Drop formation mechanisms in piezo-acoustic inkjet

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ABSTRACT

Inkjet developments in document printing move towards higher productivity and quality, requiring adjustable small droplet sizes fired at high repetition rates. New industrial applications increase the demands on drop properties and materials to be fired even further. Understanding the drop formation processes and all relevant phenomena is the basis for an own inkjet technology development.

Keywords: inkjet, drop formation, breakup, refill, wetting

1 INTRODUCTION

Inkjet is an important technology in document printing and many new industrial applications. Océ applies inkjet in its wide format color printing systems. New developments move towards higher productivity and quality, requiring adjustable small droplet sizes fired at high repetition rates. The popularity of inkjet as manufacturing technology is closely related to its unique ability to deposit various types of materials on a substrate in well defined patterns. Understanding the drop formation process and all relevant phenomena is the starting point to control drop formation, reduce cross-talk effects and to achieve a maximum reliability, necessary for all productive applications. This paper describes the main mechanisms involved in the drop formation process.

2 OPERATING PRINCIPLE

Drops are generated using a piezo inkjet device and measured with stroboscopic illumination at drop formation rate for the reproducible part of the drop formation or high-speed camera recordings for the non-reproducible phenomena. Meniscus movements without drop formation can be recorded with laser-Doppler measurements. All these measurements give details on ink flow outside the printhead. The phenomena inside the channels are hard to measure. The main experiment involved uses the actuator also as a sensor. Switching the piezo elements from the electronic driving circuit to a measuring circuit gives a recording of the average pressure inside the ink channel and enables monitoring of jetting stability [1] and feed-forward control of the driving waveform [2]. We need more information on the phenomena preceding the drop formation for a better understanding of the physical processes. Details on ink flow and acoustic pressure waves are only available through modeling [3].

2.1 Acoustics

A long ink channel with a nozzle at the right and a large reservoir at the left is the simplified geometry of the inkjet device as shown in Figure 1. A piezo actuator element drives each channel. To fire a droplet, an electric voltage is applied and the channel cross-section will be deformed by the inverse piezo-electric effect. This results in pressure waves inside the channel. The pressure waves propagate in both directions and will be reflected at changes in characteristic impedance (variations in cross-section and compliance of the channel structure).

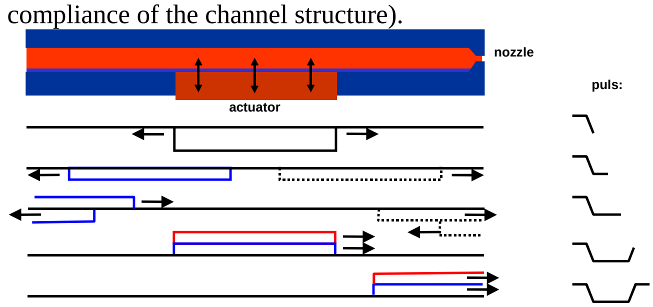

Figure 1: Actuation with channel acoustics.

The first slope of the driving waveform enlarges the channel cross-section and the resulting negative pressure wave will be reflected at the reservoir at the left. The reservoir acts as an open end and the acoustic wave returns as a positive pressure wave. The second slope of the driving waveform removes the driving voltage. This will reduce the channel cross-section to its original size and will amplify the positive pressure wave when tuned to the travel time of this acoustic wave. The resulting pressure just before the nozzle is shown in Figure 2.

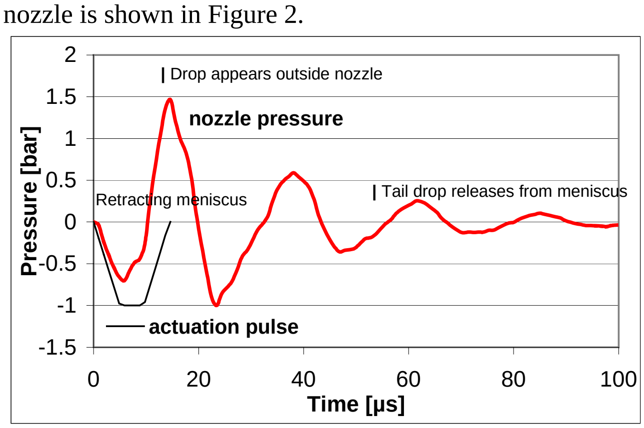

Figure 2: Calculated [3] pressure just before the nozzle.

In this case the channel geometry and driving waveform are designed to generate a large incoming positive pressure peak at the nozzle, which drives the ink through the nozzle. Acceleration of the ink movement in the small cross-section of the nozzle results in drop formation.

2.2 Drop formation

The drop formation process with an 8 mm long channel geometry is shown in Figure 3. After 15-20 µs, the time period during which the meniscus surface is retracted, also known as the fill-before-fire action, the head of the drop appears outside the nozzle with a relatively high speed. The head of the drop drags a long tail along. This slows down the head of the drop to the final drop speed of 5-9 m/s. The speed of the head at the beginning of the drop formation is 15-25 m/s and the tail breaks off after 55-60 µs resulting in a several hundred µm long tail.

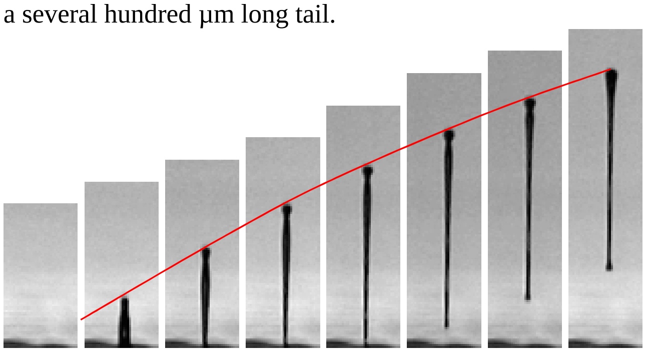

Figure 3: Measured drop formation at 10, 20…80 µs after start actuation with an 8 mm channel geometry.

3 TAIL BREAKUP

Tail properties and breakup are mainly determined by ink properties as surface tension and viscosity. The shape of the tail is highly affected by ink viscosity and not by the shape of the driving waveform and the channel geometry. High viscous inks show long symmetric tail shapes, moderate viscous inks long asymmetric tail shapes and low viscous inks show short tails [6].

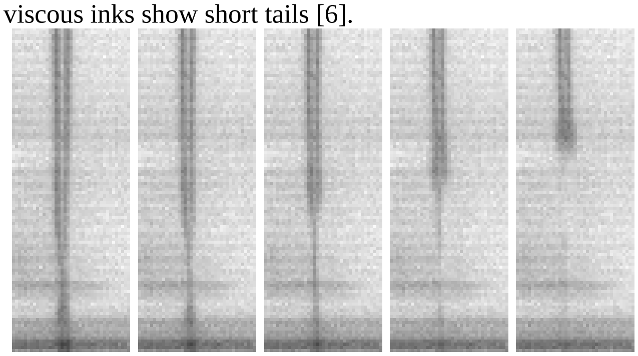

Figure 4: Measured formation of a secondary tail.

At break-off, a secondary tail is formed, Figure 4. The diameter of the secondary tail is only about 1 µm, which is close to the optical resolution, and visible over 5-10 µs between the main tail and the meniscus surface in the nozzle.

The formation of a secondary tail is a consequence of going through three flow-regimes [4] with different dominating forces [5]. First the tail width decreases slowly with only viscous forces and surface tension forces playing a role. Then, when the tail tends to break off, a third force, inertia, becomes important, and tail width decreases fast. Viscous forces play no role when the tail width becomes smaller than the viscous length scale. With two remaining forces, surface tension and inertia, the tail width again decreases slowly. These phenomena can be described with scaling laws [6] and also by numerical modeling with Flow3D, Figure 5.

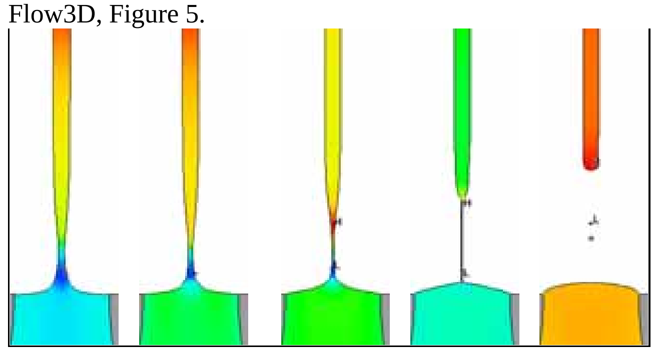

Figure 5: With Flow3D® calculated formation of a secondary tail.

The small secondary tail breaks up in very small droplets, which are dragged along with an air-flow induced by the firing sequence of drops [7]. This results in a mist of tiny droplets. After break-off the main tail-end tends to form a drop, Figure 6, which accelerates the tail-end.

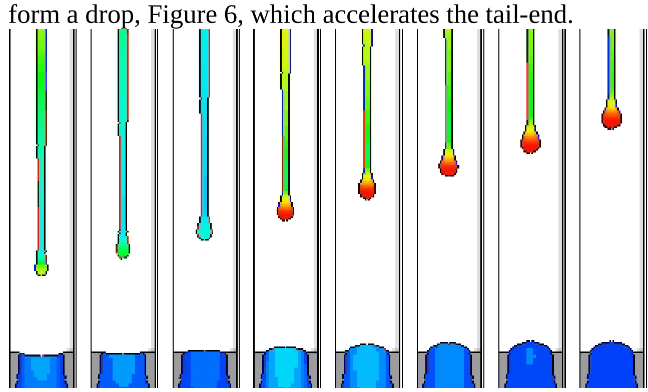

Figure 6: Flow3D® simulation of a tail drop.

The whole sequence of events results in a tail-end speed as shown in Figure 7. The tail-end moves with meniscus speed, accelerates after break-off to the speed as predicted with the scaling theory for the side with smallest curvature, denoted as Eggers-tail. Then it slows down to the speed for the side with largest curvature after break-off of the secondary tail, denoted as Eggers-head, and accelerates again because of the formation of a tail drop as shown in Figure 6.

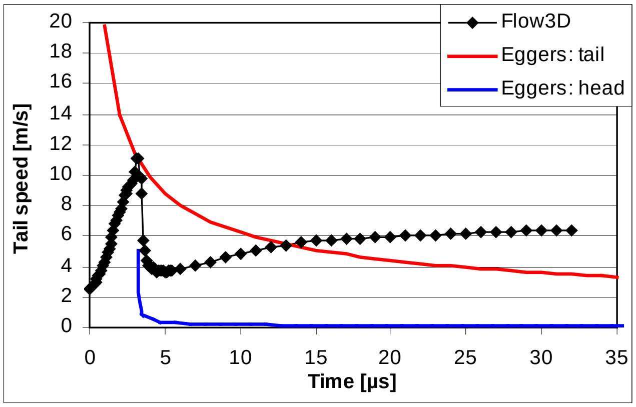

Figure 7: Calculated speed of the tail-end.

4 SATELLITE DROPS

The speed of the tail-end is not affected by the shape of the driving waveform, whereas the head of the drop is highly affected by the driving amplitude. This can be seen in the positions of the tail-end and the head of the drop at different driving voltages, both in the measurement and the Flow3D simulation in Figure 8a. This means that long tails will be formed when the drop speed exceeds the speed of the tail. This is especially the case with inks of high viscosity.

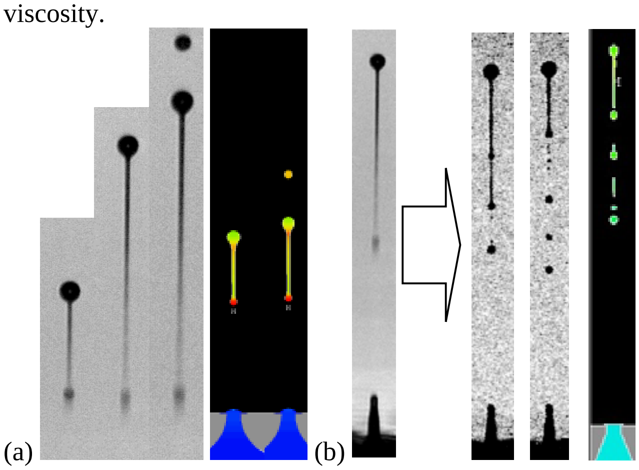

Figure 8: Tail speed at different drop speed (a) and Rayleigh instability with long tails (b).

When the head of the drop has a higher speed than the tail-end, a long tail is formed which breaks up non-reproducible into satellite droplets. In the mostly used stroboscopic recordings this is visible as a smooth tail, but high-speed recordings and Flow3D simulation show the real nature, Figure 8b. This is the well-known Rayleigh instability, initiated by surface tension driven capillary waves, which have to overcome inertia and viscous effects. The non-reproducible breakup of a long tail is the first of three satellite drop formation mechanisms that can have a negative impact on the jetting performance.

At very high drop speed, fast satellite drops are formed reproducibly, Figure 8a. A part of the drop moves away in front of the head of the drop. This happens when the first acceleration of the ink exceeds a certain critical level, where surface tension forces are no longer capable of holding the amount of ink together, Figure 9a. A maximum in the distribution of the speed of the ink inside the drop, as indicated in Figure 9a, remains also at the front of the head. This shows that this part of the head keeps moving away from the rest of the drop. Normally a maximum occurs only behind the head of the drop, meaning that ink flows from the tail to the head of the drop to form a spherical drop. The first negative pressure peak, which determine the amount of ink at the start of the drop formation, and the amplitude of the main positive pressure peak are the key numbers in the fast satellite drop formation mechanism.

The third satellite drop formation mechanism results in slow satellites, formed reproducibly from the tail of the drop when the distribution of mass and momentum in the drop are not optimal, Figure 9b+9c. Now the tail breaks off from the head and forms a slower moving droplet. The shape of the pressure wave after the main positive pressure peak is important for this mechanism.

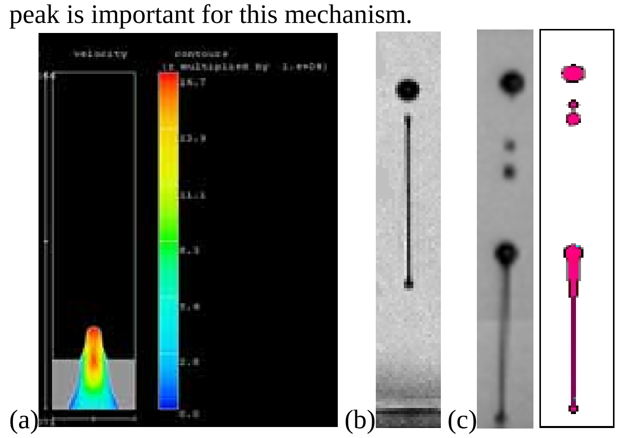

Figure 9: The formation of a fast satellite (a), and slow satellites with very long driving pulse width (b) or at high drop repetition rates (c) as measured and calculated.

5 REFILL AND WETTING

A very important effect of the interaction between the flow in the nozzle and the acoustics in the channels is the refill of the nozzle after a drop is fired. Meniscus movement in the nozzle affects the channel acoustics by changing the nozzle impedance or reflection conditions. As long as acoustic pressure waves are going on, the refill is driven by the variable mass effect in the nozzle. The variable filling of the nozzle results in an asymmetric acceleration of the ink in the nozzle, which is opposed by the micro-pump effect and an acoustic coupling effect. When the acoustic pressure waves have come to rest, the capillary forces take over.

NSTI-Nanotech 2007, www.nsti.org, ISBN 1420061844 Vol. 3, 2007

In order to fire drops at very high repetition rates, free surface flow in the nozzle and the acoustics in the channel are designed to give a very strong refill of the nozzle. This can however lead to overfill at low frequencies [3]. As a result in some cases wetting of the nozzle-plate occurs. With wetting all kind of flow phenomena on the nozzle-plate are visible [8] like Couette type of flow, due to an interaction with the induced air flow, Hele-Shaw like dipole flows from non-firing nozzles and Marangoni flows initiated by the variation of ink properties. An important negative consequence is that wetting can result in air entrapment at the meniscus surface, which can be the first step to nozzle failure [9].

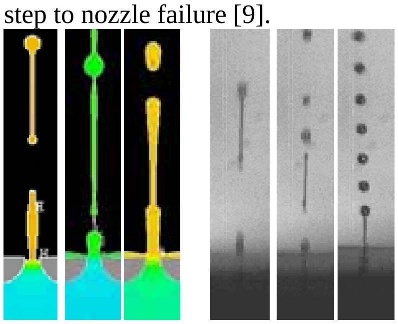

Figure 10: Calculated and measured impact of an ink layer on drop formation at 30 µs from start actuation.

Drop formation is affected as well, Figure 10. Drops will move slower because of the extra resistance of an ink layer on a nozzleplate and will become larger because some ink of the ink layer is dragged along with the drop formation.

6 DROP SIZE

As a first order approximation of the drop size we can take a cylinder as the shape of the ink column transported outside with a volume of nozzle size times length of the cylinder. The length of the cylinder equals the drop speed times drop formation time. Important parameters for the drop formation time are the width of the driving waveform, the travel time of the acoustic wave, the nozzle shape (by its impact on the acoustic impedance) and ink properties as viscosity and surface tension. The travel time of the acoustic wave is a function of the channel length, the inlet geometry (because of the phase shift of the reflected wave) and the effective speed of sound inside the channel. The effective speed of sound is a function of the speed of sound of the ink itself and the compliance of the channel cross-section. The compliance reduces the effective speed of sound as predicted by the narrow-gap theory implemented in our acoustic modeling [3].

Firing drops with maximum efficiency results in a default drop size. For printing application often the drop size is changed during printing, drop size modulation (DSM). Up to eight mechanisms give a drop size variation range of 1:10 with one printhead geometry [10]. First, DSM can be achieved by modifying the pulse width and changing the fill-before-fire level. Next, droplet size can be enlarged by using acoustic resonance, either by pre-actuating the meniscus movement or by firing bursts of multiple drops in phase with the channel acoustics. Drop size can be reduced using break pulses, especially when combined with a satellite drop formation mechanism. Finally meniscus resonance and drop formation resonance can be used.

7 CONCLUSIONS AND OUTLOOK

Understanding the drop formation process is the first step to realize a maximum jetting stability and to control and manipulate the drop formation with drop size modulation as an example. With our modeling we can predict the resulting drop properties very accurate and we can identify potential new inkjet devices by exploring new actuation principles, new acoustic principles and new drop formation mechanisms. Future developments will move more and more towards the generation of smaller and larger drops and will go to higher drop-on-demand frequencies. We will also explore the behavior of new materials, even the jetting of pure metals is one of the applications.

ACKNOWLEDGEMENTS

Thanks goes to my Océ colleagues Hans Reinten, Marc van den Berg, Wim de Zeeuw and PhD students Jos de Jong, Matthijs Groot Wassink and Roger Jeurissen. The group of Henk Tijdeman of Twente University for their work on the narrow-gap theory, the group of Detlef Lohse of Twente University for their work on bubble behavior, the group of Rinie van Dongen of the Technical University of Eindhoven for their work on wetting behavior.

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