Standardization Of Inkjet Drop Speed Measurement Methods For Printed Electronics

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Abstract

Methods for measurement of inkjet-printed drop speed at various precision levels were proposed in a draft international standard by IEC TC119: Printed Electronics WG3 - Equipment. These are reviewed and discussed for feedback by NIP31/DF2015.

Introduction to IEC TC119 WG3

An International Electro-technical Commission (IEC) Technical Committee (TC119: Printed Electronics) Working Group (WG3-Equipment) is now formulating the (ISO) standards on measurement methods for jetted ink drop velocity and volume. Measurements of inkjet drop speed and volume are important for many applications, but due to the variety of methods available the interpretation of results obtained and inter-comparisons between different print heads are still uncertain. The aim of this paper is to review and discuss some of the issues with droplet imaging methods currently being considered for the IEC standard [1]. As a university-based inkjet researcher and member of WG3, I welcome your feedback and suggestions on all aspects of inkjet drop measurement, to help improve the appropriateness, precision and accuracy of optical methods chosen for the proposed IEC standard.

In-flight measurements of inkjet-printed drops

Ideally (at least from the perspective of industrial users and machine builders) every inkjet print-head produces drops with the same speed and volume for all frequencies and printing patterns, and there would be no need to check or compare print-heads. This scenario still relies on the accuracy and the interpretation of the specifications provided by the print-head and ink manufacturers. Independent test-houses for equipment certification traceable to national or recognized standards (such as those for vacuum gages) are probably inappropriate for the industrial inkjet market because print-heads are low cost consumables and not capital equipment. So there is a need to provide standard measurement methods for the industrial world of inkjet printing, which are deemed useful, achievable and appropriate by the manufacturers and their clients.

This immediately raises questions about what yardsticks to choose and how to use them. In established inkjet applications it is the printed material that is usually of more immediate concern, rather than the material delivery system comprising the inkjet print-head and the ink (until something happens to go wrong). For establishing an inkjet application or the equipment itself, the print-head and the ink must be tested. Great progress is being made with reliable methods for the characterization of new inkjet inks, including functional materials used for printed electronics, which is assisting the design of better formulations for jetting and applications, but these techniques are still quite specialized for non-Newtonian inks and inkjet print-head jetting may still prove necessary to devise the complex ink formulations suitable for some printing applications [2, 3]. This explains why Newtonian fluids such as water, simple solvents or oils, with well-known characteristics under both the high shear-rate and extensional flow conditions encountered during jetting and the low shear-rate conditions in storage and delivery pipes, are invariably used for testing the print-heads performance. Newtonian test fluids will be assumed henceforth, so the discussions will center on the methods for measuring the inkjet printing equipment jetting performance.

Optical drop-watchers

Imaging of inkjet droplets is primarily achieved using the shadowgraph technique [4], where the light source provides a bright background that is blocked by drops in the magnified field of view. For accurate assessments, light sources should provide sufficiently short exposure times that drop motion will not blur the images beyond the sub-pixel resolution level of the optical device. The detectors commonly used are high resolution CCD or CMOS devices coupled to PCs or self-contained (video) cameras. The camera pixel size is of order 10 µm and optical magnifications of about x10 may be used to image drops to about 1 µm resolution. An atypically low 1 m/s DoD drop speed requires exposure times below 1 µs duration to avoid blur, whereas faster 10 m/s drops would require 100 ns exposure times for the same imaging system.

Optical drop-watchers [5] have already proved very effective yardsticks and the common basis for measurement of inkjet drop speeds, directionality and drop volume. Axisymmetric liquid drops are assumed for volume determinations [4, 6-8] but these are not always accurate representations of long trailing “tail-hooking” ligaments or for merging drops or grayscale sub-droplets.

Before delving into such niceties of inkjet fluidic behaviour, the interpretation of basic measurement issues should be introduced, since even single nozzle print-heads (see Figure 1) have variations that require documented assessment procedures and methods to establish the print-head performance, such as the measurement of speed, directionality, volume, shape and repeatability of the initial and subsequent droplet(s) for drop-on-demand (DoD) printing at one or more frequencies.

Now consider a typical scenario for DoD print-head jetting tests:

(a) Measurements will be made under standard conditions
(b) A suitable test fluid will be jetted by the print-head
(c) Results are needed at various steady print frequencies
(d) The print-head has several (parallel) rows of nozzles
(e) The stand-off distance is between 0.25 mm and 2.5 mm
(f) Strobe techniques are used to obtain droplet images

Each and every one of these statements has to be clear for proper specifications of methods used for inkjet droplet measurements, but none of them is sufficiently unambiguous for an ISO standard.

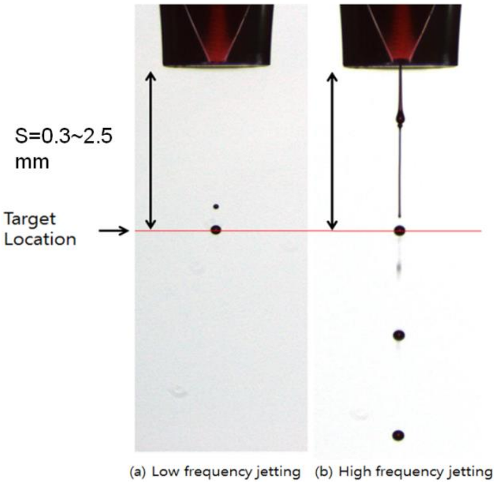

Figure 1. *Single nozzle showing stand-off distance S = 0.5~2.5mm with strobe images of drop-on-demand droplets at low and high jetting frequencies [1].*

Assessment of the complete in-flight drop behavior [9] will depend on whether there is sufficient access, illumination and contrast in a field of view that encompasses the planes of the print-head nozzles and the substrate at the stand-off distance. The different nozzle rows may lie in different vertical planes, so that drops from one row are out of focus relative to another row. Out of focus drop imply incorrect drop size and volume values will be deduced from measurements on all uncorrected drop images, unless suitable holographic measurement techniques are applied [10]. Drop-watcher systems providing assessment in 3D are already marketed. The author has previously used orthogonally mounted cameras and spark flash imaging to explore inkjet "tail hooking" events [6].

The nozzle plane is often obscured by a nozzle guard or other baffles; likewise, to permit optical assessments the substrate cannot be present. This immediately changes the airflows around the inkjet-printed drops. In addition, the airflows around individual jetting streams depend on which rows and nozzles are printing, and whether the substrate is normally moving relative to the print-head. Other external conditions can affect the inkjet print-head either directly, e.g. by cooling the device, or indirectly, e.g. by altering jetted ink viscosity or surface tension, or because relative humidity affects the ink formulations. Conditions must always be specified.

Calibration

Absolute measurements of drop speed and volume rely on calibration of the optical system, which requires placement of suitable length standards into the focal plane using the same magnification and illumination conditions. These standards may be ruled optical gratings or objects such as cylindrical wires and rods, or ceramic spheres, which have been independently measured. If an array print-head is being assessed, the manufacturers' stated nozzle-to-nozzle separation can provide checks on the calibration. Linear calibrations should be determined to 1 µm level or better.

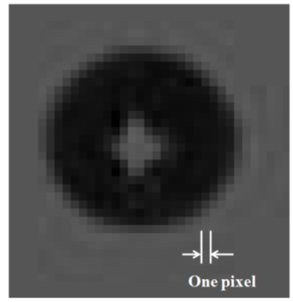

Figure 2. *Limitations to measurements caused by the pixelated drop image [1].*

Although the main focus of the present paper is discussing the proposed standard measurement methods for (DoD) drop speed of printed electronics inkjet equipment, the drop volume is also important for establishing inkjet processes and production rates. Figure 2 illustrates a key limitation for optical methods [1]. Jetted drop volume variances are rarely established accurately, because weighing a million printed drops at a fixed and relatively high frequency can only provide an average drop weight [11]. Direct drop-by-drop evaluations rely on cantilever mass balances [12].

Limits to 50 µm diameter drop volume determinations, using a 1 µm pixel resolution as for the drop speed measurements, can be estimated at 6%, rising to 15% for 20 µm diameter drops. Limits for drop speed are usually very much better than this, since determination of a spheroidal drop centroid is at sub-pixel level. Elapsed time intervals are easily controlled to better than 100ns, so timing error is only 1% for an atypically short 10 µs delay interval. For speeds at 10 m/s, the drop moves 100 µm, which for sub-pixel centroids is known to far better than 1%. Therefore drop speed can easily be measured to better than 1%, six times better than volume.

Establishing drop volume variances appears a tough enough problem, that only worsens for inks sufficiently transparent on the DoD scale that refraction effects obscure the true location of drop edges. Significant lensing effects in such inks can result in the recording of bright central spots within near spherical droplets and bright central lines along the ligament axes, e.g. in shadowgraph images of jetted water and solvent drops. Diffraction effects are also important in establishing the real size of droplets from high resolution images, since the gradient of the recorded light level varies predictably, near the curved edges around spherical drops and along ligaments, given the correct optical focus and geometry.

The determination of drop jetting direction is independent of calibration for optical systems without significant aberrations. The author has previously used triple flash measurements on array print-head drops to measure the % distortion across a field of view, getting results in good agreement with tests using an optical mesh. Typical camera pixel resolutions in drop-watchers limit jetting angle measurements to precisions of around 0.1° (2 milliradian).

Strobe or flash illumination?

A key consideration for the WG3 standards committee has emerged from discussions of some key merits and disadvantages of strobe as against single flash illumination. We consider them here, before introducing each of the approaches compared in Figure 3.

Approach 1	Approach 2	Approach 3	Approach 4	Approach 5
Elapsed time T between trigger from print head and droplet reaching specific stand-off distance D	Elapsed time T after jet tip emerges from nozzle until jet tip reaches stand-off D	"Instantaneous speed" determined from distance drops move in short time: U=(D2-D1)/(T2-T1)	Distance D between successive drops at jet frequency F=1/T gives U=D×F	High speed videos of droplet motion
U=D/T usually under-estimates average velocity over flight path	Better estimate, but nozzle plane often not observable for industrial print head	U is tracked with distance from nozzle so is a measure of impact speed at Ď; ΔT strobe: not small	Jetting (or strobe) frequency sufficient for > 1 drop in view. centroid (precision); edges (less precise)	Used for academic studies of droplet trajectories
Early method: for easy comparisons, but low accuracy	Academic method: inkjet trajectory by strobe, video, flash	Edges cope with any ligament; strobed drops (less precise)	Approximate speed for different drops; Double flash precise	HS cameras are too expensive for quite lo spatial resolution

Figure 3. *Possible standard measurement methods discussed by IEC TC119: Printed Electronics – Equipment - Inkjet. I seek NIP31/DF2015 feedback on my unofficial view, which is not (necessarily) endorsed by any on WG3 committee.*

Strobe lighting is often triggered in (delayed) synchronism with the DoD print-head drive waveform, and will operate at this frequency (rather than a sub-multiple of it). As discussed elsewhere by Kye-Si Kwon [13], such arrangements alter the recorded image brightness unless the light pulse duration can be suitably adjusted to compensate for printing frequency changes. Without fixed illumination, the usual binary image analysis and edge detection techniques can introduce bias due to thresholds and image "bleaching" differences between images recorded at different printing frequencies. Double strobe lighting provides a delay between the usual strobe and a second strobe.

Flash illumination relies on constant and very short duration pulses that occur while the camera shutter is held open [14]. Unless double flash techniques are used to determine the speed of drops then single events are recorded by single flashes, providing (in principle) the same level of brightness at all printing frequencies [15]; double flash provides a correspondingly higher but constant level of image brightness at all frequencies. Double spark flash [6] and laser flash [7] methods can determine drop speeds provided that the liquid jets and droplets from each jetting event can be distinguished on a single image. Dual color-filtered spark flash lights with RGB cameras can help achieve the fluid tracking needed for this, as was demonstrated during 2005 for DoD inkjet print-heads in our Cambridge laboratories by High-Speed Photo-Système (Wedel, Germany). The triggering and delay generation used for strobe or flash lighting systems are otherwise very similar or identical in practice. The good availability of fast high power LEDs and suitable power switching circuits has enabled industrial usage of LEDs for short duration flash illumination purposes in modern drop watchers [16] with great benefits to their adoption for rapid determination of drop speed, directionality and volume.

Tracking methods

MatLab reconstruction of position-time curves for DoD jetted droplets have been demonstrated [9] using strobe illumination that can reveal on-line general inkjet behaviour such as the slowing down of the emerging jet tip prior to ligament break-off [17] and merging of fast satellites with the main drop that normally require high speed video or repeatable behaviour if using flash imaging methods. Drop speeds are deduced from the slope of the position-time curve by fitting the positions measured at discrete times along the path.

However for higher jetting speeds, where more satellites tend to get formed, the tracking methods will become far harder to maintain reliably and efficiently as the combinations rapidly rise. Measurements at higher printing frequencies and/or with multiple print-head nozzles actively jetting will also encounter overlapping images of main drops and satellites from other jetting nozzles or printing events, which makes reliable drop tracking even harder.

Nevertheless, tracking methods do help assess where the measurements of final drop speed should NOT be attempted, i.e. so close to the nozzle outlet that merging is likely to cause big errors. They can be used to help automate the inkjet printing set-up for new print head designs, for drive waveform trimming and even inkjet fluid development.

DoD print-head assessments often start with a nominal drop speed for a standard ink formulation jetted at a certain drive frequency. The nominal drop speed has to be set up using the drive voltage level (amplitude) and drive waveform deemed optimum for the standard ink. A typical protocol for defining the location used and the method of speed measurement for the nominal drop speed involves using a pre-determined optical field of view marked with an appropriate distance scale. The image plane of the firing nozzles is focused at distance "zero" and then the suitably delayed strobe image of the main drop (or the jet tip) is shifted, using the drive voltage amplitude, until it lies at the chosen stand-off distance marked on the distance scale (as shown for a single nozzle print-head in Figure 1). However, uncertainties are already lurking within this simple scenario for drop speed measurement methods, which have to be considered when formulating inkjet standards. Several approaches to this are summarized below and in Figure 3.

Approach 1

The drop speed U=D/T, obtained from the ratio of stand-off distance D divided by flight time T equated to the strobe or flash delay, is only ever an average speed value. Delay T is taken relative to drop firing pulses (forming the drive "waveform") of finite duration, with the leading pulse edge defining "zero" delay. This simple method is the lowest level (Approach 1) considered for a standard method of measuring inkjet drop speeds. It avoids the need to observe the nozzle plane and emerging drops.

However this ignores the inherent delays between the drop firing pulse and the emergence of the drop from the nozzle and any inaccuracies due to triggering variations arising from the actual emergence of the jet tip from the nozzle plane and under-estimates the physical average speed of the jetted drop. As the final (impact) speed at the stand-off distance is usually somewhat lower than the average speed, application of measurements using Approach 1 is uncertain.

Furthermore, when the drop firing frequency is sufficiently high to produce several drop images within the stand-off distance at all times, the pulse triggered strobe method will in general give ambiguous flight times and drop speeds, unless some form of drop tracking is also used. Use of a single delayed flash would remove this ambiguity because only one jetting event is imaged at a time.

To avoid this ambiguity when printing at a high frequency f, speed averages might be obtained from measurements of the separation S of images for (apparently) successive drops along the jetting axis drops, thereby inferring the "drop" speed from U=Sf. The average location of the drop images used in this approach has to be compared with the far simpler use of the stand-off distance: average absolute speeds obtained from the drop spacing are usually more relevant to impact than to the delivery speed after fire pulses.

Approach 2

Assuming that the nozzle plane is visible and the emergence time of the jet tips can be established, the next accuracy level for average drop speed measurements (Approach 2) strictly requires either ultra-high speed video or single fire pulse double flash techniques. Although strobe techniques will smear both the tip emergence time and the attainment of the stand-off distance and inherently average over different drops, real drop by drop speed variations imply that double flash or even ultra-high speed videos are unlikely to capture drops at precisely the correct locations at either start or end flash times or at integer frame numbers, and then averaging smears these over drops too. Thus using strobe or flash methods will produce average speeds which are subtly different. As with Approach 1 the individual drop speed measured with video or double flash techniques allows the determination of the variations between drops rather than just the average speed. The average speed is now U= D/T where T is the elapsed time between the tip emergence at "zero" distance and the tip reaching D.

Approach 3

The shape of drops depends on their location and their origin: drops with ligament tails and/or merging satellites may be present at the shorter stand-off locations but absent at longer distances; at higher printing frequencies slower or delayed satellites from earlier jetting events or from misdirected liquid from nearby "failing" nozzles can apparently co-locate (as usually they are out of focus objects) or even physically merge with the focused droplets of interest. In contrast the double flash exposure can be used to find the speed of individual drops (see Figure 4), but then needs to be averaged over the same number of "strobe" drops for comparison with the value from strobe measurements. Which method is really better? In principle speed uncertainties can be found directly from the variance of the double flash measurements taken over many drops, whereas the strobe method automatically gives the average speed including this variation (which extends the image length). Extra analysis could be used to determine the speed uncertainty for double strobe measurements by finding gradients of the grayscale profiles for the drop edges in the jetting (length L) and transverse (width W) directions or more simply from the aspect ratio (L/W).

Approach 4

Measurement of the distance D between single strobe or flash images of successive drops appearing on the same image and jetted at a fixed frequency f can be used to infer drop speed from U=Df, for sufficiently high printing frequencies or relatively slow drops. For double flash measurements, where the same drop can be reliably identified and tracked, direct measurements of position change could offer highest precision speeds provided the timing interval is great enough and the slowing down in air is negligible. This method for speed measurement is a "precision grade" because the variation between the speeds of different drops is eliminated. These single drop measurements must then be averaged over many

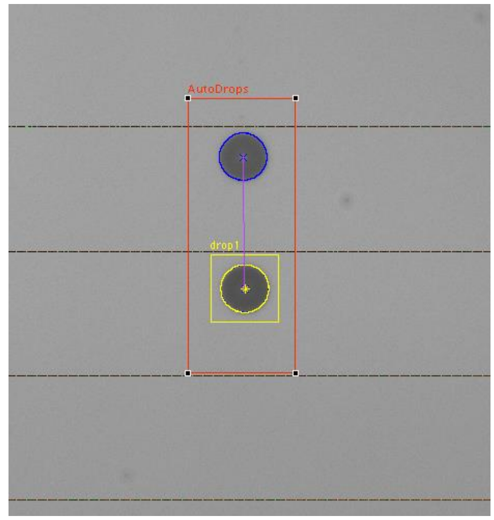

***Figure 4**. Double flash method used in automated on-line image analysis, within a rectangular region of interest, finds the centroid of one single spherical droplet having a pair of separated images corresponding to two flashes with a known time delay difference [1]. To represent the measurement of drop speed during continuous jetting of drops at a fixed frequency, these individual double flash results have to be averaged. For strobe illumination each "drop" image is extended lengthwise by timing and jetting changes occurring for different drops.*

drops in order to find the speed distribution of jetted drops at the printing frequency. This approach would then give the mean and standard deviation of the drop speed distribution at a given frequency, and can be suitably generalized for frequency sweeps.

Whenever the double flash timing interval (T=1/f) or the distance D travelled by a drop in the time T become too short that the drop images significantly overlap, then speed and directionality measurement using this method could become quite inaccurate, unreliable, or even untenable, so that the finally agreed standard should explain the estimates of the accuracy limitations expected.

Approach 5

Using ultra-high speed video cameras to record in-flight droplet behaviour is often very instructive but is primarily suited single nozzle print-heads and off-line image analysis and academic studies, rather than general industrial inkjet printing applications. Ultra-high speed cameras have relatively low spatial resolution and are very expensive compared with monochrome CMOS sensors, recording typically 100 frames for short bursts of time at fixed rate. An example of such research was shown in [3] and also at NIP30. Another application of ultra-high speed cameras is for the study of inkjet drop oscillations to deduce the values of fluid properties under inkjet printing conditions, but the low spatial resolution for drop size determination does certainly limit this technique [18, 19].

When the major requirement is to determine drop positions or size, high resolution single shot cameras usually provide a better option. Where the inkjet jetting behaviour is repeatable, e.g. jet emergence before break-off from the nozzle, single shot image sequences at short regular delay intervals (1-2 μs) are very commonly used to construct "videos" illustrating such jetting behaviour with high resolution.

Future standards

Figure 3 shows my view on five possible approaches to the measurement method standard for drop speed, without prejudice to the outcome of national committee voting on any revised WG3 documentation. Our Munich 2015 WG3 meeting concluded that development of a standard method for measurement of inkjet drop speed, though already quite challenging, will be very much easier than the next task of drafting some realistic methods for the measurement of inkjet drop volume. Please do offer your thoughts.

Conclusions

New international standards for measurement methods being developed for inkjet drop speed in Printed Electronics should provide a basis for manufacturers specifying and users comparing print head performance. The task is challenging for several reasons that were introduced for discussion purposes at NIP31/DF2015.

There does not appear to be an optical assessment method that will prove perfectly suitable under every conceivable condition of drop speed, volume, printing frequency, jetted fluid, drive waveform… Even assuming a specific fluid is used, the jetting frequency, pixel size and image plane calibration may limit the determination of jetting angle and drop size (hence volume), while the emergence of the jet at some time after the drop firing pulse limits simple flash methods for drop speed measurement.

Questions of average behaviour have to be considered, as in practice the variations and well as central values for speeds, angles and drop volumes are sought.

It is likely that the different levels of accuracy attained when following any particular approach will require full specification of the method "engineering grade" and experimental conditions used. A consensus on which methods provide the most appropriate measurement accuracy for in-flight determinations of droplet speed, direction and volume in industrial inkjet applications such as printed electronics is being actively sought for these standards [20].

Acknowledgements

This work was supported by EPSRC and a consortium of UK industrial partners (EPSRC Grant no. EP/H018913/1: Innovation in industrial inkjet technology). The informal discussion paper has originated from recent discussions with my colleagues, both within and outside the WG3 committee meeting co-located with LOPEC Munich ICM on March 3rd 2015. Any misrepresentation of their thoughts and views is entirely my responsibility. With many thanks to WG3 inkjet drop speed project leader Kye-Si Kwon, the WG3 convener Taik-Min Lee, my fellow committee members Kei Hyodo (Konica-Minolta) and Yair Kipman (ImageXpert) within WG3, my colleagues Graham Martin and Ian Hutchings, and also Paul Best (ImageXpert) for their shared thoughts and presentations.

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