Instantaneous Solidification of a Centrifuge-driven Capillary Jet with Controlled Hydrodynamic Instability in a Centrifuge-based Droplet Shooting Device through Observational Analysis

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ABSTRACT

This paper reports an observational analysis on droplet formation from a capillary-jet driven by centrifugal-gravity in a CDSD (Centrifuge-based droplet shooting device), and controlled synthesis of microbeads by instantaneous solidification of a sodium alginate solution jet breaking into drops owing to hydrodynamic instability. Our analysis may deepen understanding of micro capillary-jet and enable flexible fabrication of fluidic-based polymeric microbeads.

KEYWORDS

Microfluidics, Microfabrication, Highspeed videography, Hydrodynamic instability

INTRODUCTION

Microfluidic processing is a powerful approach for microparticle production in various fields such as chemical and biological analysis, optics and tissue engineering [1,2]. To provide particles with specific functions, enormous variety of the fluidic devices, mainly having flow focusing or T-junction geometries, have been prototyped based on extensive experimental/theoretical analysis on fluid behavior in microscale [3]. Among those devices, a CDSD (Centrifuge-based droplet shooting device) has been proposed for the synthesis of monodisperse anisotropic microparticles and fibers [4]. The CDSD is constructed from a centrifugal-tube, a glass capillary, and an acrylic holder for the capillary (Fig.1). A capillary is filled with a sodium alginate solution. A $CaCl_2$ solution is introduced in the bottom of the centrifugal-tube. Under centrifugation, the solution is ejected from the capillary by centrifugal force and form droplets. The droplets are immediately solidified in a $CaCl_2$ solution into calcium alginate particles. In spite of this simple procedure of particle fabrication, however, the process of droplet formation and related physics in the CDSD has not yet been revealed owing to lack of observational analysis. Here, we present direct observation of drop formation in the CDSD under centrifugation by high-speed videography. Using the observational setup, we analyzed two distinct droplet formation processes in the CDSD, jetting and dripping. Furthermore, we confirmed the jetting regime provides smaller particles than the dripping regime Our observational analysis and demonstration suggest the CDSD could be a further useful tool for an analysis of fluid mechanics of a micro liquid jet under ultrahigh-gravity and fabrication of polymeric microparticles.

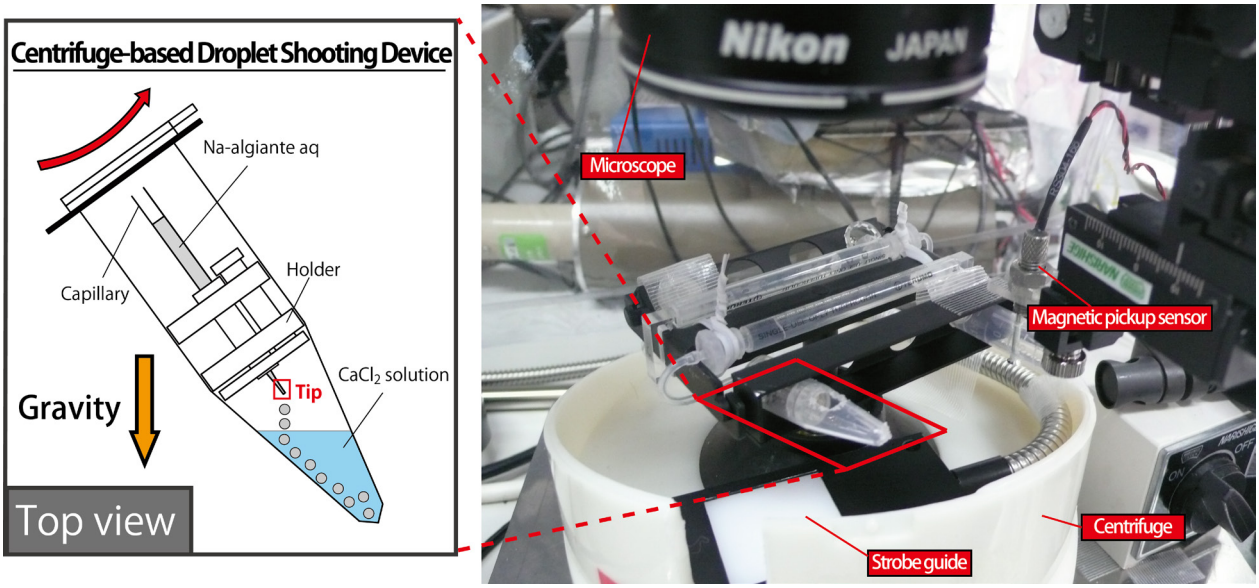

Figure 1: Experimental setup for observation of drop formation in a CDSD. The setup is composed of a nano-pulse strobe-scope, a magnetic pickup-sensor, a trigger circuit, a centrifuge equipped with the CDSD, and a microscope connected with a high-speed camera. When the CDSD passes under microscope, a storobe-flash pulsates for 180 ns and the capillary tip is captured in a high-camera through the microscope.

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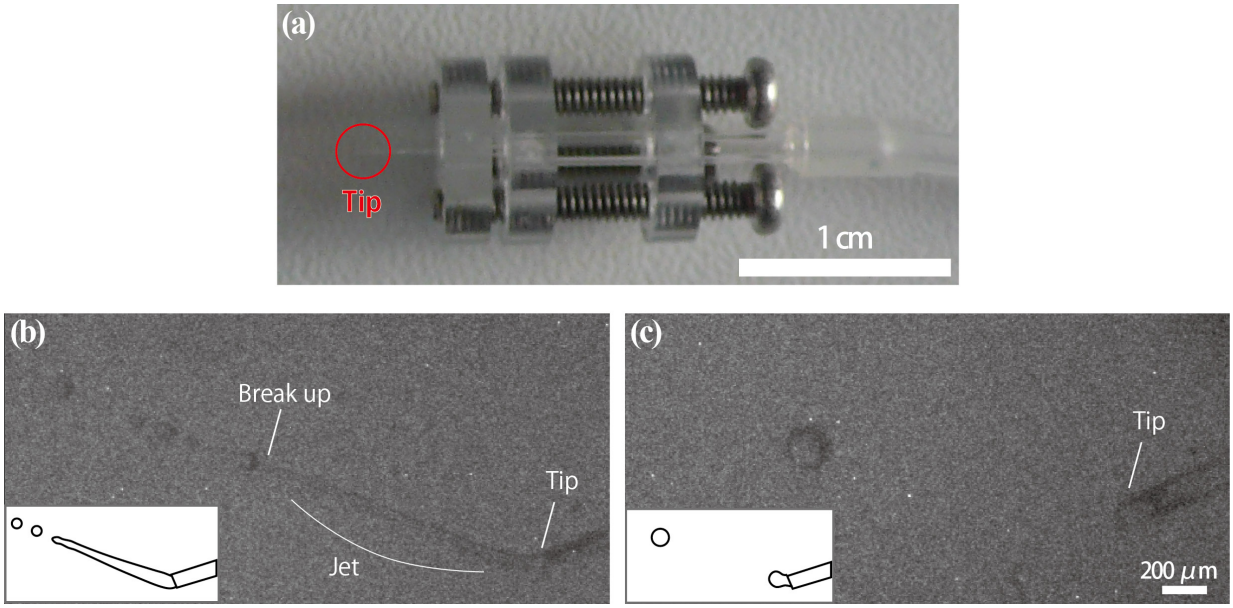

Figure 2: Images of a capillary tip ejecting a sodium alginate solution in a CDSD under centrifugation captured in a high-speed camera. (a) The holder and the capillary of the CDSD. (b) Jetting regime of droplet generation. (c) Dripping regime of droplet generation. In jetting regime, droplets are formed in the break-up of a fluid pipe. In dripping regime, droplets are directly formed at the capillary orifice.

OBSERVATIONAL SETUP

For the observation of drop formation in the CDSD, we assembled a simple setup using a strobe-scope (Fig. 1). The setup is composed of a nano-pulse strobe-scope, a magnetic pickup-sensor, a trigger circuit, a centrifuge equipped with the CDSD, and a microscope connected with a high-speed camera. When a centrifuge-rotor passed near the sensor, the sensor generates a voltage by electromagnetic induction. The circuit converts the voltage to a stable square wave which activates the strobe-scope to emit a strobe-flash from a strobe guide under the CDSD. The CDSD is set to pass under the microscope in its focus point at the same moment. Thus, when the strobe-flash pulsates, the capillary-jet in the CDSD under the strobe-flash is captured in the high-speed camera through the microscope.

The strobe-flash duration is 180 ns once in every rotation. In our system, this short flash duration enables videography with finer than 2 μm resolution at 2000 rpm centrifugation. A liquid tank is connected to the capillary in the CDSD to calculate flow rate of the capillary jet by measuring the change of the liquid volume. The resolution could be improved by using a strobe-scope with short strobe-flash duration.

VIDEOGRAPHY

Using the observational setup, we successfully captured two distinct processes of droplet formation from a capillary in the CDSD, jetting and dripping. In the jetting regime (Fig. 2a), the liquid is ejected from the capillary in a form of fluid pipe which eventually breaks up into a droplet stream. The mechanics of the break-up is explained by Plateau-Reyleigh instability [5,6]. On the other hand, in the dripping regime (Fig. 2b), a drop is formed at the capillary orifice and detached when centrifugal force surpasses surface tension force exerted on the drop. Through the videography, we confirmed high liquid flow rate tends to cause jetting. This phenomenon corresponds to the well-known capillary jet behavior that jetting occurs when inertia is dominating in a liquid jet, while it turns dripping when the flow rate decreases and surface tension becomes dominating. In our system, liquid flow rate is dependent on centrifugal gravity. Thus, a precision control of centrifugal rotational speed could provide tunability of the two flow regimes since high rotational speed produces a large centrifugal force exerted in a fluid in a capillary which generates high flow rate of the capillary jet.

At the same centrifugal rotational speed, a liquid jet with high viscosity tends to undertake dripping since the flow rate is slow. From the capillary with 100 μm diameter orifice, 3% (w/w) sodium alginate solution takes dripping form at all rage of rotational speed (0 – 670 rpm).

PARTICLE FABRICATION

To evaluate the difference in size of particles obtained from droplets in jetting regime and that of dripping regime, we fabricated particles by solidifying droplets of 2.0% (w/w) sodium alginate solutions in a $CaCl_2$ solution ejected from capillaries with various orifice diameters in the CDSD. In this experiment, we observed jetting in all the trials. As Fig. 3 shows, the capillary orifice diameter is linearly correlated to particle diameter. This linear correlation corresponds to the well-known mechanics of liquid jet breaking up into droplets [6]. Compared with dripping regime in which capillary nozzle diameter is linearly correlated to the cubic root of droplet diameter [4], capillary jet

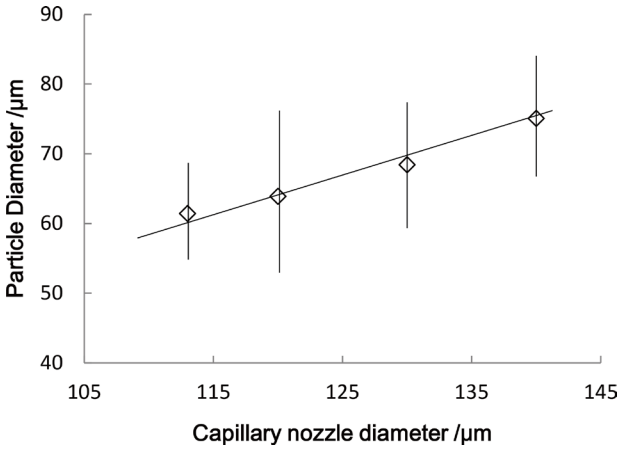

Figure 3: Correlation between capillary nozzle diameter and particle diameter when using a 2.0% (w/w) sodium alginate solution.

produces smaller droplets under the same centrifugal gravity. The flow rate of capillary jet did not influence on the particle diameter. Thus, the control of jetting regime by changing centrifugal gravity could enable flexible control on the droplets diameter.

CONCLUSION

In conclusion, we successfully observed droplet formation processes from a capillary-jet in the CDSD using a triggered strobe-flash system, and analyzed dripping and jetting regimes of the capillary jet and the size of microparticles from droplets obtained in the jetting regime. We confirmed the liquid jet in the CDSD follows established theories of fluid mechanics, and particle size can be flexibly controlled by using the jetting regime. With these versatilities, the CDSD could be a useful tool to deepen understanding of behavior of a micro liquid jet formed under ultrahigh-gravity, and provide further applications related to fabrication of micro polymeric structures.

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