A 3D easily-assembled Micro-Cross for droplet generation

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We present an off-the-shelf device combined with some commercial adapters that performs as a micro droplet generator. The advantage of this unit lies in that it is assembled conveniently, connected elegantly with other droplet detection equipment, and it is high-pressure enduring. Most importantly, this Micro-Cross circumvents the problem of hydrophilicity and hydrophobicity and produces W/O or O/W droplets at a higher frequency than PDMS chips.

Materials and methods

Micro-Cross construction

The same as the device used for particle focusing,23 our Micro-Cross (P-777, Upchurch Scientific) also contains several fluidic fitting parts such as MicroFerrules (F-152, Upchurch Scientific) and female nuts (P-416, Upchurch Scientific), as shown in Fig. 1(a). All of these adapters are from IDEX Health & Science, a part of IDEX Corporation, which designs, develops, and manufactures liquid subassemblies and precision components. The detailed structure and internal geometrical dimensions of the cross-section of the device are illustrated in Fig. 1(c). Capillary tubes with 360 μm OD should be inserted through the PEEK (polyetheretherketone) female nuts and ferrules, pushed firmly against the bottom...
In microfluidic chips, droplets are often confined to disk-like shapes between the top and bottom channel walls due to the high aspect ratio of the chip, and this is accompanied by the problem of hydrophilicity and hydrophobicity during formation.⁴,²⁷ Water-in-oil (W/O) emulsion processes always fail in the hydrophilic channels, whereas oil-in-water (O/W) dispersing systems are suitable. Because the dispersed phase liquid is squeezed radially without contacting the channel surface before break up, this 3D axisymmetric channel is proved to be effective in forming monodisperse droplets without the need for water or oil wetting. As such, our device can be used in the emulsion of both W/O and O/W systems without the need for surface wetting procedures. In the W/O emulsions, we used mineral oil containing SPAN 80 surfactant (2.5%, w/v) as the continuous liquid and deionized (DI) water as the dispersed phase. For O/W droplet formation, we mix DI water with glycerol at a ratio of 1:1 (v/v) as the continuous phase, and low viscosity silicon oil is used as the droplet phase. The hydrosoluble surfactant Pluronic F-127 (Jinsui Bio-Technology, Shanghai, China) is added to the water to resist oil droplet coalescence.

Results and discussion
Formation of monodisperse W/O and O/W droplets
We firstly use the Micro-Cross to demonstrate the generation of homogeneous W/O droplets as shown in Fig. 2(a–b). The existence of surfactant prevents droplet coalescence, even
though they are in such close proximity to each other in the capillary tube (Fig. 2(a)). The polydispersity index ($\lambda$), defined as the ratio between the standard deviation and the mean of the droplet diameters, is only about 2.12%, and this indicates that the droplets are highly monodisperse. Alternatively, the unit is also capable of generating uniform O/W droplets when silicon oil acts as the dispersed phase, as illustrated in Fig. 2(c–d). In this system, glycerol must be mixed with water as the continuous phase to increase the viscosity until it is comparable or higher than that of the silicon oil. F-127 surfactant seems to form a much thicker membrane around the oil droplet surface preventing coalescence. Smaller droplets can be generated as shown in Fig. 2(d), indicating that the flow rate ratio between the continuous and dispersed liquids determines the droplet diameter distribution.

**Droplet size distribution**

The results in Fig. 3 show that both W/O and O/W droplet size decreases with increasing flow rate ratio ($Q_c/Q_d$), and this tendency is consistent with most emulsification processes in chips. In flow-focusing droplet formation microfluidic chips, the rate-of-flow-controlled break up mechanism indicates that the droplet volume is inversely proportional to the flow ratio. In our experiments we firstly vary the flow rate of the continuous phase ($Q_c$) at a constant dispersed phase flow rate ($Q_d$), and then control the flow rate ratio to be constant by simultaneously changing the flow rate of the two liquids. It is observed that in the 3D Micro-Cross the inversely-proportional relationship between droplet size and flow rate ratio remains coincident with that of 2D chips. Furthermore, a higher flow rate ratio with higher flow rates of the two phases produces smaller droplets. Thus we speculate that the role of flow rate $Q_c$ is most significant during the droplet break up, owing to the fact that the pressure jump of the continuous liquid at the entrance of the downstream channel, caused by the occupation of the dispersed phase, leads to normal displacement of the thread and the eventual pinch-off.\(^{14}\)

**Droplet generation frequency**

In this section we show the difference of droplet formation frequency between the device described above and traditional PDMS chips. The crossing chips are fabricated through a soft-lithograph method with a uniform depth of 20 μm and the same width as the Micro-Cross (150 μm). Both the liquid properties and inlet flow rates are unaltered in the experiments and we observe that more droplets are generated during the same period in the axisymmetric 3D Micro-Cross than in the 2D rectangular cross-channel chip, as shown in Fig. 4 and Fig. 5. As the theoretical analysis demonstrated,\(^{24}\) the 2D collapse is always stable whereas the 3D collapse is always unstable. The fluctuation of the fluid thread and the radial squeezing from the outer fluid accelerate the 3D break up and thus a higher generating frequency is achieved, especially with a high flow rate ratio.

**Conclusions**

As was illustrated here, this device is competent to generate micro W/O or O/W droplets without the need for channel surface wetting modification due to 3D axisymmetric hydrodynamical focusing. Droplet size, ranging from 20–300 μm, can be easily controlled by altering the flow rate ratio, with a polydispersity index lower than 3%. This unit withstands a
high fluid pressure (about 4000 psi), which is far higher than the chip-based microfluidic bonding strength (lower than 100 psi). Under the same material properties and flow conditions, the 3D Micro-Cross achieves a higher generating frequency than a 2D PDMS chip with the same channel width. Although this adapter was designed for occasional biotechnology applications when there is a special need for more than two pieces of tubing and high-pressure region systems, we develop its capability as a micro droplet generator by the comparative preponderance that this off-the-shelf device can be assembled easily, and will be valuable for the demand where both high throughput and low-cost are needed.

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Notes and references