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Dynamic nozzles for drop generators

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In this paper, a novel mechanism allowing greater control over the formation of droplets is presented. This is achieved via the use of a dynamic nozzle of adjustable diameter. It is demonstrated that, by using such a nozzle, it is possible to greatly modify the formation and breakup of the ligament behind the main drop, leading to an overall reduction in the number of satellite droplets. Furthermore, by adjusting the delay between the beginning of the forming of the drop and the start of the nozzle constriction, a greater control over both the number of satellites and the size of the main drop can be achieved. It is also shown that only a minimal reduction of the nozzle's effective diameter is required in order to exploit the positive effects of the technique presented here. This opens the possibility of incorporating the technique into current droplet generator systems, e.g., via the use of piezoelectric driven nozzles or other micro-mechanical actuation technology. © *2015 AIP Publishing LLC*. [http://dx.doi.org/10.1063/1.4934811]

I. INTRODUCTION

Inkjet is a non-contact and digital technique involving the use of liquid droplets to deliver precise quantities of material on to a substrate. Along with its current industrial applications, there is a growing interest in using inkjet for novel applications such as in electronics and 3D printing.[1] To date, however, the adoption of inkjet technologies into these and several other fields has been slowed down by the limited range of fluids with acceptable properties for printing, the limited resolution, and speed when compared with competing technologies. Overcoming these limitations requires an in-depth understanding of the fluid flows under the condition encountered in those systems, with recent works focusing on extending the material compatibility of droplet generators Refs. 2 and 3, increasing the resolution of current systems by reducing droplet size Refs. 4 and 5, and pushing up the speed at which printing can occur Refs. 6 and 7. However, for inkjet to become a viable technology in these up-and-coming areas of research, radical improvements over existing systems need to be attained.

Several methods exist to generate droplets and reviews of these can be found in Refs. 1 and 8. These methods include flow focusing[9] where coaxial flows break up a jet into droplets, Taylor cone[10] where a high electric field jets drops from a liquid surface, acoustic generators using focused acoustical waves to induce the pinch-off of droplets from a fluid pool,[3] and Worthington jetting where the collapse of a liquid cavity ejects droplets.[2] However, in industry, there are only two common methods to produce drops suitable for inkjet applications: continuous inkjet (CIJ) and drop on demand (DoD) printing. In CIJ systems, a constant pressure is maintained inside a chamber to produce a continuous jet through a nozzle. Surface instabilities are then induced to develop (through the imposition of pressure oscillations via piezoelectric elements) on the jet, breaking it up into a uniform train of droplets. These drops can then be steered in flight by an electrostatic field to produce a printed pattern. In DoD, an electrical signal, often referred to as the *waveform*, generates a short (single) pressure pulse via an *actuator*. This sudden increase in the pressure inside an ink chamber produces the ejection of fluid through a nozzle, initiating the formation of a droplet. Ideally, every pressure pulse produces one droplet, although it is not uncommon that in both techniques additional (usually undesired) smaller droplets called satellites are also generated.

Various forms of DoD actuation exist and these range from fast-acting heaters to piezoelectric elements, please refer to Ref. 11 for a complete review. Fast-acting heaters' printheads are commonly known as bubble jets as they heat up a fluid causing its rapid evaporation and forming a bubble. This process generates enough pressure inside an ink reservoir to eject fluid through a nozzle forming droplets.[12] Piezoelectric printheads have small ink containers in which walls are made of piezoelectric elements. Electric signals deform these walls causing a large pressure increase that is used to jet the droplets.[13] In DoD, at the start of the jetting process, the liquid emerging from the nozzle quickly begins to form what will become the main droplet. As the jet continues to emerge, a filament forms between the drop and the nozzle, connecting the fluid of the main drop and the fluid left at the reservoir. As the droplet formation progresses, the filament stretches and thins, until the action of the surface tension forces it to break up. At this point, the liquid that formed the filament, depending on the jet conditions, will either be reabsorbed (by either the drop or meniscus) or break up into a number of satellite drops.[14] If the filament does break up, the quality of the print will be affected as these droplets are hard to control due to their random size and speed. Satellite droplets are also known to cause printing failure, as they can be carried by air currents back to the nozzle plate and flood it. Current techniques aimed at controlling the creation of satellites have only two controllable parameters: the properties of the fluid being jetted, and the shape of the electrical waveform (and therefore the pressure signal) used to drive the actuator. In most cases, given its practical applications, it is not possible to greatly vary the properties of the liquid. This often leaves waveform variations (unfortunately restricted to the piezoelectric characteristics) as the only source for droplet control.

In this paper, a mechanism for changing the jetting behaviour of a DoD inkjet is presented and tested. The methodology consists of implementing a nozzle which controllably varies its size during the jetting (and drop formation) process for a better control of the filament breakup and satellites formation. This technique reduces the number of satellite droplets which in turn can increase the resolution of the printing process. It is also demonstrated that this mechanism can be utilized to control the size of drops on demand.

II. EXPERIMENTAL DETAILS

The layout of the experimental setup is outlined in Fig. 1. In brief, it consists of a large scale model of a printhead, with an iris acting as a nozzle of controllable diameter. The model consists of an electro-dynamic shaker, a liquid reservoir, and the nozzle array configured for drop-on-demand printing.[15] The reservoir is formed from three parts cut from 10 mm Polymethyl methacrylate (PMMA). These parts are aligned with a impermeable diaphragm interfacing between the top of the structure and the shaker to provide a seal. The actuator (a V200 series LDS Test and Measurement shaker) was utilized to produce the pressure pulses used to generate the drops. These signals were sensed by an Entran EPX-N12-1B pressure transducer. The pressure inside the reservoir is controlled as to prevent dripping and to keep the meniscus pinned to the nozzle (iris) as in all drop on demand systems.[15]

An eight leaves iris (Comar Instruments, maximum aperture of 8 mm) was fixed onto the bottom plate of the system (nozzle plate) as the nozzle. The iris was actuated via a small lever on the side of the rim, which for these experiments varied the aperture over a range from fully closed to 1.75 mm. A connecting rod attached this lever to a wheel driven by a stepper motor (Nanotec L4118L1804-T5X5 and SMCI12 controller).

A custom program written in JAVA triggered the waveform generator (that in turn drove the actuator), the imaging system, and also controlled the closing of the nozzle. When the system is initiated, a pulse generator (TTi TGP110) sends a single electric pulse to the shaker which pushes the diaphragm. This pressure increase in the reservoir causes the meniscus at the nozzle to begin to deform (first two steps in Fig. 2). The control program can, at any time, activate the action of

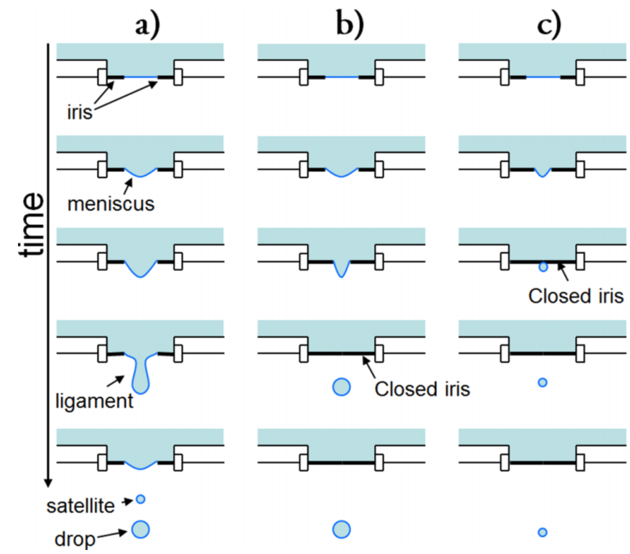

FIG. 2. Diagram illustrating the action of the iris and the dynamics of the meniscus in fully closing mode; (a) unmodified droplet generation, (b) closing of the iris as after the drop has formed and (c) premature closing as the droplet is forming.

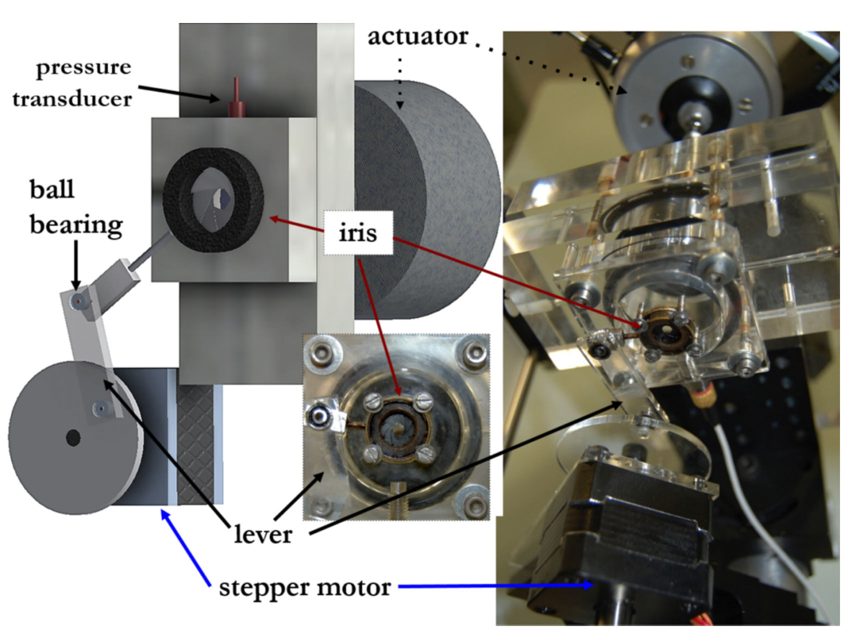

FIG. 1. Schematic diagram and pictures of the droplet generator system. The nozzle diameter and the meniscus dynamics are controlled by the action of a stepper motor through a simple lever system.

the stepper motor and adapt the size of the nozzle. This way, the deformed meniscus becomes a drop, until it is either fully ejected from the nozzle (as in a conventional DoD device) or cut down by the closing action of the iris (steps three and four). The timing of the closing action is critical, as a premature start affects the final size of the droplet, these differences are illustratively shown in Fig. 2. Experiments showed that nozzle actuation near the thinning phase of the ligament minimize changes on the main droplet size and speed while largely modify the breakup behaviour and the production of satellites.

The fluid used in all the experiments consisted of a solution of glycerol and water with a viscosity of 100 mPa s and surface tension of 0.064 N m^{-1}. The jetting conditions, i.e., waveform characteristics and maximum nozzle diameter (d_{max} = 1.75 mm), were chosen to produce jets with velocities within the range of 0.8–2.0 m s^{-1}. These conditions ensured similar dynamics to those typically found in inkjet applications, based on the Reynolds (Re) and Weber (We) numbers, i.e., $Re = \rho d_{max} v_n/\mu$ and $We = \rho d_{max} v_n/\sigma$, respectively, where μ, ρ, and σ are the viscosity, density, and surface tension of the working fluid, and v_n is the drop speed.[15] The values for these dimensionless numbers ranged from Re = 17 to 21 and We = 42–131, well within the printability region of commercial systems and inside the satellite-generation zone Refs. 16 and 17. All the experiments were carried out in air but their formation and breakup are not affected by gravity. In the conditions studied, the Bond number ($B = \rho g d_{max}^2/\sigma$) is $B < 0.6$ and droplets and satellites were smaller than the capillary length ($\lambda_c = \sqrt{\sigma/\rho g}$), i.e., $\lambda < 2.4$ mm. Therefore, gravity can be safely ignored here.[14] In addition, the dynamics of the outer fluid (air) only start to play a role at the nanometer range.[18]

Two studies are presented here. The pressure waveforms used for these are shown in Fig. 3, waveforms characteristics

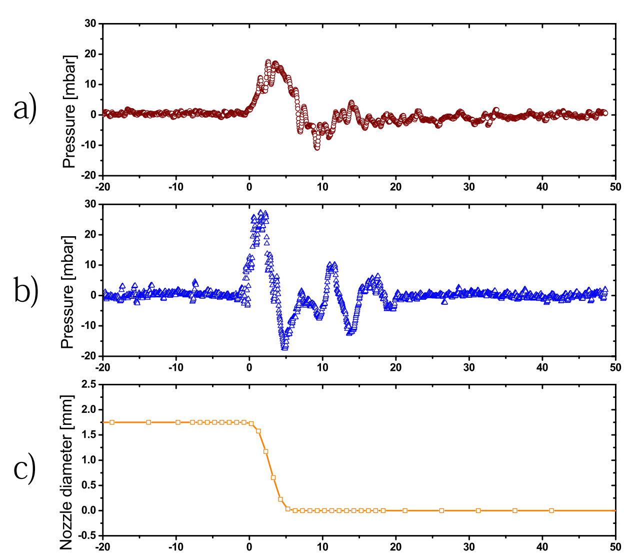

FIG. 3. Pressure waveforms used during these experiments. The waveform in (a) jets droplets with a short filament attached at 1.10 m s^{-1} for non-dynamical nozzles of 1.75 mm diameter. Waveform (b) jets droplets with a long ligament at 1.80 m s^{-1} for non-dynamical nozzles of 1.75 mm diameter. (c) shows the nozzle diameter as it varies in time after the closing action begins 1.25 ms after the arrival of the pressure pulse.

were chosen to resemble conditions and filament shapes as those found in industrial inkjet devices.[15] First, by varying the delay between the beginning of the pressure pulse (driven by the waveform generator) and the start of the closing action of the nozzle, allowed the study of the effect of constriction of the nozzle at different stages during the formation of the main drop. This was conducted by varying the delay between the trigger that initiated the waveform (and therefore the pressure change inside the fluid chamber) and the trigger that started the reduction in the diameter of the nozzle. The JAVA program simultaneously triggered both the action of the nozzle and the pulse generator. In the experiments, the timings were determined from the high speed images, captured at a rate of 3000 frames per second. Accordingly, the timing precision is <0.3 ms.

In a second set of experiments and in order to study the effect that the "degree of constriction" (defined as d_{min}/d_{max}) had over the dynamics of the drop, the formation/suppression of satellite and the final size of main drop, various final diameters (d_{min}) were tested while keeping d_{max} constant. Under this scenario, the controller was set to reducing the nozzle diameter from its maximum size of d_{max} to a desired d_{min}. Clearly, d_{min} could be chosen arbitrarily within a range from 1.75 mm to 0.00 mm (fully closed). For this second study, the delay between the pressure and nozzle actuation was kept constant at 1.25 ms.

A. Imaging system

High speed imaging was used to visualise the jetting and the iris action in these experiments. A Phantom V710 camera coupled to a Nikkor AF-S 18-55 mm lens were used in all the experiments. Two simultaneous views of the drop formation were captured using this camera. The first view was orientated perpendicular to the direction of the drop as shown in Figures 4 and 5. A second view, from below, focused on the nozzle dynamics and was provided with the use of a mirror just outside the path of the jet at roughly 45°. Care was taken to ensure that the depth of field was large enough that both views were in focus. The second view allowed to gather precise information of the relative delay between drop formation and the constriction action. The imaging system consisted of a 500 W incandescent light and a diffuser for back illumination (as in typical shadowgraphy) and a custom-made 100 W white light emitting diode for side/bottom illumination near the nozzle plate to capture the nozzle motion.

III. RESULTS

All the experiments were run an average of ten times, and the reported error in the droplet sizes and speeds take in account these variabilities. Figure 4 shows a set of results from the first study, the waveform used in this series corresponds to the one shown in Fig. 3(a). The first sequence, 4(i), shows a droplet forming without a shutting motion. This unmodified jet produces a ligament which forms a primary droplet of diameter of 2.1 ± 0.1 mm with a satellite of 1.2 ± 0.1 mm diameter. By comparison, the nozzle at the second sequence, 4(ii) begins to close 3.3 ± 0.3 ms after the start of the pressure pulse. This has

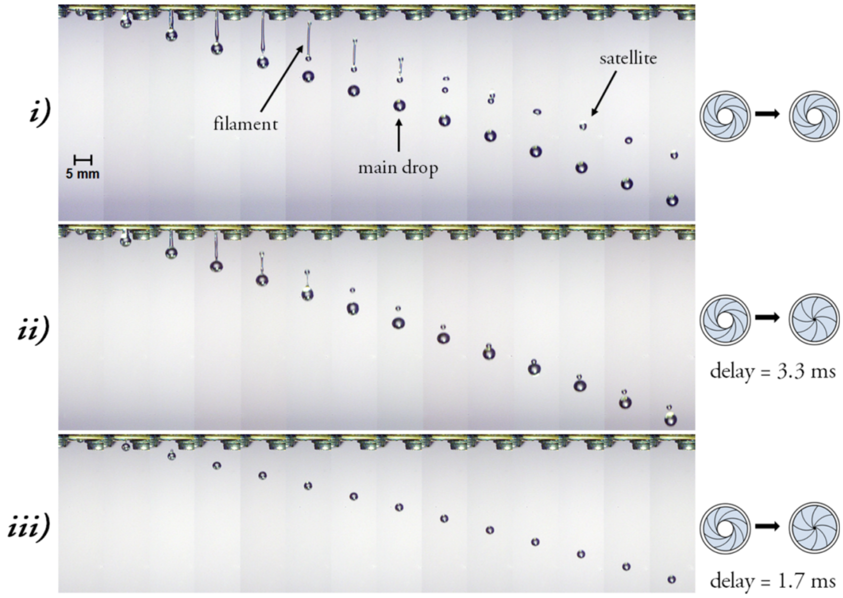

FIG. 4. Droplet generation in fully closed mode: (i) with no closing action, (ii) closing action as meniscus begins to form, and (iii) premature closing action. Frames increments in timesteps of 2.3 ms. Waveform presented in Fig. 3(a).

the effect of reducing the size of the satellite to 0.8 ± 0.1 mm and brings the satellite and main droplet much closer together, allowing for the possibility of re-merging of the drops. In both cases the size and speed (1.10 ± 0.05 m s^{-1}) of the main droplet are the same within experimental error. By closing the nozzle sooner, it is possible to completely remove the satellite; however, this also affects the size and speed of the droplet. In the example shown in Fig. 4(iii), with a delay of 1.7 ± 0.3 ms, the final droplet diameter is of 1.4 ± 0.1 mm while its final speed is of 0.81 ± 0.05 m s^{-1}.

Results from the second set of studies are presented in Fig. 5 where the waveform corresponds to the one presented in Fig. 3(b). This waveform has the effect of producing a faster droplet with a longer filament so the effect of the nozzle dynamics is easily observed. Figure 5(I) shows the jetting from a sessile nozzle while Figs. 5(II)–5(IV) show the jetting of various degrees of restriction. As observed in Fig. 5(II), changes in diameter as small as from 1.75 mm to 1.30 mm already yield noticeable effects on the behaviour and production of satellite droplets, i.e., reducing their final number from

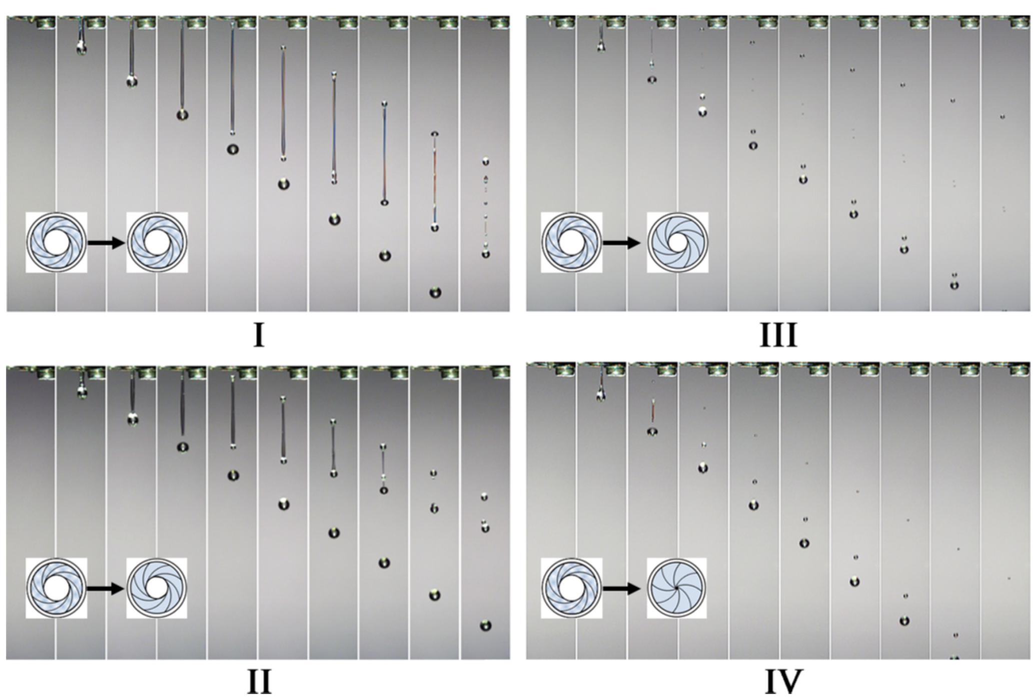

FIG. 5. Droplet generation in partially closed mode: (I) normal or no closing action produces a 2.1 mm diameter droplet with $v_n = 1.80 \pm 0.05$ m s^{-1}, (II) 25% closing jets a 2.1 mm main droplet at $v_n = 1.54 \pm 0.05$ m s^{-1}, (III) 50% closing ejects a 1.6 mm droplet at $v_n = 1.78 \pm 0.05$ m s^{-1}, and (IV) full closing action gets a 1.8 mm droplet at $v_n = 1.92 \pm 0.05$ m s^{-1}. Frames from left to right with increments in time-steps of 6.6 ms. The waveform used in these experiments is presented in Fig. 3(b) and the nozzle dynamics for (IV) is shown in Fig. 3(c).

10 to only 3. Under this settings, the size of the main droplet is not affected within experimental error but its speed is reduced. Larger changes in diameter produces more noticeable effects, a nozzle reduction down to 0.88 mm in Fig. 5(III), reduces the overall volume of satellites but not its numbers and also affects the main droplet speed and size. Further constriction to a final fully closed nozzle demonstrate that both the number and size of satellites can be greatly controlled and their behaviour affected. In the last two cases the speed of the main droplet is consistent, within experimental error, with the jetting from a sessile nozzle.

It has been demonstrated that the local dynamics at the thinning region rule the breakup behaviour of liquid filaments.[18] In the setup presented here, the closing action of the nozzle, the final size of the nozzle, and the characteristics of the waveform all affect the inner dynamics of the filament and consequently influence the droplet breakup dynamics. In commercial drop on demand systems great efforts are taken on the engineering of the waveform (this is often a try and error process) to find jetting conditions free of satellites.[13] Waveforms commonly have several parameters, such as multiple pulses with different amplitudes and widths. The experiments shown in this article demonstrate that both the timing of the nozzle closure and its extent can be used to achieve satellite free conditions. The parametric space of this or any other droplet generator is wide and includes variables such as the liquid properties, the dynamical response of the fluid, the mechanical response of the actuator, the waveform characteristics, and the nozzle dynamics.[5,13] Inkjet manufacturers explore this space as to find the best or desired conditions of jetting.

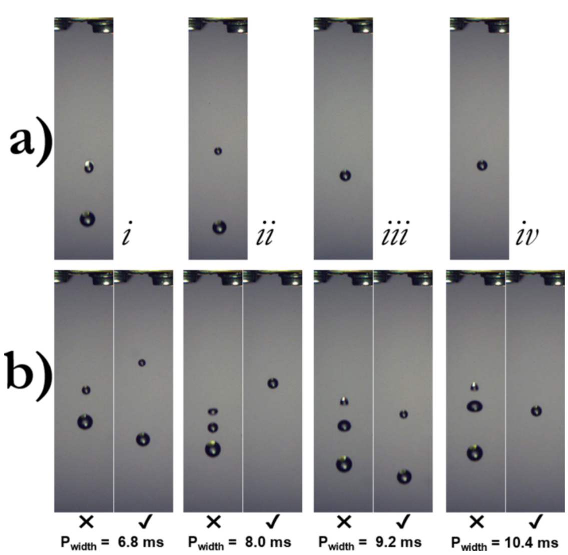

FIG. 6. Examples of droplets jetted under different conditions: (a) droplets produced by a nozzle that *i* does not close, *ii* fully closes 4.6 ms after the start of jetting, *iii* fully closes 3.3 ms after the start of jetting and *iv* closes after 2.3 ms. Examples in (b) compare droplets that are jetted by closing (✓) and non-closing (×) nozzles. In this series, droplets are jetted by an electric single-pulse waveform and (when indicated) the nozzle fully closes 3.3 ms after the beginning of jetting. The amplitude of the pressure waveform has a maximum at 18 mbar, as the waveform shown in Fig. 3(a), but the pulse width of the electric waveform is varied from 6.8 to 10.4 ms. The differences in jetting behaviour occur because the dynamical response of the fluid system, the response of the actuation, and the inner dynamics of the liquid filament formed after jetting are affected.

This work expands this parametric space by adding both the timing and extent of nozzle closure aiming to provide greater flexibility in droplet generator technologies. Figure 6 presents: (a) experiments where different nozzle closing times were explored for a fixed single pulse waveform and (b) a parametric study where the electric pulse width is varied. The examples in Fig. 6 demonstrate that both the waveform width and the closing action affect the jetting behaviour. In an industrial application, these two parameters would be varied along all the others until satellite-free or other desired conditions are found.

These experiments have demonstrated that both, the timing and the extent of closure, can be, additional to the pulse characteristics, used as variables to modify the behaviour of jetted droplets. Combining the timing and/or the extent of closure to the waveform characteristic should allow a greater control of satellites, a greatly desired aim in inkjet applications.

IV. CONCLUSIONS

The results presented here demonstrate that the use of a dynamic nozzle can lead to changes in drop volume and velocity, but more importantly, in satellite production. The ability of this technique to reduce the size and number of these auxiliary droplets could potentially be applied to increase the resolution and reliability of drop generators, i.e., inkjet printing. Consequently, this technology could have repercussions in printing applications where satellites are known to generate issues with the quality of the final print, i.e., single pass printing or the printing of electronics.

While waveform characteristics alone can significantly modify both the size and speed of jetted droplets and the number and size of satellites,[5] the method presented here also aims to introduce a greater control over the break up process in order to improve operational performance of droplet generators.

The results from this prototype demonstrate that by beginning the closing process prematurely, i.e., at the same time as drop formation begins, it was possible to reduce the volume of the generated drop. This could be useful in applications where smaller droplet size is desirable, for instance, high quality non-time-intensive prints. It is also an appropriate mechanism to vary the resolution on demand, i.e., grey-scale applications.

In this prototype, the nozzle takes ≈4 ms to progress from fully opened to fully closed (or otherwise), as seen in Fig. 3(c). The time to droplet detachment and jetting depends on the waveform and the closing action but it is in the range of 5–12 ms. Consequently, the prototype can be mechanically reset in 9–16 ms. Within these values, the prototype can print in the region of 63–111 Hz. In a micrometre commercial system (with 50 m nozzles), a droplet formation event normally last ≈30 μs.[13,19] Scaling down this technology would mean that the nozzle closing action (total or partial) should be carried out within a fraction of that total time in order to be effective. The reset time of the system presented in this work is limited by the responses the of stepper motor and the actuator, yet there are existing technologies that can be miniaturized and operated in the microsecond range, i.e., magneto-electro mechanical actuators, thermally actuated flexures, or piezoelectric actuators. In fact, several mechanical actuation methods already exist and are used commercially in inkjet applications, e.g., Silverbrook printheads use fast flexures to push the nozzle plate towards the ink reservoir to produce jetting,[20,21] and The Technology Partnership printhead consists of an axially vibrating nozzle actuated by piezoelectric elements.[22,23] Recent developments in microelectromechanical systems (MEMS) have demonstrated that micro-manufactured mechanical devices can work at the microsecond/micrometre regimes[24] potentially offering a possible means to produce dynamic nozzle designs at the right scales used inappropriate scales to be compatible with commercial inkjet technologies. The experiments shown here, in Fig. 5, demonstrate that only a partial reduction in the nozzle size is sufficient to produce a noticeable effect on the jetting process. This feature should facilitate the manufacturing and implementation of this technology into current commercial inkjet systems.

ACKNOWLEDGMENTS

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