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Supporting Information

Microfluidic production of nanoscale perfluorocarbon droplets as liquid contrast agents for ultrasound imaging

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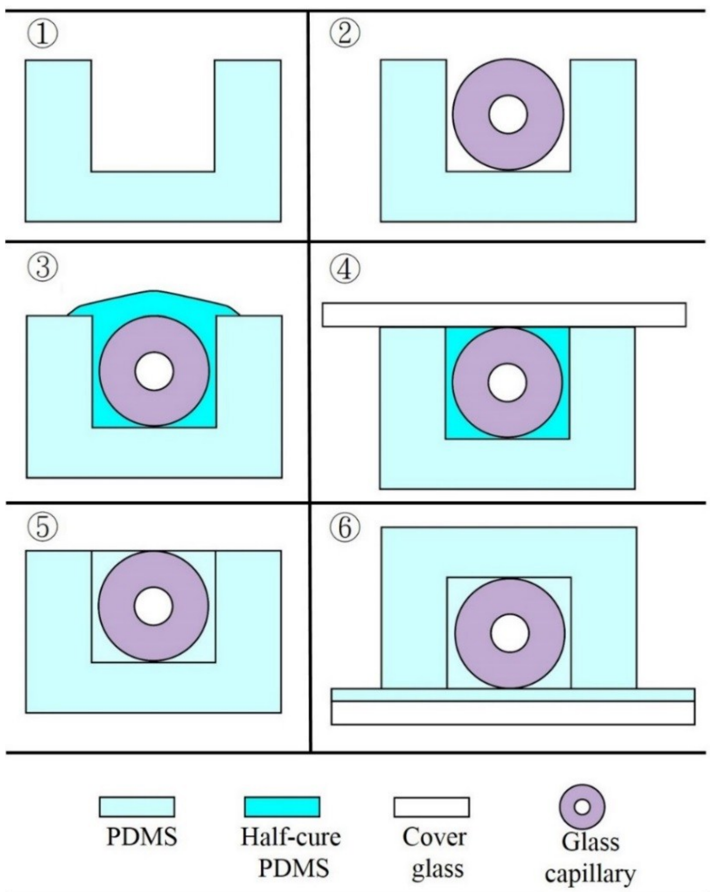

Fig. S1. Schematic process of assembling the glass capillary into the PDMS device. Briefly, the glass capillary was first placed on the intersection of the channel (1, 2) and half cured PDMS was applied to seal the corners (3). After removing excess PDMS and flattening the surface (4, 5), the device was bonded with a cover glass after plasma treatment (6).

The flow circuit model

According to the flow circuit model,[1,2] the volumetric flow rate of a channel can be calculated when the applied pressure and flow resistance are given. The driving pressure ΔP is proportional to the volumetric flow rate Q.

$$\Delta P = Q \cdot R_{hyd} \tag{1}$$

where R_{hyd} is the hydraulic resistance.

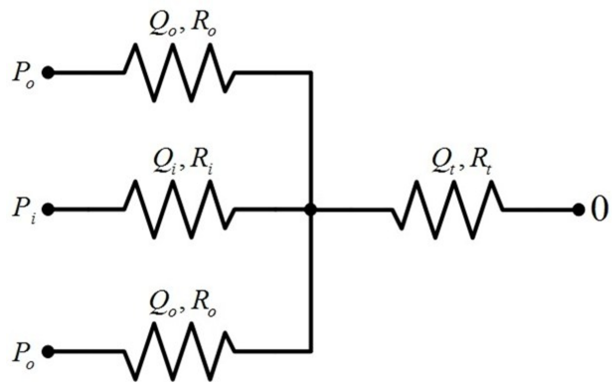

Fig. S2. Schematic of the flow resistance circuit network.

A flow resistance circuit model (Fig. S2) is developed based on the design of the microchannels in our device. R_i, R_o, and R_t are the hydraulic resistances of the inlet centre, side, and exit channels, respectively. Q_i and Q_o are the flow rates of the centre and side channels, and $Q_t = Q_i + 2Q_o$ is the flow rate of the exit channel. P_i and P_o are the pressures applied on the centre and side channels, and the pressure on the exit channel is set as zero. In this work, as the glass capillaries are inserted into the channels, the hydraulic resistances in the flow circuit cannot be simply calculated based on the geometry.[1] Instead, we calculate the resistances using the applied pressures and the flow rates obtained via micro-PIV. In micro-PIV, we apply two different sets of pressure (P_o^1,P_i^1) and (P_o^2,P_i^2) and measure all flow rates correspondingly. The notation 1 and 2 here represents the first and second set of data. Using the flow circuit model, we have:

$$\begin{cases} Q_o^1 R_o + Q_t^1 R_t = P_o^1 \\ Q_i^1 R_i + Q_t^1 R_t = P_i^1 \end{cases} \tag{2}$$

$$\begin{cases} Q_o^2 R_o + Q_t^2 R_t = P_o^2 \\ Q_i^2 R_i + Q_t^2 R_t = P_i^2 \end{cases} \tag{3}$$

From equations (2) and (3), we obtain the flow resistances of different channels:

$$R_o = \frac{P_o^1 Q_t^2 - P_o^2 Q_t^1}{Q_t^2 Q_o^1 - Q_t^1 Q_o^2} \tag{4}$$

$$R_t = \frac{P_o^1}{Q_t^1} - \frac{Q_o^1}{Q_t^1}\frac{(P_o^1 Q_t^2 - P_o^2 Q_t^1)}{(Q_t^2 Q_o^1 - Q_t^1 Q_o^2)} \tag{5}$$

$$R_i = \frac{P_i^1}{Q_i^1} - \frac{P_o^1}{Q_i^1} + \frac{Q_o^1}{Q_i^1}\frac{(P_o^1 Q_t^2 - P_o^2 Q_t^1)}{(Q_t^2 Q_o^1 - Q_t^1 Q_o^2)} \tag{6}$$

Once the flow resistances are obtained, the volumetric flow rates can be calculated for the pressures applied on the device using the equations below:

$$Q_i = \frac{(R_o + 2R_t)P_i - 2R_t P_o}{R_o R_t + R_i R_o + 2R_i R_t} \tag{7}$$

$$Q_o = \frac{(R_i + R_t)P_o - R_t P_i}{R_o R_t + R_i R_o + 2R_i R_t} \tag{8}$$

Comparison of 2D and 3D flow focusing devices

We tried to make liquid perfluorocarbon (PFC) droplets in a 2D flow focusing device, in which the nozzle width (the smallest width in the centre channel) is 25 μm, same as the orifice diameter in our hybrid 3D focusing device. 41% glycerol/water mixture with 0.5wt% Zonyl FSO-100 and perfluorohexane (PFH, C_6F_{14}) were used as the continuous phase and dispersed phase, respectively. Fig. S3 shows the PFH droplet formation in this 2D flow focusing device for the disperse phase to continuous phase flow rate ratio (Q_d/Q_c) of 0.05, 0.017, and 0.0071. Although the PFH droplet size gradually became smaller as the flow rate ratio decrease, we were unable to obtain the tip-streaming mode for generating extremely small droplets even at Q_c/Q_d=0.0071. The thread formed at the tip started to retract when the flow rate ratio was further decreased. Fig. S3(b) compares the resulted droplet size using the 2D and 3D flow focusing devices under the approximately flow rate ratio. Obviously the 3D flow focusing device produced much smaller PFC droplets.

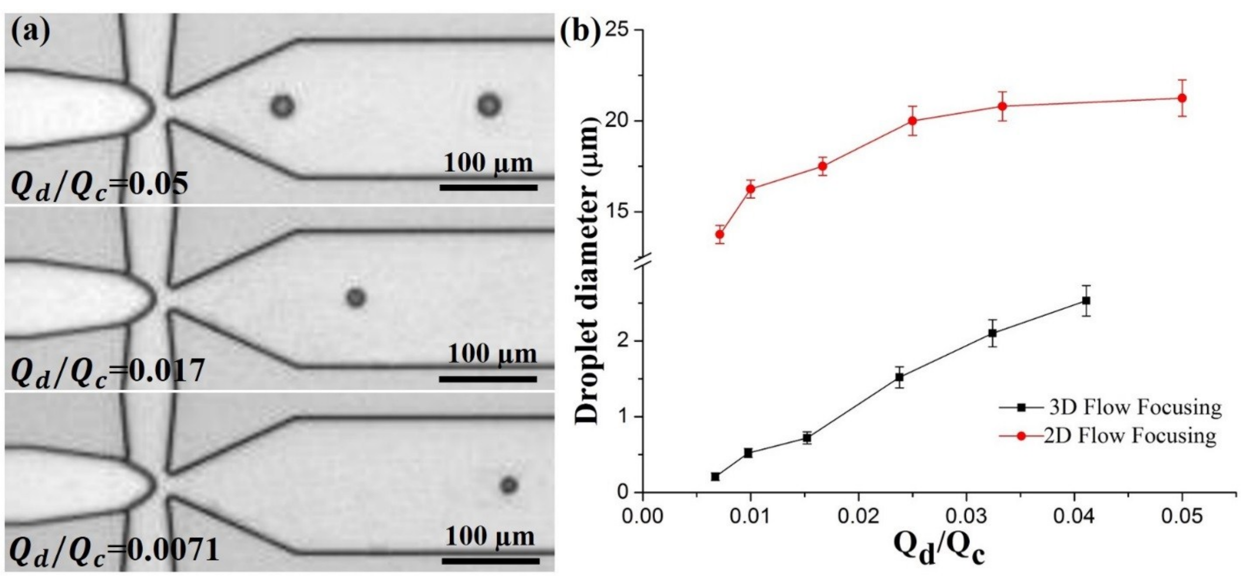

Fig. S3. (a) Images of PFH droplet formation in a 2D flow focusing device for the flow rate ratio (Q_d/Q_c) at 0.05, 0.017, and 0.0071, respectively. Tip-streaming can hardly be obtained. (b) Comparison of the PFH droplet diameter using the 2D and 3D flow focusing devices.

References

1. H. Bruus, *Theoretical microfluidics*, Oxford university press Oxford, 2007.
2. L. Jiang and S. Yao, *IEEE Transactions on Nanotechnology*, 2016, **15**, 828-835.