# Methods and Results from the Cambridge Inkjet Research Centre

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## ABSTRACT

Methods and tools for fluid characterization, drop visualization and drop formation physics, as used at the Cambridge Inkjet Research Centre, are presented.

Some recent results and interpretation for drop on demand inkjet printing of some model fluids and their implications for general inkjet fluids are also discussed.

***Keywords***: fluid characterisation, drop visualisation, drop formation, timing resolution

## 1 INTRODUCTION

The Cambridge Inkjet Research Centre started its first major project work in 2005, aiming to provide a local academic centre of excellence funded by, UK's Engineering and Physical Sciences Research Council together with local industrial print head companies (e.g. Xaar, Linx, Domino), some of their customers (e.g. Inca Digital, FFEI) and inkjet fluid manufacturers (e.g. Sun Chemical, Fujifilm Sericol). Inkjet consortium work has been co-ordinated with other specialist academic groups and departments at Cambridge (Malcolm Mackley of Chemical Engineering and John Hinch of DAMTP) and at other UK universities (Colin Bain of Chemistry at Durham, Oliver Harlen of Physics & Astronomy and Tom McLeish of Mathematics at Leeds, Brian Derby of Material Science at Manchester, and Ken Walters of Mathematical Sciences at Aberystwyth).

General results from our activity have been reported primarily for drop-on-demand inkjets at the Non-impact printing (NIP) conferences and in our papers to JIST [1]. Further publications and additional projects are underway or planned (the physical location of the Cambridge inkjet research centre will be moving to Cambridge West Campus site this summer). We report here on our basic approach to jetting studies, detailing methods and some results from the research work conducted within the Inkjet Research Centre.

## 2 METHODS

High resolution high speed flash imaging using commercial cameras (e.g. Nikon D70) with optical magnifiers (e.g. Navitar) forms the basic method for much of the work. Pixel resolutions down to 0.71 µm were used for jetting studies. The high speed flash sources used were 20 ns spark flash (e.g. HSPS Nano-light or Ministrobokin) or Xenon flash lamps (e.g. HSPS-XL). Figure 1 has a depth of focus of the same order as ~ 50 µm main drop diameter.

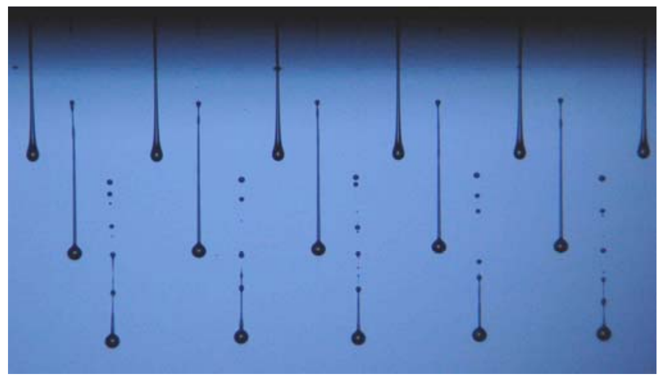

Figure 1: Image of drop-on-demand inkjets from a print head recording drops, satellites, ligaments and nozzle plane.

Drop-on-demand print heads (e.g. Xaar XJ126-200) run with fixed drive "pull-push" waveform timing at controlled print frequencies of 1.5 to 3.0 kHz help us characterise the changes observed when jetting different fluids through 50 µm diameter nozzles. For the majority of the studies the speed of drops at 1 mm substrate distance from the nozzle plane was adjusted to 6 m/s using the drive voltage. This procedure ensures that the comparisons are made under more realistic application conditions than achievable by using fixed drive voltages, but does restrict the maximum loading of the fluids (e.g. with polymer or particulates).

Our initial studies focussed on solvent jets based on diethyl phthalate (DEP low-shear rate viscosity of ~ 0.010 Pa s and surface tension of ~ 0.037 N/m at 21°C). Figure 1 and Figure 3 were for DEP while data in Figure 2 were obtained using a DEP and DOP (dioctyl phthalate ~ 0.050 Pa s and surface tension of ~ 0.031 N/m) solvent mixture.

Model polymer fluids [1] have been prepared for our experiments in relatively small (< 250 mL) quantities but every batch we test for jetting is also well characterised using bubble surface tension meters (e.g. SITA pro-line15) and standard low shear-rate viscometers (e.g. ARES) and special high frequency PAV viscometers [3] by colleagues.

## 3 TEST RESULTS

Detailed test results are presented first because they demonstrate the reliability of our fluid image interpretations.

### 3.1 Tests of Precision

In some circumstances, such as for our precision studies of emergent jets that now allow stringent tests of numerical simulations, it proves necessary to measure the actual time (e.g. SRS SR620) between demand and response by utilising the print image clocking signals and the monitor output of the light source. Figure 2 illustrates the improvement to “good” (~ 250 ns) timing we obtained for emergent jet tip studies by paying attention to this issue, and exploiting the generally smooth behaviour for emergent tips.

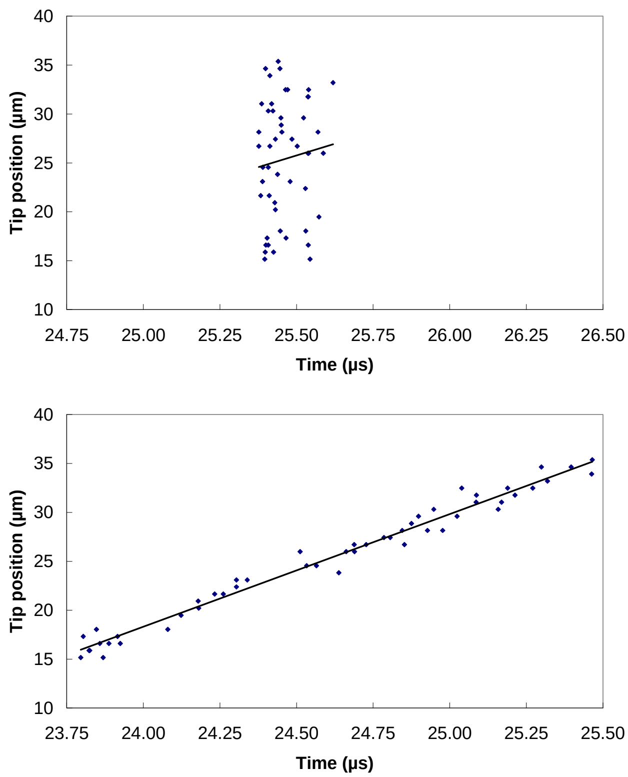


Figure 2: Print timing effects can distort true tip position: before (upper) and after (lower) use of the actual timing.

For the data shown in Figure 2 a print head clock cycle time of 1.75 µs was used; the upper graph has an apparent timing spread of ~ 0.25 µs, but the tip position appears smeared by ~ 20 µm, i.e. ~ the nozzle radius, which is very significant for emergent jets. The apparent timing is well measured (e.g. SRS DG525) but its start triggering is asynchronous with actual printing. The lower graph, using actual timing, explains the apparent spatial position spread shown in the upper graph. The straight line fit to the data validly associated with the emergent tip timing is merely there to guide the eye to the expected smooth behaviour of tip position with time. Figure 2 also demonstrates that the reproducibility of timing and spatial resolution in our tip emergence studies is < 0.1 µs and < 2 µm (i.e. < 0.1 in units of the nozzle radius) respectively.

Images are more routinely recorded at preset delay times (e.g. SRS DG535) between the print drive waveform time and the high speed flash, in order to reconstruct the average behaviour of inkjets, because in most cases the spatial effect of triggering timing variations can be ignored.

### 3.2 Tests of Optical Distortion

There is a major difference between high resolution imaging of a single jet and high resolution imaging an array of jets, quite apart from the additional alignment required for narrow depth of focus work: large area optics may produce extra pin-cushion/barrel distortions into the images.

We have measured these effects in two ways: the first more conventional way using analysis of a ruled optical grid imaged at the normal optical settings for our inkjets, and the second by triple flash imaging the straight flight paths of fast inkjet drops and image analysing their apparent positions. These methods agreed to better than 10% for a typical maximum distortion of 2% at the corners. The triple flash method was simultaneously used to measure air drag on inkjet drops and also the influence of attached ligaments. The self-consistency of these tests and expected air drag on small fluid drops was better than ~ 10% of theory at ~ 3 m/s.

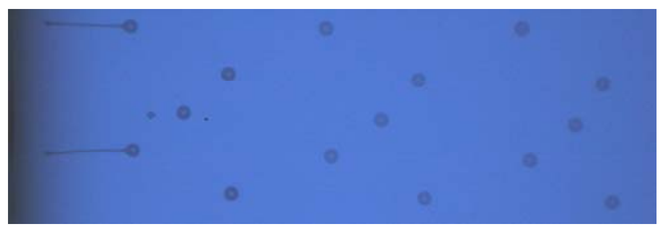

Figure 3: Part of a triple flash image used to determine both image distortion and drag on drops due to air or a ligament.

### 3.3 Tests of image processing limits

Image analysis of inkjets at Cambridge has used custom automated software to cope with actual variations in spark flash intensity from image to image. This procedure detects edges and converts the image to a binary form as discussed elsewhere [1]. The appropriate choices of thresholds and limits for the image processing software were determined by comparing the axisymmetric volumes deduced for jets with long ligaments and spherical drops in multi-flash images (such as those like Figure 3), and the minimum reliable ligament width was deduced to be 5 pixels. At our normal resolution (~ 0.71 µm per pixel) this is equivalent to a ~ 3.6 µm thread. In our previous published work [1] we showed that fast DEP jets had ligaments that narrowed down to this order of width before they tended to rupture rather close (within about a nozzle diameter) to the nozzle plane. These DEP ligaments also have conical rather than cylindrical shape and can rupture from 3.6 µm on < 1 µs timescales [1].



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## 4 FLUID RESULTS

Fluid experiments [2] show that the volume expelled in a 6 m/s jet depends on the head drive voltage that is needed; increases in the low shear-rate viscosity or the elasticity of a fluid can be caused by < 1 wt% addition of high (<0.1 MDa) molecular weight polymer (e.g. polystyrene, polyethylene oxide), and so the drive voltage needed increases, resulting in longer ligaments and an increase in the satellite numbers. Despite this, it appears that particular molecular weights for some polymers minimise the number of satellites formed, and we continue to study the underlying physical reasons for such behaviour so that we can predict better formulations.

We have been able to relate the concentration of a given polymer to the jetting performance and to the persistence of the ligament length before and after break off. Polymers can be stretched within the rapid fluid flows through a narrow print head nozzle and/or during the subsequent stretching of the ligament before break off but also have a characteristic relaxation time (back to their normal state) in dilute polymer solutions. For polymers which have characteristic times that are long compared with the break off time for pure solvent jets, the polymer fluid jetting can be seriously influenced by the additional elasticity even for quite low concentrations; for characteristic times that are shorter than the print head drive waveform the stretched polymer has time to relax back and barely influences the polymer jetting. It appears, in our studies, that the optimal conditions for polymer enhanced ligament recoil are achieved if the polymer timescales in the fluid roughly equal the print head drive waveform timescale.

Although this finding has been checked for 2 different polymer-solvent systems, choosing the fastest recoil speed for that fluid does not imply that the number of satellites is minimised, and in fact rather higher molecular weights, but at lower concentrations, could more fully suppress satellites.

## 5 DROP-ON-DEMAND PRINTING

The length of the ligament when it breaks off from the nozzle plane sets a lower limit for the separation distance between the nozzle and the substrate for drop-on-demand printing for most applications, whereas variable jet directions can set upper limits. The reduction of the length of the ligament, due to ligament recoil driven by surface tension and elasticity, takes some further time, which would increase this separation limit where spherical drops are to be deposited and/or image distortion due to ligaments are to be avoided. We found [2] that this reduction depends on the composition or state of the (complex) fluid in the ligament. Using slower jetting to avoid satellites is not an option for many applications, but designing better fluids can help out.

## 6 DISCUSSION

Our timing investigations suggest the level of reliability that can be associated with our imaging of inkjets and hence whether jet profiles can challenge numerical simulations for fluids used in inkjets. Complex mixtures can be jetted and so the hope is that such imaging can validate not only these codes but also some of the assumptions used in the jetting physics (e.g. pinning of the meniscus to the nozzle edges) to permit the better development of fluids for jet applications.

Results from our investigations of the volume of fluid jetted from Xaar XJ126 print heads are consistent with the concept of a universal jetting curve for a given print head type, dependent on the inverse Ohnesorge number Z, that was introduced by Reis and his co-workers [4], but also extends testing of this concept to include elastic fluid types.

Ligament imaging details events and processes are not readily apparent to workers using stroboscopic lighting methods: further measurements and also physical modelling of the ligament recoil speed after break off from the nozzle plane is reported by ourselves and co-workers elsewhere [5].

The suppression of satellites by the addition of PAM (polyacrylamide) polymer of various molecular weights and low concentrations to fluids for jetting has been independently reported by Bazilevskii and co-workers [6]. One common aspect of all this work is the trade off between the added viscosity associated with higher concentrations of relatively low molecular weight material and the elasticity of relatively low concentrations of relatively high molecular weight material: there could well be a preferred combination of molecular weight and concentration for optimum jetting.

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## REFERENCES

[1] I.M. Hutchings, G.D. Martin and S.D. Hoath, ‘High Speed Imaging and Analysis of Jet and Drop Formation’, The Journal of Imaging Science and Technology vol. 51, no. 5 p. 438-444, September/October 2007.

[2] S.D. Hoath, G.D. Martin, T.R. Tuladhar, M.R. Mackley, D. Vadillo and I.M. Hutchings, “Links between fluid rheology and drop-on-demand jetting and printability”, The Journal of Imaging Science and Technology JIST #4459, accepted February 2009.

[3] J.J. Crassous, R. Regisser, M. Ballauff and N. Willenbacher, “Characterization of the viscoelastic behavior of complex fluids using the piezoelastic axial vibrator”, Journal of Rheology, **49**, 851 (2005)

[4] N. Reis, C. Ainsley, and B. Derby, “Ink-jet delivery of particle suspensions by piezoelectric droplet ejectors”, Journal of Applied Physics, **97**, 094903 (2005)

[5] S.D. Hoath, G.D. Martin and I.M. Hutchings, “A model for ligament contraction in drop-on-demand inkjet printing”, submitted to NIP25 Conference Louisville Kentucky (2009)

[6] A.V. Bazilevskii, J. D. Meyer and A.N. Rozhkov, “Dynamics and Breakup of Pulse Microjets of Polymeric Liquids”, Fluid Dynamics, **40**, No. 3, 2005, pp. 376–392.