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REVIEW PAPER

Microdroplet generation in gaseous and liquid environments

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Abstract As trends in biology, chemistry, medicine and manufacturing have pushed macroscopic processes onto the micro scale, droplet generation has been a key factor in allowing these methods to translate. For both surface-based liquid-in-gas generation and lab-on-a-chip-based liquid-in-liquid generation, the ability to create small monodisperse liquid droplets is critically important in constructing reliable and practical devices. This article reviews liquid microdroplet generation in gaseous and liquid environments, covering the general characteristics of generators and the specific methods and technologies used for generation. Furthermore, this study compiles the issues encountered when operating generators, and the measurements and instrumentation used to characterize generated droplets. Applications of droplet generation in printing, analysis, synthesis and manufacturing are also discussed.

1 Introduction

1.1 Background

Since the end of the nineteenth century, scientists have studied the ways in which droplets are formed by the manipulation of liquid. Lord Rayleigh pioneered this study by computationally modeling the breakup of a fluid jet into a continuous stream (CS) of droplets (Rayleigh 1878). Based on this and subsequent theoretical research, in 1948, Siemens-Elema patented the first practical continuous stream inkjet device with an actuator capable of changing the direction of the jet flow based on a measured or generated input signal (Elmqvist 1951). In the 1960s, Dr. Richard Sweet of Stanford University developed pressure-based CS droplet generation, where pressure wave patterns are focused into an orifice, causing the continuous stream to predictably and uniformly break up (Sweet 1965). In the 1970s, IBM utilized Dr. Sweet's work to develop commercial printers (Buehner et al. 1977).

In the late 1970s, scientists also began developing drop-on-demand (DoD) droplet generation as an additional commercial printing technology. Clevite (Zoltan 1972) and Silonics (Kyser and Sears 1976) initially developed piezoelectric droplet generators, devices that utilize a piezoceramic element to convert an electrical signal into a physical displacement that is used to create a droplet. Later, Canon (Endo et al. 1979) and Hewlett-Packard (Vaught et al. 1984) independently developed thermal bubble droplet generation (Canon "bubble jet", HP "ThinkJet"), where a bubble of rapidly evaporated ink forces droplet formation at an orifice in the generator (Le 1998; Brünahl and Grishin 2002).

1.2 Motivation

The primary motivation of this work is to integrate and compare the previously separate fields of liquid-in-gas and liquid-in-liquid droplet generation. While these two subjects share the same fundamental tenant of encapsulating a finite volume of liquid in a fluid medium, little has been done to relate the two fields to one another. By addressing the theories, problems and technologies in each of these fields in parallel with the other, there is hope there may be synergies between the two.

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More generally, work in droplet generation (and in turn, microfluidics) aims to miniaturize biological, chemical, medical and industrial processes to increase their efficiency and efficacy. In diagnostic and analytical applications, where the amount of sample is limited by cost or availability, a wider variety of tests can be performed on smaller sample volumes by breaking down those samples into microdroplets using a droplet generator. In synthetic and reaction-based applications, by reducing the reaction vessel size to a microdroplet, the kinetics of the reaction occur on a much shorter time scale. In micromanufacturing applications, waste during manufacturing can be reduced or eliminated by replacing traditional material-removal processes with material-additive processes. Furthermore, excess toxic reagents used in various processes will no longer exist to be disposed of.

Additional and more specific justification for the development and improvement of droplet generation technologies are found in Sect. 6.

1.3 Report overview

Section 2 introduces the fundamental concepts of characterizing droplet generators by the general properties of most generators. Section 3 describes the techniques and technologies associated with droplet generation. Section 4 moves onto the issues associated with the operation of these devices and manipulating the droplets generated. Section 5 describes the characteristics of droplets after generation and outlines the instrumentation used to measure those characteristics. Section 6 outlines the various applications of droplet generators in use and in development. Section 7 presents conclusions drawn from the review and potential areas for future development.

2 Characterization of droplet generation

To aid in the analysis of droplet generating technology, the basic properties and categories of droplet generators are presented.

2.1 Fluid environment

Depending on the application, droplets can be generated in either a gas or liquid environment.

2.1.1 Gas

In a gaseous environment, the relative viscosity of the droplet liquid and surrounding gas (generally air[1]) is relatively high. Furthermore, droplets generated in air are usually deposited on a solid support for further use there.

2.1.2 Liquid

In a liquid environment, the relative viscosity between the droplet and the surrounding liquid (carrier fluid) is relatively small. For these types of generators, droplets generated in an immiscible carrier fluid are used in various microfluidic applications.

2.2 Droplet dispensing mode

A droplet generator can operate in either one of two dispensing modes: CS or DoD (Fan et al. 2008; Castrejón-Pita et al. 2008; Cooley et al. 2001; Le 1998).

2.2.1 Continuous stream

Also known as an overpressure generator, a CS droplet generator utilizes the inherent instability in a narrow jet (generally 50–80 μm in diameter) to form a continuous line of droplets downstream of the jet orifice. This instability—also known as Rayleigh breakup, due to Lord Rayleigh publishing his initial investigation into the subject in 1878 (Rayleigh 1878)—is exploited by imparting a parasitic frequency on the jet, causing it to decompose into monodisperse droplets of predictable size (Cooley et al. 2001). The diameter range for droplets generated in CS droplet generators is 50–300 μm (Ulmke et al. 2001).

2.2.2 Drop-on-demand

Also known as a non-pressure generator, a DoD droplet generator generates a single or finite quantity of droplets in response to an external stimulus. Droplets generated in this manner are generally 10–100 μm in diameter (Ulmke et al. 2001).

A function-driven DoD droplet generator is one where an input waveform of specified frequency and amplitude controls the operation of the generator. A burst-type DoD droplet generator, shown in Fig. 1 is a function-driven generator where the driving signal of the generator is created using two function generators at different frequencies,

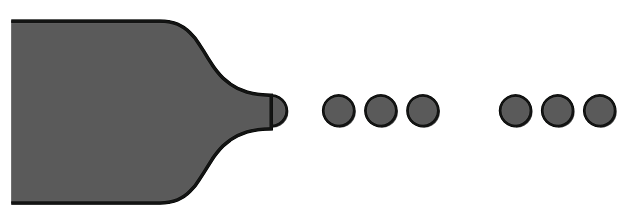

Fig. 1 Burst-type generator operation

[1] In this review, air will be the assumed gas in liquid-in-gas generators unless otherwise noted.

forming "bursts" of droplets with short separation(s) between the droplets within a single burst and longer separations between bursts (Switzer 1991).

2.2.3 DoD-to-CS transition

The transition of a droplet generator between DoD and CS droplet generation has been studied and quantified. Meacham et al. described the transition between no ejection, DoD ejection and CS ejection in terms of characteristic time scales for the ejection process, inertial forces, capillary action and viscous forces (Meacham et al. 2005). This transition is important because devices have been designed with the capability of operating in both modes, depending on how the device is driven (Perçin and Khuri-Yaku 2002).

2.3 Liquid transfer mode

For liquid-in-air deposition of droplets on a solid support, droplets can be generated by the device contacting the surface or not.

2.3.1 Contact

For contact droplet generation, the generated droplet touches the generator's tip and solid support surface simultaneously during formation, as shown in Fig. 2. Contact printing can be facilitated by actuation or performed simply by viscous and surface tension forces (Piracci 2000).

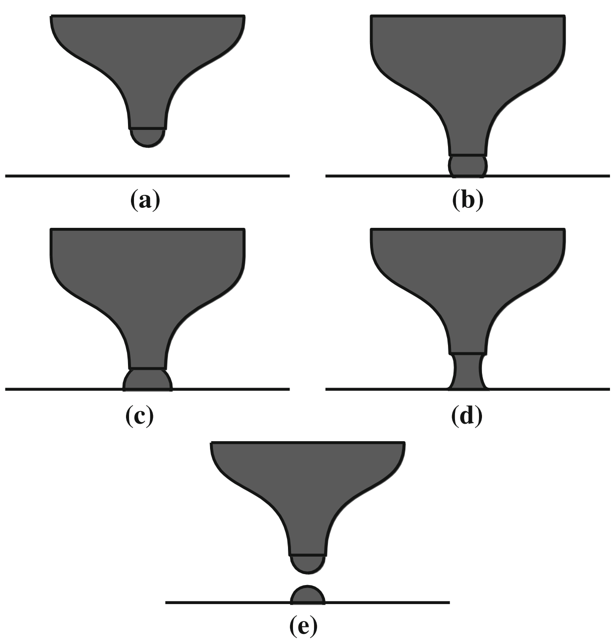

Fig. 2 Contact droplet generation process. **a** Generator approaches surface. **b** Droplet connects generator and surface. (**c**, optional) Actuation deposits additional liquid on the surface. **d** Generator recedes from surface; liquid connection begins to neck. **e** Liquid connection shears; droplet forms on surface

In contact droplet dispensing, properties of the dispensing surface become factors affecting droplet generation. Furthermore, the possibility of contamination of the dispensing head is increased because of this contact with another material (Cooley et al. 2001).

Contact droplet generators must also be able to move the device tip relative to the surface in three dimensions to print multiple drops: along the x- and y-axes to change the droplet location and along the z-axis to form the droplet on the surface.

2.3.2 Non-contact

For non-contact droplet generation, droplet generators induce momentum in a liquid to overcome viscous and surface forces and cause a droplet to break free. This momentum can be provided to the liquid by the actuators described in Sect. 3.

Because the droplet is generated before reaching a surface, that surface's properties are not relevant to the droplet generation process, simplifying the design of a non-contact droplet generator compared to a contact droplet generator.

Furthermore, most non-contact droplet generators only need to move in two dimensions (along the x- and y-axes) because of the relative unimportance of the distance between the generating head and solid support. This reduction and simplification of "tip" movement compared to contact dispensing allows for faster printing of multiple droplets across a surface.

2.4 Liquid supply mode

The droplet liquid can be supplied to the generator in one of three ways: aspiration, flowing into the generator or flowing through the generator.

2.4.1 Aspiration

In aspiration-supplied droplet generation, the generator moves to a droplet liquid source to refill, as shown in Fig. 3. Once situated with the generator tip in the liquid,

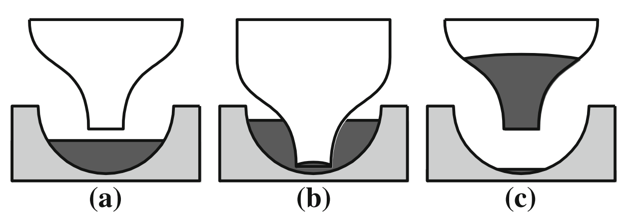

Fig. 3 Aspiration-type liquid supply. **a** Generator approaches liquid source. **b** Generator immerses in liquid source. **c** Generator pulls in liquid and recedes from source

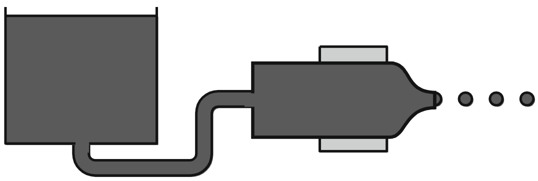

Fig. 4 Flow-in-type liquid supply

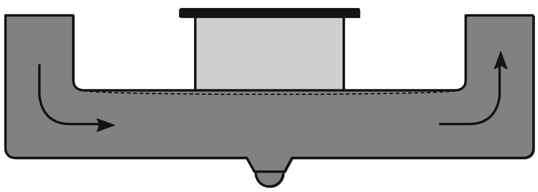

Fig. 5 Flow-through-type liquid supply

bulk actuation, e.g. a lead screw (Ben-Tzvi et al. 2007) or syringe pump (Takahashi et al. 2002), pulls the liquid into the generator.

2.4.2 *Flow-in*

In flow-in-supplied droplet generation, a droplet liquid reservoir directly supplies liquid to the generator, seen in Fig. 4. As droplets are ejected by the generator, additional liquid will flow in at a prescribed rate and pressure. A common method of controlling that rate and pressure is by varying the reservoir height relative to the generator. As droplets are generated and the reservoir liquid amount decreases, the reservoir height relative to the droplet generator increases, maintaining constant pressure (Fan et al. 2008; Castrejón-Pita et al. 2008).

2.4.3 *Flow-through*

In flow-through droplet generation, shown in Fig. 5, droplets are generated by ejecting liquid from a flow through the droplet generator. This capability allows for samples to be taken of flowing systems in real time as a process (e.g. liquid chromatography or a chemical reaction) takes place without significantly disrupting the flow (Laurell et al. 1999; Miliotis et al. 2000).

3 Methods and technologies of droplet generation

In this section, a survey of droplet generators is presented. Current techniques are categorized by the medium in which the droplets are generated (gas or liquid) and the general formation principal (e.g. actuation type).

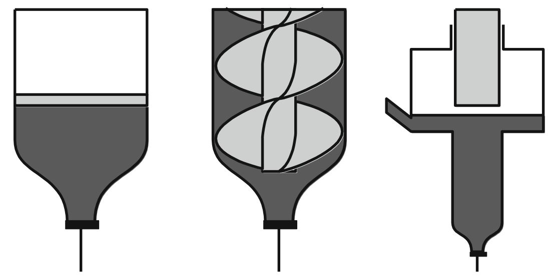

Fig. 6 Types of contact droplet generators. **a** Time/pressure dispenser. **b** Auger pump dispenser. **c** True positive displacement pump dispenser

3.1 Liquid-in-gas droplet generation

3.1.1 *Contact*

For contact dispensing, two types of dispensing exist: direct contact dispensing and actuated contact dispensing. In direct contact dispensing, a droplet is generated by a "spotter" (a solid pin, capillary tube, tweezers, split pin or microspotting pin) depositing a liquid volume onto a solid support surface. This volume is obtained by dipping the spotter in a sample and the spotter retaining a small sample volume on its tip (Rose 1999).

The transfer is governed by the physical properties of the spotter, fluid and surface; no external impetus causes the droplet to form. However, the droplet size can be controlled (to an extent) by the spotter's and deposition surface's material, geometry and surface quality. However, due to liquid pick-up variations, spot-to-spot variation can be anywhere from 10–25% CV.[2] Advantages of direct contact dispensing include its simplicity, low cost and capability of producing densely packed arrays. Disadvantages include its deposited volume variability and dependence on surface conditions.

For actuated contact dispensing, an external force is used to form a droplet of a specific size on a surface. Three types of actuated dispensing are illustrated in Fig. 6: time/pressure dispensing, auger pump dispensing and true positive displacement pump (TPDP) dispensing (Piracci 2000).

Time/pressure dispensing, also known as air/over dispensing, uses pressurized air controlled by a needle valve to dispense droplets onto a surface. In addition to the geometric and surface properties, the magnitude(s) and length(s) over which pressure is applied influence the final droplet size (Zhao et al. 2005).

Advantages of time/pressure dispensing include its low cost, droplet liquid flexibility and operational flexibility.

[2] Coefficient of variation (CV): ratio of the standard deviation to the mean.

The components of a standard time/pressure droplet generator are relatively inexpensive, with some low cost syringes practically disposable after use. This disposability allows dispensing of a wider variety of droplet liquids because cleaning or maintaining the syringe after use is not a concern. Operationally, time/pressure dispensing is flexible because a variety of planar patterns and droplet sizes can be created by modifying operational parameters instead of hard tooling (Nguon and Jouaneh 2004).

Disadvantages of time/pressure dispensing include their extreme sensitivity to temperature change (depending on the droplet liquid) and syringe depletion. When using temperature sensitive liquids, a slight change in temperature can significantly change the liquid viscosity, changing subsequent droplet generations. These changes can be caused by ambient temperature change and/or internal heat generation due to rapid pulsed air applications. Syringe depletion refers to how the volume of air in a syringe will increase as liquid is dispensed from the syringe. As the air volume increases, it will compress more easily, absorb more actuation energy and transmit less energy to the fluid, lessening droplet size or preventing formation. To compensate, the magnitude or duration of the pressure pulse must increase (Dixon 2004).

Auger pump dispensing uses an auger screw, controlled by a motor, to force material through the thread and out the needle tip onto the surface. The screw's turning duration is the primary factor that controls the size of the dot, with highly accurate and consistent dots a result of this technique (Piracci 2000).

True positive displacement pump dispensing uses a piston to seal off a dispensing chamber from the reservoir and force the liquid from that dispensing chamber out the needle tip onto the surface. When the piston is retracted, liquid flows back into the dispensing chamber from the reservoir. As opposed to time/pressure displacement, the volume dispensed by a TPDP droplet generator is fixed by the geometry of the piston, making it relatively immune to changes in viscosity. The piston can be actuated by an electric motor or a solenoid valve and compressed air (Nguon and Jouaneh 2004).

Advantages of TPDP dispensing include its droplet volume independence from temperature, pressure and viscosity changes and its high repeatability and accuracy. A disadvantage of TPDP dispensing is its high cost (Piracci 2000).

3.1.2 *Piezoelectrically actuated*

In piezoelectric droplet generators, piezoelectric material is incorporated into a droplet generator to convert an electric potential difference into a physical displacement, which directly or indirectly generates a droplet. Piezoelectrically actuated droplet generators can either be CS, direct DoD or indirect DoD.

In CS piezoelectric droplet generators, the piezo is used to physically impart a frequency disturbance on the ejected liquid jet to create droplets via the Rayleigh instability (as discussed in Sect. 2). The piezo is driven to expand and contract at the desired disturbance frequency, but the type of vibration used can vary.

One type utilized is longitudinal vibration, where the piezoceramic elements are vibrated along the same axis as the liquid jet. Another type is torsional vibration, where the piezo elements are vibrated about the liquid jet axis (Kanda et al. 2007; Harada et al. 2008).

In direct DoD droplet generators, droplet generators are characterized by how the piezoelectric element deforms during operation. There are four modes of piezo deformation: push, squeeze, bend and shear.

For push-mode piezoelectric actuation, depicted in Fig. 7a, the direct linear displacement of a piezoceramic element generates a droplet. This displacement can cause a diaphragm (Kim and Park 2008; Steger et al. 2002), tripod (Bergkvist et al. 2005) or piston (Ben-Tzvi et al. 2007) to change the volume in a chamber or capillary, generate pressure waves and eject a droplet from an orifice.

For squeeze-mode piezoelectric actuation, depicted in Fig. 7b, a piezoceramic element is designed to fit around a capillary tube and squeeze it, causing a volumetric change in the tube, forcing out a droplet. In forming a droplet, squeeze-mode actuators utilize various waveforms to control the capillary's pressure distribution, including sawtooth (Takahashi et al. 2002) and rectangular (Wu et al. 2005).

For bend-mode piezoelectric actuation, depicted in Fig. 7c, a piezoceramic element is forced to bend during deformation due to the constraints of the piezo in an assembly. This bending is then applied to a fluid (generally through a thin diaphragm) to generate pressure waves,

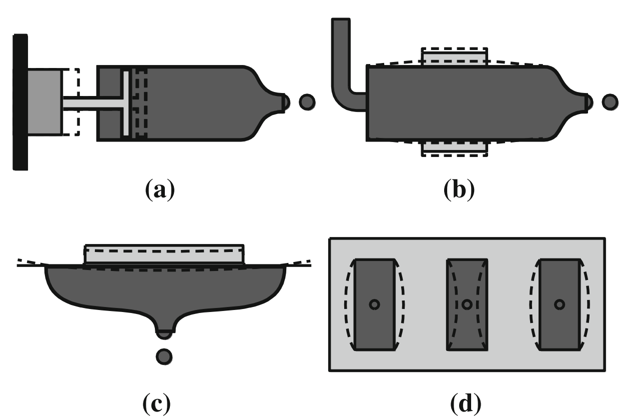

Fig. 7 Types of direct DoD piezoelectric generators. **a** Push-mode. **b** Squeeze-mode. **c** Bend-mode. **d** Shear-mode

generating a droplet. Bend-mode piezoelectric elements in droplet generators can be rectangular (Laurell et al. 1999) or circular (Fan et al. 2008).

For shear-mode piezoelectric actuation, depicted in Fig. 7d, piezoceramic elements are mounted on micro-channel walls and force the walls to deform. As the walls deform, droplets are ejected based on the driving waveform (Brünahl and Grishin 2002).

These deformation modes are caused by the polarization of the piezoceramic element and how the electric voltage is applied relative to the polarization. Push-, bend- and shear-mode actuators all have linear polarization, but push- and bend mode actuators apply voltage parallel to the polarization and shear-mode actuators apply voltage perpendicular to the polarization. Squeeze-mode actuators have radial polarization, and the voltage is applied along the radius (Le 1998; Brünahl and Grishin 2002).

For indirect DoD droplet generators, a piezoceramic element vibrates at ultrasonic frequencies, where the cumulative action of the device's vibration—as opposed to a single actuation—causes droplet formation. Different types of vibration can be utilized to generate droplets, including: reservoir vibration (Meacham et al. 2005; Demirci et al. 2005), capillary vibration (Lee and Lal 2004) and needle vibration (Tan et al. 2008).

Piezoceramic vibrators can also be designed (with or without a lens) to focus vibration to generate droplets without a nozzle. The acoustic waves' constructive interference in the liquid generates sufficient momentum to overcome viscous forces and surface tension (Huang and Kim 2001).

Hybrid CS/DoD droplet generators can be designed to behave as both generator types, depending on their operation. In essence, two types of actuation are needed for a hybrid device: bulk actuation and finite actuation. In CS operation, the bulk actuation must be able to generate the constant pressure to eject a continuous jet of fluid for a specified period of time, and the finite actuation must be able to impart the desired frequency to the continuous jet and/or stop the continuous jet from flowing. In DoD operation, either of these two elements (or their actuation together) must be able to accurately generate the pressure required to overcome viscous and surface forces to eject a single droplet.

Perçin and Khuri-Yaku described such a device where two different piezo elements were used as the bulk and finite actuators: the bulk actuator was mounted above the reservoir of an array of nozzles, while the finite actuators were mounted on each individual nozzle. When acting as a CS droplet generator, the bulk piezo would actuate with enough displacement to eject fluid and the finite piezo will contract to temporarily stop flow at each nozzle. When acting as a DoD droplet generator, the bulk and finite actuators would need to actuate together to form a drop, providing control over which nozzle ejects droplets (Perçin and Khuri-Yaku 2002).

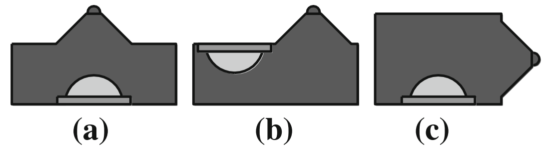

Fig. 8 Types of thermal bubble generators. **a** Roof-shooter. **b** Back-shooter. **c** Side-shooter

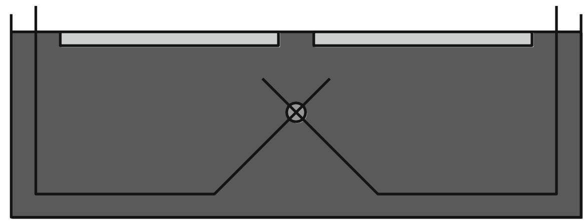

Fig. 9 Spark bubble generator set-up

3.1.3 *Thermally actuated*

In thermally actuated droplet generators, thermal energy is used to actuate droplet generation. Three types of thermally actuated droplet generation exist: thermal bubble, spark bubble and thermal bulking.

In thermal bubble droplet generators, a heater is used in a liquid chamber to rapidly and locally heat the liquid, causing a gas bubble to develop. As this bubble grows, it creates pressure waves in the liquid chamber, eventually ejecting a droplet from an orifice. Thermal bubble droplet generators are classified by the relative position of the heater and ejection nozzle, and direction of bubble growth. The three types of thermal bubble generators are roof-shooters, side-shooters and back-shooters.

In roof- and back-shooter generators, shown in Fig. 8a, b, the nozzle surfaces are parallel to the heaters; however, bubbles grow toward the nozzle in roof-shooters and away from the nozzle in back-shooters. In side-shooter generators, shown in Fig. 8c, the heater and bubble growth are perpendicular to the nozzle surface (Le 1998; Baek et al. 2004; Tseng et al. 2002a).

In spark bubble droplet generation, a spark- or laser-created bubble induces droplet formation through a hole in a solid surface separating the liquid and air interfaces, with the set-up shown in Fig. 9. When ignited, a bubble rapidly forms and creates pressure waves as it expands and contracts with diminishing magnitude. These pressure waves, depending on the geometries of the bubble location, plate and hole, may cause a jet to form and a bubble smaller than the plate aperture to break off (Dadvand et al. 2009).

In thermal bulking droplet generation, thermal energy is used to cause a portion of the droplet generator to bend, generating a droplet from the bending motion. This bending can be caused by the constraint of an expanding metal (Hirata et al. 1996) or the difference in thermal expansion coefficients of a bimetallic cantilever (Cabal et al. 2005).

3.1.4 Acoustically actuated

In acoustically actuated droplet generators, an audio speaker is used to actuate either DoD or CS droplet generation, with a typical set-up shown in Fig. 10. For DoD generation, a single pulse of sufficient duration and amplitude will eject a droplet with a suitable meniscus position. In CS generation, the speaker agitates the liquid jet at a desired frequency, causing Rayleigh breakup in the jet. However, an additional pressure transducer is necessary in each case to control the meniscus position in the nozzle (for DoD droplet generation) or to form the liquid jet (for CS droplet generation) (Castrejón-Pita et al. 2008).

3.1.5 Pneumatically actuated

In pneumatically actuated droplet generators, pressurized air actuates droplet generation. The pressurized air can be drawn from a reservoir (e.g. an air tank) or continuously generated (e.g. by a syringe). In both cases, a valve (typically solenoid) is used to separate the pressure source from the droplet generator. Two types of pneumatic droplet generators exist, classified by their liquid supply mode: aspirate-dispense and bulk-dispense (Rose 1999).

In aspirate-dispense droplet generation, shown in Fig. 11a, b, liquid is drawn into and ejected from the generator through a single channel. Though a simpler design, this type of droplet generator generally requires the use of a syringe as the pressure generator to control the inward and outward liquid flow (Rose 1999).

In bulk-dispense droplet generation, shown in Fig. 11c, d, separate channels are used to draw in and dispense liquid. This pneumatic droplet generator design is more common because the pressure source acts in a single direction through the device. Pneumatically actuated droplet generators have been designed where the pressurized air either directly controls the fluid (Amirzadeh Goghari and Chandra 2008; Koltay et al. 2002) or moves an intermediate piston in the droplet generator (Nguon and Jouaneh 2004).

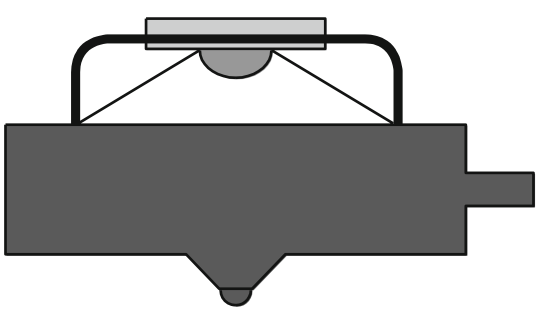

Fig. 10 Acoustically actuated generator

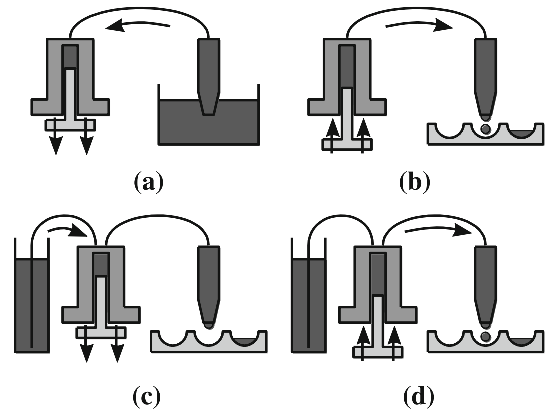

Fig. 11 Pneumatically actuated generation. **a** Aspirate-dispense mode, aspiration. **b** Aspirate-dispense mode, dispensing. **c** Bulk-dispense mode, aspiration. **d** Bulk-dispense mode, dispensing

3.1.6 Electrostatically actuated

In electrostatically actuated droplet generation, as seen in Fig. 12a, a generator is designed with a pressure plate as a liquid chamber wall and an electrode opposite the "free" surface of the plate. When a voltage is applied between the pressure plate and electrode, the pressure plate will bend toward the electrode (shown by the dotted lines), drawing liquid into the generator. When the voltage is removed, the pressure plate returns to its original position, forcing out a liquid droplet from the generator (Kamisuki et al. 1998, 2000).

3.1.7 Electrohydrodynamically actuated

In electrohydrodynamically actuated droplet generation, as seen in Fig. 12b, an electric field is applied to a liquid capillary to form a sharp cone at the site of the meniscus (original meniscus shape shown by a dotted line). By manipulating the strength of the electric field, droplets can be generated from

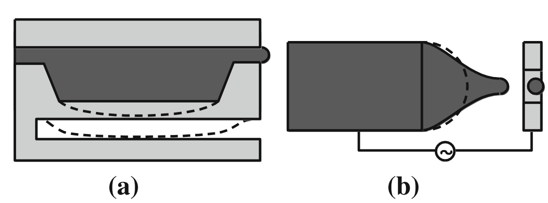

Fig. 12 Electo-actuated generators. **a** Electrostatically actuated generation. **b** Electrohydrodynamically actuated generation

the tip of the cone by overcoming the viscous and surface forces. Depending on the capillary geometry and the electric field's geometry and driving parameters, CS or DoD generation can occur (Lee 2003; Kim et al. 2006).

3.1.8 Droplet subdivision

In droplet subdivision-based droplet generation, a previously placed surface droplet is manipulated to divide into smaller droplets. Two types of subdividing droplet generators are textured plate vibration and liquid-dielectrophoresis (l-DEP).

In textured plate vibration droplet generation, smaller droplets pinch off from a larger droplet during excitation of a specific vibrational mode of the droplet. These pinched off droplets are prevented from returning to the original droplet by the surface texture of the plate; the surface is less rough surrounding the original droplet, making them less hydrophobic and a preferred location for the new droplet (s) (Erdem et al. 2008).

In l-DEP droplet generation, droplets are formed by the manipulation of a liquid "finger" drawn out from a droplet located on a pair of electrodes embedded in a solid surface. The finger is drawn out when an AC voltage is applied between the electrode pair. The electrodes also contain semispherical bumps at regular intervals. When the voltage between the electrodes is removed after drawing out the liquid finger, droplets will form on these bumps (Hosseini et al. 2008; Kanagasabapathi and Kaler 2007).

This process has also been shown to work iteratively, where a droplet drawn out by one l-DEP system is decomposed into smaller droplets on a second l-DEP system. To actuate the process, the electrodes A, B, C and D in Fig. 13 are charged in a series of specific configurations: first, electrodes A and C are connected together, as are electrodes B and D. A voltage applied over these two pairings will draw a liquid finger between the two, and when the voltage is removed, a droplet will form on the A/B/C/D "bump." Then, the previous electrode connections are removed and electrodes A and B are connected together, as are electrodes C and D. A voltage over these two connections will draw a finger out on the second path, and when the voltage is removed, a sequence of droplets will form on the bumps (Jones et al. 2001).

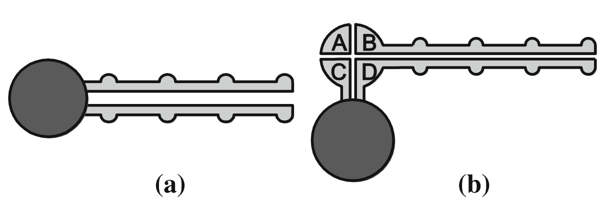

Fig. 13 Liquid-dielectrophoresis. **a** Single set-up. **b** Iterative set-up

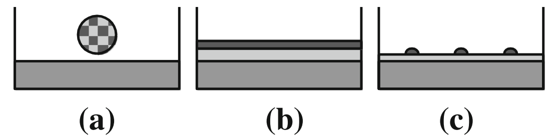

Fig. 14 Evaporation instability generation process. **a** Deposition of a two-phase liquid droplet onto a liquid (water) base. **b** Separation of the two fluid phases and evaporation of each. **c** Formation of droplets on the second liquid layer

3.1.9 Evaporation instability

In evaporation instability droplet generation, shown in Fig. 14, two layers of different solutions are made to sit atop one another, with the top fluid layer's solvent evaporating more rapidly than the bottom's. Once the top layer reaches a critical thickness (on the order of a few nanometers), it will decompose into droplets on the lower fluid layer (Govor et al. 2005).

3.1.10 Comparison of liquid-in-air actuation mechanisms

Droplet volume and generation cycle execution time are two critical parameters to consider when choosing an actuation mechanism to utilize in a droplet generator. Table 1 compares the minimum droplet diameters and actuation cycle times for liquid-in-air actuation mechanisms as presented in the literature surveyed.

3.2 Liquid-in-liquid droplet generation

3.2.1 Channel-geometry-driven

In channel-geometry-driven droplet generation, droplets are formed by the controlled flow of fluids in microchannels of specified geometries. By controlling the interface position and manipulating interfacial tension between two immiscible fluids via geometric and flow parameters, droplets can be formed. Among the types of channel-geometry-driven droplet generators are chambered microchannel, grooved microchannel, microchannel array and controlled fission.

In a chambered microchannel droplet generator, droplets are formed by breakup of a liquid stream in a chambered microchannel filled with a second, immiscible liquid, as shown in Fig. 15. Specifically, a channel is designed with a series of chambers and necks. The channel is filled with the carrier fluid, and a droplet fluid stream is run through the device, as seen in Fig. 15a. Once the channel length contains the stream, the flow stops and the carrier fluid breaks apart the droplet fluid stream at each neck. Droplet fluid recedes from the necks to the chambers, forming a single droplet in each chamber, shown in Fig. 15b (Wu et al. 2006).

Table 1 Comparison of minimum droplet size and actuation cycle times for selected liquid-in-air actuation mechanisms (Bergkvist et al. 2005; Wu et al. 2005; Laurell et al. 1999; Demirci et al. 2005; Lee and Lal 2004; Tan et al. 2008; Tseng et al. 2002b; Dadvand et al. 2009; Hirata et al. 1996; Castrejón-Pita et al. 2008; Amirzadeh Goghari and Chandra 2008; Kamisuki et al. 2000; Kim et al. 2006; Jones et al. 2001)

Actuation mechanism	Minmum droplet diameter (μm)[a]	Cycle time (s)	Actuation mechanism	Minmum droplet diameter (μm)[a]	Cycle time (s)
Piezo, push mode	35	0.000333	Thermal, Spark	1,500	0.0546
Piezo, squeeze mode	55	0.0000120	Thermal, Bulking	65	0.000555
Piezo, bend mode	90	0.000588	Acoustic	1,800	0.000300
Piezo, reservoir vibration	5	–	Pneumatic	110	0.00431
Piezo, capillary vibration	2.5	–	Electrostatic	21 ng[b]	0.0000555
Piezo, needle vibration	2,600	–	Electrohydrodynamic	22	0.120
Thermal, bubble	12	0.0000286	Subdivision, LDEP	225	0.250

[a] If generated droplets were not spherical, the diameter was found by approximating the volume as a sphere

[b] Density of ink used in experimentation was not provided in reference; mass of deposited droplet in nanograms (ng) provided instead

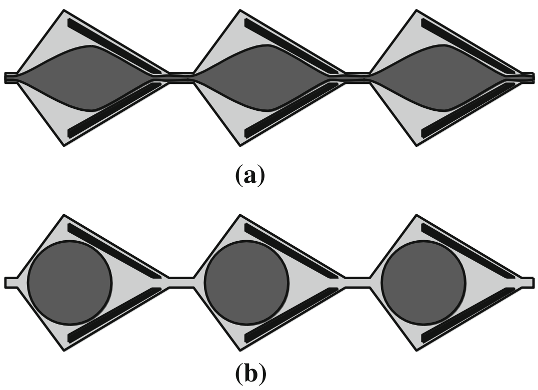

Fig. 15 Chambered microchannel generation process. **a** Fluid flows through the microchamber array and fills each chamber. **b** Once the flow stops, droplets will break apart and stabilize in each chamber

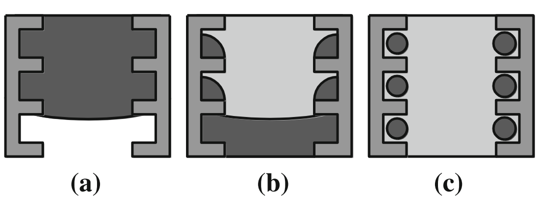

Fig. 16 Grooved microchannel generation process. **a** Droplet liquid flows through the generator. **b** Carrier liquid flows through the generator, trapping droplet liquid in the channel grooves. **c** Droplets form in each groove from the trapped liquid

In a grooved microchannel droplet generator, droplets are formed by trapping droplet liquid in the corners of grooves in a microchannel, as seen in Fig. 16. Specifically, grooves of specified pitch, height and width are designed into the two edges of a rectangular microchannel. The channel fills with droplet liquid, shown in Fig. 16a, and the carrier liquid flows in. As the interface between the two liquids passes each groove, all the droplet fluid except a small amount trapped in the downstream corner flows away, seen in Fig. 16b. Once the carrier liquid stops flowing, spherical droplets will form in each groove due to interfacial equilibrium, as illustrated in Fig. 16c (Kim et al. 2009).

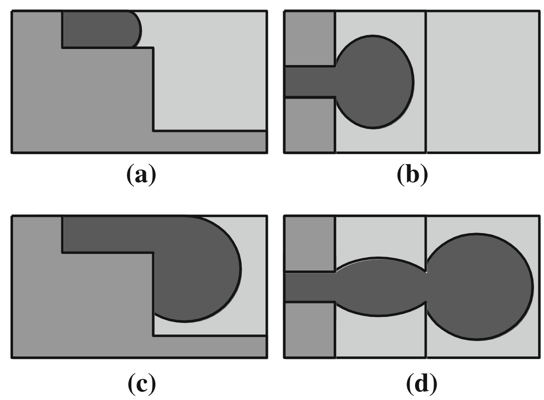

Fig. 17 Microchannel array generation process. **a** *Side view* during initial liquid flow onto the terrace. **b** *Top view* during initial liquid flow onto the terrace. **c** *Side view* during droplet formation in the well. **d** *Top view* during droplet formation in the well

In a microchannel array droplet generator, droplets are formed by the interfacial tension of the droplet fluid being pumped through an array of microchannels into the carrier fluid, as shown in Fig. 17. Specifically, a collection of microchannels is designed to separate a chamber filled with carrier fluid and a reservoir filled with droplet fluid. The microchannels "empty" onto a terrace that separates the microchannel exit from a drop off into the well. To begin droplet formation, the droplet fluid reservoir is pressurized to force droplet fluid through the microchannels. At the microchannel's mouth, a droplet will begin to form on the terrace and extend toward its edge, seen in Fig. 17a, b. Once the droplet reaches the terrace edge, it drains off and begins forming a new droplet on the well's wall, seen in Fig. 17c, d. Once the droplet reaches a critical size, it will break off and the remaining fluid will recede back onto the terrace, starting the process over again (Sugiura et al. 2001).

In controlled droplet fission droplet generation, a droplet splits into two smaller droplets, with the relative sizes of the droplets based on the geometry and lengths of the inlet and two outlet channels. The outlet channels can either be perpendicular (Link et al. 2004) or oblique (Tan et al. 2003) to the inlet channel, as seen in Fig. 18a, b, with that angle affecting the how the droplets break up.

3.2.2 Shear-flow-driven

In shear-flow-driven droplet generation, the shearing force of one flowing fluid against another is used to form droplets. Two main types of shear-flow-driven droplet generation exist: T-junction and flow focusing.

In T-junction droplet generation, as seen in Fig. 19a, fluid droplets are generated by the shearing of a droplet liquid flow by a carrier liquid flow at a channel intersection. Specifically, a channel containing the droplet liquid is designed to perpendicularly intersect a channel of flowing carrier liquid. To generate droplets, fluid flow is induced in the droplet liquid channel as liquid flows past in the carrier liquid channel. As the droplet flow enters the carrier flow, a droplet will form in the carrier flow due to the shearing of the droplet fluid by the carrier flow (Garstecki et al. 2006; Nisisako et al. 2002).

In flow focusing droplet generation, shown in Fig. 19b, a stream of liquid is sheared into droplets by a surrounding carrier liquid flow. Specifically, two carrier liquid flows are designed to surround a droplet liquid flow. As the three flows meet and move through an orifice, the carrier fluid flows force the droplet fluid flow into a narrow stream. This narrow stream will break up into droplets downstream of the orifice (Anna et al. 2003; Ward et al. 2005).

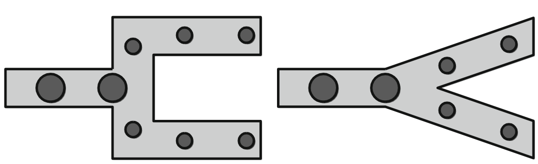

Fig. 18 Controlled droplet fission generation. a Perpendicular outlet channels. b Oblique outlet channels

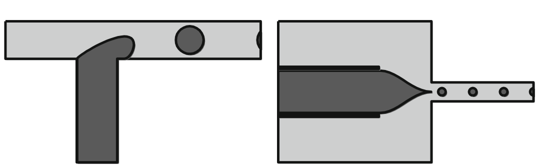

Fig. 19 Shear-flow-driven generation. a T-junction generation. b Flow focusing generation

3.2.3 Piezoelectrically actuated

For liquid-in-liquid piezoelectrically actuated droplet generation, like liquid-in-air, a piezoceramic actuator converts electrical signal to physical displacement to control the properties of the droplet being dispensed. Examples of piezo-based liquid-in-liquid droplet generators include syringe-jet and piezo-valve.

Stachowiak et al. described a syringe-jet droplet generator where the plunger position is controlled by a push-mode piezoceramic. To form droplets, the syringe discharged a small amount of jetting liquid into a droplet liquid environment toward a droplet/carrier liquid interface. As the jetting liquid approached and contacted the interface, a droplet began to form containing jetting and droplet liquid. As more time passed, the droplet pinched off from the interface and moved forward in the carrier fluid (Stachowiak et al. 2008).

Bransky et al. described a droplet generator where a push-mode piezoceramic acted as a valve to control the amount of droplet liquid able to pass into a carrier liquid channel (Bransky et al. 2009).

3.2.4 Liquid bridge

In liquid bridge droplet generation, droplets are formed by manipulating the flow of a droplet liquid bubble formed between two channels in a carrier fluid reservoir, as shown in Fig. 20. Specifically, a chamber is designed to have a droplet liquid inlet port (DLIP), a carrier liquid inlet port (CLIP) and a droplet/carrier liquid flow outlet port (OP). The DLIP and OP are oriented across from each other with the distance between the ports specified. To form a droplet in the OP, a droplet is first formed on the tip of the DLIP at a constant rate, seen in Fig. 20a (the chamber is already filled with the carrier liquid). Once the droplet is large enough, it will bridge the distance between the DLIP and the OP, shown in Fig. 20b. Then, carrier liquid flow through the CLIP will start to cause the DLIP/OP liquid

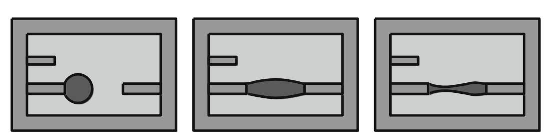

Fig. 20 Liquid bridge generation. a Initial chamber droplet formation. b Liquid bridge formation. c Liquid bridge deformation before shearing

bridge to deform (as seen in Fig. 20c) and rupture and form a droplet in the OP, surrounded by carrier liquid (Forget et al. 2008).

3.2.5 *Electrowetting*

In electrowetting droplet generation, a potential difference is applied over a two-phase liquid flow to form droplets of an electrowetting liquid. Specifically, a droplet generator is designed to cause two flows, a wetting (droplet) and nonwetting (carrier) liquid to meet in a channel with an electrode on two opposite channel walls. The two liquids have different electrical conductivity and permittivity, which causes an interfacial discontinuity in liquid properties. When an electric field is applied across the channel electrodes, this difference in properties causes an interfacial electric force, which causes a "transversal secondary flow" and destabilizes the interface between the liquids, causing the interface to rupture and droplet to form with sufficient electric field strength (Ozen et al. 2006).

3.2.6 *Comparison of liquid-in-liquid actuation mechanisms*

Depending on the size of droplet a system needs, different actuation methods can be chosen and (sometimes) scaled to meet that need. Table 2 compares the minimum droplet diameters for liquid-in-liquid actuation mechanisms as presented in the literature surveyed.

4 Operational issues surrounding droplet generators

As the consideration of droplet generators moves from their design to their use, a variety of issues arise regarding their operation.

Table 2 Comparison of minimum droplet size for selected liquid-in-liquid actuation mechanisms (Wu et al. 2006; Kim et al. 2009; Sugiura et al. 2001; Nisisako et al. 2002; Ward et al. 2005; Bransky et al. 2009; Forget et al. 2008; Ozen et al. 2006)

Actuation mechanism	Minimum droplet diameter[a] (μm)
Channel geometry, chambered	326
Channel geometry, grooved	25
Channel geometry, array	18
Shear flow, T-junction	100
Shear flow, flow focusing	50
Piezoelectric	42
Liquid bridge	243
Electrowetting	418

[a] If generated droplets were not spherical, the diameter was found by approximating the volume as a sphere

4.1 Key issues

In operating CS and DoD droplet generators, a single operating parameter in each is the most critical for creating monodisperse droplets. For CS generators, that parameter is maintaining a uniform liquid back pressure. If unintentional pressure variations are allowed, velocity gradients will be induced in the stream of droplets. This would cause changes in the stream appearance over time, as opposed to the desired steady-state form.

For DoD generators, the critical parameter is controlling the fluid interface position. This fluid interface can be a meniscus (in the case of nozzle-based generators) or the droplet-/carrier-liquid junction in liquid-in-liquid generators (Castrejón-Pita et al. 2008).

Each mode's parameter is influenced by a variety of factors inside of and external to the device itself. By better understanding these influential factors, each operating parameter can be better controlled and used to create the desired droplet or stream of droplets.

4.2 Frequency

The droplet generator frequency describes the number of generation cycles the generator can perform in a period of time. Generally, that time period is a second, and the frequency is expressed in hertz or kilohertz. A system's optimal frequencies for generating droplets are governed by the system's resonance and the actuation method.

4.2.1 *Resonance*

Resonance describes the tendency of systems to oscillate with higher amplitudes at specific frequencies. These frequencies correspond to a system's natural frequencies, which are controlled by the system's geometry (Meacham et al. 2005). Depending on the generator, resonance may have a positive effect, allowing the system to generate droplets at specific frequencies because of the resonant amplifying effects, or a negative effect, causing droplet volume variations due to unusually high vibrational amplitudes.

Kanda et al. described a situation where resonance was beneficial: a CS generator imparting a frequency on a liquid jet by longitudinal vibration was able to form smaller droplets with lower standard deviation by increasing the amplitude of vibration. Increased amplitude naturally occurred at the frequencies closest to the generator's natural frequency. However, while this limits a generator's operating frequencies when specific size and deviation requirements are in place, different generators with the same function but slightly different geometries can be designed to change the allowable frequencies (Kanda et al. 2007).

Bergkvist et al. described a situation where resonance was detrimental: in a DoD piezoelectric droplet generator, in frequency ranges affected by resonance, the sizes of droplets had higher variability. This led to the categorization of the generator's frequency spectrum: the frequency range before resonance affected generation was the "primary stable frequency region," the frequency immediately before resonance affected generation was the "primary stable frequency," the frequency range after the primary stable frequency but before generation halted or completely randomized was the "secondary stable region" and the highest frequency in the set of ranges beyond the secondary stable region capable of producing stable droplets was the "maximum dispensing frequency" (Bergkvist et al. 2005).

4.2.2 Actuation method

Depending on the system, different factors serve as limits for droplet generating frequency. In contact dispensing, the bulk motion of the pin array is the primary factor limiting generation speed. The faster the dispenser can move from site to site, the faster droplets will be formed. Furthermore, restrictions in bulk movement of any generator (including non-contact) can serve as a "synthetic" frequency limitation; regardless of a device's maximum generation frequency, the generator can only usefully generate droplets as fast as the deposition site can be moved into the droplet's path.

In pressure-based droplet generators, liquid damping and cavity length play key roles determining the maximum dispensing frequency. Liquid damping sets the speed pressure waves in a liquid dissipate. To produce monodisperse droplets, pressure waves from the previous actuation must fully dissipate (Fan et al. 2008). Furthermore, a droplet generator's cavity length causes a time delay in the transmission of pressure from the actuator to the nozzle (Bogy and Talke 1984). This delay causes a tradeoff in aspiration-supplied droplet generators between the maximum frequency and the generators' droplet liquid volumetric capacity.

In thermal bubble droplet generators, controlling the resistance between the fluid chamber and its reservoir during generation is the key factor in maximizing generator frequency. Periodic droplet generation alternates between droplet formation/ejection and chamber refilling as the thermal bubble expands and contracts. During formation/ejection, maximum fluid resistance is needed between the cavity and reservoir to force the droplet out of the nozzle; however, during refilling, minimal resistance is needed to accelerate the process. Statically, the geometry of the nozzle/cavity/reservoir connections can be optimized to increase maximum dispensing frequency (Lindemann et al. 2007), but dynamic solutions have also been explored.

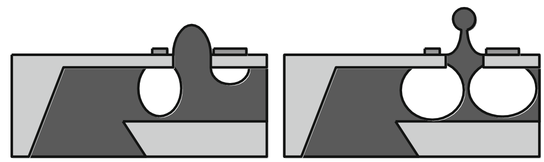

Fig. 21 **a** Bubble valve formation. **b** Tail cutting process

Tseng et al. have implemented a "bubble valve," where a heater is located between the reservoir and nozzle, as shown in Fig. 21a. As the bubble forms on the heater and expands, it partially blocks the channel between the reservoir and cavity, increasing the channel's fluidic resistance and forming a droplet at the nozzle. After the droplet is ejected and the heater is turned off, the bubble collapses and decreases the fluidic resistance, allowing the cavity to be rapidly refilled. By speeding up droplet formation and chamber refilling, the generator's maximum frequency was increased (Tseng et al. 2002a).

4.3 Satellite droplets

Also known as daughter droplets, satellite droplets are smaller droplets formed in addition to the main droplet during a droplet generation cycle. In liquid-in-air generators, satellite droplets are generally formed due to velocity gradients along the length of an ejected droplet's tail (Lee and Lal 2004). In liquid-in-liquid generators, satellite droplets can be formed due to instability at the fluid interface during ejection or trapped fluid in portions of the channel geometry during flow cycles (Anna et al. 2003; Kim et al. 2009).

Depending on the actuation method utilized to generate the main droplet, different strategies can be used to eliminate satellite droplets. For nozzle-based generators, reducing the droplet's ejection velocity can reduce velocity gradients along the droplet, resulting in a lower likelihood of satellite droplet formation (Castrejón-Pita et al. 2008). In pressure-based generators, pressure pulse amplitude and duration can be optimized to achieve the smallest droplet without satellite droplets (Gutmann et al. 2003). In thermal bubble generators, tail cutting can eliminate satellite droplets; it consists of forming two bubbles around a nozzle to expand and fuse with one another over the nozzle, seen in Fig. 21b. This fused air bubble would create a gap between the droplet being formed and the fluid chamber, ejecting the droplet before overcoming the viscous and surface forces (Tseng et al. 1998a). In channel geometry generators, flow rates and channel geometry can be optimized to prevent the formation of satellite droplets (Kim et al. 2009).

4.4 Crosstalk and overfill

Crosstalk occurs when one nozzle's actuation in a multi-nozzle droplet generator affects the other nozzles' operation (particularly thermal bubble). Two types of crosstalk have been observed: hydraulic and thermal.

4.4.1 Hydraulic crosstalk

Hydraulic crosstalk occurs when droplet generators sharing a common fluid source generate pressure waves in that common source and affect the other generators' operation. A key consequence of hydraulic crosstalk is overfilling, where a nozzle's meniscus is pushed past its normal rest position, changing the following actuation cycle's droplet properties.

Hydraulic crosstalk and overfill can be minimized by increasing the fluidic resistance between the individual generator fluid cavity and the fluid reservoir. Statically, resistance can be increased by increasing channel length or designing a neck in the system; dynamically, resistance can be increased by incorporating the bubble valve discussed in Sect. 4.2 (Tseng et al. 1996, 1998b). Furthermore, crosstalk behavior has been modeled and predicted to improve droplet generation by thermal bubble droplet generators, allowing actuation parameter modification to account for overfill and maintain droplet monodispersity (Lee et al. 2004).

4.4.2 Thermal crosstalk

Thermal crosstalk occurs when heat generated in a multi-nozzle droplet generator transfers to other system components and influences other nozzles' droplet generation. Transferred heat is problematic because rapid cooling is needed during bubble collapse for thermal bubble actuation. Thermal crosstalk is especially problematic in systems experiencing hydraulic crosstalk overfill because spontaneous droplet ejection may occur under certain conditions (Tseng et al. 2002a).

4.5 Clogging and misfires

In contact, nozzle-based and channel-based droplet generators, one of the most common methods of decreasing drop size is reducing the size of the pin/nozzle/channel due to the correlation between droplet diameter and nozzle diameter. However, as these components' sizes decrease, the likelihood of clogs, misfires and component failures increase (Amirzadeh Goghari and Chandra 2008). Clogging can be caused by a variety of factors: solid contaminants or suspended particles in the liquid, dust from the generator's surroundings, use of a high viscosity fluid or solvent evaporation causing solid formation on the aperture (Chang et al. 2006; Rose 1999).

Regardless of cause, clogging poses a major problem if undetected during generator use. To solve this problem, control methods have been proposed and explored for sensing droplet formation and deposition in real time. Ben-Tzvi et al. proposed integrating an additional piezoelectric sensor into a push-mode piezoelectric droplet generator to sense the pressure in a gas bubble separating a piston from a fluid cavity. Due to syringe depletion, the bubble will increase in volume after a droplet is dispensed, causing a decrease in pressure detectable by the piezoelectric sensor; if a change in pressure is not measured, a droplet must not have formed (Ben-Tzvi et al. 2007). Chang et al. (2006) described an optical sensor integrated into a contact generator that helps control the droplet formation process as the pin approaches and recedes from the surface by observing changes in the light detected.

4.6 Size controllability

Because some applications require droplets smaller than a nozzle can be designed without clogging, different methods of producing droplets smaller than the nozzle diameter (depending on the actuation method) have been emphasized and explored. Pressure-based generators have generated droplets half the size of the nozzle by using a specific waveform to drive a piezoelectric generator (Chen and Basaran 2002) or by using a specific nozzle/gas supply setup and operating parameters with a pneumatic generator (Amirzadeh Goghari and Chandra 2008). Both methods drive the generator to create a specific sequence of negative and positive pressure pulses within the cavity.

4.7 Generator priming

Priming is the process in which liquid is initially supplied to a droplet generator's reservoir and chambers. When priming a generator, bubbles should not be able to form or be trapped in the reservoir or chambers, due to the negative effects bubbles have on operation (Laurell et al. 1999).

In liquid-in-air and liquid-in-liquid droplet generators, using an exhaust port in the generator is a common method of addressing this issue; when using an exhaust port, the droplet fluid, the carrier fluid or a separate priming fluid (chosen for its reduced capacity for trapping bubbles) evacuates the system's air through the port. However, using a priming fluid may contaminate or dilute the samples later introduced into the system.

4.8 Actuation efficiency

In droplet generators, the energy required to form droplets varies drastically depending on the droplet dispensing mode and the actuation method. Generally, DoD generators require more energy per droplet (approximately three orders of magnitude more) than CS generators. This disparity exists because CS droplet generation uses minimal actuation with a natural fluidic instability to form droplets, whereas DoD generators require individual actuations to induce momentum and overcome viscous and surface forces in a droplet (Cooley et al. 2001).

However, while DoD inherently requires more energy per droplet formed, strategies exist for minimizing actuation energy use and waste. Reducing a generator's moving and/or deforming material is one way this can be done, with emphasis on designing systems to concentrate deformation where the primary actuation occurs. For example, Laurell et al. (1999) proposed a piezoelectric generator with three stands to separate the piezo from the liquid chamber wall (as opposed to mounting the piezo directly to the wall), as shown in Fig. 22, allowing the piezo deformation to force the fluid chamber wall to deform in a specific location.

Furthermore, actuation method-specific strategies exist to ensure maximum actuation with minimal energy expenditure and waste. For thermal bulking generators, Cabal et al. (2005) designed a tightly encased chamber surrounding a paddle actuator, ensuring maximum fluid displacement during actuation. For ultrasonic generators, Demirci et al. (2005) utilized a single reservoir design for an array of micronozzles to reduce energy waste from reservoir wall interactions.

4.9 Contamination

In designing and operating droplet generators, preventing droplet liquid contamination is a key consideration in ensuring the effectiveness of a system. Beyond utilizing "clean room" environmental precautions, choosing inert contact materials for a droplet generator is the most critical way of reducing the likelihood of contamination. Designing generators to minimize rubbing (and subsequent particles produced by rubbing) is another method to reduce the possibility of contamination (Fan et al. 2008). In devices utilizing more than one liquid, the generator should be

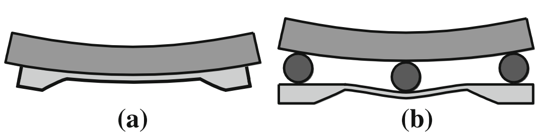

Fig. 22 Deformation concentration illustration. **a** Piezoceramic directly mounted on a channel wall that deforms the entire component **b** Piezoceramic indirectly mounted on a channel wall through three stands that deforms the most critical section of wall

designed to assemble and prime without the possibility of liquid cross-contamination (Steinert et al. 2003).

4.10 Overcoming liquid viscosity

In many systems (particularly nozzle-based), high fluid viscosity is often an obstacle in generating small, monodisperse droplets. For temperature-insensitive liquids and solutions (i.e. liquids/solutions that are not degraded by an increased temperature), localized heating has been used to reduce the viscosity at critical junctions (e.g. a nozzle), allowing droplets to form and return to ambient temperature (Fuller et al. 2002).

4.11 Surface placement

In liquid-in-air droplet generators, allowing rapid and accurate droplet placement on a surface is critical to system design. Depending on the dispensing mode (DoD or CS), different mechanisms are needed to control the generator location and droplet path.

4.11.1 Drop-on-demand

For liquid-in-air DoD droplet generators, droplet placement is determined by the relative motion of the generation site (nozzle, needle tip, etc.) to the deposition surface. Depending on the generator, either planar (2D) or spatial (3D) relative motion is needed.

Spatial relative motion is always needed in contact droplet generation. A key component in droplet formation is how the generating tip approaches, contacts and withdraws from the deposition surface. Planar relative motion is standard for non-contact droplet generation because the droplet is formed independently of the surface quality or location. However, a minimum distance is necessary for the droplet to stabilize after ejection. If the ejection site to surface distance is less than this stabilizing distance, irregularities will occur in how the droplet will come to rest on the surface. Furthermore, if the deposition surface is not relatively level (i.e. the height differences are comparable to the system dimensions), droplets may deposit differently based on their velocities at different positions after ejection. In each case, planar relative motion is not sufficient to accurately deposit droplets on a surface; spatial relative motion is required.

In addition, a system's degrees of freedom need not be manifested in a single system component. While a device requiring planar relative motion can be designed with the droplet generator capable of moving in a plane on its own relative to the deposition surface, it can also be designed with the droplet generator moving along one line of action and the deposition surface moving along a second oblique or orthogonal line of action.

4.11.2 Continuous stream

For liquid-in-air CS droplet generators, like DoD generators, the device is mounted on a moving platform and/or the desired droplet location is moved below the nozzle. However, because of the continuous nature of generation, a mechanism is needed to differentiate droplets intended to be deposited onto a surface from droplets intended to be discarded or recirculated back into the liquid reservoir.

Electrostatic deflection is the most common method of accomplishing this differentiation, where individual droplets can be charged and deflected after ejection. Two types of electrostatic deflection systems exist: binary and multiple, each of which use a system as depicted in Fig. 23.

For binary electrostatic deflection, a system is designed with a charging electrode surrounding the droplet ejection path from the droplet generator. As a droplet passes through it, the electrode will either charge the droplet as it passes through or allow the droplet to pass through unchanged. Only one magnitude of charge can be applied to a droplet for a binary system, allowing for two specific types of droplets to emerge (charged and uncharged).

After the charging electrode, the droplet will pass a high voltage deflection plate. The uncharged droplets will continue past the defection plate unaltered and will usually deposit on the solid surface. However, the charged droplets will deflect based on the plate voltage and droplet charge magnitudes. Because both are constant in binary electrostatic deflection, the deflection path is constant. The deflection path generally leads to a receptacle for collecting the unused droplets, which are discarded or recirculated back into the fluid reservoir (Le 1998).

For multiple electrostatic deflection, a binary electrostatic deflection system set up is used, but the possible droplet charge magnitude varies. This allows for deflection path variety as the droplets pass the high voltage plate. Therefore, a finite charge (including zero charge) can be set to direct to the droplet receptacle. This methodology, compared to binary electrostatic deflection, allows for a

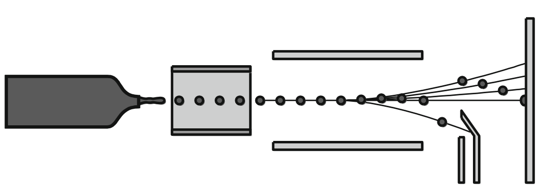

Fig. 23 CS generation deflection system, where the ejected droplet passes through a charging electrode, between two high voltage plates and either on the surface or into a collection vessel for potential recirculation

wider area to be covered by a single "pass" of the generator, lessening the number of passes needed to print a specific area, but may increase the time of each pass, due to the generator needing to deposit more ink (Cooley et al. 2001; Le 1998).

5 Characterization of generated droplets and measurement instrumentation

In this section, descriptions of droplet properties after generation are presented, and methods used to measure those properties are discussed.

5.1 Droplet characterization

Once generated, a droplet has a variety of properties that contribute to its motion and potential use. Though these properties manifest after generation has occurs, factors including the generator and its operating parameters will influence these properties.

5.1.1 Volume/diameter

A droplet's volume is its most critical physical property; it is the primary determinant of a droplet's acceptability for use in an application. In most liquid-in-air and some liquid-in-liquid situations, the droplet will assume a spherical or hemispherical shape to minimize surface area, allowing the droplet size to be characterized by the droplet diameter.

In liquid-in-air CS droplet generation, droplet size is determined by the liquid properties of the fluid jet, the excitation frequency imparted on the liquid jet, the nozzle diameter and the nozzle pressure (Castrejón-Pita et al. 2008). In DoD pressure-based droplet generation, pulse duration and amplitude determine droplet size (for a fixed nozzle size) (Castrejón-Pita et al. 2008; Bergkvist et al. 2005).

5.1.2 Ejection direction

In liquid-in-air droplet generators, droplet ejection direction is another property that defines robust operation. In nozzle-based generators, surface wetting is the key cause of oblique droplet ejection, as shown in Fig. 24. Wetting potential can be reduced in a number of ways: by designing nozzles to protrude from planar surface (Laurell et al. 1999), by selecting nozzle materials or coatings that reduce or eliminate wetting (Samuel et al. 2005) and by ensuring nozzle uniformity and high surface quality (Demirci et al. 2005; Fan et al. 2008).

Beyond the generator itself, certain dispensing liquids and liquid properties have been shown to play a role in

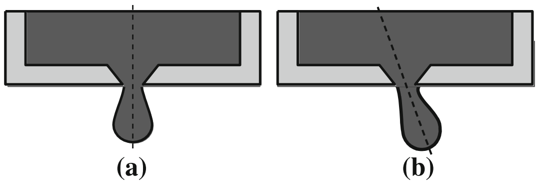

Fig. 24 Ejection direction variation. **a** Without wetting. **b** With wetting

determining ejection direction. In pressure-based droplet generators, the nozzle meniscus geometry and the liquid reservoir pressure distribution can cause irregular ejection direction (Demirci et al. 2005). In experiments depositing molten aluminum, impurities in the melt have caused angular irregularities during ejections (Orme et al. 2000).

5.1.3 Separation

In CS generators, droplet separation occurs due to the jet breakup from a continuous liquid stream to discrete droplets. Separation length and time depend on the jet velocity, the actuator amplitude, the actuator frequency and the fluid's viscosity and surface tension. Droplet separation is an important factor in creating a droplet placement control system because the charging electrode's dependence on how the droplets are separated (Bruce 1976).

5.2 Instrumentation

In order to quantify a droplet's physical characteristics (including volume, position, velocity, ejection direction and separation), a variety of technologies and techniques are used.

5.2.1 Photography

Photography is the primary method used for visualizing droplets. As droplets are generated, a camera and light source record discrete frames during generation for subsequent processing and analysis.

However, modifications to this simple technique have enhanced the images collected. Utilizing the stroboscopic method is one such modification. Stroboscopic photography is set up by incorporating a light source and/or camera into a droplet generator's control system. A controller and time delay are used to take numerous photographs at discrete times during droplet generation. For each time, multiple photographs are overlain, testing the uniformity of generation cycles for different droplets. Then, once arranged chronologically, the images track the droplets' positions and can be used to calculate velocities (Koltay et al. 2002).

A variety of cameras can be used to capture droplet images as they are generated. The most common device utilized is a charge coupled device (CCD) camera (Amirzadeh Goghari and Chandra 2008; Fan et al. 2008; Meacham et al. 2005; Lee and Lal 2004; Takahashi et al. 2002; Tseng et al. 1998b); however, complimentary metal–oxide–semiconductor (CMOS) (Forget et al. 2008), high speed (Dadvand et al. 2009) and single-lens reflex (SLR) (Castrejón-Pita et al. 2008) cameras have also been used.

In addition, a variety of light sources can be used to illuminate droplets as they are generated. While a clear preference does not exist as there was for the CCD camera, light-emitting diodes (LEDs) (Fan et al. 2008; Meacham et al. 2005) and lasers (Lee and Lal 2004; Takahashi et al. 2002) were among the most common devices utilized, with fluorescent light bulbs (Forget et al. 2008), incandescent light bulbs (Amirzadeh Goghari and Chandra 2008) and white reflective boards (Dadvand et al. 2009) also used.

5.2.2 Dispensed volume weight measurement

To determine the average volume of a single or sequence of droplets generated, a high resolution scale can be used in conjunction with a droplet generator to measure the dispensed liquid's volume and divide that amount by the number of droplets dispensed onto the scale. However, to ensure accuracy, potential effects such as evaporation must be taken into account (Berggren et al. 2002; Koltay et al. 2002).

5.2.3 Anemometry

Laser Doppler Anemometry (LDA) is another technique available to measure droplet size. Two laser beams are crossed at a sharp angle and the frequency shifts between each original beam and the reflected beam are measured. These two signals can then be used to compute the size of the droplet (De Heij et al. 2000).

5.2.4 Fluorescence spectroscopy

Fluorescence spectroscopy is a fourth way of measuring droplet volume; it consists of measuring the fluorescence of a liquid volume and comparing that fluorescence value to a previously compiled calibration curve. Generally, the liquids used are not fluorescent and a dye is added to the liquid. While the measurement process is simple once a calibration curve is compiled, there is a high error potential if the calibration is slightly erroneous (Koltay et al. 2002).

5.2.5 Interferometry

Interferometry is a method of measuring velocity where the changing interference between two light beams (generally lasers) is measured and quantified. Lee and Lal (2004) used an interferometer to measure capillary tip velocity in a piezoelectric droplet generator, providing another basis for systematic analysis.

6 Applications of droplet generation

In this section, descriptions of various applications of droplet generation are presented and discussed.

6.1 Printing

Ink-based printing was the first and remains the most common use of droplet generation technology today. As described in Sect. 1, thermal bubble and piezoelectric droplet generation were the first DoD technologies developed and remain the most common methods for commercial inkjet printing. When performing inkjet printing (as with other droplet-based applications) a tradeoff exists between droplet size and printing time. As the size of the deposited droplet decreases, the time required to print a fixed area will increase, due to the increased number of generation cycles (Le 1998).

6.2 Biological and chemical synthesis and analysis

6.2.1 Microarrays

Microarrays are one of the most promising applications of droplet generation being researched today. Because of their immense potential in investigating biochemical processes, substantial research has been performed investigating the creation and use of DNA and protein microarrays.

DNA microarrays are a multiplex assay where thousands of DNA sequences (called features) are fixed to a solid support and tested in parallel for interaction with complementary DNA (cDNA), genomic DNA or proteins. The testing molecules are tagged with fluorescent dyes to provide a signal to observe which fixed DNA sequences bind with the testing molecules. Test molecules and feature sequence that bind together have complimentary sequences, demonstrating a genetic link between the two (Chang et al. 2006; Moore 2001).

Among the benefits of DNA microarrays are their capability for parallelism, miniaturization, multiplexing and automation. Parallelism describes the capability to "wash" thousands of features simultaneously with the same testing molecule solution in a single step, simplifying the experiment and increasing its speed. Miniaturization describes the capability of these assays to have high feature densities, allowing reduced reagent consumption, less reagent volumes required and accelerated reaction kinetics. Multiplexing describes the capability of rapidly analyzing the sequences in parallel. Because the sequences are treated identically on a chip during an experiment, meaningful comparisons can be made between signal intensities from one feature to another; chip-to-chip variations and inconsistencies in experimental conditions are not present. Automation describes the capability to mass produce DNA microarray chips, allowing standardized quality, availability and affordability (Schena et al. 1998).

Two factors limit minimum DNA microarray size: the fluorescence detection threshold and the minimum droplet size. As microarrays become more compact, the quantity of strands in each feature decreases, lowering the number of binding sites for test molecules. As fewer test molecules bind to each feature, the fluorescent signal strength weakens, requiring a higher threshold sensor. Depending on the sensor, there may be a minimum feature size needed to ensure fluorescent detection. Alternatively, there is a minimum droplet size that can be generated by each actuation method, setting an absolute size limitation depending on the generator type chosen (Roth and Yarmush 1999).

Two methods exist to create microarrays using droplet generation. The first is to deposit previously synthesized oligonucleotide DNA (oDNA) or cDNA on a microarray chip. To deposit the DNA, contact or non-contact droplet generation methods are used (Zhang et al. 2006; Jaklevic et al. 1999).

In contact deposition, an oDNA or cDNA well for each sequence are placed adjacent to the chip being created. For each feature, a microspotter (hollow pin, tweezers, etc.) dips into the sequence well, draws up the sequence solution, moves to the feature site, deposits the feature and is washed. Advantages of this method include its low cost, ease of automation and versatility. Disadvantages include the need to synthesize, purify and store each individual feature before use, the potential for variability in spot to spot volume and the relatively low array density (due to higher droplet volume) compared to other methods (Schena et al. 1998; Chang et al. 2006).

In non-contact deposition, samples of oDNA or cDNA are supplied to droplet generators and jetted onto each individual feature site on the microarray. Advantages of this method include those traditionally associated with non-contact dispensing: high maximum frequencies, droplet formation independent of surface properties, etc. The primary disadvantage, like before, is the high number of samples needed to be deposited in traditional microarrays. However, this issue is magnified because of the increased difficulty of cleaning non-contact droplet generators compared to contact generators. This disadvantage can be minimized in applications with few features to be tested (e.g. in specific genetic resequencing experiments, where the number of features varies from 10 to 100) or microarrays where a single feature is tested multiple times in parallel (Cooley et al. 2001; Schena et al. 1998).

A second way droplet generators create DNA microarrays is by in situ synthesis of oDNA on the surface of a microarray chip. Instead of requiring a separate clean channel for each feature to be deposited, only five droplet generators are needed: one for each protected DNA base pairs (adenine, thymine, guanine and cytosine) and one for an activator (e.g. tetrazole). At each feature site, the oDNA sequence is built up step by step in layers of protected base corresponding to the desired sequence (with deprotection and washing steps between), with the number of these cycles in the process corresponding to the number of bases in the desired sequence. Because each generator is controlled independent of the others, unique sequences can be built at each feature site. Advantages of this method include its flexibility and high yield (~99% per step). Disadvantages include its inability to create cDNA microarrays, the sequential building process for each feature site (i.e. only one base of one feature can be added at a time for a single array of nozzles), the significance of oDNA growth mechanics and the array density limitations (Cooley et al. 2001; Roth and Yarmush 1999; Jaklevic et al. 1999; Zhang et al. 2006).

Protein microarrays, like DNA microarrays, are a multiplex assay where thousands of proteins are fixed to a solid support and tested in parallel for interaction with other proteins, nucleic acids, lipids or other small molecules. Because of the relative complexity of proteins compared to DNA, the protein microarrays types, manufacturing processes and analytical processes are more complex.

Two general types of protein microarrays exist: analytical and functional. Analytical microarrays use antibodies, antibody mimics or other proteins to detect protein presence and measure protein concentration in complex mixtures. Alternatively, functional microarrays use a protein set (sometimes an entire proteome) to monitor biochemical reactions with test molecules in parallel.

When manufacturing protein microarrays, it is critical the microarray surface allows each protein to retain its 3D geometry at high densities and remain in a moist environment during and after deposition. Retaining the 3D structure is critical because of the role secondary, tertiary and quaternary structure play in determining protein function. Protein microarray analysis is primarily performed by fluorescence detection, where fluorescent or potentially fluorescent[3] test molecules are used (Zhu and Snyder 2003).

Droplet generation plays a similar role in creating protein microarrays as in DNA microarrays, where generators can deposit pre-synthesized or isolated proteins on the microarray or synthesize the protein in situ. However, unlike DNA microarrays, depositing prepared proteins is the preferred method for creating protein microarrays, due to the twenty amino acids that make up protein and the importance of the synthesized protein's 3D structure (Cooley et al. 2001).

6.2.2 *Protein identification and crystallization*

One method by which proteins can be identified is by breaking down the protein into a unique set of peptide chains using a proteolytic enzyme and analyzing those chains in a matrix-assisted laser desorption/ionization time-of-flight mass spectrometer (MALDI-TOF MS). In an effort to speed up a process typically requiring 6 to 24 h incubations and substantial manual intervention, droplet generation technology has been incorporated into an automated process that reduces the time to analyze 100 protein samples to 3.5 h. The droplet generator is used to transfer protein samples from the enzyme reactor to the MALDI target plate for ionization and analysis (Ekström et al. 2000).

Once a protein has been identified, in order to determine its three dimensional structure using X-ray crystallography, high quality protein crystals are needed. To create these, a battery of tests using salts, buffers and precipitating agents are performed to determine optimal crystal nucleation and growth conditions. Droplet generation can reduce the volumetric requirement of these tests and integrate this process into "lab-on-a-chip"-type devices (Hansen et al. 2004; Hansen et al. 2002).

6.2.3 *Mass spectrometry*

In addition to depositing samples for MALDI-TOF MS analysis, droplet generating technology can be incorporated into an electrospray ionization (ESI) source, an alternative to MALDI for preparing ions for mass spectrometry. Both single-nozzle (Berggren et al. 2002) and multi-nozzle (Aderogba et al. 2005) ultrasonic piezoelectric droplet generators have been implemented, but with an additional electrode incorporated in the liquid chamber to ionize the dispensing fluid. Like MALDI, ESI can be coupled with a TOF mass analyzer to form an ESI-TOF mass spectrometer with detection limits similar to traditional nanoelectrospray mass spectrometry.

Furthermore, a flow-through droplet generator has also been used for in-line sampling of a liquid chromatography separated solution for use in a MALDI-TOF MS. After separation, the liquid flows through the droplet generator and liquid samples are dispensed orthogonal to the flow, minimizing disruption and ensuring robust sampling. The

[3] Potentially fluorescent molecules are tagged with a probe that can later be reacted with a fluorescently labeled affinity reaction.

generator faces a MALDI plate and each droplet deposits in its own location for further processing and analysis, with the plate or the generator moving to accommodate the placement of different drops in different spots (Miliotis et al. 2000).

6.2.4 Single cell encapsulation and analysis

Droplet generators can also be used to isolate cells from their surroundings and analyze their makeup and processes. Both water (He et al. 2005) and alginate hydrogel (Tan and Takeuchi 2007) have been utilized to encapsulate cells in microfluidic devices. Once isolated, these cells can be analyzed to determine their chemical contents (Wu et al. 2004) or protein expression (including antibodies) (Huebner et al. 2007; Köster et al. 2008). Furthermore, research has shown cells are capable of surviving droplet generation and can be recovered and cultured after use (assuming use of the encapsulated cell did not intentionally harm it) (Köster et al. 2008; Kim et al. 2007).

6.2.5 Cellular environment emulation

Beyond encapsulating cells, droplet generation can also create droplets that emulate the cellular environment for experimentation and modeling. Creating vesicles around biomolecules is one way this is performed (Stachowiak et al. 2008). A droplet generator creates the vesicle by ejecting a biomolecule solution stream into a solution liquid toward a lipid bilayer interface separating the solution liquid from the carrier liquid. When the biomolecule liquid encounters the lipid bilayer, it will deform the bilayer and a droplet will begin to form, containing a biomolecule and solution liquid mixture. The carrier liquid will eventually surround the biomolecule/solution liquid droplet and pinch it from the lipid bilayer, forming a vesicle.

Liposomes can also be constructed to mimic cells in microfluidic applications. Flow focusing droplet generation with an internal flow containing dissolved lipids surrounded by an external flow containing buffered saline solution can predictably form monodisperse liposomes under certain conditions that manipulate the length scale and applied shear forces (Jahn et al. 2004).

6.2.6 Chemical microreaction

Generated droplets can also encapsulate chemical reactants to form chemical microreactors. Depending on reaction needs, different strategies can be employed to design a microfluidic system. Microfluidic systems are able to initiate reactions within a microreactor droplet, control the time a reaction occurs before subdividing its microreactor droplet, control the fusion of microreactor droplets and quench reactions within a microreactor droplet. Furthermore, systems have been designed that are capable of increasing the mixing speed in microreactor droplets without dispersion (microfluidic systems generally operate at low Reynolds numbers, preventing natural turbulence from aiding the mixing) (Song et al. 2003; Hung et al. 2006). One use of microreactors has been to experimentally measure reaction kinetics (Song and Ismagilov 2003).

6.2.7 Solid support creation and modification

Beyond creating vessels where reactions take place, droplet generation can also be used to design solid supports to serve as attachment or synthesis sites for biomolecules. Alternatively, these solid supports can serve as time dependent flow obstructions or as local blocks of wetting or reactivity (Cooley et al. 2001).

6.2.8 Fuel combustion

Droplet generation can also be applied to liquid fuel delivery in combustion chambers. Because microdroplets have a higher surface-area-to-volume ratio, they will evaporate more rapidly than fuel delivered in larger droplets or in a liquid stream, increasing the combustion rate. Generators also have the capability of producing monodisperse droplets, minimizing shape and volume variation to allow the injected fuel volume to be more tightly controlled. Furthermore, if an array of droplet generators is used to inject fuel, the generators' ejection control can regulate the combustion's heat generated and manipulate the combustion's flow dynamics to make heat transfer more efficient (Tseng et al. 1996; Ederer et al. 1997).

6.3 Medicine

6.3.1 Inhalation drug therapy

The use of droplet generation technology in inhalation drug (or aerosol) therapy allows monodisperse droplet bursts to be formed in air for inhalation into the lung. To ensure good inhalation characteristics, droplet volume magnitude and deviation must be highly controlled. Furthermore, initial droplet velocity is also important: if a droplet's velocity is higher than the inhalation flow's velocity, it has a higher likelihood to deposit in the mouth or throat and not travel to the deep lung (De Heij et al. 2000; Yuan et al. 2003).

6.3.2 Drug delivery

Creating vessels for controlled therapeutic agent delivery within the human body is another droplet generation application. By manipulating the droplet's size and shape (from a simple sphere to a complex plug, disk, rod or thread), the vessel's release profile can be designed. Polymer (Cooley et al. 2001), alginate hydrogel (Liu et al. 2006) and vesicles (Stachowiak et al. 2008) have all been studied as media capable of delivering drugs.

6.3.3 Tissue engineering

Droplet generation can also be applied to creating biocompatible three-dimensional structures using cells, growth factors and biopolymer or hydrogel. Tissue is created by printing the biopolymer or hydrogel as the desired three-dimensional structure and seeding that structure with cells. As the cells grow and multiply (as aided or hindered by the growth factors applied), they replace the synthetic structure with the cellular, creating a tissue free of foreign material for integration into an organism (Cooley et al. 2001; Tan and Takeuchi 2007).

6.3.4 Glucose detection

In an effort to reduce required sample sizes, droplet generation has been applied to clinical glucose detection in human liquids (e.g. blood). By discretizing a liquid sample into droplets, as opposed to using a continuous flow, this goal is achieved while retaining high detection accuracy (Srinivasan et al. 2004).

6.4 Micromanufacturing

6.4.1 Electronics manufacturing

Because of their small size and the materials used, electronic components are one class of products easily created by droplet generators.

Photoresist coating is one of the most expensive, wasteful and rigid steps in lithographic processes in MEMS fabrication. Traditionally, spin coating, a process that wastes approximately 95% of the photoresist used, is used to create a uniformly thick and chemically isotropic coat. Furthermore, spin coating cannot uniformly coat large or irregularly shaped surfaces, cannot selectively thicken specific areas of the photoresist coat and often causes radial thickness variations about the axis of rotation. Droplet generation alleviates many of spin coating's negative consequences: there is minimal waste due to the additive nature of depositing photoresist droplets, the generator can operate independently of the size or planar shape of the surface and the generator can selectively thicken specific surface areas with additional photoresist (Perçin et al. 1998).

Depositing electroluminescent polymer via droplet generation has also surpassed spin coating as an effective manufacturing method to produce polychromatic organic or polymer light emitting devices (OLED/PLED). When creating a LED of more than one color, patterns of different luminescent-doped polymers must be generated on a surface with finite resolution, an inherent capability of liquid-in-air droplet generating technology (De Gans et al. 2004; Hebner et al. 1998).

Droplet generators have also been used to create circuit components using both metal and polymer. Silver and gold particles in solution have been used to create circuit connections on chips based on a CAD drawing (Szczech et al. 2002). Furthermore, polymer solutions have been used to create inexpensive electrical components: both transistors and capacitors have been successfully fabricated in laboratory settings (De Gans et al. 2004).

Utilizing droplet generators to deposit surface mount adhesive is one of the principal methods by which electronic components are assembled. Traditionally, contact droplet generators have been used to transfer the adhesive from a reservoir to the desired surface via a specially designed array of pins or dispensers. However, non-contact droplet generation allows adhesive droplets to be jetted directly onto the surface, letting the device controller direct the adhesive pattern (as opposed to the physical layout of a pin or dispenser array) (Piracci 2000).

When manufacturing liquid crystal displays (LCDs), a critical step is depositing the liquid crystal between two glass substrates. Traditionally, glass substrates are assembled opposite one another and the liquid crystal is slowly injected between them, a process that can take 2 days in a 22-in. panel. However, an alternative method, one-drop-fill, has been investigated where liquid crystal is deposited on one of the glass substrates and the opposite substrate is pressed down upon it. When performing one-drop-fill, the volume dispensed must be highly regulated, and the fluid dispensed must be free of contaminants. Droplet generation accommodates both conditions, with droplet volume monitoring performed via image processing and contaminant reduction ensured by minimizing the likelihood of producing particles by rubbing parts in the generator (Fan et al. 2008).

6.4.2 Net-form manufacturing

Beyond small-scale electronics manufacturing, droplet generation can also be used in net-form manufacturing based on CAD models using a variety of materials.

Investigating the rapid prototyping possibilities using molten metal is a key research area in manufacturing-related droplet generation. Both CS and DoD droplet generators have been used in various net-form applications, with purified aluminum used with CS generation and solder used with DoD generation (Lee et al. 2007; Orme et al. 2000; Orme and Smith 2000).

An advantage of using molten metal in net-form manufacturing (as opposed to particulate metal in solution) is the lack of post processing required after depositing the material, reducing the potential for volumetric change of the manufactured structure. Disadvantages of using molten metal include the susceptibility of the melt to oxidation after jetting, the high temperature required to maintain the metal's liquid phase and the high liquid viscosity, even at an elevated temperature.

Strength can be maintained in the final component by ensuring each dispensed droplet's thermal energy is sufficient to remelt a portion of the previously deposited and solidified droplet. By remelting, boundaries are not maintained between iterations of droplets, creating a stronger metallic structure. Furthermore, because of the droplets' scale, solidification occurs rapidly after the local remelt, supplementing the material's strength (Orme and Smith 2000).

Alternatively, particulate metal, when delivered in solution, can be deposited using droplet generation. Advantages of utilizing particulate metal deposition include the capability of dispensing and sintering the particles at relatively low temperatures (the melting point of metal nanoparticles can be up to 1,000°C lower than the corresponding bulk metal) and the low liquid viscosity during dispensing (depending on the solvent used). Disadvantages of particulate metal deposition include the need to remove the solvent liquid after droplet deposition and the added sintering step needed after deposition.

Polymers have also been utilized with droplet generation for net-form manufacturing. Specifically, both liquid epoxy resins and molten polymers have been deposited to manufacture various components. Work has also been performed to measure the mechanical properties (such as ultimate tensile strength and tensile modulus) of deposited components. Speckle interferometry with electron microscopy (SIEM) measurement is one non-destructive way these measurements have been taken (Chang et al. 2004; MacFarlane et al. 1994).

Ice is another material out of which components can be made by droplet deposition. The process is carried out by ejecting water droplets from the generator onto an initial substrate or a previously frozen layer. Each ejected droplet fuses with the previously deposited droplet, and droplets' temperatures are controlled to not immediately freeze upon deposition. Therefore, during deposition, a "water line" follows the deposition path, slowly freezing along the line. This ensures each ice layer is not built out of discrete "bricks" of frozen water droplets with boundaries between each droplet; however, there will be a boundary between each layer as the generator traces a path about the desired bulk shape. Creating both vertical and slant part walls have been considered with this method (Sui and Leu 2003).

7 Conclusions and recommendations

This paper provides a review of the classification, technologies, operation and applications of liquid-in-gas and liquid-in-liquid droplet generators and the properties and measurement of liquid droplets they generate. Generator designs were also compared for their minimum droplet size and the time required to execute a generation cycle.

Based on the reviewed literature, the primary area in which advances need to be made is closed loop generation control. While some actuation-specific methods have been discussed, actuation-independent methods should be explored capable of detecting failed operation and monitoring droplet size in real time in liquid-in-air and liquid-in-liquid applications. Generators should also be able to quickly recover from erroneous operation either automatically or with minimal external assistance. Novel actuation methods, manufacturing processes and operating conditions should also be developed to further enable the creation of smaller monodisperse droplets. Actuation methods developed should be easy to manufacture, assemble and control, and capable of handling a wide variety of droplet liquids and environmental conditions. Manufacturing processes utilized in creating generator components should be chosen or developed to allow for high quality generators to be produced inexpensively, allowing wider access to droplet generating technology. Operating conditions for existing and novel actuation methods should be optimized to allow for robust generation over a wide range of frequencies. Finally, the fields of liquid-in-gas and liquid-in-liquid droplet generation need to be further integrated and considered as a single field. As novel generation methods are conceptualized and developed, they should be considered for both modes of generation; currently, a designer might not consider a liquid-in-liquid application for a mechanism designed for liquid-in-gas generation (or vice versa), even when it might be more advantageous. An initial product of this integration could be a platform capable of generating liquid droplets in gas onto a solid support or in liquid into a carrier liquid stream, synergizing the capabilities of each field and better allowing laboratories to utilize droplet generation in their operation.

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