in a WMS2-2 chip (Figure 1(b)) consisted of a slot ($10 \times 70\text{-}\mu\text{m}$ size and $30\text{-}\mu\text{m}$ depth) and a circular channel ($10\text{-}\mu\text{m}$ diameter and $120\text{-}\mu\text{m}$ depth). Refined soybean oil was used as the to-be-dispersed phase, and Milli-Q water solutions containing sodium dodecyl sulfate (SDS) or polyoxyethylene (20) sorbitan monolaurate (Tween20) were used as the continuous phase. Emulsification experiments were conducted by injecting the to-be-dispersed phase via asymmetric through holes into the upper continuous phase region.

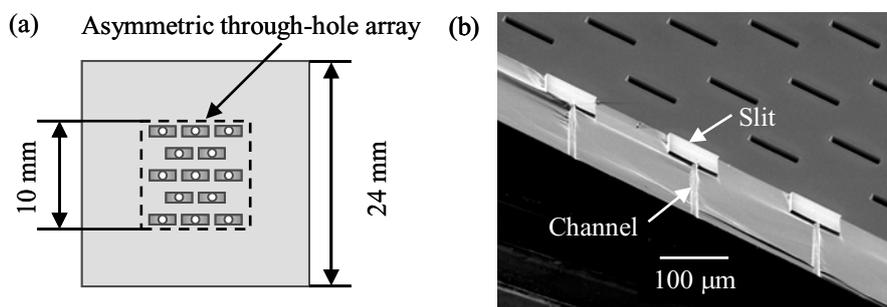


Figure 1. (a) Schematic top view of a silicon chip consisting of a microfabricated asymmetric through-hole array. (b) Scanning electron micrograph of asymmetric through holes microfabricated in a WMS2-2 chip.

A CFD code (CFD-ACE+ version 2004) with a finite volume method was used to calculate the generation of soybean oil-in-water droplets via an asymmetric through hole presented in Figure 3. All the walls in the computational domain were set to be not wetted by the to-be-dispersed phase.

3. RESULTS AND DISCUSSION

As presented in Figure 2, a monodisperse O/W emulsion with an average droplet diameter, d_{av} , of 32.0 μm was stably produced using the WMS2-2 chip at a high flow rate of the to-be-dispersed phase, Q_d , of 10.0 mL/h, which is equal to a droplet production rate of approximately $2.4 \times 10^5 \text{ s}^{-1}$. This Q_d value was higher than those for our previous MC array devices by at least two orders of magnitude.



Figure 2. Typical micrograph of the production of a monodisperse emulsion composed of a soybean oil-in-water of 1.0 wt% SDS system via asymmetric through holes (WMS2-2).

A typical example of the results obtained from CFD calculations (Figure 3) demonstrates that an O/W emulsion droplet is stably generated via an asymmetric through hole without applying a forced cross-flow of the continuous phase. Below the critical to-be-dispersed phase velocity inside a channel, U_d , the resultant droplet diameter slightly increased with increasing U_d , and the droplet generation rate linearly increased with increasing U_d . The CFD results for the resultant droplet diameter and droplet generation rate agreed quantitatively with the results obtained from emulsification experiments using a soybean oil-in-water of 2.0 wt% Tween20 system and a WMS1-3 chip (slit: $10 \times 70\text{-}\mu\text{m}$ size and $30\text{-}\mu\text{m}$ depth, channel: $10\text{-}\mu\text{m}$ diameter and $70\text{-}\mu\text{m}$ depth).

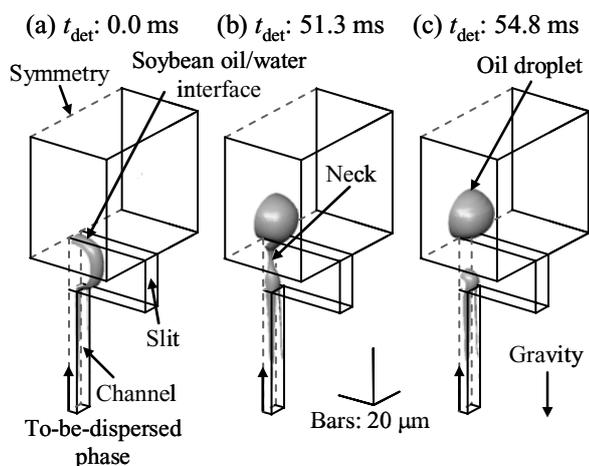


Figure 3. Oil droplet generation via an asymmetric through-hole with a 10 μm -diameter channel obtained from CFD calculation using the Volume of Fluid (VOF) method. U_d was 1.0 mm/s. t_{det} is the droplet detachment time.

4. CONCLUSIONS

We have demonstrated that a microfabricated device consisting of numerous asymmetric through holes enables producing monodisperse emulsions at very high droplet production rates. The generation of uniform emulsion droplets via an asymmetric through hole was simulated excellently using CFD. The numerical CFD results reported in this paper agreed quantitatively with the experimental results. We will scale up microfabricated asymmetric through-hole array devices to achieve the production of monodisperse emulsions at practical droplet production scales.

ACKNOWLEDGEMENT

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