NON-CONTACT NANOLITER & PICOLITER LIQUID DISPENSING

P. Koltay and R. Zengerle
Laboratory for MEMS Applications, Department of Microsystems Engineering (IMTEK),
University of Freiburg, Georges-Koehler-Allee 103, 79110 Freiburg Germany
(Tel : +49-761-203-7477; E-mail: koltay@imtek.de, zengerle@imtek.de)

Abstract: This paper presents an introduction to non-contact dispensing technologies gaining increasingly importance in numerous application fields, ranging from the life sciences and medical applications to industrial fabrication. Besides a brief overview on typical applications the basic dimensionless numbers to describe droplet breakup are introduced. Based on this formalism criteria for droplet breakup are given and a classification of droplet dispensers according to their working principle is proposed. Examples of dispensing devices are presented for selected applications and it is shown how these fit into the proposed classifications scheme.

Keywords: droplet, dispensing, non-contact, drop-on-demand

1. INTRODUCTION

Small liquid droplets with volumes of only a few nanoliter or picoliter are used in many applications today. Still much research work is dedicated to understand and to describe the numerous existing droplet generation mechanisms, as well as to propose new technologies and devices particularly designed for specific applications. The major areas of interest that can be identified today are printing and coating, the life sciences, industrial fabrication, and some other smaller applications.

Printing and coating is certainly the biggest industrial and consumer market. The well known home and office printers based on inkjet technology [1] make up the largest market share of all microfluidic devices sold today. The same technology is also applied by many industrial large format printers and also in industrial production for example for optical devices like flat screen displays. High quality color image, low machine cost and low printing noise are basically the main advantages of such inkjet printers producing droplets in the 1 – 100 picoliter range.

The life sciences as another important application area exhibit completely different requirements compared to printing and coating. For the fabrication of microarrays, lab-on-a-chip systems and liquid handling for drug discovery research for example, a large number of very complex liquids with ever varying properties has to be dealt with [2]. Furthermore hundreds and thousands of different solutions have to be handled simultaneously and contamination has to be avoided by all means. In more and more cases even particle laden liquids containing cells or beads have to be dispensed which presents additional technical challenges due to clogging and related issues. In most cases the well established inkjet technology does not fit these requirements and other approaches have to be followed, like for example the TopSpot dispensing technology [3] for printing microarrays.

Droplet dispensing in the field of industrial fabrication like for the assembly and packaging of semiconductor chips or the fabrication of printed circuit boards (PCB) has again requirements of its own. In this important application area many hot and aggressive as well as highly viscous and particle filled liquids have to be dispensed. Some of these requirements can be met by inkjet techniques, like for example the deposition of molten solder on chips and circuit boards [4] or adhesives for packaging. However, in many cases the liquids are too viscous for inkjets and often pressure driven fast switching valves are applied to generate nanoliter sized droplets.

Besides the mentioned modern application areas there are also very classical applications especially for spray generation like fuel injection systems for combustion engines or spray technologies for painting, coating and production of powders and micro particles. These applications have developed their own set of specific technologies not dealt with in this article. The focus of this paper will remain on devices being able to deposit individual droplets one by one in a controlled way. Amongst them there are the classical drop-on-demand inkjet devices but there are also other technologies capable to produce individual droplets like the following sections will show.

2. DROPLET BREAKUP CONDITIONS

2.1 Criteria for droplet breakup

In a very simple model a droplet dispenser can be considered to consist of a circular orifice with diameter D filled with a liquid having density ρ surface tension σ and viscosity η like sketched in figure 1. One can assume that by some kind of actuation mechanism power is supplied to the orifice to eject a droplet or jet. In order to determine suitable conditions for the ejection process droplet generators are studied throughout the literature in terms of the Weber number and the Ohnesorge number [5, 6]. Such dimensionless numbers are commonly used in fluid dynamics to characterize the flow situation qualitatively. The Weber number being defined as the ratio of surface tension energy to kinetic energy

$$We = \frac{\rho \cdot D \cdot v^2}{\sigma} \qquad (1)$$

provides a good estimate to determine whether a droplet has sufficient kinetic energy to overcome the surface tension at the orifice and to create a free flying droplet. In other words the Weber number helps to distinguish a situation where a droplet drips out of an orifice (low Weber number) from a free flying droplet shot from a nozzle at sufficiently high velocity (high Weber number, cf. figure 1 a) and b)). In particular it turns out that for inviscid liquids a free droplet of approximately the size of the orifice can be produced only for Weber numbers larger than 12, which is the so called critical Weber number.

In cases where the liquid's viscosity is not negligible the critical Weber number can be much larger than 12 and a second quantity – the Ohnesorge number - is required to determine the conditions for free droplet ejection. The Ohnesorge numbers helps to discriminate "water like" flow situations (i.e. liquid jets disintegrating due to surface instabilities into many droplets) form "honey like" situations (i.e. liquid jets which form long tails, cf. figure 1 c) and d)). The Ohnesorge number considers all liquid properties and is defined as follows:

$$On = \frac{\eta}{\sqrt{\rho \cdot D \cdot \sigma}} \qquad (2)$$

In terms of physical properties the Ohnesorge number can be interpreted as the ratio of kinetic energy compared to the energy dissipated by the viscous flow. The higher the Ohnesorge number the higher becomes the critical Weber number and the more difficult it is to create a free flying droplet at all. The steep increase of the critical Weber number with increasing Ohnesorge numbers is the reason why creating small droplets from viscous liquids is so difficult.

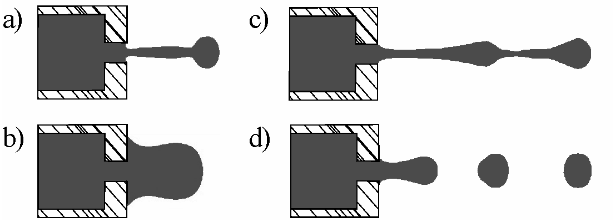

Fig. 1 Simulation of the droplet ejection from a orifice for different Weber and Ohnesorge numbers. a) We = 17.4 b) We =7.9 (no ejection) c) On = 1.9 d) On =0.1

Depending on the actual values of the Weber number – assuming the Ohnesorge number to be close to zero for the remainder of this paper - in general three different regimes of droplet or jet breakup can be distinguished [7]:

2.2 Drop-on-demand regime

This breakup regime is characterized by an ejection of a single droplet or jet with a diameter equal or slightly bigger than the nozzle diameter. The ejected droplet or jet can be followed by smaller satellite droplets or a tail which could also disperse into single satellite droplets after a while. To ensure droplet breakup a fast actuation is required to create a sufficiently high Weber number in the range from We = 12 to We < 40. All of the devices discussed in the following sections are operating in this regime.

2.3 Rayleigh breakup regime

The Rayleigh breakup regime is characterized by a continuous operation. A liquid jet is ejected out of a nozzle continuously that disperses into single droplets due to the so called Rayleigh instability. Typical Weber numbers are in the range of about We = 8 to We < 12. Below a value of We = 8 no free flying jets or droplets, but dripping is observed.

2.4 Atomization regime

The atomization breakup is mainly characterized by a high speed liquid jet which disperses into a fine spray of many single droplets directly behind the nozzle exit. The actuation is continuously and very strong which leads to very high velocities at the orifice producing Weber number larger than We > 40.

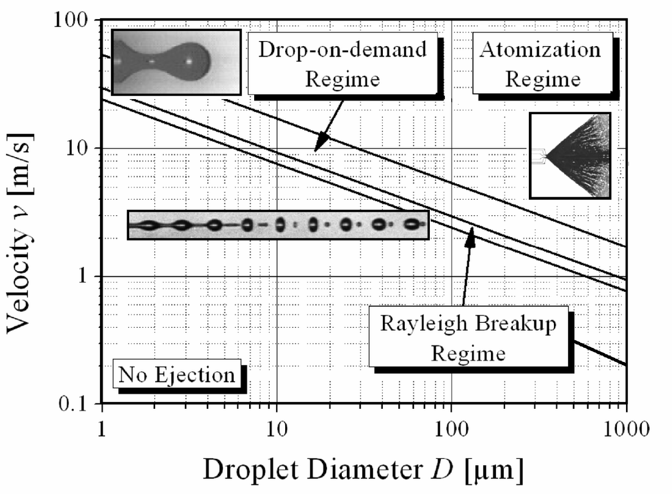

Fig 2 Different breakup regimes separated by lines representing Weber numbers We=8, We=12 and We=40 as function of the velocity v versus the droplet diameter D.

Based on this very basic consideration, relying on the Weber number only, important design rules can be derived readily. In figure 2 for example the Weber number is plotted as function of liquid velocity at the orifice and droplet diameter. It can be deduced easily which flow velocity has to be achieved by an actuator mechanism to be able to eject a droplet of given size. How this velocity can be achieved technically is a different matter. In particular this turns out to be the most difficult part in practice; or in the words of E.R. Lee: *"The process of drop ejection is not as simple as taking a fluid chamber with a small hole and pressurizing it enough for fluid to start emerging from the ejection nozzle hole"* [8].

3. CLASSIFICATION OF DISPENSERS

As pointed out before the actuation method which drives the droplet ejection is a key element of any dispensing device and therefore it is natural and common practice to classify dispensers according to the adopted actuator (e.g. piezo-electric, thermo-electric, pressure driven etc.). However, ultimately the *effect* of the actuator on the liquid determines the droplet ejection and not the actuator itself. Therefore it is more precise to consider the fluidic boundary condition (BC) applied to eject a droplet from the orifice of a dispenser for classification.

Grounded on the concept applied in computational fluid dynamic (CFD) simulations to apply pressure boundary conditions respectively flow boundary condition to model the effect of the actuation, dispensing devices can be classified in two categories: Either a predetermined pressure is provided by the actuator and the flow is free to evolve or the flow is set by the actuator and the pressure is free to take on a certain value depending on the liquid properties, geometry, etc.. In both cases the actuator is assumed to be able to provide infinite pressure respectively flow, which is obviously an idealization.

In fact, there exist real droplet generators where a combination of pressure and flow represents the correct boundary condition. In this case neither an ideal pressure source nor an ideal flow source is the correct assumption. The pressure provided by the actuator is influenced by the flow and vice versa. Due to this also a third group of droplet generators with a combined pressure and flow boundary condition has to be considered.

Finally, a fourth group is required to complete the classification that accounts for acoustic actuation. Devices driven by acoustic actuation are characterized by rapid pressure oscillations which propagate through the liquid without inducing a substantial net flow. The basic model of a dispenser sketched in figure 3 illustrates the difference: A pressure or flow BC produces a net liquid flow through the dispensing device where pressure and flow are closely coupled. In contrast an acoustic actuation generates a periodic pressure distribution inside the device and pinches the droplet off at the nozzle due to a high local pressure gradient. The net liquid flow through the device is negligible in that case.

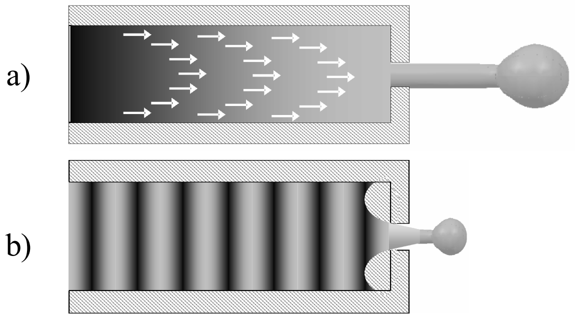

Fig. 3 Schematic sketch of the droplet ejection driven by a) pressure or velocity BC b) acoustic BC (pressure is indicated by grey levels, flow velocity field by arrows).

4. EXAMPLES

4.1. Pressurized valve technology

One of the most common methods to generate droplets in the nanoliter range is to apply fast switching solenoid or piezoelectric valves. Such valves are typically fed by a fluidic line from a pressurized reservoir or by syringe pumps. Upon fast opening of the valve droplets are ejected.

For this technology to function properly it is very important that the droplets are issued right from the orifice of the valve. Any fluidic resistance downstream of the valve reduces the attainable velocity and by this the Weber number. It is equally important that the valves are switching fast and that no fluidic inductivity is present downstream to create a steep velocity increase at the nozzle. If the flow would increase too slowly resulting in a low Weber number, first a pending droplet would be created (cf. figure 1 b) and even if afterwards a higher velocity is achieved no proper drop-on-demand condition can be achieved anymore. For optimum jet or drop breakup it is very important that the area surrounding the orifice is clean, dry and non-wetting. This is equally true for any other non-contact dispensing technology!

The pressurized valve technology has the advantage that in principle arbitrarily high pressures can be applied to realize the required Weber numbers. Therefore this technology is very prominent for jetting adhesives in industrial applications. Main draw backs of the technology based on switching pressurized valves are the costs of the high performance valves, the low degree of miniaturization, clogging issues with particle laden liquids and high maintenance efforts for cleaning the valves. The smallest volumes achievable with this method are about 50 nL.

In terms of the presented classification the pressurized valve technology clearly falls into the category of a device driven by a pressure BC. The pressure in the reservoir – which is created typically by some large external compressor – can be considered to be not influenced by the droplet that is issued from the orifice. The control of the pressure inside the system is complete and defined by the settings of the device (pressure, valve opening time, resistance of tubings etc.)

4.2. PipeJet technology

In contrast to the pressure driven valves discussed before, the PipeJet technology proposed by the authors and others [9] has to be considered as to be driven by a flow BC. The key element of the PipeJet technology is an elastic plastic tube which is squeezed by a piston as sketched in figure 4. By the deformation of the tube a volume displacement and subsequently a liquid flow is induced. If the flow is fast enough to overcome the critical Weber number a droplet is ejected. The volume of the droplet is adjustable by the tube size and the piezo displacement in a range from one to several hundred nanoliters.

Because the applied piezo stack actuator is typically very stiff and has a high clamping force (approx. 1000 N), the movement of the piston is not influenced by the liquid flow. Thus the flow conditions inside the tube can be controlled completely by the actuator. This type of displacement controlled actuation (sometimes also termed “direct displacement” or “positive displacement”) has the advantage that the volume of the droplet is independent of the viscosity in a certain range. Due to the strong actuator also liquids with higher viscosity can be dispensed with this method. With tube diameters of 500µm viscosities up to 1000 mPas have been successfully dispensed.

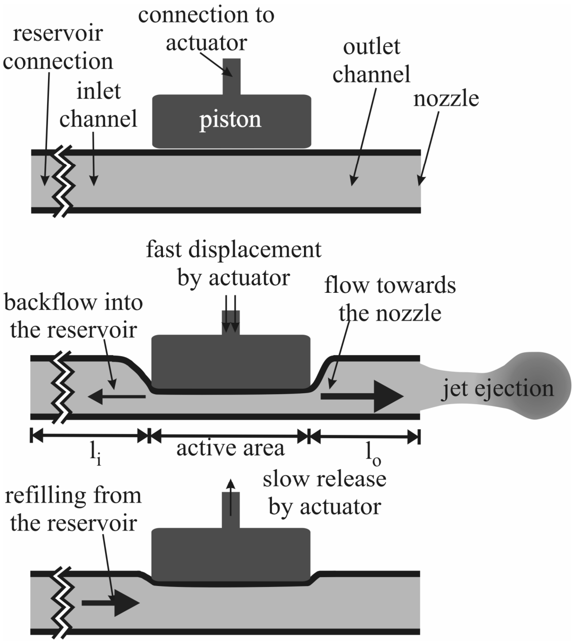

Fig. 4 Schematic sketch of the PipeJet working principle.

Another nice feature of the PipeJet technology is that all fluid contaminated parts can be exchanged very easily. Due to the low costs of the plastic tube they can even be used as a disposable. Thus, many drawbacks associated with cleaning and cross contamination in other dispensing systems can be eliminated. Due to the straight geometry of the tube (no corners, edges or bends hinder the liquid flow) clogging is hardly observed for this method compared to valve based or inkjet systems where this is a frequent problem.

4.3. Inkjet technologies

Inkjet printheads are the most popular and well known droplet dispensing devices today. The most prominent technologies are the thermal inkjet or bubble-jet technologies closely followed by piezoelectric methods. An excellent overview on all the inkjet technologies is given by [1]. Though all inkjet devices are mainly used for the same purpose, namely printing, they can rely on quite different actuation methods. In terms of the proposed classification they can fit in various categories depending on the design of the device and the power of the actuator. Typically the integrated actuators are small and have not more power than ultimately required. Therefore often a coupling between fluid flow and actuator movement is given. In these cases the classification as a device being driven by a combined BC is appropriate. In other cases the actuation is guided or amplified acoustically. Such devices are best characterized by an acoustic BC. As an example the bubble-jet technology will be briefly discussed in the following.

The functional principle of a thermal bubble-jet printhead is displayed in figure 5. An electrical current applied to a micro heater leads to a very short heating pulse at the solid-liquid interface. Consequently a small vapor bubble is generated which expands explosively. The increasing vapor bubble leads to a volume displacement of the ink towards the nozzle and finally to a droplet ejection. After switching off the heater the bubble cools down and collapses. The suction of the collapsing bubble and the capillary forces inside the printhead lead to refilling of the nozzle chamber that is finished before the next shot within typically 10 µs.

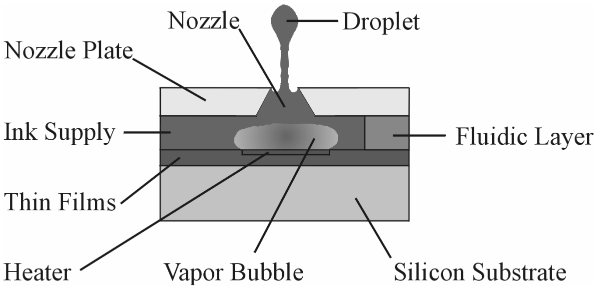

Fig. 5 Schematic sketch of a thermal bubble-jet printhead.

On the one hand the expanding bubble can be indeed regarded to create a volume displacement which pushes out the bubble. On the other hand the bubbles can also be seen as a pressure source which starts instantaneously with a very high pressure of about 7 MPa to 9 MPa and decreases exponentially during a few microseconds [10]. In any case volume and pressure are closely coupled through the dynamics of the bubble, which itself is influenced by the fluid dynamics inside the printhead. Therefore bubble-jet devices should be regarded as to be driven by a combined BC in terms of the proposed classification scheme.

4.4. TopSpot technology

In dispensing applications it is often required that a multitude of different liquids can be handled at a time. For printing applications these are typically the different color components (e.g. red, green, blue and black). For fabrication of microarrays or biochips often even more, like hundreds to thousands of different solutions have to be printed to form a regular array of DNA, antibody or protein spots. Such printing can be achieved by inkjet technologies in a serial way (spot by spot) which takes considerable time. Alternatively the authors and others [3] have proposed the TopSpot method to print microarrays in a highly parallel way (see figure 6).

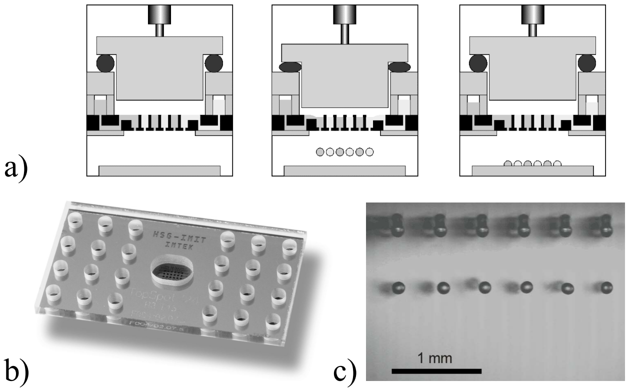

Fig. 6 a) Working principle of TopSpot b) TopSpot printhead c) parallel droplet ejection produced by shown printhead.

The TopSpot technology relies on a micro machined printhead which can be filled with different liquids. The liquids are transported from the reservoirs to the nozzles by capillary forces. The nozzles are pressurized from the back by a piezostack actuator driving a piston. The piston movement compresses the air in a closed cavity in the back of the nozzles and generates the required pneumatic pressure. The pressure pulse acts equally upon all the nozzles, causing them to simultaneously eject a single droplet. The process of liquid ejection is similar to inkjets discussed above. In the case of TopSpot however, the driving mechanism is based on pneumatic pressure. This fact illustrates once more the usefulness of the proposed classification scheme: Though a piezoelectric actuation is applied the liquid is in fact driven by the pneumatic pulse which finally results in a pressure BC at the back of the nozzles. Various kinds of actuators could be applied to achieve this operation.

The volume of the droplets ejected by TopSpot devices is typically in the order of 1 nL. The exact amount of the dosage volume is determined – like in inkjet devices - by a complex interplay between liquid properties and actuation parameters. Different volumes can be achieved by using different nozzle diameters and liquids.

5. CONCLUSIONS

As demonstrated by the presented examples there are many ways to overcome the critical Weber number and to produce droplets on demand. Each method can have its specific advantages and there is still room for new technologies to be invented. In principle dispensing of droplets is still only about actuating "*a fluid chamber with a small hole*". But this hole has to be driven *the right way.* And that is what makes things more complicated – and interesting.

REFERENCES

[1] H. P. Le, Journal of Imaging Science and Technology, vol. 42, no. 1, pp. 49-62, Jan.1998.
[2] J. Comley, Drug Discovery World, vol. summer 2004, pp. 1-8, July 2004.
[3] J. Ducrée, et al., in Proc. IEEE-MEMS 2007, Mizyazaki, Japan, pp. 317-322, 2000.
[4] D. Schuhmacher, et al., Proc. IEEE-MEMS 2007, Kobe, Japan, pp. 357-360, 2007.
[5] C. Weber, Zeitschrift für angewandte Mathematik und Mechanik, vol. 11, no. 2, pp. 136-154, 1931.
[6] W. von Ohnesorge, Zeitschrift für angewandte Mathematik und Mechanik, vol. 16, no. 6, pp. 355-358, 1936
[7] S. P. Lin and R. D. Reitz, Annual Review of Fluid Mechanics, vol. 30, pp. 85-105, 1998.
[8] E. R. Lee, Microdrop Generation, 1 ed. Boca Raton: CRC Press, 2002.
[9] W. Streule, et al. J. of the Assoc. for Lab. Automation, vol. 9, no. 5, pp. 300-306, Sept.2004
[10] A. Asai, et al., Journal of Imaging Technology, vol. 14, no. 5, pp. 120-124, Oct.1988.