W.-K. Hsiao, S. D. Hoath, G. D Martin and I. M Hutchings, in Proc 27th Int. Conf. on Digital Printing Technologies, NIP27, Minneapolis, MN, USA, 2011 66-69, 'Jetting, In-Nozzle Meniscus Motion and Nozzle-Plate Flooding in an Industrial Drop-on-Demand Print Head.’

Jetting, In-Nozzle Meniscus Motion and Nozzle-Plate Flooding in an Industrial Drop-on-Demand Print Head

Journal:	*NIP and Digital Fabrication 2011*
Manuscript ID:	38
Presentation Type:	Oral
Date Submitted by the Author:	05-Jul-2011
Complete List of Authors:	Hsiao, Wen-Kai; University of Cambridge, Engineering Hoath, Stephen; University of Cambridge, Engineering Martin, Graham; University of Cambridge, Engineering Hutchings, Ian; University of Cambridge, Engineering

Jetting, In-Nozzle Meniscus Motion and Nozzle-Plate Flooding in an Industrial Drop-on-Demand Print Head

Wen-Kai Hsiao, Stephen D Hoath, Graham D Martin and Ian M Hutchings, Inkjet Research Centre (IRC), Institute for Manufacturing, Department of Engineering, University of Cambridge, Cambridge, UK

Abstract

The state of the ink film at and near the nozzles of a drop-on-demand (DoD) print head during jetting has a direct impact on printing performance and reliability. We have developed high-speed imaging apparatus and analytical techniques to investigate the ink film dynamics on an industrial print head nozzle-plate in real-time. In addition to a direct correlation between the jet emergence velocity and drive voltage, drive-dependent variations in the oscillation of the ink meniscus in adjacent nozzles were also observed. Using a ray-tracing model to analyze the meniscus shape, the meniscus oscillations for both printing and non-printing nozzles were found to be complex and involve elements such as pre-oscillation and high-order surface waves. The flooding of non-firing nozzles, deliberately caused by the application of maximum drive voltage to a neighboring nozzle, has been recorded and analyzed dynamically. The build-up of fluid in an annulus around the nozzle (flooding rate) has been characterized and compared with models for the net ink flow through the nozzle.

Introduction

In a commercial drop-on-demand (DOD) inkjet print head, the ink meniscus at nozzles is maintained by the manifold pressure, ink surface tension, and ink-nozzle wetting force. The dynamic shape and position of the ink meniscus play an important role in optimizing the print head jetting performance. For example, the stationary nozzle meniscus prior to jetting has been suggested to contribute to the “first drop” variation commonly observed when a nozzle is commanded to fire after an idle period [1]. In addition, images of the nozzle plate taken during drop ejection have shown evidence of significant ink meniscus movements in nozzles adjacent to the firing one [2], suggesting a possibility of a cross-talk effect. However, our earlier imaging equipment set-ups [3, 4] are neither arranged properly to image the nozzles directly nor have the necessary temporal resolution to capture meniscus oscillations. Therefore, a new imaging arrangement using an ultra high-speed video camera and long-duration, high-power flash has been developed to study nozzle meniscus dynamics in real-time.

In addition to studying the nozzle meniscus dynamics, the imaging apparatus has also been used to study nozzle plate flooding, a phenomenon affecting printer reliability. Studies have been published using particle-seeded ink on a print head nozzle plate to study the flooding layer dynamics [5]. However, the very high temporal and spatial resolutions of our apparatus allow us to directly assess the dynamics of ink flow near the nozzle in real-time. It is hoped that the results will help to optimize printing parameters as well as improve ink formulations.

Experimental setup

The imaging rig, shown in Figure 1, consists of a Shimadzu HPV-1 ultra high-speed camera which is capable of capturing 102 full resolution gray scale images (310 X 260 pixels) at 1,000,000 fps with exposure time down to 0.25 μs. The illumination is provided by an Adapt Electronics Photoflash system (CU-500) which produces 2 ms duration, 500 J flashes. Due to the short recording and flash durations, the print head firing, camera and flash triggers are synchronized using a precision delay/pulse generator (Stanford Research System DG535).

A Xaar XJ126/200 DOD print head (with wetting nozzle plate) is mounted, on a motorized multi-axis positioning stage, with its nozzle array vertically oriented and facing the camera and the flash. The camera, fitted with a microscope lens (Navitar 12X ultra zoom with Mitutoyo LWD objective) is angled 14 degrees off-axis to the nozzles imaged. The flash, focused by a condenser, illuminates the nozzles about 21 degrees off-axis from the opposite direction. The arrangement is configured to maximize the illumination reaching the camera lens within the space constraints. A protective glass plate is placed between the print head and lens to prevent printed ink from misting the optics. Standard Xaar model fluid (XJ5007281), used as an ink analogue, has a contact angle with the nozzle plate of ~ 10°.

To capture the firing of the nozzles, a command pulse is generated from a pulse generator (TTi TGP110) which is fed to a PC-based print head controller (Xaar XUSB) and the SRS delay generator. The command pulse triggers printing of a pre-loaded bitmap which fires three adjacent nozzles 5 to 20 times with frequencies up to 5 kHz. The SRS delay generator applies set delays based on the print head cycle time and the flash rise time and produces two precisely timed command pulses to trigger the flash and camera separately. The images captured by the Shimadzu camera are in a proprietary format which encapsulates timing information such as frame rate and shutter speed. These raw images are converted to either AVI format movies or individual TIFF files for further analysis.

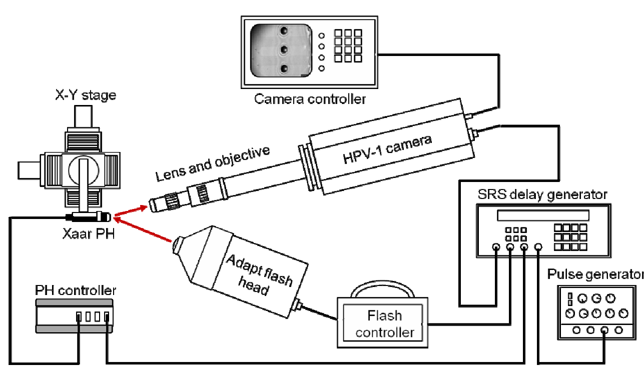

***Figure 1**. Schematic of the imaging apparatus (PH and optics in plan view)*

Results

Nozzle meniscus behavior – firing nozzle

The main parameter used to control DOD drop velocity is the drive amplitude. In a Xaar print head, the amplitude is controlled by altering the "efficiency factor" or the EFF value. For the purpose of optimizing the print head jetting performance in practice, the EFF value is used to adjust the drop velocity in order to balance the drop placement accuracy versus the number of satellites produced.

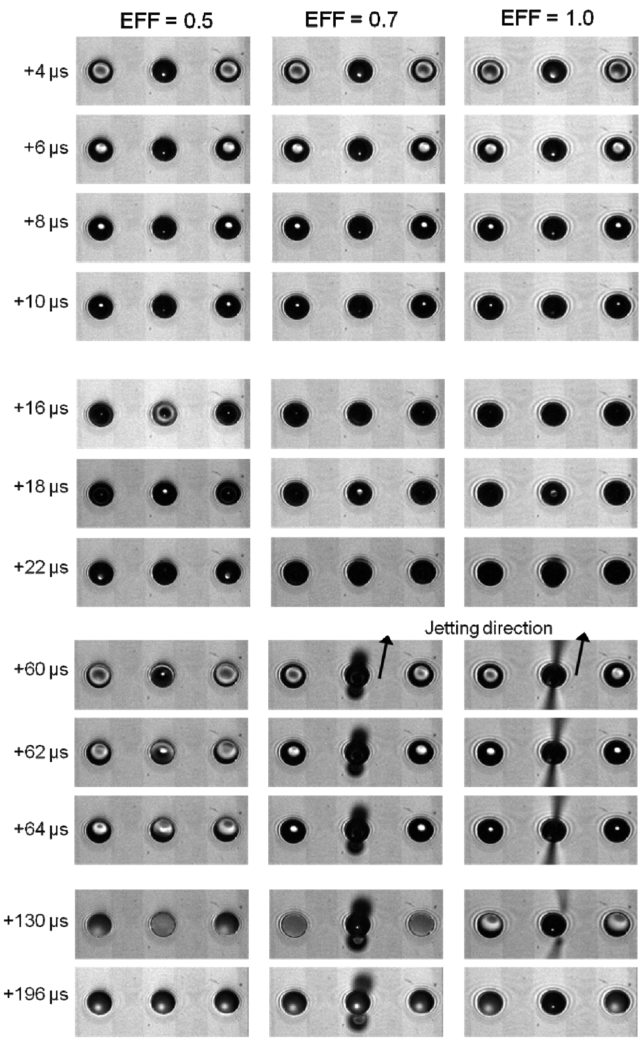

***Figure 2**. Meniscus dynamics of firing (center nozzle) and non-firing nozzles. (Note: these images have been rotated clockwise for presentation purposes.) The nozzle was jetting toward the direction of illumination and a reflection of the jet appears in the opposite direction in the timed images relative to the trigger.*

As expected, variation in the drive amplitude produces clear variations in the firing nozzle meniscus behavior. As shown in Figure 2, higher EFF value, or higher drive amplitude causes greater meniscus oscillation prior to drop ejection. However, the images reveal additional details about the meniscus motions that were impossible to observe previously. It is apparent from the images that the nozzle meniscus oscillates before it retracts back into the nozzle channel during drop ejection, roughly 60 µs after the meniscus motion begins (see images for EFF = 0.7 and 1.0 where reflections on the meniscus inside the center nozzle are momentarily visible at +18 µs). While imaging the retracting meniscus within the nozzle channel remains difficult due to the illumination limitation, the shape and position of the meniscus when it is near the nozzle plane can be estimated by ray-tracing and solid modeling, as shown in Figure 3.

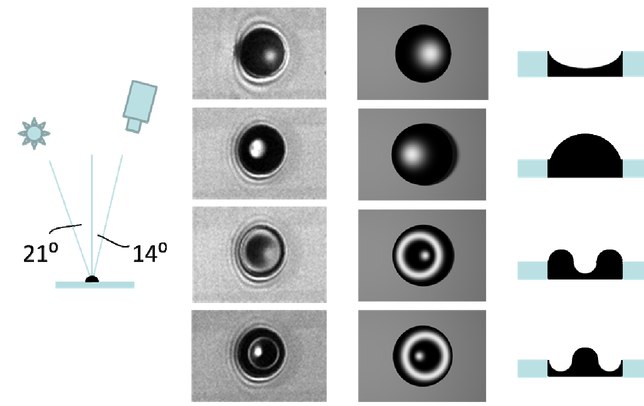

***Figure 3**. Reconstructing a nozzle meniscus by ray-tracing, showing that the meniscus is not just dome-shaped but can be at times far more complicated.*

Nozzle meniscus behavior – non-firing nozzle

As shown in Figure 2, the variations in EFF value affect not only the firing, but the adjacent, non-firing nozzles as well. The meniscus oscillations seen in the nozzles immediately adjacent to either side of the firing nozzle show the same phenomena. This behavior is expected as the adjacent nozzles in this particular print head design share the same piezo actuator which also separates their ink channels. A wall deflection that creates positive pressure in one channel to eject a drop, therefore, will result in negative pressure generation and consequent meniscus retraction in the adjacent channel. However, the effect of a single firing nozzle can be felt beyond the immediate neighboring nozzles. As shown in Figure 4, the meniscus of the nozzle two places away from the firing nozzle (left nozzle in the images) is also disturbed by the firing pulse. As expected, the meniscus oscillation of the remote nozzle is lagging in phase and is now closer to being in-phase with that of the firing nozzle.

Close inspection of Figure 2 reveals visible fringe patterns near the nozzles. As these patterns change over periods of jetting as well as after wiping the nozzle plate, they are thought to be associated to optical interference as a function of local ink layer thickness. The fringes can be enhanced by illuminating with monochromatic light. By adding a 530 nm filter in front of the Adapt flash, monochromatic illumination can be approximated. As a result, similar fringe patterns as observed in Figure 2 are greatly enhanced in Figure 4. The local variation of the ink layer thickness can be deduced from the fringe spacing [5], if a reference thickness is known; otherwise, simply counting the fringes encountered moving away from the nozzle exit (where the film layer is pinned) can be used to explore this quantitatively. A simple topographic map using the fringes as contour lines can be constructed to depict the relative variation of ink layer thickness.

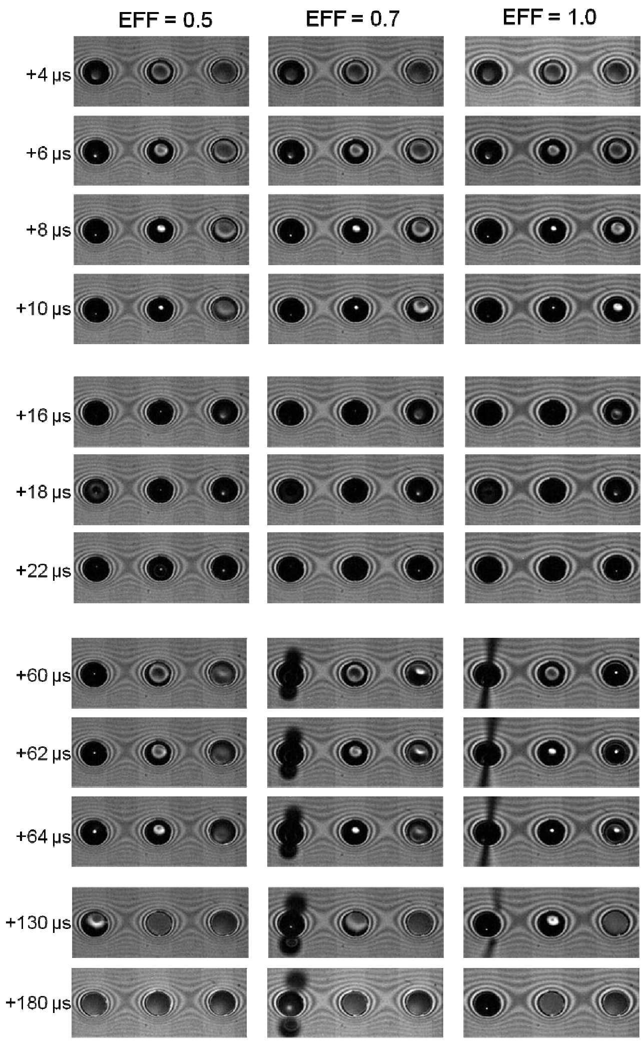

***Figure 4**. Meniscus dynamics of the adjacent, non-firing nozzles. Fringe patterns on the nozzle plate have been enhanced by filtering the illuminating flash with a 530 nm filter.*

Based on this method, a 3-D model of the ink layer around the nozzles is shown in Figure 5, showing how the ink layer thickness grows as one moves further away along the direction perpendicular to the row of nozzles.

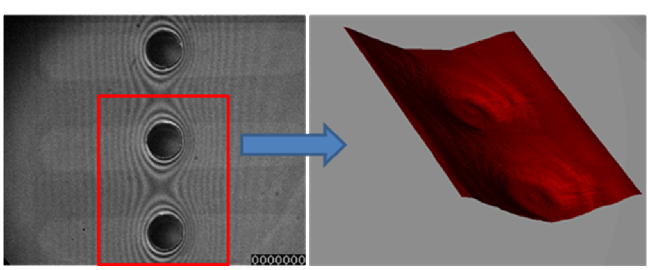

***Figure 5**. Relative topographic map of the ink layer near nozzles, with ink layer thickness not scaled to the nozzle diameter. The map is shown in color on-line.*

Nozzle plate flooding

Flooding of a nozzle plate during continuous printing is a serious reliability concern for DOD inkjet print head and printer manufacturers. Floods typically arise after a period of continuous printing when an ink layer gradually builds up on the nozzle plate to a point where it begins to interfere with normal drop ejection. Typical strategies addressing the flooding issue include scheduled pauses during printing to allow recovery of the flooded ink layer and regular nozzle plate wiping and cleaning. However, these solutions interrupt the continuous printing cycle and hence reduce the overall process efficiency. In addition, since the actual dynamics of nozzle plate flooding is not well characterized, most solutions are devised by trial-and-error only.

Using our high-speed imaging apparatus, the nozzle flooding can now be monitored in real-time. One of the potential sources of flooding identified, as shown in Figure 6, is the ink outflow from the adjacent, non-firing nozzles when the highest possible drive voltage, corresponding to maximum EFF values, are used for jetting.

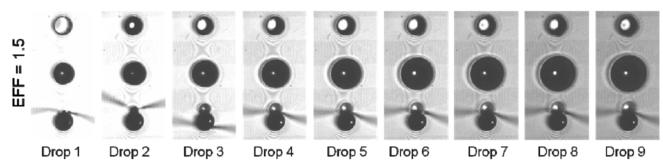

***Figure 6**. Flooding of the adjacent nozzle when jetting with high drive amplitude*

In the relatively short printing duration (9 drops at 5 kHz), a pool of excess ink is seen to grow around the adjacent non-firing nozzle. The growth of this ink pool is cyclical and distinctively linked to the firing of the individual drops, as shown in Figure 7.

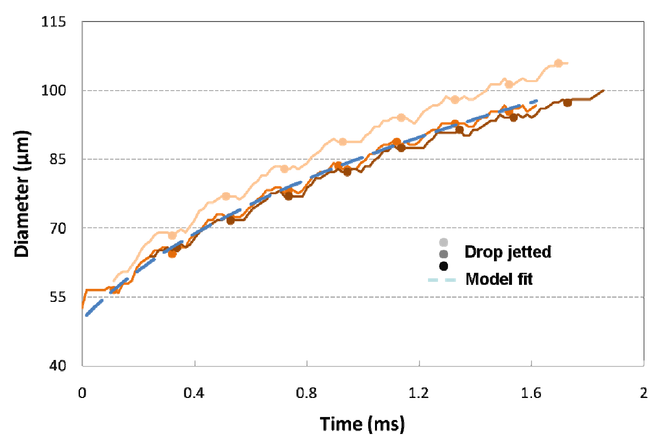

***Figure 7**. The growth of flooding pool diameter of the adjacent nozzle*

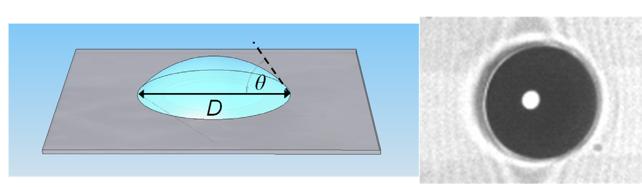

***Figure 8**. Spherical cap model of the flooded pool over a non-firing nozzle*

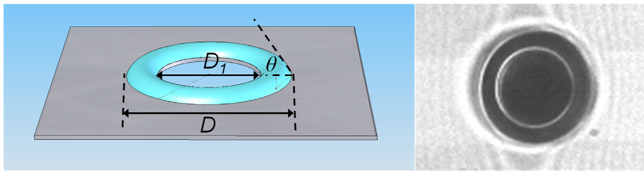

Figure 9. *Annular ring model of the flooded pool over a non-firing nozzle*

The growth in diameter of the ink pool does not appear to be linear, but is likely to correspond to a constant volume growth rate based on specific ink pool geometries. Over a single nozzle meniscus oscillation cycle, the ink pool over the non-firing nozzle will either resemble a spherical cap, as shown in Figure 8, with its instantaneous volume estimated as:

$$V_{cap} = \frac{\pi}{3}\left(\frac{D}{2}\right)^3 \frac{\left(2 - 3\cos\theta + \cos^3\theta\right)}{\sin^3\theta} \quad (1)$$

where D is the ink pool diameter and θ is the equilibrium contact angle, or an annular ring of fluid pinned at the nozzle, as shown in Figure 9, with a volume of :

$$V_{ann} = \frac{\pi}{32}(D_1 + D)(D - D_1)^2 \frac{\left(\theta - \sin\theta\cos\theta\right)}{\sin^2\theta} \quad (2)$$

where D_1 is the nozzle diameter. Given that θ is measured to be 10° ± 2° for the model fluid on the nozzle plate and assuming a constant average flow into the ink pool, the volumetric flooding rate can be determined from the fitted curve in Figure 7 to be ~ 42 pl/s (spherical cap model) and ~ 19 pl/s (annular ring model). These estimated flooding rates are sensitive to the value of θ. For example, a 20% variation in the value of θ will either double or halve the estimated flooding rates and such an effect will be amplified if θ is significantly higher than 10°. However, these predictions should still be useful as order-of-magnitude approximations for this particular type of print head flooding during printing.

Discussion and summary

The reconstruction of the nozzle meniscus by ray-tracing has shown that the meniscus shapes are far more complex than the simple concave or convex forms previously assumed. The ripple form suggests that higher order oscillation modes exist during meniscus motion. These higher order modes are likely to be affected by ink surface tension (hence ink formulation) and nozzle geometry. In addition, as the ejected drops appears to emerge from the nozzle while the meniscus is deep within the channel, the actual drop formation from the meniscus is likely to be similar to the case depicted by the bottom image and model of Figure 3, where a central peak is growing from a retracting annulus. Verifying this behavior can be important to ongoing efforts [7] in developing models for DOD drop and satellite formation.

Our observation has also revealed meniscus oscillations in the neighboring, non-firing nozzles that are correlated to the meniscus motion and jetting of the firing nozzle. This potential issue is particularly acute for print heads which are designed to fire their nozzles in a grouped sequence. Specifically, in this design the nozzles are tied into three groups which are fired sequentially depending on the group firing order and bitmap demands. Therefore, the meniscus oscillations caused by firing of other nozzles can interact and adversely affect the jetting performance of any individual nozzle in seemingly random fashion. Additional study on the meniscus oscillations as a result of multiple nozzle firings should be conducted to understand this interaction better. Finally, the flooding of the adjacent, non-firing nozzles appears to follow a constant volumetric flow rule based on either a spherical cap or an annular ring ink pool model. Further work is continuing to link this flow to the drive amplitude applied to eject ink drops. If this can be verified, the volumetric outflow rate of a non-firing nozzle can then be quantitatively correlated to the EFF value and ultimately, drop velocity and volume. Such information can assist in optimizing print head jetting parameters to address nozzle plate flooding in practice.

Acknowledgements

The authors would like to acknowledge the financial support of UK EPSRC (project: EP/H018913/1) and the EPSRC equipment loan pool for the use of the Shimadzu high-speed camera and light source. The extended cooperation of collaborators in Xaar plc and their permission to publish details of print head flooding phenomenon are appreciated.

References

[1] A. Famili, S.A. Palkar and W.J. Baldy, "First drop dissimilarity in drop-on-demand inkjet devices", Phys. Fluids 23, 012109 (2011)
[2] H. Wijshoff, "The dynamics of the piezo inkjet printhead operation", Phys. Rep.-Rev. Sec. Phys. Lett. 491, 77 (2010)
[3] I.M. Hutchings, G.D. Martin & S.D. Hoath, "High speed imaging and analysis of jet and drop formation", J. Imaging Sci. Technol. 51, 438 (2007)
[4] W-K Hsiao, S D Hoath, G D Martin and I M Hutchings, "Ink Jet Printing for Direct Mask Deposition in Circuit Board Fabrication", J. Imaging Sci. Technol. 53, 50304 (2009)
[5] B. Beulen, J. de Jong, and H. Reinten, "Flows on the nozzle plate of an inkjet printhead," Exp. Fluids 42, 217-224 (2007)
[6] R. Aveyard , J.H. Clint, D. Nees and V. Paunov, "Size-dependent lens angles for small oil lenses on water", Colloids Surf., A 146, 95-111 (1999)
[7] N.F. Morrison and O.G. Harlen, "Viscoelasticity in inkjet printing", Rheol. Acta 49, 619 (2009)

Author Biography

Wen-Kai Hsiao received his BS from the University of California, Santa Barbara and his MS and PhD from Massachusetts Institute of Technology, all in Mechanical Engineering. He joined the Cambridge, UK, Inkjet Research Centre in 2007 with research interests in drop deposition behavior of Newtonian, non-Newtonian, and functional colloidal fluids. In addition, he is also active in developing novel inkjet-based manufacturing processes for electronic and biological applications.