Jet Formation and Late-Stage Ligament Instability in Drop-on-Demand Printing

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Abstract

High-resolution, short flash duration photography (with flash duration of 20 ns) has been used to determine the profiles of emergent jets from a drop-on-demand print-head. By quantitatively analysing these profiles the development of fluid flows and velocities within the evolving jet can be followed.

Various features of the forming drop and ligament have been examined in some detail. This close observation shows that the ligament forms in a characteristic cone shape which is disturbed at later stages by the end of the ligament moving away from the centre of the nozzle and by the bunching of material within the tail leading to break off and satellite formation.

Introduction

The availability of high-resolution, accurately timed images and edge processing software enables us to closely study inkjets formed with model inks of established characteristics under controlled conditions, as an aid to future studies of other jetted fluids for non-contact printing.

We have examined model inks jetted from a Xaar drop-on-demand print-head as part of development work at the Inkjet Research Centre, in some cases repeating previous studies in order to establish techniques and to underpin more novel analyses. In particular we present some work used to provide input to current theoretical models by our research partners [1].

Elsewhere [2] we have presented a detailed description of the use of a short-duration non-coherent spark light source for inkjet image capture, and of the processing methods used to determine drop and jet profiles from these images. Here, after a short description of the methods that were used, we mainly consider analysis of the emerging fluid jets and ligaments.

Experimental methods

The Xaar XJ126-200 drop-on-demand print-head exploits the so-called shared-wall technology to reduce the head drive voltage needed to form inkjets of a given velocity. As a result, neighbouring nozzles are influenced by the need to actuate the shared walls. The print-head can be driven in a single-shot mode that fires a particular group of nozzles at one time, cycling around the three groups A-B-C-A-B-C- and so on, but in our application a single trigger caused the print-head to print out A-B-C with fixed short time delays between the three groups. The actual nozzles fired depend on the image presented to the print-head. In this work the images were solid blocks arranged either to print all the nozzles, a designated block of 16 nozzles, a single A-B-C set or a single nozzle from group A, B or C, according to the phenomenon under study.

A logic circuit was devised to handle the asynchronous nature of the print command and the print-head cycle time clock, in order to ensure reproducible firing of individual nozzles on a timescale of <1 µs. The actual inkjet printing starts at a fixed time in relation to the clock edge, so that without the use of this logic circuit an additional undesirable timing jitter, equal to the clock cycle time of ~1.75 µs, would be introduced, thereby disrupting pseudo-sequences obtained with shorter time steps. Residual timing uncertainties were ~0.70 µs, due to randomness in the triggering of some flashes, which were also associated with weaker light output and thus darker images. An oscilloscope was used to determine the precise relative timing of the nozzle firing and image capture to a precision of 20 ns. Better methods becoming available for driving the light source will greatly ease the future collection of validated timed images, but we are confident that the timings of all images presented here are accurate to <0.1 µs.

Observations and discussion

The print-heads were operated with model UV-curable inks and the main ink drops had velocities of ~6 m/s after a 1 mm flight. Inkjets emerging from an array of nozzles (spaced at 137 µm), together with more fully developed ligaments, are shown in Figure 1. These sharp images resulting from a single ~20 ns flash may be compared with those reported elsewhere [e.g. 3, 4].

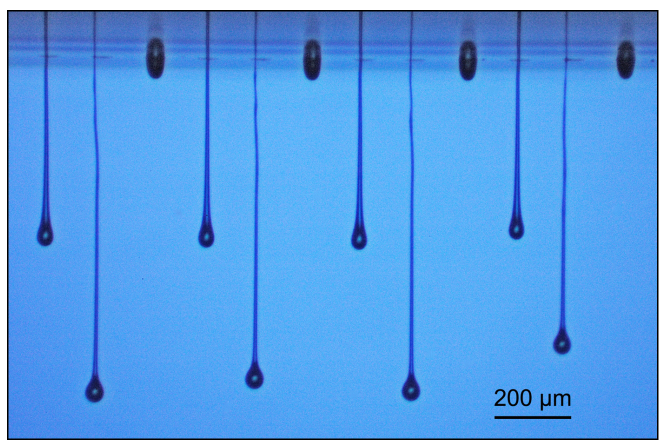

Figure 1. *Group of jets emerging from a Xaar XJ-126 print-head. The distance between neighbouring nozzles is 137 µm*

During the early stages of the ejection of ink through the nozzle, the jet ligament becomes rapidly narrower, down to a diameter smaller than that of the orifice at the nozzle plate. This implies that the meniscus must lie inside the channel, thereby allowing some air to enter the channel.

Figure 2 displays jets at various later stages, showing ligament stretching, the snapping of ligaments, the formation of satellites, and almost spherical main drops followed by trails of satellites.

Figure 2. *Image at a later time, for the nozzles shown in Figure 1, showing the evolution of the jets to form ligaments, satellites and main drops.*

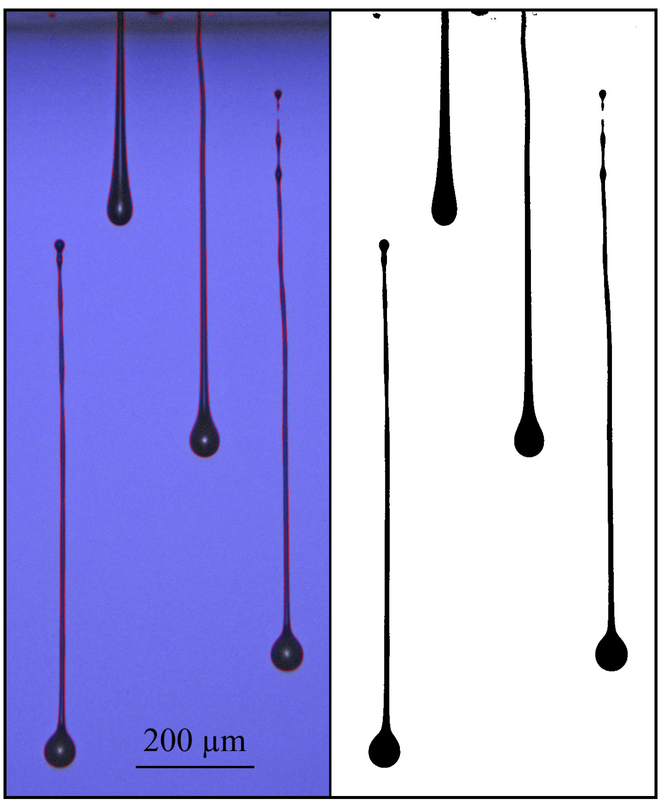

Figure 3. *Raw and processed images showing satellite separation and lateral fluctuations*

Example images are shown in Figures 3 and 4. Figure 3 shows a raw image and corresponding processed image [2] with four jets, one after separation of a tail satellite, with lateral fluctuations, tail ligament thinning and beading visible. Figure 4 was obtained by firing a single nozzle only, and demonstrates that the tail deflection can occur without aerodynamic, acoustic or other influences from jets fired from neighbouring nozzles. The time of the occurrence of deflection after firing was similar in all images, whether in single jets or multiple groups, or after cleaning the nozzle plate. Figure 4 also shows the ink patches associated with the orifices of the two unfired neighbouring nozzles.

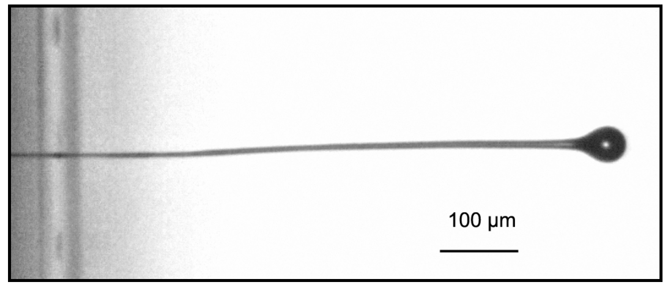

Figure 4. *Image showing tail deflection while the ligament is still attached to the nozzle; the orifices of the neighbouring nozzles are visible and no other nozzles were fired.*

Break-off occurs when the stretched ligament thins down and snaps. The two sections then follow independent histories: one will probably move backwards into the nozzle orifice and the other will retract towards the main head. Either or both sections may then produce satellites, but usually the initial rupture is close to the nozzle and all satellites originate from the long ligament.

Figure 5 shows the edge profile, derived by the methods described elsewhere [2], from an inkjet that has broken. The time after the first rupture was enough to allow a satellite to form, and so at least one more ligament break has occurred between the nozzle plane and the main ligament. The ligament width fluctuations suggest that other breaks may be imminent.

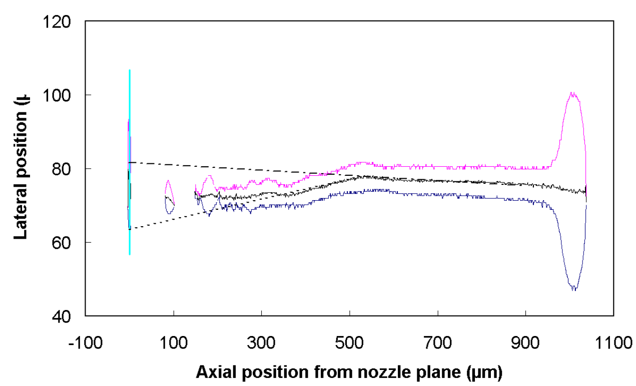

Figure 5. *Edge profile for a jet that has broken away from the nozzle (vertical bar), showing a satellite and the centre projection (dot-dash broken line) of the mass flow from the nozzle. A dotted line represents the lateral deflection of the end of the tail. The lateral scale is exaggerated.*

In this image the ligament does not appear to point at the same location (dot-dashed line) as its apparent origin throughout its length, but shows a distinct angular deviation by ~1° at ~520 μm. The later tail section and the satellite appear to point (dotted line) at another location ~10 μm off-centre.

We believe that this implies that the thin inkjet ligament became attached to the edge of the nozzle. It is possible that at some point as it thins, the ligament is not stable in its centre position and that some disturbance or asymmetry will cause it to move to the edge of the nozzle.

Ligament development proceeds, as described earlier, with the stretching of the material between the nozzle plane and the inkjet head. The stretched ligament has a small but finite minimum radius during the process; we have found that the inkjet ligament can be represented by a truncated cone with a specific half angle at the typical distance at which ligament rupture occurs near the nozzle, even if the ligament happens to rupture elsewhere before this due to the width fluctuations in the thinning ligament.

As evidence for this we have analysed the volumes and the change of centre of mass positions for satellites produced by ligament rupture, in order to determine average velocities for this material following rupture. The ligament radius inferred at the nozzle plane at rupture is typically ~3 μm. However, average velocities deduced for early satellites are often quite close to the centre of mass velocity for the inkjet ligament, as expected and as measured by other means.

The tail width fluctuations observed in still-attached ligaments are consistent with net mass movements along a truncated cone shape fitted to the downstream ligament behind the jet head, which also had a radius of ~3 μm at the position of the nozzle plane.

This is illustrated in Figure 6 where an average of 3 different images of the jet is plotted: 0.6 mm of the ~0.9 mm long ligament attached to the nozzle is shown, together with a straight line representing an equivalent undisturbed conical profile matching the ink material volume inside the 0.6 mm length. The inkjet head is not shown in the figure as it was ~49 μm wide at this time. The ligament width is clearly not constant or zero near the nozzle plane: the minimum ligament width corresponds to a radius of ~3.2 μm. The average reference time for this image was 118 μs after printing, and width fluctuations appear strong at positions up to ~210 μm from the nozzle.

The trajectories of the main drop and its ligament accurately pointed from the centre of the nozzle orifice for a long time, until the tail was apparently disturbed in some way. This implies that an axi-symmetric analysis would no longer be valid, although the deviations are extremely slight. Even later, the ligament tail appeared to be straight but offset, and originating from the edge of the nozzle opening. These effects were not random, but consistent and different for each nozzle, which may reflect imperfections at the nozzle edges, or other variability such as nozzle wetting or contamination.

Nearby undisturbed jets visible in the same image were used to fix the lateral positions of the nozzle openings relative to the inkjet ligaments in images far from the nozzle plane, using the methods previously described [2], showing that undisturbed (sections of) ligaments do point accurately away from nozzle centres.

Figure 6 also shows the lateral position of the ligament tail plotted on the same scale as the width fluctuations.

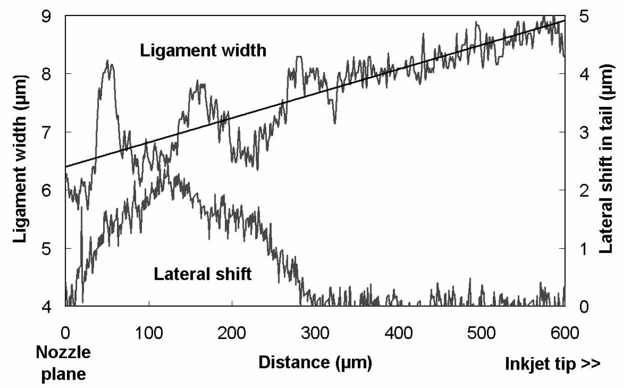

Figure 6. *Independence of tail deflection and tail width fluctuations. The centre of the jet head was at a position of 888 μm.*

The centre of the ligament lies accurately on the line joining the centre of the head to the centre of the nozzle back to a distance of 300 μm from the nozzle, then shows a lateral displacement of up to 2 μm before returning to the nozzle centre. The corresponding angles between the original ligament axis direction and the tail lay between -½° at 300 μm and +1° at the nozzle plane.

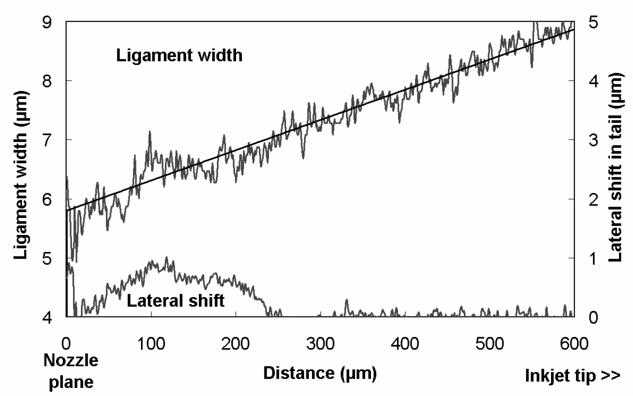

Figure 7. *Tail deflection without width fluctuations at an earlier time for the nozzle of Figure 6. The centre of the head was at a distance of 826 μm.*

Figure 7 shows similar information to Figure 6, for the same nozzle but 16.1 μs earlier. The absence of appreciable width fluctuations contrasts with the visible but small lateral shift. These two phenomena therefore appear to be uncorrelated. Furthermore, the timing and distance information implies that the lateral shift has moved consistently with the axial stretching rate, while width fluctuations have appeared within 20 μs of Figure 7, which shows a similar width at the nozzle plane in both Figs. 6 and 7.

Main drops appeared always to originate from the nozzle centre, even if the jet axis was not exactly aligned with the image axis. In the images shown above the misalignment was typically 0.23°, so that the inkjets appear to be travelling to the left-hand side in the vertical images. These small misalignments were corrected for in the final image analysis.

From a simple model, it is possible to extract new information about satellite velocities from accurately timed single-flash images of stretched ligaments taken both before and after break-up. We assume that satellites form from local material in ligaments, ignoring the 3-D flows and transfers that undoubtedly occur under some conditions. A smooth shape for the ligament is first constructed to represent an unperturbed ligament mass distribution along the ligament length; we found a truncated cone provides a good starting approximation, as supported by the data and profiles shown in Figures 5-7 above. Each satellite detected in images taken after break up, starting from the nozzle plane end, is then allocated a length of this smooth shape with the same volume as the satellite; the difference between the centre of mass of the length at the break-up time and the centre of mass of the corresponding satellite in the later timed image is used to deduce the average satellite velocity (figure 8). Errors arising from unknown break-off positions near nozzles are small relative to other experimental uncertainties.

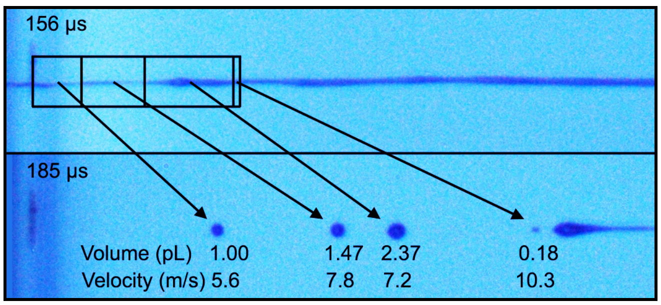

Figure 8. *illustration of drop velocity extraction*

Conclusions

The level of quantitative information which can be extracted from high-speed flash images allows jet profiles and satellite formation to be studied over time. As examples, tail-width fluctuations, lateral deflections and satellite velocities have been quantitatively analysed.

It has been shown that at a late-stage the jet ligament is unstable and tends to move away from the centre of the nozzle. At similar times the ligament rapidly forms fluctuations leading to break off and satellites. The late-stage lateral displacement of the inkjet ligament can occur without aerodynamic, acoustic or other influences from adjacent jets.

Information about satellite velocities can be obtained by calculating the movement of the centre of mass of the satellite from a point prior to jet break-off by finding the conical profile which fits the ligament.

Acknowledgments

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Author biography

Dr Graham Martin is currently Director of the Inkjet Research Centre at the Institute for Manufacturing, University of Cambridge, a project jointly funded by the UK EPSRC and an industrial consortium. He has a PhD in solid state physics and has worked in NIP-related research, consultancy and product development for many years. The companies he has worked for include: Cambridge Consultants Ltd (Non Impact Printing Systems group leader), Elmjet (Technical Director) and Videojet (Director of Technology).