Active control on droplet generation in axisymmetric flow focusing

Kai Mu[1,*], Ting Si[1], Hang Ding[1]

[1]Department of Modern Mechanics, University of Science and Technology of China, Hefei, China

*corresponding author: mukai@ustc.edu.cn

Abstract Droplet-based microfluidics is of great significance in scientific and industrial fields, and offers promising advantages in a variety of applications such as pharmacy, chemistry, biomedical and other subjects. Up to now, the most commonly used microfluidic devices are the two-dimensional PDMS micro-channels and the glass micro-capillaries, in which the liquid viscosity and the interfacial tension often play a crucial role in generating droplets at microscales as the Reynolds (*Re*) and the Weber (*We*) number are usually much smaller than unity. In our group, we have developed a liquid-driven flow focusing (LFF) method to produce monodisperse micro-droplets or micro-capsules, where the fluid interfaces can be stretched into thin jets down to micrometric scale by the high speed outmost driven fluid, and the jets finally break up into droplets in an open space with inertia dominated regimes (with *We* larger than 1). There are two typical flow modes exist in LFF: jetting and dripping mode. In jetting mode, a long jet forms downstream the focusing orifice and breaks up due to interface instabilities, while in dripping mode, the droplets are generated right at the exit of the orifice. However, due to the uncertainty of jet breakup, uniform droplets are hardly formed in the jetting regimes. Besides, satellite droplets often exist because of the nonlinear effects of the perturbations. Moreover, even in the dripping mode, which usually provides a better monodispersity than the jetting mode, the droplet uniformity can be destroyed by the nonlinear breakup dynamics. Thus, it is desirable to provide manipulation of on-demand droplet generation to achieve highly ordered breakup of liquid interface in flow focusing. This work focuses on the active control of interface breakup by experiments and numerical simulations. An experimental platform is developed to form the cone-jet configuration in LFF system and record the breakup of liquid interface. In brief, one syringe pump is used to supply the focused liquid (density ρ_1, dynamic viscosity μ_1, flow rate Q_1 and averaged inlet velocity U_1) into a stainless steel needle, and the other syringe pump is used to inject the focusing liquid (density ρ_2, dynamic viscosity μ_2, flow rate Q_2 and averaged inlet velocity U_2) into the chamber. The interface tension of the double liquids is denoted by σ. The flow is monitored by a CCD camera equipped with a microscopic lens under the illumination of a strobe flashlight (flashing frequency 3 kHz) from the other side of the chamber. For convenience, transparent PMMA plates are used to manufacture the LFF chamber. In numerical simulations, the Navier-Stokes equations are solved coupling with a diffuse interface method, where the interface is represented by the volume fraction of the liquid, *C*, and its time evolution is governed by the convective Cahn-Hilliard equation. After carefully validated with experiments, the numerical results are further utilized to quantitatively explore the flow characteristics and physical mechanisms. Through applying external perturbations on the liquid jet downstream the focusing orifice, the breakup dynamics in jetting mode is investigated. In numerical simulations, as the focused phase is singly actuated, four typical breakup regimes are observed when the frequency *f* and amplitude *A* changes, and the corresponding phase-diagram of jet breakup in the *f-A* plane is drawn combined with experiments. It is found that the size of the uniform droplets can be obtained and manipulated by adjusting *f* and *A*. In particular, the jet breakup has the same frequency as the external perturbations when uniform droplets can be generated. It is observed that there exists a cut-off frequency beyond which the perturbation cannot control the jet breakup, even with very large *A*. This is found to be associated with the critical condition for the onset of the Rayleigh-Plateau instability, i.e., the unstable perturbation wavelength must be larger than the perimeter of the jet. In addition, it is found that the reservoir effect of the cone in the FF effectively reduces the influence of the perturbation on the liquid supply to the liquid jet, accounting for the presence of jetting at large *A*. Moreover, we apply the perturbations either singly to the focusing phase or simultaneously to the focused and focusing phases and assess their effects on the jet breakup, which shows that the addition of perturbations on the focusing phase can promote the instability of the cone-jet flow. Apart from the jetting regime, the droplet generations under the dripping mode are also studied. Typical dripping patterns and their transitions are obtained by adjusting the flow rates of focused and focusing phases. Particularly, the liquid cone can be either stable or unstable, and an unstable cone may lead to the aperiodic nonlinear dripping within some parameter ranges. Taking advantage of the numerical simulations, the effect of liquid viscosity and interface tension on the nonlinear dripping patterns is further investigated, which shows that either an increase of viscosity or a decrease of interface tension can suppress the nonlinear patterns effectively. In order to control and regulate the dripping mode, a geometrical method with adding a guiding rod along the

symmetry axis of the capillary tube is proposed. It is found that through increasing the length or the width of the guiding rod, the nonlinear patterns can be avoided, and the droplet size and productivity can be manipulated actively. Discussions are performed to explain the mechanisms of nonlinear dripping, which shows that the nonlinear patterns are mainly attributed to the inertia of liquid cone interface. In summary, this fundamental research on droplet generation either at jetting or dripping regimes provides a guidance on producing microdroplets with high monodispersity, and has great potential in various applications including biomedical, pharmaceutical, chemical and some other fields.

Keywords: flow focusing, droplet generation, jetting, dripping, active control