Nozzle Wetting Dynamics on Inkjet Printhead and its Impact on Jetting

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Abstract

As the drop formation from the inkjet nozzle strongly depends on the meniscus shape and position, how inks wet around and inside the nozzle is crucial for inkjet printing. The wetting dynamics can affect drop velocity/volume, straightness, and jetting robustness. This effect becomes more significant at high jetting frequencies because the meniscus has no time to recover between ejections. In document printing, it is possible to engineer inks to mitigate wetting induced problems and optimize the jetting performance. As the inkjet technology expands to digital fabrication, the wetting is not an ink engineering problem any more since one printhead must jet tens of different inks. This work can help to better understand the nozzle wetting dynamics and can provide valuable insight for selection of anti-wetting material and coating process for better jetting performance.

Introduction

Inkjet is an important technology in document printing and now expands to many new digitial fabrication applications [1]. The excellent jetting performance is the key to be successful in these new markets [2, 3]. Since each industrial printhead usually has hundreds of nozzles, the jetting performance of a printhead is not only affected by the single nozzle performance but also affected by the nozzle to nozzle variation. At low jetting frequencies, the drop to drop variation on the same nozzle is small and the nozzle to nozzle variation can be minimized by controlling each nozzle differently. However, the operation frequency of industrial printheads is very high due to the demanding throughput. The jetting performance becomes more difficult to control at high jetting frequencies because the earlier drop ejections strongly affect the next drop ejection. The cause of drop interference comes in two folds: excessive residual energy and nozzle meniscus condition.

The drop to drop varaition and the nozzle to nozzle variation can be huge if the nozzle wetting is not well controlled since the drop formation strongly depends on the meniscus shape and position. An antiwetting material can be applied to coat the printhead front surface to control wetting. In document printing, it is possible to engineer inks to be compatible with the antiwetting coating. As inkjet technology expands to digitial fabrication where many different inks, especially the low surface energy inks, are used, ink engineering becomes inadequate and a more robust antiwetting material and a better coating process are needed.

Nozzle Wetting Dynamics

We focus on piezoelectric inkjet printhead in this paper. A schematic diagram of a nozzle with an antiwetting coating is shown in Figure 1a. After a drop is ejected from a piezoelectric inkjet nozzle, the ink inside the nozzle and its meniscus oscillate under the oscillating residual pressure of the inkjet channel. Under the large positive pressure, the nozzle is filled with ink and the meniscus is pushed outward as shown in Figure 1b. Under the large negative pressure, the meniscus is pulled back and forms an inward shape as shown in Figure 1c. The oscillation energy is eventually damped out by viscous force. If we assume the residual energy is mainly dissipated by the viscous force in the nozzle, the damping time can be estimate by the viscous time scale $t_\eta \sim \rho r^2/\eta$, where ρ is ink density, η is ink viscosity, r is nozzle radius [4]. A typical damping time is tens of microseconds. After residual pressure is damped, the meniscus starts to slowly recover its initial static condition. To describe a meniscus condition, we can use the meniscus position (the three-phase contact line position) and the meniscus shape.

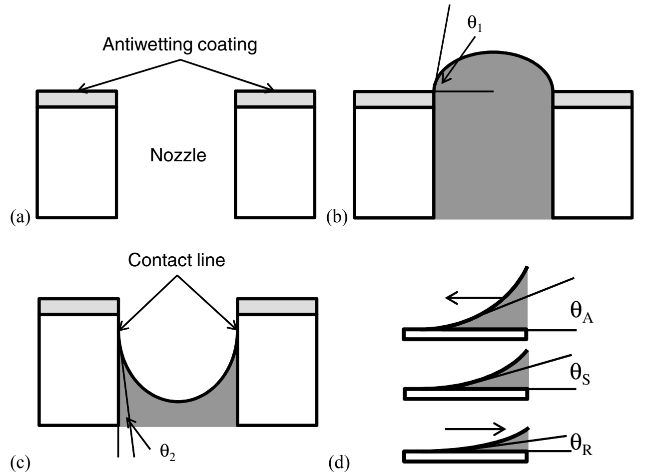


***Figure 1**. (a) An empty nozzle with an antiwetting coating on the top surface. (b) The meniscus is pushed outward and the contact line is hold by the antiwetting coating on the nozzle edge. (c) The meniscus is pulled inward and the contact line moves into the nozzle. (d) The static contact angle, advancing angle, and receding angle at the three-phase contact line.*

Because the meniscus movement is dynamic, a static contact angle is not sufficient for calculating the contact line movement; instead a dynamic contact angle model incorporating contact angle hysteresis is needed. As illustrated in Figure 1d, θ_S is the static contact angle at equilibrium; when contact line slowly advances or recedes, an advancing angle θ_A or a receding angle θ_R is formed respectively. If the apparent contact angle θ_0 is between θ_R and θ_A, the contact line cannot move. The threshold forces per unit length to advance or recede the contact line are $f_A = \gamma(\cos\theta_S - \cos\theta_A)$ and $f_R = \gamma(\cos\theta_R - \cos\theta_S)$ respectively, where γ is ink surface tension [5]. The net contact line move direction during oscillation is determined by $\Delta f = f_A - f_R$:

$$\Delta f = \gamma[\sin\theta_S(\sin\Delta\theta_A - \sin\Delta\theta_R) + \cos\theta_S(2 - \cos\Delta\theta_A - \cos\Delta\theta_R)] \quad (1)$$

where $\Delta\theta_A = \theta_A - \theta_S$ and $\Delta\theta_R = \theta_S - \theta_R$, $\Delta\theta_A$ and $\Delta\theta_R$ are usually different.

The nozzle wall typically has a very small θ_S for better ink wetting, leading to a very small Δf and thus a symmetric contact line movement on the wall. If the θ_S on the wall is large and $\Delta\theta_R$ is much larger than $\Delta\theta_A$, f_R will be much larger than f_A, e.g., $\Delta f = -0.25\gamma$ for $\theta_S = 60°$, $\Delta\theta_A = 10°$, and $\Delta\theta_R = 35°$, therefore the contact line will advance forward more easily than recede from the nozzle edge.

Outside of the nozzle, the meniscus is held by the antiwetting coating at the nozzle edge as shown in Figure 1b. The contact angle θ_1 must be smaller than θ_A to stop contact line movement. If the peak hydrodynamic force on the contact line is larger than $f_A = \gamma(\cos\theta_S - \cos\theta_A)$ during jetting, the ink expands onto the printhead front surface.

It is well known that the density, surface tension, and viscosity of inks strongly influence the drop formation. On the other hand, it is not guaranteed that inks with the same density, surface tension, and viscosity have the same jetting performance in the same printhead. This is because the different θ_S, θ_A, and θ_R lead to different meniscus conditions and therefore different drop formations. In Figure 2, we use a series of flow3d® simulations to demonstrate the significant influence of the meniscus position and shape on the drop velocity.

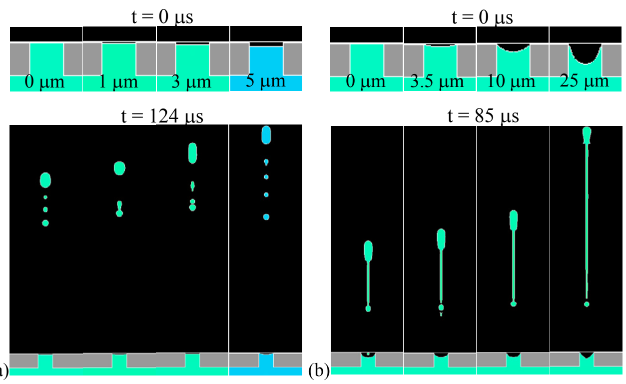


***Figure 2**. (a) Flow3d® simulation of drop ejections from nozzles with different initial meniscus positions. (b) Flow3d® simulation of drop ejections from nozzles with different initial menisucs shapes.*

In our flow3d® simulations, the same cylindrical nozzle is implemented and the same pull-push pressure profile is supplied on the nozzle entrance boundary. For the first simulation, we chose flat initial menisci with 4 different initial contact line positions (0 µm, 1µm, 3µm, and 5µm away from the nozzle edge respectively) as shown in Figure 2a. The drops travel at different velocities after ejection as evidenced by the distance from the nozzle at t = 124 µs. The velocity increases with the gap between the initial meniscus position and the nozzle edge. Next we fix the initial contact line position, and chose 4 different initial menisci of concave shapes (0 µm, 3.5µm, 10µm, and 25µm between its bottom and its top respectively) to run the second simulation. From Figure 2b, it clearly shows that the drop travels faster when the initial meniscus is more concave.

Different Nozzle Wetting Scenarios

In this section, a number of scenarios are analyzed based on simulations and experiments in order to demonstrate the importance of the nozzle wetting dynamics in inkjet printheads.

Degradation of Antiwetting Coating

The antiwetting coatings are made from low surface energy materials and their quality strongly depends on their material properties as well as the coating process. Any defect such as pinhole, impurity, weak adhesion, and poor mechanical strength, certainly leads to the degradation of the antiwetting coating. A good antiwetting coating has to survive ink soaking as well as the printhead maintenance. When new developed inks are not compatible with the current antiwetting coating, the undesired jetting occurs and gradually worsens over time.

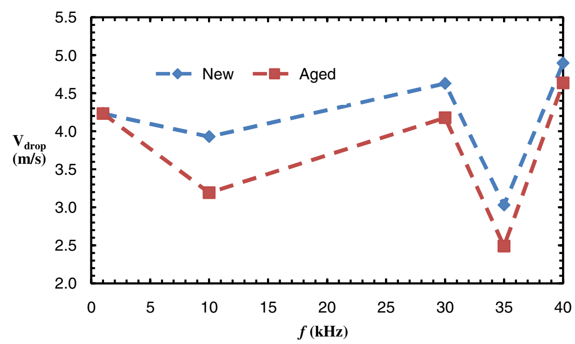


***Figure 3**. The average drop velocity changes over time as the antiwetting coating degrades.*

We measured the average drop velocity of one problematic ink on the same printhead at two different days as shown in Figure 3. When the coating is new, it could hold the meniscus at the nozzle edge across all frequencies. After the coating aged, the contact angle decreased, and the ink expanded onto the front surface under large hydrodynamic force. At 1 kHz jetting frequency, the drop velocity did not change because the meniscus had enough time to withdraw into the nozzle between ejections. However, a pool of ink formed outside the nozzle and hindered the drop emergence at high frequencies.

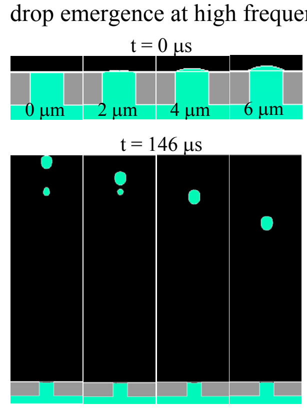


***Figure 4**. Flow3d® simulation of drop ejections from nozzles with different amounts of ink outside the nozzle in the initial condition.*

To understand the effect of ink pool, the results of the simulation for different amounts of ink outside the nozzle are presented in Figure 4. The drop velocity is reduced when there is more ink in the ink pool. This is consistent with the experimental results in Figure 3.

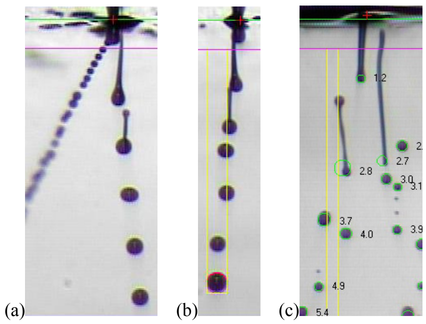
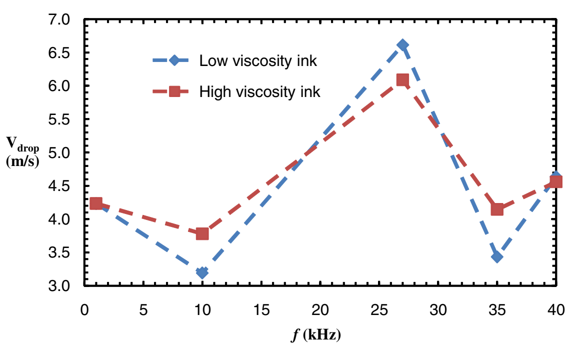


***Figure 5**. Images acquired from the strobe stand provided by Palo Alto Research Centre (PARC): (a)Satellites and misdirection. (b) Multi-mode drop formation. (c) Eruptive behavior before ceasing ejection.*

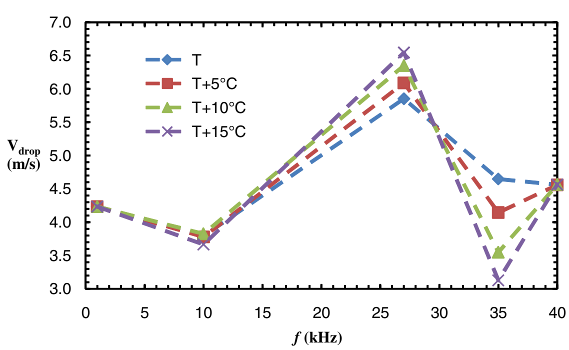
When the aniwetting coating failed to prevent the ink forming a large pool outside the nozzle, poor drop formation happened, leading to severe problems including satellites, misdirection, unstable ejection, and ceasing ejection as illustrated in Figure 5.

Viscosity Effect

The contact line movement is driven by the capillary force and is retarded by the viscous force. As the ink viscosity increases, we expect a slower contact line movement and less variation of the meniscus position across different frequencies. Figure 6 presents the experimental results to support this argument. The average drop velocities of two inks that have the same properties except viscosity are shown in Figure 6a. The voltage was adjusted to compensate for the viscosity difference at 1 kHz. A smaller velocity variation (the peak-to-valley change) was found for the higher viscosity ink, indicating a smaller meniscus movement. Similarly we measured the average velocities of the same ink at various temperatures (20°C changes). Since the density and the surface tension did not change much in our temperature range, the viscosity is the dominant factor in our test. We observe that the peak-to-valley variation increases as the temperature increases.



(a)



(b)

***Figure 6**. (a) The average drop velocities of inks with different viscosities. (b) The average drop velocities of the same ink at different temperatures.*

Antiwetting Coating inside Nozzle

No matter which coating process (vapor or liquid) is used to apply the antiwetting materials on the printhead front surface with preformed nozzles, there is a great chance that the nozzle wall is also partially coated during the coating process. Figure 7 is a schematic diagram showing such a nozzle condition. Because θ_S, θ_A, and θ_R of the antiwetting coating are higher than those of the original nozzle wall, the meniscus movement and the drop formation are certainly different.

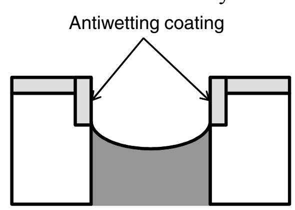


***Figure 7**. Nozzle wall is partially coated with antiwetting materials.*

We measured the average drop velocity of some nozzles with partially coated walls. In the first experiment we did velocity measurement at 5 different voltages (incremented by a constant voltage, dV) on one problematic nozzle as shown in Figure 8. The velocity curve of a normal nozzle that has a clean wall is also added as a reference. Apparently the average velocity linearly increases with the voltage and the velocity increment is similar at

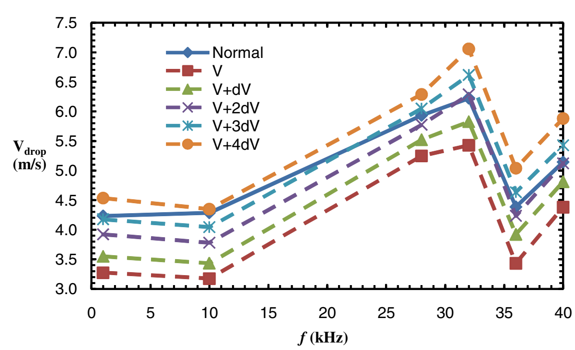


***Figure 8**. The average drop velocities at different voltages as a function of frequency.*

all frequencies (all curves are almost parallel). It is interesting to note that the high frequency segment of the normal nozzle curve is also parallel to other curves. Therefore we were able to adjust the voltage of the problematic nozzle such that its curve overlaps that of the normal nozzle at the high frequency range.

Once we set the voltage to match the high frequency velocity, we fixed the voltage and varied the backpressure. The results are presented in Figure 9. The backpressure shows no effect on drop velocity at the high frequencies, which is not a surprise because the nozzle pressure is always orders of magnitude larger than the backpressure at any moment between ejections. At the low frequencies, the nozzle pressure approaches zero after the residual pressure is damped and the meniscus shape is determined by the difference between the capillary pressure and the backpressure. As the backpressure increased, the meniscus changed from more concave shapes to less concave shapes and the drop velocity also decreased. This is consistent with Figure 2b. When -2 inch water backpressure was applied, the problematic nozzle had a velocity curve very close to that of the normal nozzle. This pressure was required to maintain the same meniscus shape between two different cases. The estimation of this pressure from the contact angles is $2\gamma(\cos\theta_1 - \cos\theta_2)/r \sim -2$ inch water.

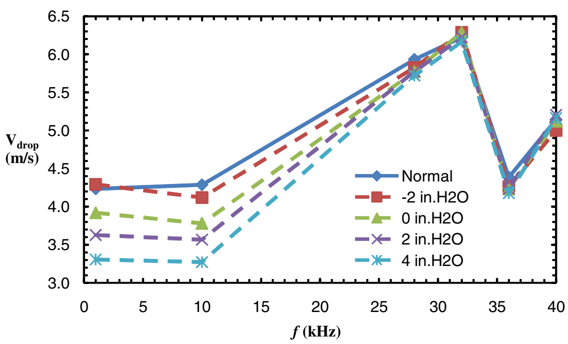


***Figure 9**. The average drop velocities at different backpressure as a function of frequency.*

We repeated the same experiments on 3 other problematic nozzles as well. The average drop velocity curves at -2 inch water backpressure are compared in Figure 10. The nozzle 1 and nozzle 2 have very similar cuves. So do the nozzle 3 and nozzle 4. The average drop velocities of 5 nozzles are nearly identical at the very low and high frequencies. At high frequencies, the contact line has no time to move. At low frequencies, the menisucs reaches the same condition. But the drops of nozzle 3 and nozzle 4 at 10 kHz are considerably slower than that of the normal nozzle, while the drops of nozzle 1 and nozzle 2 at 10 kHz are slightly slower than that of the normal nozzle. This difference can be a measure of the depth of coating inside nozzle as the meniscus tends to move close to the nozzle edge on the partially coated nozzle wall (asymmetric contact line movement we discussed earlier in Equation 1).

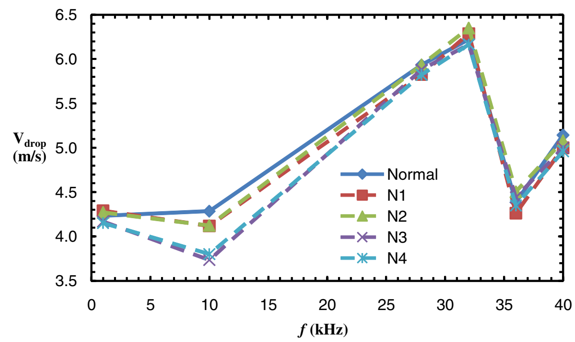


***Figure 10**. The average drop velocities of different nozzles as a function of frequency.*

Conclusion

The simulations and experiments demonstrate the importance of the nozzle wetting dynamics to the jetting performance of inkjet printheads. By incorporating the contact line movement theory, we can well explain the experimental results. Our work suggests a chemically and mechanically robust antiwetting coating and a well controlled coating process are required to achieve excellent jetting for the current and future inkjet applications.

References

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