This highlight refers to the PhD Thesis by Maaike Rump (2022)

Meniscus dynamics and evaporation in inkjet printing

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There are many challenges encountered in the inkjet printing process when droplets are desired to be jetted with a higher velocity or smaller volume, or have a multicomponent composition. The phenomena studied in this thesis are the bubble entrainment from an oscillating meniscus, the meniscus shape as function of the driving frequency, the measurement method of the liquid composition in the nozzle during drying via the acoustics in the channel, and the role of surfactants on the droplet formation.

Bubble pinch-off

We studied the bubble pinch-off from an oscillating meniscus in an optically transparent DOD printhead as a function of the driving waveform. We show that bubble pinch-off follows from low-amplitude high-frequency meniscus oscillations on top of the global high-amplitude low- frequency meniscus motion that drives droplet formation. In a certain window of control parameters, phase inversion between the low and high frequency components leads to the enclosure of an air cavity and bubble pinch-off. Although phenomenologically similar, bubble pinch-off is not a result of capillary wave interaction such as observed in drop impact on a liquid pool. Instead, we reveal geometrical flow focusing as the mechanism through which at first, an outward jet is formed on the retracted concave meniscus. The subsequent high-frequency velocity oscillation acts on the now toroidal-shaped meniscus, and it accelerates the toroidal ring outward resulting in the formation of an air cavity that can pinch-off. Through incompressible boundary integral simulations we reveal that bubble pinch-off requires an unbalance between the capillary and inertial time scales and that it does not require acoustics. The critical control parameters for pinch-off are the pulse timing and amplitude. To cure the bubble entrainment problem, the threshold for bubble pinch-off can be increased by suppressing the high frequency driving through appropriate waveform design.

We continued our study using ultrafast X-ray phase-contrast imaging and direct numerical simulations to study the factors underlying bubble entrainment in a piezo-acoustic printhead. We first demonstrate good agreement between experiments and numerics. The numerical results are then used to show that the baroclinic torque that is generated at the gas-liquid interface due to the misalignment of density and pressure gradients, results in a flow-focusing effect that drives the formation of the air jet from which a bubble can pinch-off.

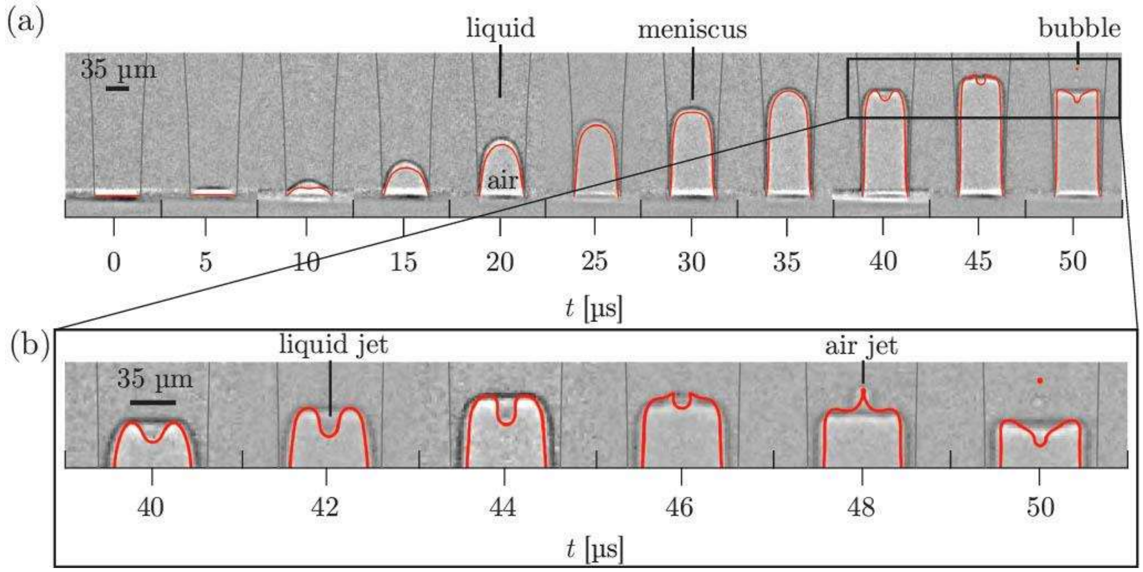

Figure 1: (a) Meniscus position during different time instants of the bubble entrainment phenomenon as observed in the experiment (grayscale images) and the numerical simulations (red curves) for V_{max} = 70V and τ = 34 µs. (b) A zoomed-in image of the same bubble entrainment phenomenon. The outline of the nozzle is highlighted with gray lines.

Shape of the oscillating meniscus

We obtained experimental time-resolved 3D topography profiles of an oscillating meniscus driven at frequencies from 1 kHz to 400 kHz with an accuracy of length scales down to tens of nanometers and microsecond timescales. Furthermore, we obtain the resonance curve for multiple axisymmetric and non-axisymmetric modes of the system. The resonance frequency does not correspond to the eigenfrequency obtained from the capillary dispersion equation for an undriven system. The resonance frequencies for a driven system determined using boundary integral simulations show an improved understanding of the system.

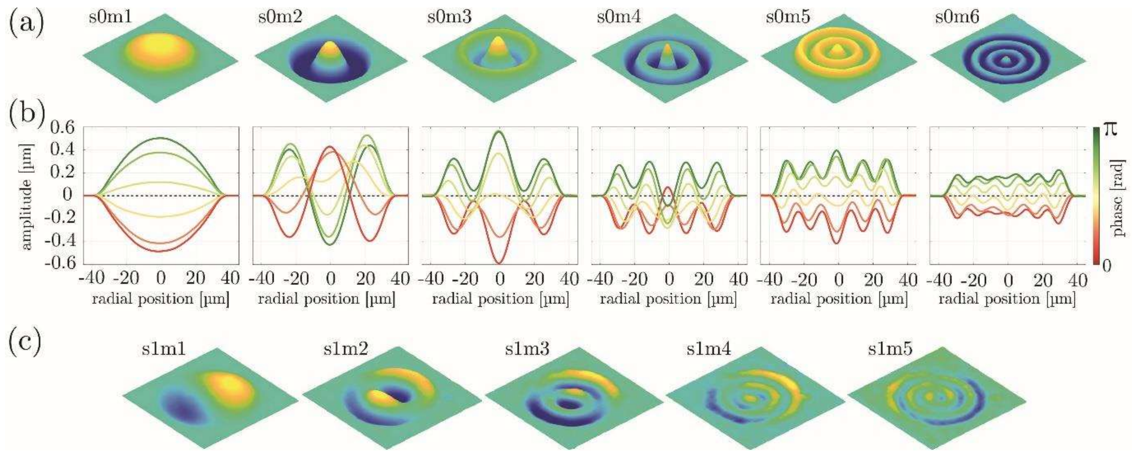

Figure 2: Measured axisymmetric surface oscillation shapes obtained at different frequencies and a nozzle radius of 35 μm and (b) the corresponding cross sections. (c) Measured non-axisymmetric surface oscillation shapes using the same nozzle.

Selective evaporation

We studied selective evaporation from an inkjet nozzle for water- glycerol mixtures. Through experiments, analytical modeling, and numerical simulations, we investigate changes in mixture composition with drying time. By monitoring the acoustics within the printhead, and subsequently modeling the system as a mass-spring-damper system, the composition of the mixture can be obtained as a function of drying time. The results from the analytical model are validated using numerical simulations of the full fluid mechanical equations governing the printhead flows and pressure fields. Furthermore, the numerical simulations to reveal that the time independent concentration gradient we observe in the experiments, is due to the steady state of water flux through the printhead. Finally, we measure the number of drop formation events required in this system before the mixture concentration within the nozzle attains the initial (pre-drying) value, and find a stronger than exponential trend in the number of drop formations required.

Furthermore, we studied the influence of surfactants on droplet formation in piezo-acoustic inkjet printing while we vary the time between the formation of two successive droplets over 5 orders of magnitude, i.e., from microseconds to minutes. During jetting, a large amount of new surface area is created when the liquid is ejected from the nozzle. Jetting occurs on a microsecond timescale, which is shorter than the typical timescale of surfactant adsorption. Here, we vary the time between the ejection of two droplets to allow surfactants to accumulate on the meniscus. At a waiting time of milliseconds to one second, we observe a change in break-up dynamics, but no effect on the droplet velocity and volume. When the waiting time is longer than one second, when evaporation starts to play a role, the droplet velocity and volume increases. We measured the surface tension of the ejected droplets from their dynamics in flight, which showed that the increased local concentration of surfactant due to evaporation allows for faster surfactant adsorption on the freshly formed surface. Interestingly, increasing the bulk concentration of surfactant does not lead to an increase in droplet velocity, as viscosity starts to play a role as well. Thus, the increased local concentration of surfactant due to evaporation is required to increase the droplet velocity. Numerical simulations demonstrate that the increased concentration at the nozzle exit covers the droplet during the droplet formation process, thereby allowing for surfactant adsorption along the freshly formed surface.

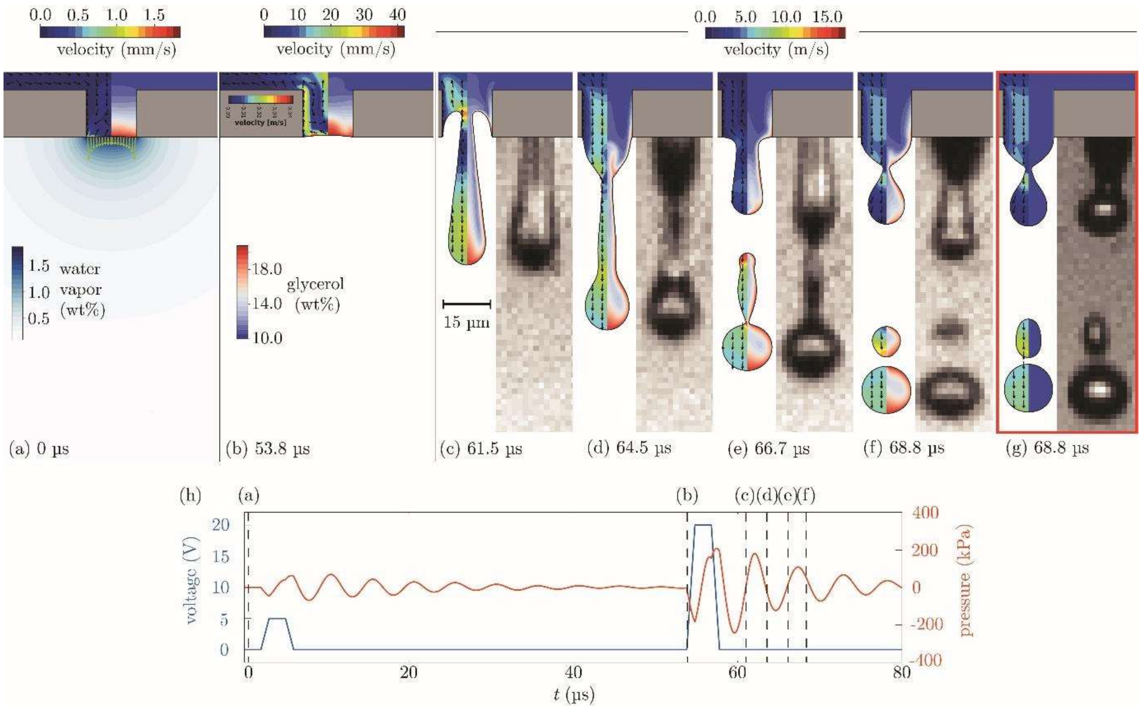

Figure 3: Snapshots from numerics and the corresponding experiment for the droplet formation process with a drying time of 100 ms (Movie available online). The numerical simulations provide two colour schemes inside the liquid: the left-hand side of the nozzle shows the velocity profile while the right-hand side shows the glycerol concentration. The water evaporation rate is around 100 g/(m2s). Snapshots (a) and (b) show the nozzle before droplet formation, and (c)-(f) show the droplet formation process. (g) Snapshot at same time as (f) but for the case of 1.5 ms drying time. (h) Demonstrates the actuation pulses (blue) and numerical pressure signal in the link chamber (red), where the time instants of the snapshots are also indicated.

Reference

Maaike Rump, 2022. Meniscus dynamics and evaporation in inkjet printing. PhD Thesis, Twente University of Technology.