Generation of Uniform Droplets through the Breakup of a Liquid Sheet Using a Novel Microfluidic Device

On-line Number 735
Qingyi Xu and Mitsutoshi Nakajima
Food Engineering Division, National Food Research Institute, 2-1-12 Kannondai, Tsukuba, Ibaraki 305-8642, Japan  E-mail: xuqingyi@affrc.go.jp; mnaka@affrc.go.jp

ABSTRACT

A novel microfluidic device was designed and fabricated to overcome size dependence of droplet on microchannel (MC) dimension with microchannels having three inlet channels. The microchannels have rectangular cross-section with a depth of about 5 micrometers. A viscous stream (i.e., the dispersed phase) flowed centrally between two inviscid streams (i.e., the continuous phase). Increasing the flow rate ratio of the side flow to the central flow ($F_s / F_c$) resulted in the reduction in the width of the central flow and flow instability. As the width of the central flow was narrowed down below a critical breakup width, the breakup of the viscous liquid sheet occurred and droplets with the diameters smaller than channel size were formed. The effect of channel configuration on the narrowing down and the breakup of the central flow is presented. With this microfluidic system, it is possible to observe real-time process of droplet formation and precisely control droplet size. This approach shows promise for the applications of such as microemulsification and precision fluid microdispersing.

KEYWORDS

microfluidic device, droplet generation, liquid sheet breakup, microchannel

INTRODUCTION

Over the past few decades, attentions have turned to the miniaturization of experimental systems to reduce cost, save time, and so on. The significant progresses have been made in the development of microreactors, micromixers and microextraction devices (Stone and Kim, 2001). Since the droplet-based applications cover a wide range from food to pharmaceuticals and cosmetics, development of effective miniaturized devices for dispersing precious drugs and functional compounds is urgently required.

Microfluidic devices with different channel configurations have been fabricated to generate monodisperse droplets (Kawakatsu, et al., 1997; Kobayashi, et al., 2002). In these cases, the dispersed phase was injected perpendicular to the flow direction of the continuous phase, the diameters of obtained droplets were 3-5 times larger than the size of microchannels. Consequently, further downsizing of droplets is greatly restricted by the limitation of micromachining technology.

Multiple liquid streams flow side-by-side without turbulent mixing inside a microchannel, permitting precise control of the width of individual stream by changing the relative flow rate. For example, Knight et al. (1998) have succeeded in using a three-stream laminar flow system to narrow down the width of the central stream by increasing the flow rate ratio of side stream to central stream to improve mixing efficiency. An excessive thinning of flow stream may result in Rayleigh instability (1897), where a capillary stream longer than its circumference is unstable and lead to breakup into droplets. Therefore, their experiments were carried out under the flow condition of not causing the disruption of the thinned stream.

In the present study, in order to overcome the size dependence of droplet on channel size we designed and fabricated a microfluidic channel system with three inlet channels; the central inlet channel...
meets with two side inlet channels at an angle of 60°. The dispersed phase flowed centrally between two side streams of the continuous phase. We used this three-stream laminar flow system to narrow down the width of the dispersed phase to cause the Rayleigh instability and its eventual breakup into small droplets. The breakup of capillary streams of macroscopic dimensions into drops have been intensively investigated and widely used in many industrial processes, such as fuel injection, spraying and coating, needle injection, and ink-jet printing (Moseler and Landman, 2000). However, the phenomena of the breakup of liquid streams, especially liquid sheets, of microscopic dimension within a confined space are still poorly understood. The information about the breakup of liquid sheets is not only useful to precisely control the size and monodispersity of droplets, but also to design more effective microfluidic devices.

The first purpose of the present work was to examine the effects of flow rate ratio and channel configuration on the narrowing down of the dispersed phase and, secondly, to gain insights on the effect of the channel configuration on the formation and monodispersity of droplets. Consequently, both the narrowing down and breakup at the channel junction and in the outlet channel were discussed.

MATERIALS AND METHODS

The microfluidic channels were micromachined on an 8 mm × 22.5 mm × 0.5 mm silicon plate with a dry etching process. A schematic top view of channel configuration is shown in Fig. 1. The continuous phase was injected into the microfluidic system through inlet hole 1 and then diverged into two side streams; the dispersed phase was injected into the central inlet channel through inlet hole 2. The inlet channels are 100 µm in width but tapered down to 50 µm near the junction of channels. Two side flows meet with the central flow at the junction with an angle of 60°, where they enter into a 1000 × 1000 µm channel, or “pool”, and then a 100 µm width outlet channel leading to outlet hole 3 to collect droplets. The change in the width of joined channel enables the investigation on the effect of channel configuration on the behaviors of the narrowing down and breakup of the central flow. All the channels are rectangular in cross section with about 5 µm in depth. The silicon MC plate was placed upside-down onto a glass plate to form confined microfluidic geometry.

![Figure 1. Schematic of channel configuration](image)

Figure 2 shows a schematic of the experimental setup. It includes two microsyringe pumps (PHD 2000, Harvard Apparatus, USA) for delivering the dispersed phase and the continuous phase into the microfluidic system, a module for holding silicon microchannel plate, and a video microscopy system for observing and recording the narrowing down and droplet formation.
In the present work, soybean oil (Wako Pure Chemical Industries, Japan) was used as the dispersed phase and 1 wt% sodium dodecyl sulfate (SDS; Wako Pure Chemical Industries, Japan) solution as the continuous phase. The flow rate of the continuous phase was always kept higher than that of the dispersed phase to avoid the dispersed phase flowing out from the central inlet channel into two side inlet channels. The flow rate ratio of the side flow to the central flow \( \frac{F_s}{F_c} \) at a given \( F_c \) was always kept below a threshold to avoid the continuous phase eventually rushing out from side inlet channels and flowing into central inlet channel, forcing the dispersed phase completely regressed back into the central inlet channel. Experiments were carried out with an inverted microscope. The narrowing down of the dispersed phase was observed with a portable CCD camera (WA-LCL211H, WATEC America CORP., USA) and the width measurements of the central stream were obtained from microscopic images. The droplet formation was observed with a high-speed video camera (FASTCAM-Rabbit mini, Photoron Ltd., Japan) with 400 frames per second.

**RESULTS AND DISCUSSION**

Generally, the width of the central phase is dependent of the \( \frac{F_s}{F_c} \) and \( F_c \). At a small \( \frac{F_s}{F_c} \) at a certain \( F_c \), the central flow (i.e., the dispersed phase) forms a continuous stream, which swelled in the “pool” due to the sudden enlargement of channel configuration. Increasing the \( \frac{F_s}{F_c} \) resulted in the decrease in the width of the central flow and the increase in the width of the side flow. As the width of the central flow is narrowed down to a critical value, the breakup of viscous liquid sheet occurs. The breakup of the focused liquid sheet takes place firstly in the outlet channel then at the channel junction. A detailed discussion about the narrowing down and the breakup of the central flow in the outlet channel and at the channel junction is presented below.
Narrowing down and breakup of the central flow in the outlet channel

Figure 3 shows an example of the narrowing down of the central flow in the downstream of outlet channel near the outlet hole 3 by increasing the \( \frac{Fs}{Fc} \) at a certain \( Fc \). As shown in Fig. 3A, the central flow occupied most of the flow area of the outlet channel, and the two side flows were squeezed into thin streams at a low \( \frac{Fs}{Fc} \) of 4 with \( Fc \) of 0.001ml/h. Figure 3B shows that the central flow became a very thin stream immediately before the breakup at \( \frac{Fs}{Fc} \) of 120.

![Figure 3. Microscopic images of the narrowing down of the central flow in the outlet channel by increasing the \( \frac{Fs}{Fc} \) with \( Fc = 0.001\text{ml/h} \) (A: \( \frac{Fs}{Fc} = 4 \), B: \( \frac{Fs}{Fc} = 120 \)](image)

When the width of the central stream was narrowed down below 6 \( \mu \)m, rapid breakup of the focused liquid sheet took place in the outlet channel as the \( \frac{Fs}{Fc} \) was increased to above 120. It is found that whenever the width of the central flow in the outlet channel is narrowed down below to 6 \( \mu \)m, the breakup takes place. We designated it as the critical breakup width, which is independent of the \( \frac{Fs}{Fc} \) at any given \( Fc \) studied in the present work. Correspondingly, the \( \frac{Fs}{Fc} \) for the breakup is designated as the critical breakup \( \frac{Fs}{Fc} \), which is dependent of the given \( Fc \).

Droplets with size of several micrometers were formed through the breakup of the focused liquid sheet (Fig. 4). Although the droplets formed within the microfluidic channel are disc-like in shape due to the depth of channel is only about 5 \( \mu \)m, the diameter reported here were converted into diameter of spherical droplets for the sake of data comparison. The polydispersity of the formed droplets is supposed due to the nonlinear of the central flow in the “pool”, causing the irregular breakup of the central flow in the outlet channel.

![Figure 4. High speed image of the droplets formed in the outlet channel at \( \frac{Fs}{Fc} = 120 \), \( Fc = 0.001\text{ml/h} \)](image)
Narrowing down and breakup of the central flow at the channel junction

The narrowing down of the central flow at the channel junction under the same flow condition described above is shown in Fig. 5. As shown in Fig. 5A, the central flow at channel junction slightly expanded its both sides into the side inlet channels at a low $F_S/F_C$ of 4 with $F_C$ of 0.001ml/h. Figure 5B shows that the central flow was narrowed down to be a very thin stream but still remaining as a continuous stream at the channel junction when $F_S/F_C$ was increased to 120.

![Figure 5. Microscopic images of the narrowing down of the central flow at the channel junction by increasing the $F_S/F_C$ with $F_C = 0.001\text{ml/h}$ (A: $F_S/F_C = 4$, B: $F_S/F_C = 120$)](image)

When the width of the central stream was narrowed down below 3.5 µm, rapid breakup of the focused central flow took place within the channel junction or within the “pool” as $F_S/F_C$ was increased to above 150. It is confirmed that the critical breakup width at the channel junction is also independent of the $F_S/F_C$ at any given $F_C$, while the critical breakup $F_S/F_C$ is dependent of the given $F_C$. After a transition from unsteady breakup of irregular-shaped droplets and polydisperse droplets, the focused central flow was subjected to a periodic breakup and highly monodisperse droplets with a size of about 16 µm were formed (Fig. 6). Precise control of size, production rate and patterning is achievable by varying the flow condition, which was discussed in a separate paper.

![Figure 6. High speed image of the droplets formed in the “pool” at $F_S/F_C = 150$, $F_C = 0.001\text{ml/h}$](image)
CONCLUSIONS

Through the precise fabrication of a new microfluidic device with three inlet channels, it is possible to control the width of the individual stream. By increasing the flow rate ratio of $F_s / F_c$ at a certain $F_c$, the width of the dispersed phase, centrally located between two streams of the continuous phase, can be narrowed down to a critical breakup width, leading to the breakup of the focused liquid sheet into droplets. Channel configuration plays a significant role in the narrowing down and the breakup of the central flow, reflecting in the larger critical breakup width, lower critical breakup $F_s / F_c$, and polydispersity of droplet in the outlet channel comparing with those at the channel junction. Highly monodisperse droplets with size smaller than the channel size can be formed within the channel junction or within the “pool”. This approach provides an effective way to precisely control droplet size and production rate by varying the flow condition.

ACKNOWLEDGMENTS

This work was financially supported by the Nanotechnology Project of The Ministry of Agriculture, Forestry and Fisheries of Japan.

REFERENCES