High Speed Imaging and Analysis of Jet and Drop Formation

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Abstract

New techniques have been developed for analyzing in detail the shape and development of ink jets and drops. By using flash illumination of very short duration (ca. 20 ns), high-quality, single-event digital images of jets and drops can be captured. A computer program, PEJET, has been written to automate the processing of such images and to generate quantitative data about the whole ink stream. From this data it is then possible to compute the variation in fluid volume, volume flow and velocity as a function of both position and time. The method has been shown to have high accuracy. The results can be used to study the influence of nozzle design, drive waveform and fluid properties on jet and drop formation, as well as to provide accurate data for comparison with the results of computational modelling.

Examples of typical results from a drop-on-demand system are presented that illustrate the potential of the method to compare quantitatively the performance of print systems and inks.

Introduction

As the range of applications of inkjet systems expands, so the need grows to understand their performance with an ever-widening range of sometimes difficult fluids. These may be fluids with complex rheologies or fluids containing high loadings of solid particles.

The visualization of jet and drop formation close to the print head can lead to insights into how the system is behaving [1, 2]. From detailed measurement of the shape and size of jets as they develop over time, the volumes and velocities of the jets and the drops which form from them can be computed. These results can then be used to compare the performance of print head designs and printing fluids, and check the validity of numerical models.

This paper describes techniques which have been developed to make such quantitative observations and gives examples of different ways in which this information can used to explore the performance of inks and print heads.

Apparatus

Figure 1 illustrates the equipment used during the course of this work. The key elements are:

- a high-resolution digital camera with a lens capable of imaging a field of view of a few millimetres connected to a PC for control and image storage;
- an inkjet print head with drive electronics and data source;
- a very short duration (~20 ns) flash light source with delivery optics;
- means to delay the flash relative to the initiation of the printing event, and to measure that delay time.

The experiments for the measurements described below used a Xaar 126-200 print head with a linear array of 50 µm diameter nozzles. The fluid was a simple semi-transparent UV-curable ink.

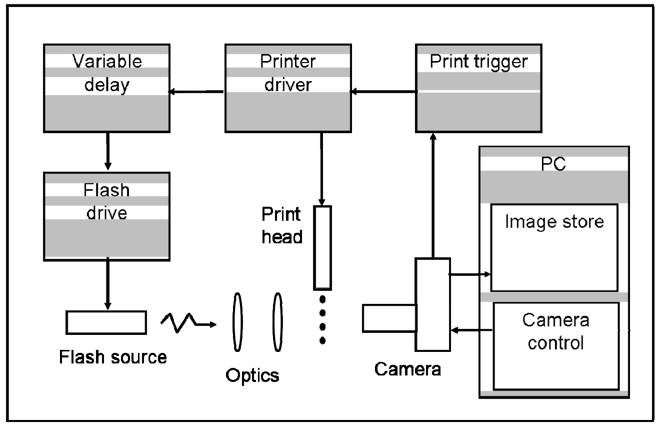

Figure 1. *Schematic diagram of apparatus*

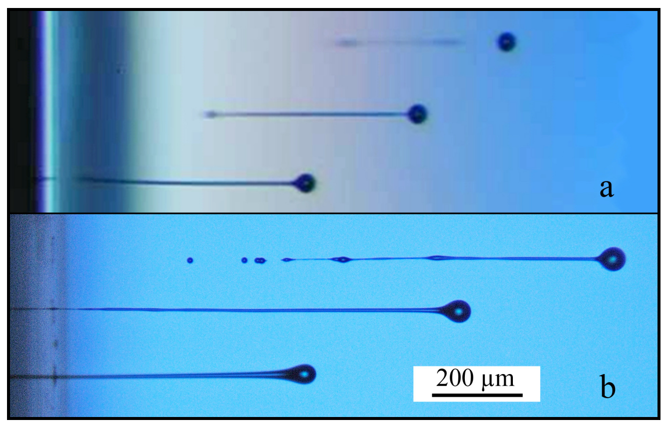

Figure 2. *Comparison of images from different techniques: (a) composite image (strobed illumination); (b) single event (20 ns flash illumination)*

Experimental techniques

Jets and drops emerging from inkjet printers are commonly visualized by creating composite images by superimposing tens or hundreds of individual events in a single frame [3]. This relies on the repeatability of the drop formation process to give the impression of observing individual jets and drops. In some cases, as shown in Figure 2(a), the events are not completely reproducible which results in some blurring of the image, particularly at long times after drop ejection. For stroboscopic images of this kind the flash duration is typically >1 µs which, given the velocity and size of the objects being observed, can result in significant movement blur. However, some information about the development of the jet and drops can be obtained from strobed images by changing the timing or phase of the flashes relative to the printing event.

Alternatively, a high-speed camera can be used to observe single events as they occur [4]. This requires the use of a camera with a very high framing rate (~ MHz), but typically the pixel resolution of such equipment is poor and only a small number of frames can be captured.

The apparatus shown in Figure 1 was used to capture individual print events. A typical image is shown in Figure 2(b). Because of the short duration of the flash there is no significant motion blur. In cases where the events are reproducible the time development of the event can be investigated by capturing a series of images with different delays. Less reproducible events can also be captured repeatedly and information on the variability of the event determined. Because of the high quality of the imaging it is possible to determine drop and ligament sizes and shapes and then to use this information to compute drop and ligament volumes. By comparing images within timed sequences, the velocities of the various components of the ink stream can also be determined.

Image processing

To extract quantitative information from the images it is necessary to analyse them and decide which parts of the image belong to the background and which to the ink drops and ligaments. Standard techniques and various proprietary image processing tools are available to find edges and objects within images [5]. However there are particular features of these images which make the use of such tools laborious and sometimes inaccurate. In particular, the background intensity often varies both within each image and from image to image. Within a single image there is often a thin extended ligament which starts at or near the nozzle. Shading by the nozzle means that the background intensity varies significantly along the length of the ligament. Although the light source provides a very short-duration pulse, the nature of the source means that the intensity can vary by 10% or more from image to image. Drops and ligaments from a transparent fluid often show light central regions because light from the bright-field source passes straight through these areas, rather than being refracted away from the optical path as it is at the edges of these features.

Figure 2(b) illustrates some of these issues. An image processing method was developed which would cope with these variations and artefacts, and allow hundreds of images at a time to be analysed automatically. Information that is known about the image can be used to simplify this task. For example, liquid drops and jets will not have holes within them and the edges should vary smoothly at a pixel level. The area within which the drops and ligaments are expected to appear within the image is often known. Fixed features within all the images in a timed sequence can be used to compensate for any small, inadvertent positional movement between the object and the imaging system during the process of image capture.

The image processing is carried out in several steps, as shown in Figure 3. First, from a selected area of interest (a) a relatively fast but inaccurate technique is used to find the approximate edges of the features by looking for regions of rapid contrast change (b). In the next step (c), the edges are examined in detail to determine which parts of the edges are inside and which parts are outside the feature, based on a threshold level determined by the local ranges of levels. Finally any 'holes' within the features are filled (d).

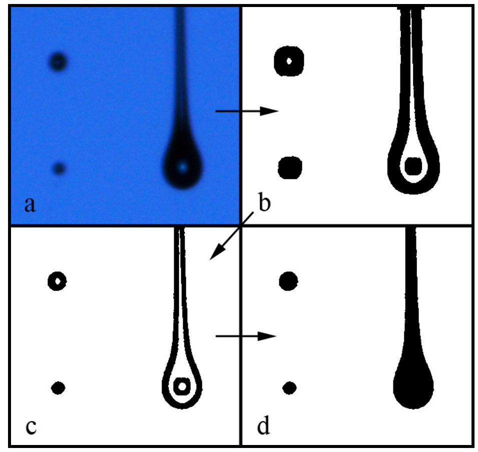

Figure 3. *Image processing sequence*

A computer program, PEJET, was written which incorporates these processing techniques, together with a way to select a region of interest within a set of images. The program allows a fixed datum to be defined within the image which is then used to correct for any slight shift of the camera relative to the object over the course of the experiment. The program also includes a way to detect and label each feature and to output images indicating the features selected. It also outputs the size data associated with each feature into a text file or spreadsheet. The program can be set up to process a complete set of images (for example, a timed sequence) without operator intervention. Figure 4 is an example of the image output from this program in which the various drops and ligament have been recognised and their edges indicated.

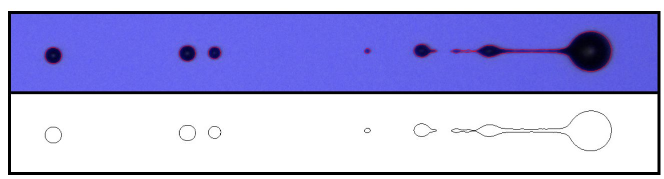
Figure 4. *Raw image(above) and processed version (below), showing the results of automated feature selection and edge detection*

The threshold level selected to make these measurements can have some effect on the measured sizes of the objects. The correct threshold value can be determined in a number of ways. A calibration object of known size can be used in the system instead of the jets and the correct threshold determined by experiment. Alternatively, an image feature of known size (such as the nozzles themselves) can be used to check the accuracy of the measured objects. It is also possible to consider the effect of optical blurring on a sharp edge, and compare edges in the images with those in computed images.

Data extraction

Once the images have been processed, the dimensions and volume of each component of the ink stream can be computed. The camera and print head are usually arranged so that the drop and ligaments move along the vertical axis of the image. If it is assumed that the ink stream has a circular cross-section at all points, then each horizontal line of pixels in an object represents a circular slice through that object. By summing these slices the volume of the whole stream, or of any horizontal slice through the stream, can be estimated. By comparing such measurements at various stages of drop development, a picture can be built up of how the volume of the object, or any part of it, changes over time. Particular features such as the tip of the jet or drop, or its centre of mass, can be tracked, and the method thus provides a powerful tool to generate velocity and flow information.

Examples of quantitative results

Ligament widths and tip diameters determined by processing single-flash images as described above vary with time in a systematic fashion. Figure 5, for example, shows tip profiles of jets at several short times after emerging from the nozzle. The precision of the technique is illustrated by the linear uncertainty in this example of only 1 pixel = 0.61 µm, similar to the wavelength of the imaging light.

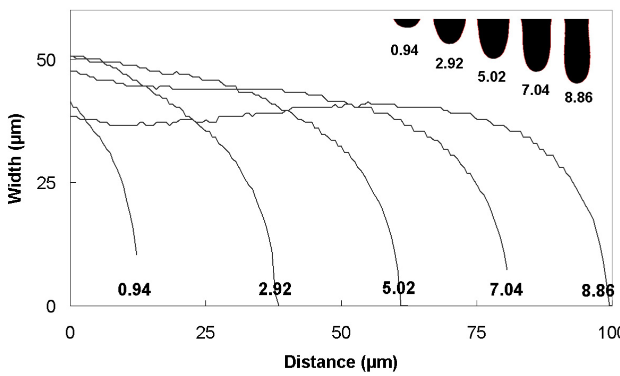

Figure 5. Jet tip profiles for (nominally) 6m/s ink drops emerging from a 50µm diameter nozzle, at various times (µs) following emergence

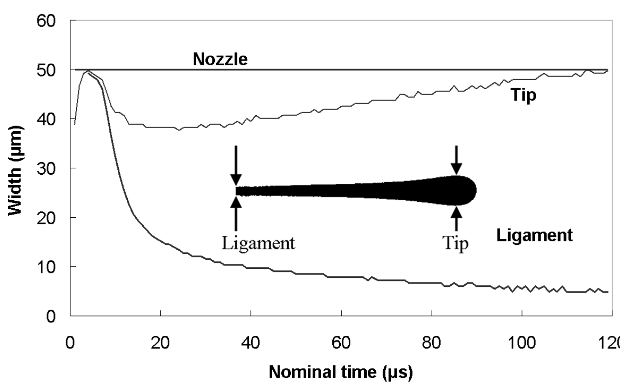

Figure 6. Evolution of the diameters of the jet tip (maximum width) and ligament (minimum width)

Figure 6 shows the rapid growth in the tip width of the emerging jet, followed by a rapid fall and then a rise towards the final drop size (corresponding to ~100 pL printed drop volume in this example). The nozzle width is shown for comparison. The minimum ligament width falls quickly after the emergent tip starts necking, and continues to shrink as the ligament stretches.

When the ligament is long and unbroken, the volume lying beyond the nozzle plane stretches as the ligament extends, while the volume fraction in the head increases. For the example shown in Figure 7, the ratio of the length of the ligament to the diameter of the head reaches ~20 before the ligament snaps, at which point there is still ~30% of the total volume in the tail and ~70% in the head section.

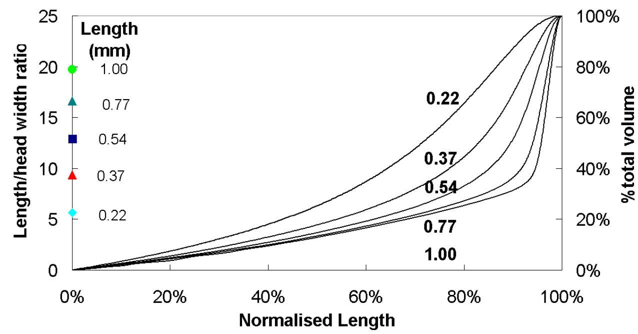

Figure 7. Percentage of total ink volume along a jet beyond the nozzle plane, for various ligament lengths and ratios of length to main head width.

The total downstream ink volume can be calculated (assuming reproducible ligaments with circular cross-section) at different locations. Figure 8 shows that the ink volume beyond the nozzle plane initially overshoots the final drop volume, whereas it undershoots at downstream locations even as close as 17 µm (one third of the nozzle diameter).

This indicates that some ink flows backwards into the nozzle from very close range, while the rest moves forwards as a ligament. This ligament stretched for tens of µs before it broke off, for the particular ink and operating conditions of the print head, with a final printed drop volume of ~100 pL.

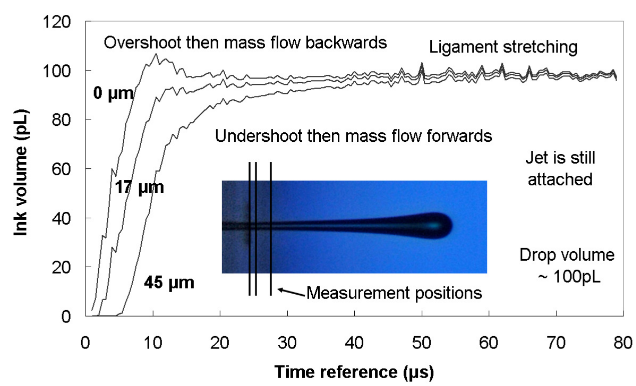

Figure 8. Ink volume passing beyond various downstream planes, versus time

The tip velocity would be expected to change with jet length because the fluid in the tip first emerges at perhaps twice the speed of the final velocity of the centre of mass (CoM) of the droplet.

These changes arise from mass averaging as the whole drop tends to coalesce after ejection due to surface tension forces, with energy dissipation from the fluid viscosity or air drag being rather less significant at these short timescales. For a jet with a nominal velocity of ~6 m/s, Figure 9 shows the measured positions of the CoM and the tip plotted against time, and also their velocities, derived by numerically differentiating the position data. At longer times the CoM and tip velocities would converge.

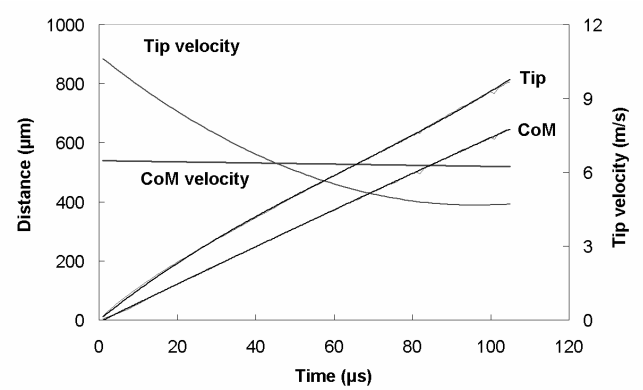

Figure 9. *Examples of centre of mass and tip positions and velocities*

The average positions of the jet edge profiles can be used to determine the local direction of motion of the jet and any deviation from the axis. Observation of ligaments close to break-up has shown asymmetric behaviour as the tail of the ligament moves away from the centre to the edge of the nozzle. This phenomenon is discussed in detail elsewhere [6].

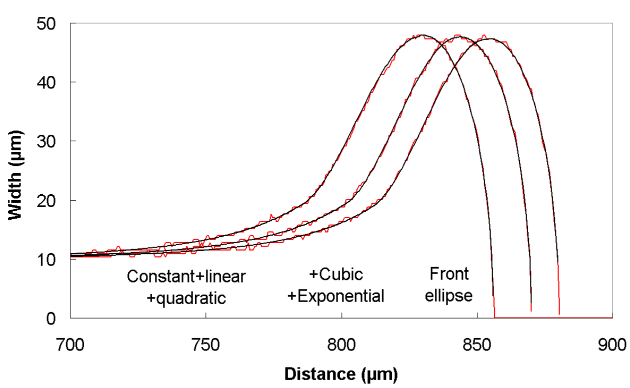

Figure 10. *Illustration of the shapes of three long jets which have been fitted by simple empirical functions*

The leading surfaces of the jets studied in this work have been found to be very closely hemispherical, once the emergent phase has been passed, as expected if the shape is controlled by surface tension and negligible aerodynamic flattening occurs. The rear surface of the head exhibits a shape which can be modelled by constant, linear and quadratic terms linked to the nozzle plane via ligament stretching, with additional exponential and cubic terms extending to the main drop hemisphere (see Figure 10).

It is clear that the ligament behind the main head varies smoothly in width, and is not a cylinder of constant diameter.

Conclusions

By using flash illumination of very short duration (ca. 20 ns), high-quality, single-event digital images of jets and drops can be captured. A computer program, PEJET, has been written to automate the processing of such images and to generate quantitative data about the whole ink stream. From this data it is then possible to compute the variation in fluid volume, volume flow and velocity as a function of both position and time. The method has been shown to have high accuracy. The results can be used to study the influence of nozzle design, drive waveform and fluid properties on jet and drop formation, as well as to provide accurate data for comparison with the results of computational modelling.

Acknowledgments

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Author biography

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