PROGRAMMABLE DIGITAL DROPLET MICROFLUIDICS USING A MULTIBARREL CAPILLARY BUNDLE

Renee R. Hood, Tommy Wyderko, and Don L. DeVoe*
University of Maryland College Park, USA

ABSTRACT

The integration of multibarrel glass capillaries into a microfluidic co-flow configuration is demonstrated for enabling digital control over the production of nanoliter scale droplets. The multibarrel system supports continuous-flow generation of single-phase and dual-phase droplets with digital control over droplet content, enabling the formation of dynamically-programmable and tunable emulsions. Using this unique co-flow system, the generation of water-in-oil droplets is explored, with the capacity to regulate both chemical composition and particle size through binary control over multiple flow pathways. The results presented here demonstrate an innovative method for rapid generation of customizable emulsions containing nearly-monodisperse droplets of tunable configurations.

KEYWORDS: emulsions; microfluidics; multi-barrel capillary

INTRODUCTION

A wide range of microfluidic methods for the generation of complex droplet have been developed, such as the realization of multi-phase droplets [1] and emulsions with tunable characteristics [2,3]. However, established microfluidic systems do not offer direct means for dynamically controlling droplet configuration joined with multiplexed droplet formation for the generation of fully customizable emulsions. The technique presented here is unique in its ability to manipulate droplet size and content, including controlled merging of multiple droplets, in a highly multiplexed and scalable format.

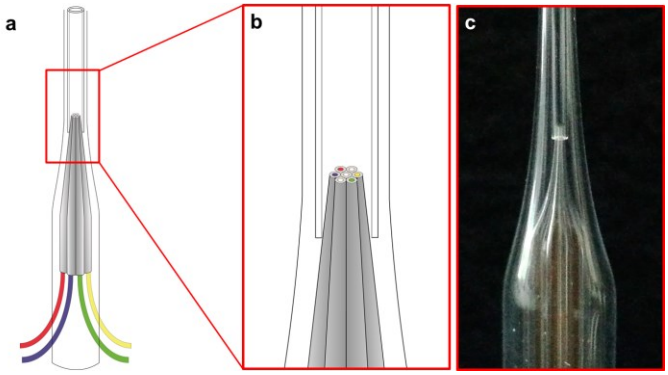

Figure 1. (a) Schematic of the pulled multibarrel capillary device with oil and water input tubing, (b) magnified view of the pulled end of the capillary bundle, and (c) image of an assembled device.

The co-flow microfluidic system consisting of a 7-barrel glass capillary is shown in Fig. 1. Although similar to conventional co-flow microfluidic droplet generators, the multibarrel configuration allows the interaction of multiple fluid streams within the co-flow system, enabling higher order droplet formation and a variety of possible emulsion combinations using a single configuration for the droplet generator. Here, multiple inlets to the multibarrel capillary device were connected to oil and water phases through micro-splitter valves, allowing selected inlets to be dynamically switched between different dispersed aqueous phases as well as continuous oil phase. When adjacent capillaries are both configured to emit dispersed phase, the developing droplets merge, thereby enabling the multibarrel output to alternate between single droplet and dual droplet formation through digital control of the inlet valves (Fig. 2). This approach allows digital control of droplet size using binary flow switching of adjacent capillary emitters, as well as the ability to form multiphase droplets comprising different solutes from each of the adjacent emitters.

EXPERIMENTAL

Microfluidic capillary devices were fabricated from an assembled combination of a multibarrel glass capillary and various tubing. Each capillary of the 7-barrel pipette was interfaced with PEEK tubing and

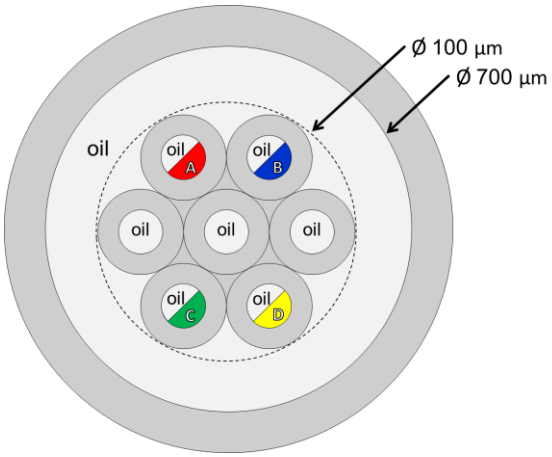

Figure 2. Configuration of inlets: the 7-barrel capillary contains 3 center inlets which are connected to oil phase and two sets of adjacent capillaries connected to oil and water (A,B,C,D) phases separated by a valve, enabling rapid switching between phases for digital control over droplet formation for programmable emulsions.

Tygon tubing for supply of dispersed (water) and continuous (oil) phases for droplet production. Individual capillaries were connected to micro-splitter valves to enable dynamic switching between continuous and dispersed phases. The opposite end of the multibarrel capillary was pulled to a total tip diameter of 100 µm, and positioned within a glass microcapillary with an approximate inner diameter of 700 µm. A glass Pasteur pipette was used to align the microcapillary to the multibarrel capillary as well as to hold the apparatus together.

The continuous phase solution comprised corn oil with Span 80 (2 vol %) as a surfactant. The dispersed phase aqueous solution contained deionized water with various colors of food dye to aid in visualization. For droplet formation, when the oil phase was connected through the switch valve, the linear velocity was constant at V_{oil}=0.34 cm/s (corresponding to Q_{oil}=0.18 µL/min) to match the overall sheath flow linear velocity (Q_{oil}=100 µL/min). When the water phase was connected to the valve, such that the inlet was forming two-phase or single droplets, the velocity remained constant at V_{water}=1.53 cm/s (Q_{water}=0.8 µL/min) unless otherwise noted.

Populations of droplets were collected at the outlet of the device and transferred to standard glass microscope slides for characterization. The droplets were visualized using standard microscopy and measured manually for diameter using Nikon NIS Elements software. Images of the collected droplets in Figures 3 and 4 were modified for clarity using background subtraction and contrast enhancement to aid in visualization.

RESULTS AND DISCUSSION

Independent control of droplet size was achieved by varying the flow velocity of the dispersed aqueous phase from 0.38 cm/s to 38.2 cm/s, with a continuous phase flow velocity of 0.34 cm/s, resulting in a dispersed:continuous flow rate ratio spanning two orders of magnitude. Diameters of the corresponding droplets were directly correlated with flow rate ratio and varied between approximately 100 µm and 450 µm (Fig. 3), demonstrating the ability of the multibarrel system to manipulate the diameters of the resulting droplets by simply varying flow conditions. Size distributions of multiplexed single and dual merged droplets formed simultaneously within the multiplexed system were also investigated across multiple inlet configurations and compared to distributions for droplets formed alone to assess the effect of multiplexed formation on particle size (Fig. 4). Controlled generation of single droplets, merged dual droplets, and multiplexed single/single and

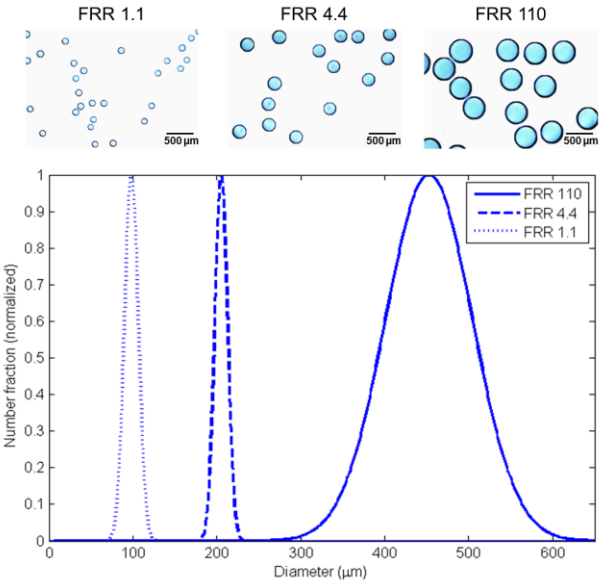

Figure 3. Size distributions for droplets formed using a single capillary within the multibarrel system as a function of flow rate ratio (FRR), defined as the ratio of dispersed:continuous flow rates.

single/dual droplets was successfully achieved. Although slight variations occurred across the various inlet combinations, this issue can be alleviated with careful calibration of flow velocities and control over device symmetry. Overall, the multibarrel capillary device demonstrated the generation of a continuous stream of tailored droplets with tunable diameters.

CONCLUSION

Here we have demonstrated multiplexed droplet formation utilizing a pulled multibarrel capillary device with the ability to generate a continuous stream of customizable droplets. Unlike conventional microfluidic droplet generators, the multibarrel capillary device enables simultaneous formation and merging of droplets containing discrete fluid species, allowing rapid digital tuning of droplet composition without the need to disrupt fluid flow or reconfigure the device. The resulting system presents unique opportunities for the multiplexed formation of complex and dynamically tunable emulsions. Furthermore, a similar system can also be utilized for continuous-flow production of unilamellar liposomes [4].

ACKNOWLEDGEMENTS

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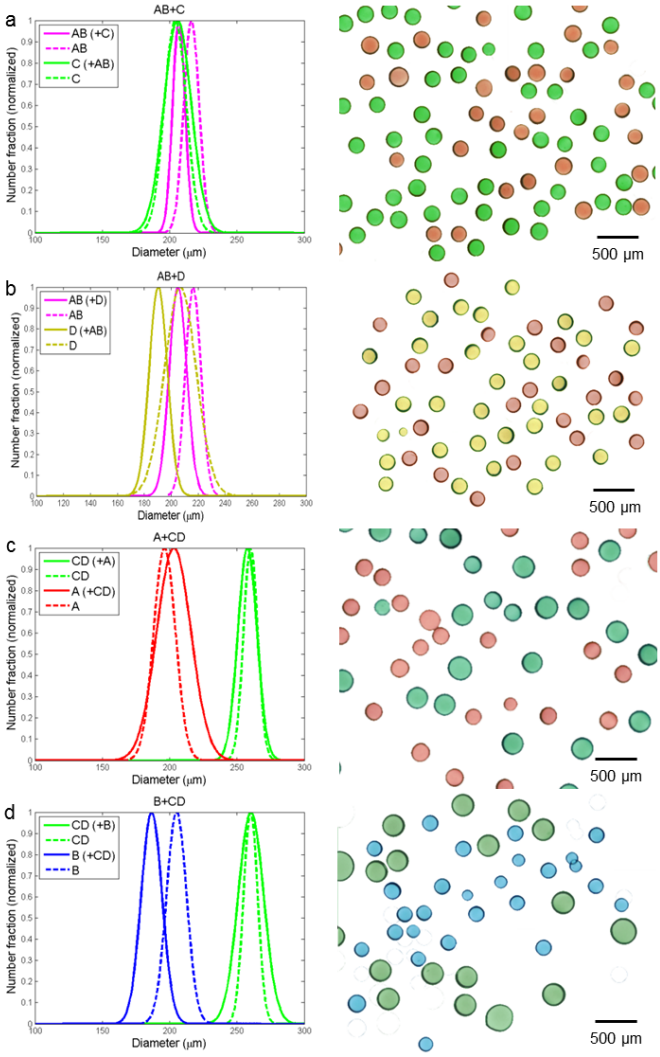

Figure 4. Size distributions of single and dual droplets formed simultaneously, compared to each droplet type when formed alone.

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CONTACT

* D.L. DeVoe; phone: +1-301-405-8125; ddev@umd.edu