Concentration-adjustable micromixer using droplet injection into a microchannel

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Electronic supplementary information

Experimental setup

The flow inside the device is recorded with 2000 fps from downward direction using a high-speed camera attached on an optical microscope (Fig. S1). We use two different lighting: a bright-field observation with white light emitted by an LED light is carried out for the measurement of the dye solution, whereas a dark-field observation with 505 nm incident light is carried out for the measurement of the fluorescent particle solution. DI water and oleic acid are chosen as the continuous phase and dispersed phase, respectively. We used dye solution (mixture of the brilliant blue FCF and DI water) and particle solution [mixture of fluorescent polystyrene particle (1 μm in diameter) and DI water] as the sample solution. The diffusion coefficient of the dye and the particles in water are estimated as 10^{-10} m^2 s^{-1} and 10^{-16} m^2 s^{-1}, respectively. The fluorescent particles are excited by the 505 nm light and emit 515 nm (peak wavelength) light. We did not add any surfactant in this experiment. The emitted light is extracted by the camera through a dichroic mirror and a bandpass filter. The working fluids are infused by syringe pumps at constant flow rate and the mixture of them are extracted from two outlets connected to an outlet reservoir.
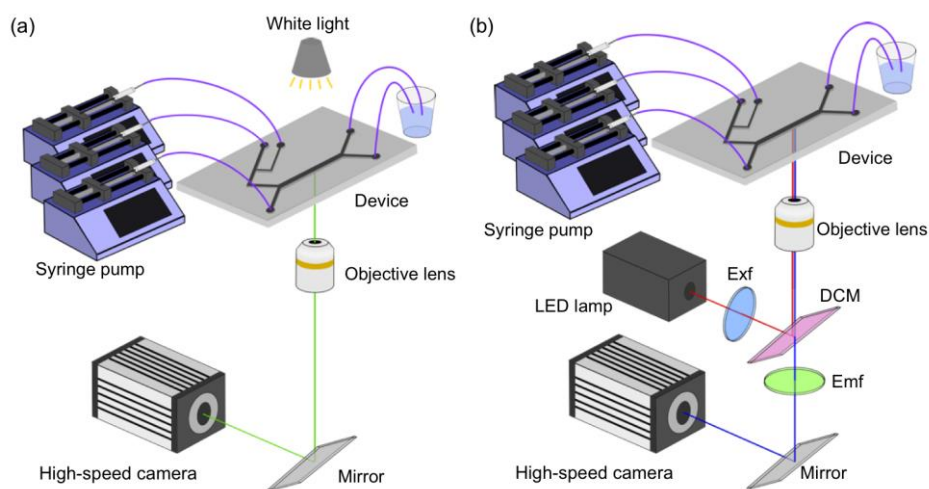

Fig. S1 Experimental setup for mixing of (a) the dye and (b) the particle solutions. (a) An LED white light is used for the bright-field imaging in the case of the dye mixing, whereas (b) the dark-field imagin with the incident light of the wavelength of 505 nm is irradiated in the case of the particle mixing. The particles emit 515 nm light.

Control of the droplet injection frequency

The droplet injection frequency (*i.e.*, droplet generation frequency at the T-junction) is stably varied by controlling the flow rate ratio of the continuous and the dispersed phases. In our system, the flow rate ratio φ can be varied from 0.01 to 0.20 (Fig. S2). For the case of $\varphi > 0.20$, co-flows are formed. This is mainly because we did not add any surfactant.
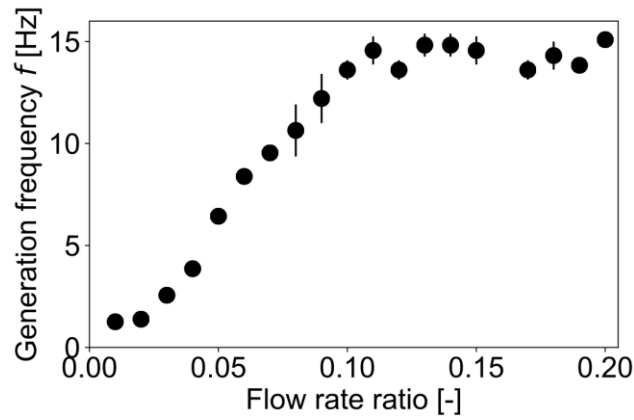

Fig. S2 The droplet generation frequency as a function of the flow rate ratio φ.

Effects of the velocity

The effect of the velocity is investigated in a mixing channel of $W_m = 200$ µm. Figure S3 shows the mixing with three different mean velocity in the mixing channel ($u = 5.0, 20.0,$ and 50.0 mm s^{-1}). The droplet Reynolds number and the Peclet number (Pe = uL / D, where u, L, and D are the characteristic velocity, characteristic length, and the diffusion coefficient of the sample, respectively) for the three cases are $\mathrm{Re_d} = 0.5, 2,$ and 5, and Pe = 1×10^4, 4×10^4, and 1×10^5, respectively.
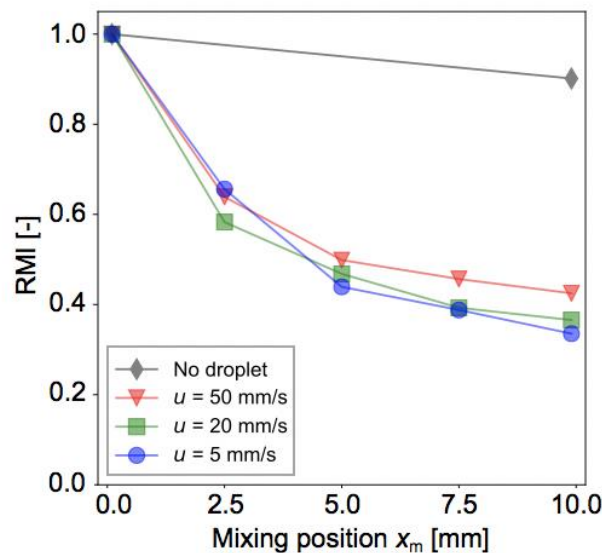

Fig. S3 Measured RMI for three different mean velocities ($u = 5, 20,$ and 50 mm s^{-1}). The result indicates that the resulting concentration does not depend on the velocity in the mixing channel.

Concentration distribution in the mixing channel

Although the mixing is significantly enhanced by the disturbance generated by the droplets, the mixing in the downstream region is the diffusion dominant. For that characteristics, concentration of the mixed solution has distribution in the cross-sectional direction as shown in Fig. S4. This non-uniformity of the concentration can be, *e.g.*, exploited to obtain finely diluted solution by extracting the solution flowing in the near-wall region, or homogenized using the dispersed phase[S1,S2].
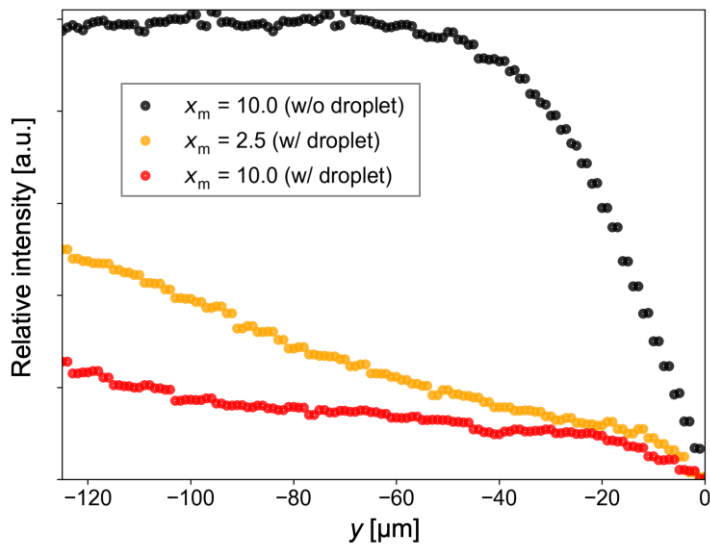

Fig. S4 Cross-sectional concentration distributions in a mixing channel (width: 250 μm, length: 10.0 mm, and $y = 0$ corresponds the channel center). Black, yellow, and red plots indicate the distributions at $x_m = 10.0$ mm (without droplet injection), $x_m = 2.5$ mm (with droplet injection) and $x_m = 10.0$ mm (with droplet injection).

Mixing of particles in an expanding channel

A mixing experiment in an expanding channel (Fig. S5) is conducted. The channel width expands from 200 μm (at the confluence point) to 600 μm (at the end of the mixing channel, 10 mm downstream of the confluence point) and the sample and the buffer are introduced in the channel with $Q_{sample} = (Q_{cont} + Q_{disp}) = 420$ μL h^{-1}. In contrast to Fig. S5(a), the mixing of the particle solution is significantly enhanced by introducing the droplets [Fig. S5(b)]. In this channel, the mixing is more enhanced than the case in the constant-width channel, because the migration of the droplets in the cross-sectional direction increases as the channel expands whereby the droplets touch each other and generate a chaotic advection. Although some droplet coalescence are observed because of the absence of surfactants, it is observed that the mixing enhancement effect is significant regardless of the coalescence. The channel is considered to be suitable to achieve homogeneity rather than the concentration control.
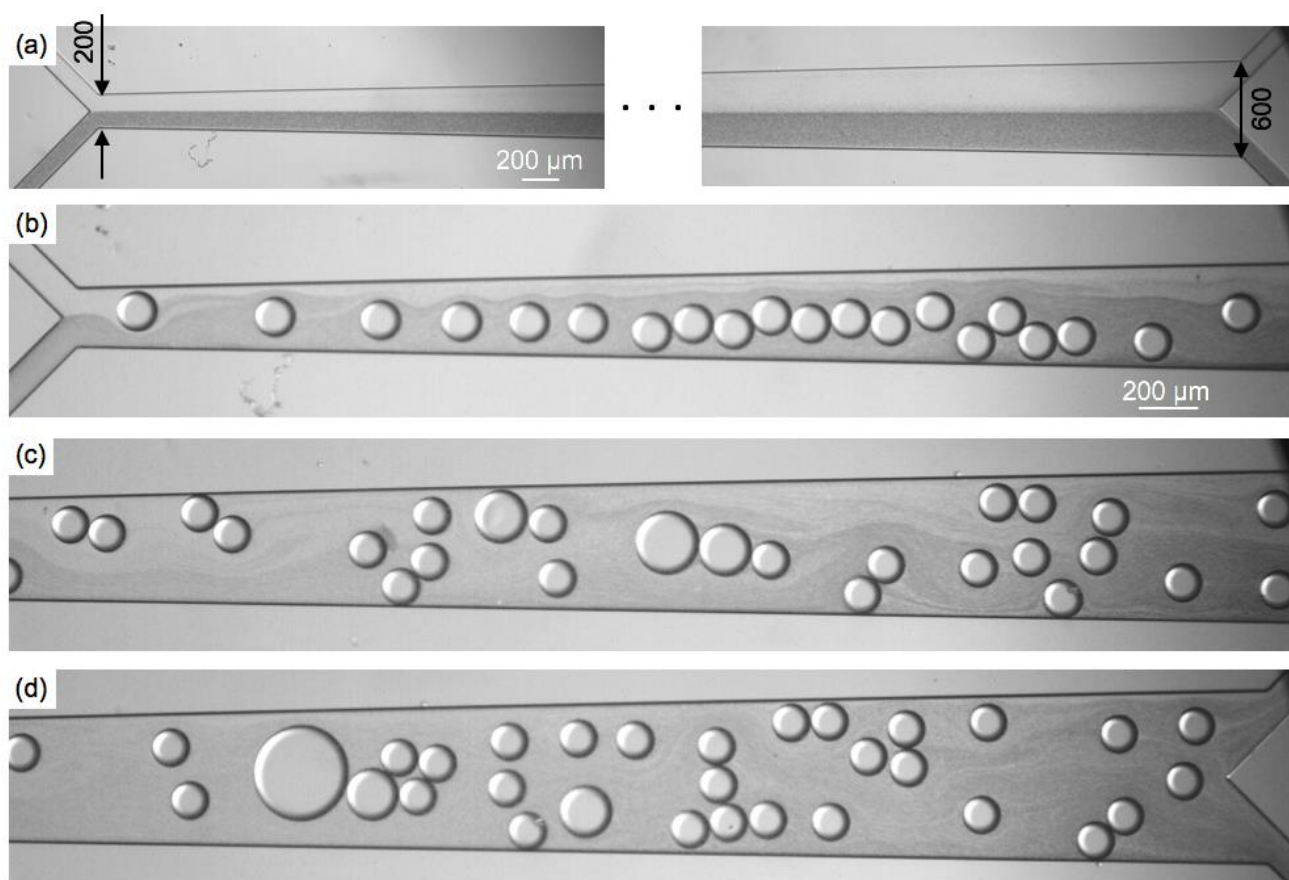

Fig. S5 Mixing of the particles (1 μm in diameter) in an expanding channel in which W_m gradually changes from 200 to 600 μm. (a) Diffusive mixing is dominant on the interface of the continuous phase and the sample in the case of no droplet injection. (b)–(d) A series of the injected droplets collapse each other due to the channel-width expansion and the mixing efficiency is enhanced by the chaotic advection induced by the droplets.

References

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