Drop formation: Methods and applications

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From rain drops to very tiny, pico-liter sized drops produced in an ink-jet printer, drop formation is seen in a wide range of occurrences—both natural and man-made. A variety of modern applications employ drop formation to achieve different purposes. For example, small drops are created to coat a thin layer of paint on a surface in spray-painting and to form tiny pools containing reagents such as DNA in lab-on-a-chip type applications. Depending upon the final requirement, drops of different volumes and compositions are produced in these applications. Here, a short list of different methods available to make drops and their applications is included. (For a detailed review, see Basaran (2002).) In particular, techniques that are used to produce small, micron-sized (in diameter) drops are elaborated.

Drop formation through jet breakup

One can see a jet of water coming out of, say, a kitchen faucet just by turning on the tap. The water jet so formed breaks up into drops due to surface tension. Whereas there exists no external field in this example other than the passive ambient air, an applied electric field or an externally flowing fluid can also be employed to cause jet break up into drops. Figure 1 shows schematics of two such methods employed to produce drops. An externally applied electric field causes the interface of the liquid coming out of a nozzle to become conical in shape. This is called a Taylor cone (Taylor 1964). A small jet (called cone-jet) is issued from the tip of the Taylor cone, which eventually breaks into drops due to the action of surface tension (see Fig. 1 (a) for illustration). The entire process is known as electrohydrodynamic (EHD) tip streaming (Collins et al. 2007) and is used in, among other applications, electrospray mass spectroscopy (Cooks et al. 2006).

An external flow can also be used to cause jet breakup. The commonest apparatus used to

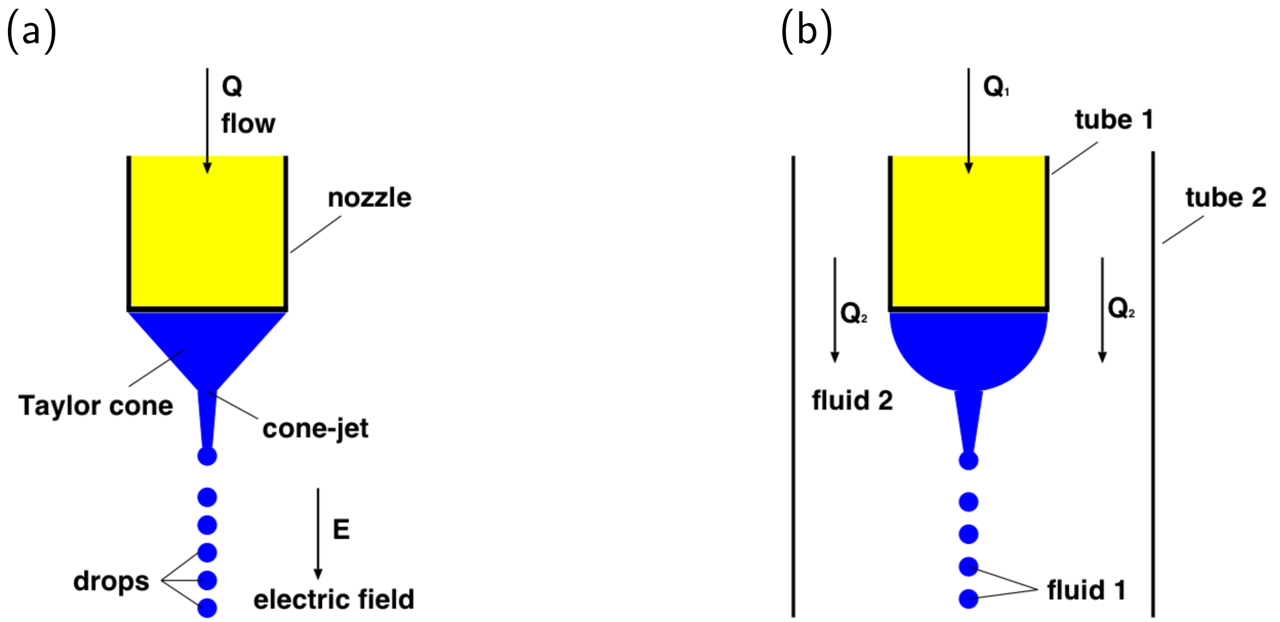

Figure 1: Production of drops through (a) electrohydrodynamic (EHD) tip streaming and (b) flow-focusing.

achieve this purpose is illustrated in Fig. 1 (b). In this apparatus, two fluids are made to flow in concentric tubes, each in separate tubes. Unlike an electric field, here, flow of the external fluid causes tip-streaming in the interior fluid. Basaran and Suryo (2007) have recently published a perspective on the employment of this method to produce really small jets, and Barrero and Loscertales (2007) have recently reviewed this and other methods to produce micro- and nano-particles. The apparatus depicted in Fig. 1 (b) can be cleverly modified to encapsulate the inner fluid inside the outer fluid.

Drop layering

In the methods described so far, jets of fluids are issued out of a nozzle to produce drops. If an application requires drops to be layered on a surface, then layers of such sessile drops can also be created using what is known as the "pin-tool" technique. As illustrated in Fig. 2, in a pin-tool method, a rod (pin) whose tip contains a small amount of the liquid is first brought in contact with the substrate forming a liquid bridge between the rod and the substrate. It is then

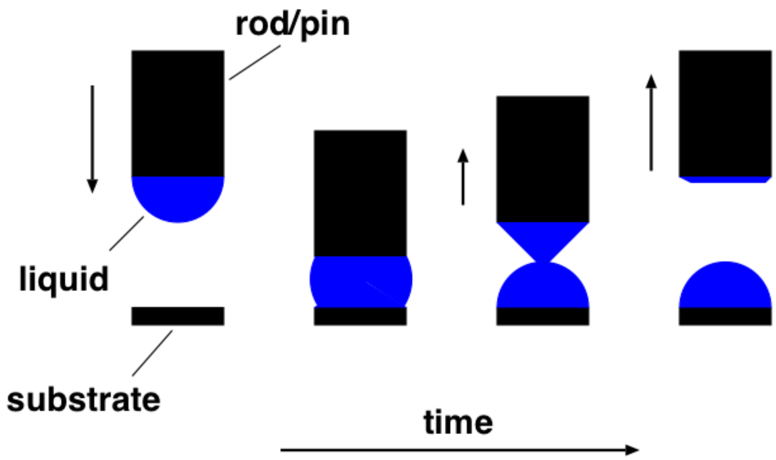

Figure 2: Layering of drops using the "pin-tool" technique.

pulled away from the substrate. During this process, the liquid bridge is stretched until it snaps and leaves behind a free drop still attached to the substrate. Such a technique is commonly employed in DNA microarraying.

Drop-on-demand

The breakup of jets of fluids results in drops being produced continuously as explained in the earlier sections. In applications such as ink-jet printing, producing drops only when required, i.e., making *drops on demand*, can be advantageous. Such a dispensing technique is known as the drop-on-demand (DOD) technique. Figure 3 shows schematics of two such DOD dispensing methods. In the first method, as shown in Fig. 3 (a), the tip of a capillary tube, which is typically made of glass, is surrounded by a sleeve made of a piezoelectric material. The liquid in the tube is squeezed out of the capillary through the mechanical action of the sleeve which is made to deform by the application of an voltage pulse. Unlike mechanical action used in this method, the second method employs heat pulses to create bubbles which then pushes the liquid out of the nozzle as illustrated in Fig. 3 (b). Apart from ink-jet printing, drop-on-demand method is being exploited increasingly in several emerging applications such as creation of three-dimensional biological structures (Calvert 2007) that are helpful in the study of artificial

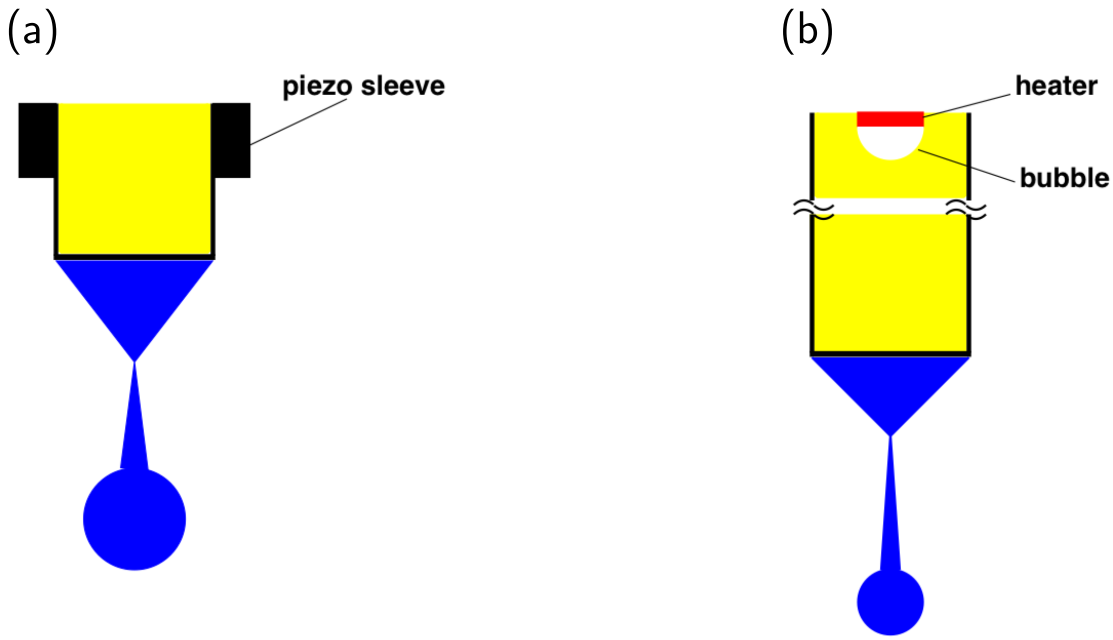

Figure 3: Drop-on-demand dispensing techniques: (a) piezo actuated and (b) heat-pulse actuated.

organs and fabrication of all-polymer transistors (Sirringhaus et al. 2000) and solar cells (Hoth et al. 2007, Hoth et al. 2008).

Bibliography

Barrero, A. and Loscertales, I. G. 2007 Micro- and nanoparticles via capillary flows. *Annu. Rev. Fluid Mech.* **39** 89–106.

Basaran, O. A. 2002 Small-scale free surface flows with breakup: Drop formation and emerging applications. *AIChE J.* **48** 1842–1848.

Basaran, O. A. and Suryo, R. 2007 The invisible jet. *Nat. Phys.* **3** 679–680.

Calvert, P. 2007 Printing cells. *Science* **318** 208–209.

Collins, R. T., Harris, M. T. and Basaran, O. A. 2007 Breakup of electrified jets. *J. Fluid Mech.* **588** 75–129.

Cooks, R. G., Ouyang, Z., Takats, Z. and Wiseman, J. M. 2006 Ambient mass spectrometry. *Science* **311** 1566–1570.

Hoth, C. N., Choulis, S. A., Schilinsky, P. and J., B. C. 2007 High photovoltaic performance of inkjet printed polymer:fullerene blends. *Adv. Mater.* **19** 3973–3978.

Hoth, C. N., Schilinsky, P., Choulis, S. A. and J., B. C. 2008 Printing highly efficient organic solar cells. *Nano Lett.* **8** 2806–2813.

Sirringhaus, H., Kawase, T., Friend, R. H., Shimoda, T., Inbasekaran, M., Wu, W. and Woo, E. P. 2000 High-resolution inkjet printing of all-polymer transistor circuits. *Science* **290** 2123–2126.

Taylor, G. I. 1964 Disintegration of water drops in an electric field. *Proc. R. Soc. London Ser. A* **280** 383–397.