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INTERNATIONAL STANDARD

Printed electronics –
Part 302-2: Equipment – Inkjet – Imaging-based measurement of droplet volume

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Part 302-2: Equipment – Inkjet – Imaging-based measurement of droplet volume

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The text of this International Standard is based on the following documents:

FDIS	Report on voting
119/204/FDIS	119/216/RVD

Full information on the voting for the approval of this International Standard can be found in the report on voting indicated in the above table.

This document has been drafted in accordance with the ISO/IEC Directives, Part 2.

A list of all parts in the IEC 62899 series, published under the general title *Printed electronics*, can be found on the IEC website.

The committee has decided that the contents of this document will remain unchanged until the stability date indicated on the IEC website under "http://webstore.iec.ch" in the data related to the specific document. At this date, the document will be

- reconfirmed,
- withdrawn,
- replaced by a revised edition, or
- amended.

A bilingual version of this publication may be issued at a later date.

PRINTED ELECTRONICS –

Part 302-2: Equipment – Inkjet – Imaging-based measurement of droplet volume

1 Scope

This part of IEC 62899 specifies the method for determining accurate inkjet droplet volume based on images obtained by drop-in-flight measurement systems. It does not apply to imaging systems using interference fringes, such as holography or phase doppler anemometry. This document is not limited to drop-on-demand inkjet systems, but might not be applicable to continuous inkjet or liquid dispensing systems. This document includes a description of the issues concerning such measurements and consideration of the limits to measurement accuracy.

2 Normative references

There are no normative references in this document.

3 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

- IEC Electropedia: available at http://www.electropedia.org/
- ISO Online browsing platform: available at http://www.iso.org/obp

3.1
droplet volume
amount of jetted fluid from an inkjet print-head nozzle measured by single event imaging

Note 1 to entry: For a single event drive pulse designed to produce sub-drops that are intended to merge in-flight to form a larger droplet, for example to form a specific greyscale image value on deposition, droplet volume refers to the large merged droplet and not to smaller component sub-drops.

3.2
native drop volume
amount of fluid within the smallest sub-drop jetted from a greyscale inkjet print-head used to create images with droplets formed by multiple sub-drops within a single event

Note 1 to entry: Native drops (or threads or satellite drops) might be too small for accurate measurements by flash imaging, but satellite drops that have merged in-flight might be large enough for drop analysis systems. (See Figure 1 for a representation of the relative sizes for greyscale droplets in-flight.)

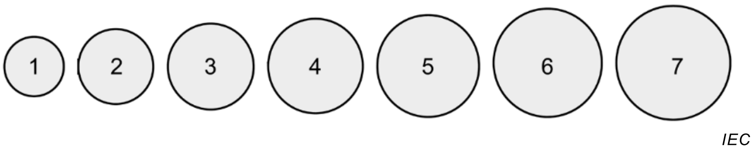

Figure 1 – Representation of greyscale drop size 1 (“native drop”) to size 7

4 Droplet volume measurement

4.1 General

4.1.1 Overview

This document concerns accurate determination of inkjet droplet volume from high speed flash images of inkjet droplets travelling in-flight from inkjet print-head nozzles. Accurate relative (rather than absolute) droplet volumes are useful for industrial inkjet-printed electronics applications. Short flash durations avoid significant motion blurring in droplet images. Two widely used scenarios, for flash imaging as applied to measurement of inkjet drop speed, are considered in this document because they produce slightly different information about droplet volumes. Images that contain superposed nominally identical and similarly placed droplets can provide an average size for volume measurements, whereas the single event images give measures of the size and variations of the size and centroid location produced during volume measurements. Clause A.1 gives further information about specific instrumentation limits.

Shadowgraph imaging can readily determine individual inkjet droplet sizes if the fluid bodies appear dark against a light background [1[1]]. However, droplets should be well-focused, and the optical images have a suitable pixel resolution and background intensity with low intensity variations, and image blur due to droplet motion during the flash should have minimal effect on droplet size determination. For liquid droplets, background intensity level, refraction and diffraction can alter apparent image size, and if the liquid is not opaque refraction often produces a bright central spot. As spherical droplet shapes are preferred for the most accurate and rapid online image analysis and conversion to volume, all in-flight measurements should be made only where any sub-drops (and satellites) from the same single event pulse have merged, and also any droplet shape oscillations have fully damped out. Droplet volume is then inferred from the diameter (pixels) or area (number of pixels covered) of the dark region by assuming spherical geometry and image symmetry about the focal plane and linear calibration of the optical system (in µm/pixel). Accurate fitting algorithms determine droplet size to sub-pixel levels, but also depend on an assumption about where the droplet boundary is located in an image. This can provide an absolute droplet volume if calibrated using a suitable traceable method. For example, the measured weight of a known number of drops of known density gives the average drop volume which may be compared with that deduced by the drop measurement system [2].

More commonly, reference objects of known dimension(s) placed in the drop measurement system are imaged and analysed using the same optical conditions as for the inkjet droplets. Relative volume comparisons can be made between droplets without an absolute calibration.

4.1.2 Volume measurement and droplet shape equalization processes

In principle, once droplets have been ejected from an inkjet print-head nozzle, their volume does not change if evaporation losses or drop merging are negligible. However the resultant droplet shapes can alter markedly from their jetted shapes until they relax towards their final shapes (see Figure A.5). Accurate in-flight measurements always analyse spherical shapes, avoiding long thin jet shapes [1] (or spinning non-spherical blobs of liquid) that might not actually lie symmetrically in the (2D) image focal plane and hence might not be convertible into volume. Some inkjet fluids used in printed electronics and other applications do not always form fully smooth or spherical droplets under all jetting conditions [3] and in such cases the drop analysis system provides less accurate (or even misleading) results. Examples are highly shear-thinning high viscosity fluids, gels and fluids with large particles. Accurate droplet volume measurement systems using multiple event imaging also require very stable jetting by the inkjet print-head and avoidance of first droplet and burst printing effects in inkjet printing [4, 5].

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[1] Numbers in square brackets refer to the Bibliography.

4.1.3 Imaging optics

Drop-on-demand inkjet drops move at 5 m/s to 10 m/s and typically need sub-microsecond high power flash illumination and also high resolution digital cameras with 10X magnification (or more) for in-flight measurement of droplet volume using shadowgraph imaging. Tele-centric optical designs and high power LED flash can deliver (background) illumination and imaging conditions with a depth of focus sufficient for accurate inkjet droplet volume measurements using drop analysis systems. Appropriate flash delay times can locate droplets near the centre of the optical field of view for accurate droplet volume determination. Optical field of view is determined by the magnification and camera sensor area and spans typically a few hundred micrometers. Multiple-event imaging increases the background image level where the single event flash intensity is limited, at the cost of achievable droplet volume accuracy. Background intensity levels, expressed as a greyscale intensity level, are ideally specified for the drop analysis system, as is apparent from recent studies of image analysis errors [6]. Proper focusing of drop analysis systems can reduce unwanted blurring of droplet images, which can otherwise cause inaccurate analysis of the droplet shape, size and volume.

4.1.4 Image shape processing

One or more regions of interest, within the total field of view of the drop imaging system, may be set (by a user or automatically) to contain the particular droplet images for analysis. This assists automatic identification of droplets and speeds up the analysis and presentation of results. Either axial or spherical symmetry of droplet images should be assumed by the drop analysis system so that droplet volumes can be computed from individual shadowgraph images. The image shape processing used by the drop analysis system may involve thresholding, edge detection, boundary location, circles, ellipses, equivalent circular diameters, maximum lengths and widths, area, sliced drums or cones, or even evolving shapes [6, 7, 8, 9]. Accurate determination of droplet volume requires sub-pixel techniques, as shown in Clause A.1.

4.1.5 Calibration

The linear calibration of the optical field of view should be established with grids, lines or objects of suitable known size and spacing under similar light conditions and flash duration; the threshold value used for such calibrations should equal that used for drop measurements. Calibration factors of 1,00 µm/pixel or less are typical for drop analysis systems accurately measuring drop-on-demand inkjet droplet volumes, using camera pixel sizes of 10 µm or less. An approximate (~1 %) calibration factor can be conveniently found for some measurements by imaging several inkjet nozzles or emerging jets within the same field of view (i.e. > 100 µm) and comparing the (nominal) nozzle pitch with the apparent pixel separation. However this is often not feasible for industrial inkjet print-heads because they have a shielded nozzle plane.

4.1.6 Uncertainties

Imaging-based measurements of droplet volume depend on the cube of the linear calibration factor, so that droplet volume uncertainty is three times that of the calibration factor uncertainty. Thus the minimum uncertainty in accurate droplet volume measurements is ± 3 % for a linear calibration factor known to ± 1 %. As a typical example, the calibration factor of 1,00 µm/pixel in 4.1.5 has no error shown, so that the minimum assumed linear uncertainty is ± 0,01 µm, i.e. ≥ ± 1 %, and therefore the minimum assumed absolute volume uncertainty is ≥ ±3 %. Traceable standards should normally have an absolute uncertainty more than ten times lower than this. Uncertainties in droplet volumes appropriate to relative comparisons of images recorded with a drop analysis system are given in Clause A.2.

4.2 Processes for measurement of inkjet droplet volume

4.2.1 General

Inkjet droplet volume shall be measured by using one of the two following methods, unless there is an alternative user and supplier agreement. These two methods principally differ in the use of single- or multiple-event-mode images to determine droplet diameter, but may also differ in calibration procedures: single-event mode is appropriate for highest accuracy and absolute measurements while multiple-event mode provides smeared “droplet size” measures often used for relative comparisons.

4.2.2 Process for measurement of inkjet droplet volume – Method 1

This process describes the in-flight method for inkjet droplet volume measurements using the single-event mode: individual droplet images are recorded for analysis without any superposition of other droplets.

1) Commence inkjet printing with the desired specifications (frequency, ink selection, waveform, etc). It is recommended to record jetting conditions, including these specifications and other relevant details, as described in Clause A.3.
2) Ensure that the desired jets and merged droplets are “in focus” at the focal plane of the imaging optics, adjusting the delay time of the single event light flash such that fully merged and equalized droplet shapes are located in the analysis region of interest. This process may be performed automatically or manually, and it may be combined with a measurement of instantaneous droplet speed using double flash, as described by IEC 62899-302-1 (analysis method 4) [13]. The duration of the flash should not be greater than a few hundred nanoseconds to avoid image blur of the droplet. The (double) flash intensity should be sufficient to allow discrimination between the drop edge and the background, without saturating the image.
3) Extract the single event mode droplet diameter D (pixel) by suitable analysis of the recorded image. The average and statistical variance of repeated single-event-mode droplet diameters are used to represent the average droplet diameter with a standard error free from smearing by any velocity and timing variations. This process may be performed automatically or manually, and it is recommended that this and the number of drops used in the average also be recorded, as described in Clause A.3.
4) The calibration factor F (µm/pixel) should be determined at the optical magnification used by the drop analysis system to determine droplet volume (picolitre). This calibration is preferably made using traceable standards placed in the focal plane, or using the average pitch of inkjet nozzles in array print-heads. It is recommended that all details of the calibrations used be recorded, as described in Clause A.3.

4.2.3 Process for measurement of inkjet droplet volume – Method 2

This process describes the in-flight method for inkjet droplet volume measurements using the multiple-event mode: different droplets are recorded as a single image and analysed as if they were a single droplet.

1) Commence inkjet printing with the desired specifications (frequency, ink selection, waveform, etc). It is recommended to record jetting conditions, including these specifications and other relevant details, as described in Clause A.3.
2) Ensure that the desired jets and merged droplets are “in focus” at the focal plane of the imaging optics, adjusting the delay time of the single event light flash such that fully merged and equalized droplet shapes are located in the analysis region of interest. This process may be performed automatically or manually, and it may be combined with a measurement of drop speed, as described in IEC 62899-302-1 (methods 1 to 3) [13]. The duration of the flash should not be greater than a few hundred nanoseconds to avoid image blur of the droplet. The flash intensity should be sufficient to allow discrimination between the drop edge and the background, without saturating the superposed image.

3) Extract the multiple-event-mode droplet diameter (pixel) by suitable analysis of the recorded image. This gives an average droplet diameter (potentially) smeared by any velocity and timing variations. This process may be performed automatically or manually, and it is recommended that this and the number of drops used in the average is also recorded, as described in Clause A.3.
4) The calibration factor F (µm/pixel) should be determined at the optical magnification used by the drop analysis system to determine droplet volume (picolitre). This calibration is preferably made using traceable standards placed in the focal plane, or using the average pitch of inkjet nozzles in array print-heads. It is recommended that all details of the calibrations used be recorded, as described in Clause A.3.

Annex A
(informative)

Key considerations for in-flight droplet volume measurement

A.1 Jetted droplet volume in printed electronics

A.1.1 General

Accurate measurement of jetted droplet volume is an important issue in printed electronics applications because the amount of material deposited on the substrate is directly related to device performance. The jetted droplet amount should be consistent (uniform) for all nozzles in a multi-nozzle head to ensure device uniformity. This requires reliable measurements of the droplet volume at all times and for all nozzles for use in printed electronics applications. Reported inkjet droplet volumes may not be reliable or traceable to any national standard. Droplet volume measurement issues identified for drop analysis systems are discussed below.

A.1.2 Image resolution

There has been strong demand for the generation of smaller droplets with higher printing frequencies. Unless the digital camera used to record the image of a smaller droplet has correspondingly improved pixel resolution there is increasing difficulty to measure droplet volume accurately. As an example, for an inkjet print-head generating 20 µm diameter droplets, the typical image resolution setting of 1µm/pixel implies the droplet grey image will be only 20 pixels across. Figure A.1 (for a droplet with a diameter of 28 pixels) illustrates how a one-pixel uncertainty due to image resolution limits the determination of droplet diameter.

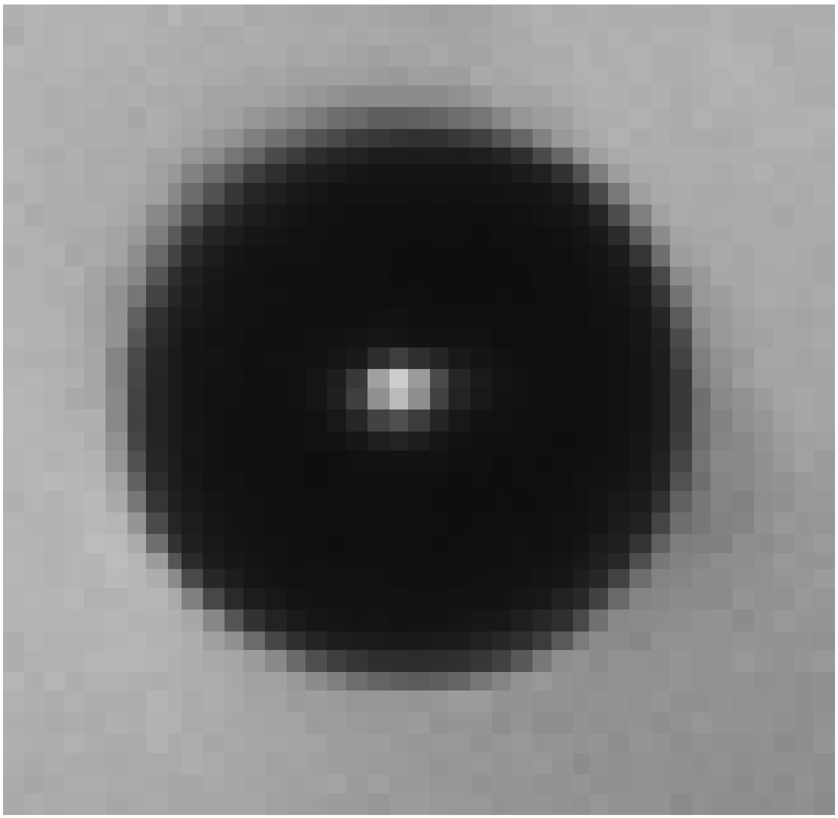


Figure A.1 – Magnified droplet grey image

A one-pixel resolution limit for twenty pixel droplet diameters would itself imply a minimum of ± 5 % diameter error and ± 15 % volume errors; these are completely unacceptable uncertainties in inkjet droplet volume determination for use in printed electronics. Even for comparison purposes inkjet droplet images should have more pixels/diameter (i.e. higher resolution and/or higher optical magnification) and a higher raw background greyscale level (i.e. higher intensity or longer flash duration or lower optical magnification) than for Figure A.1, which clearly shows individual square pixels. Accurate drop analysis systems should also use sub-pixel techniques rather than one-pixel techniques to extract accurate droplet diameters.

To reduce measurement errors, higher zoom magnification with an optical lens may be used. If the one-pixel size is significantly small compared to the droplet, the pixel-related error can be minimized. High magnification (M) might not be beneficial for drop volume measurements because image intensity is proportional to $1/M^2$ and the image noise is increased with magnification, thereby changing the conditions for determining the boundary. More sensitive higher-resolution cameras can be used to reduce the pixel errors. Nonetheless, there are cost issues, and the image acquisition rate (frames per second) might decline when using such cameras. Compromises between all these factors are often necessary.

The apparent diameter of an imaged drop is also affected by other physical effects on the light rays used to illuminate typically 20 µm diameter droplets in-flight, principally arising from optical diffraction effects [12] around (and refraction through a semi-transparent) liquid body. Such effects are (usually) ignored in industrial applications using relative size calibrations.

A.1.3 Greyscale-to-binary image conversion

Inkjet printing with greyscale droplet sizes (represented in Figure 1) can achieve a targeted material deposition profile on the substrate but in inkjet droplet image processing terms, even with nominally identical droplet sizes, greyscale-to-binary image conversions (from say Figures A.1 to A.2) are also relevant for accurate droplet volume determination.

Each image pixel of an 8-bit greyscale image has a value ranging from 0 to 255 according to the brightness of the image. The greyscale image can be converted into a binary one where the pixels hold values of 0 or 1. The binary image can be obtained by setting an appropriate threshold value where values higher than the threshold are mapped to one (or zero) and those lower than the threshold are mapped to zero (or one) [7]. By using the binary image, the ink droplet can be extracted and analysed based on particle analysis or other methods. Here, by appropriately setting a threshold for discretization, the ink droplet's pixels have a value of zero (or one), and the background can be one (or zero). When using a binary image to measure the droplet volume, the measured droplet size can be significantly affected in the greyscale-to-binary image conversion process. As shown in Figure A.1, there is a relatively smooth transition of image value near the boundary between the droplet image and the lighter background. The smooth transition of image value depends on various conditions such as lighting brightness and lens focus. As a result, the identified droplet size (and droplet volume) differs according to the threshold value for binary conversion. Figure A.2 shows binary images converted from a similar drop, where two very different threshold values are compared.

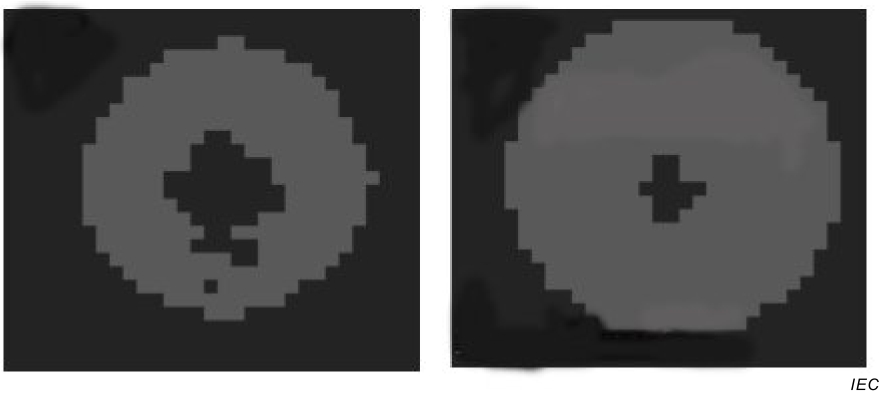


Figure A.2 – Threshold value influence on binary image: on the left, a threshold of 25; on the right, a threshold of 75

The measured droplet volume may contain errors because the measured results differ according to the threshold value needed for binary image conversion and flash light intensity. When a threshold value of 25 is used for binary conversion, the diameter of the droplet can be identified as 20 pixels. On the other hand, a threshold value of 75 can result in a diameter of 24 pixels; hence the difficulty in measuring an accurate inkjet droplet volume (or size) from the images. As shown in Figure A.2, the errors related to binary conversion are much larger than the one-pixel resolution of the CCD camera, which produces volume uncertainties exceeding ± 15 %. Other techniques for determining the “edges” and hence droplet volumes corresponding to the images have been compared and applied to simulations of droplets imaged with various numbers of pixels in the drop shape and different levels of background noise and intensity in order to understand the possible percentage variations. In many cases, provided there are sufficient pixels, the simplest threshold method is the most effective in terms of computation speed at providing a reasonably accurate droplet volume [6].

Focusing and magnification distortion can also influence the apparent size of imaged droplets. Where control of the illumination, available resolution and image processing reduces particular uncertainties to a low level, approximately < ± 1 % in volume, droplet image focusing and other optical effects may dominate the volume uncertainty. Poor drop focus is usually the most significant issue for inkjet drop analysis systems, if the optical magnification varies within and beyond the depth of focus, since inkjet droplet diameters cannot always be located exactly within the focal plane. Figure A.3 gives a schematic for the effects on out-of-focus objects arising from image height magnification using a conventional lens.

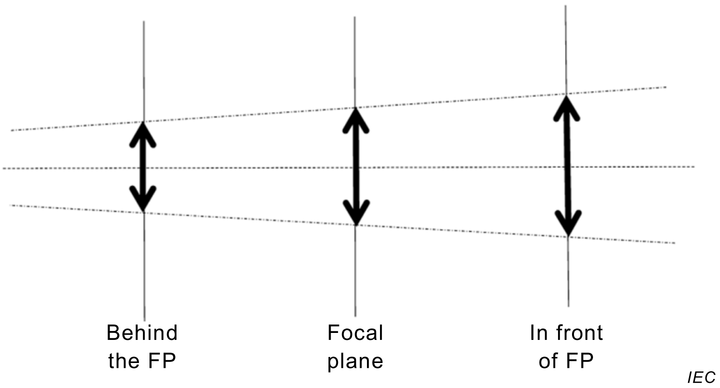


Figure A.3 – Apparent image height of objects imaged near the focal plane (FP) using a conventional lens

Such an optical system's depth of focus can be improved by using a smaller aperture (as in a "pinhole camera" where everything in view appears well-focused), but only with reduced image intensity (background grey level). Modern telecentric lenses are compound lenses with a constant magnification inside and symmetric blurring of edges beyond the depth of focus, and are very useful for accurate machine vision purposes within inkjet drop watchers.

For relative measurements, if droplets appear at the same location in the field of view, magnification distortion errors are usually negligible. For absolute measurements, the central region of the optical system's field of view should provide the lowest magnification distortion. Figure A.4 provides an extreme example of magnification distortion for conventional optics.

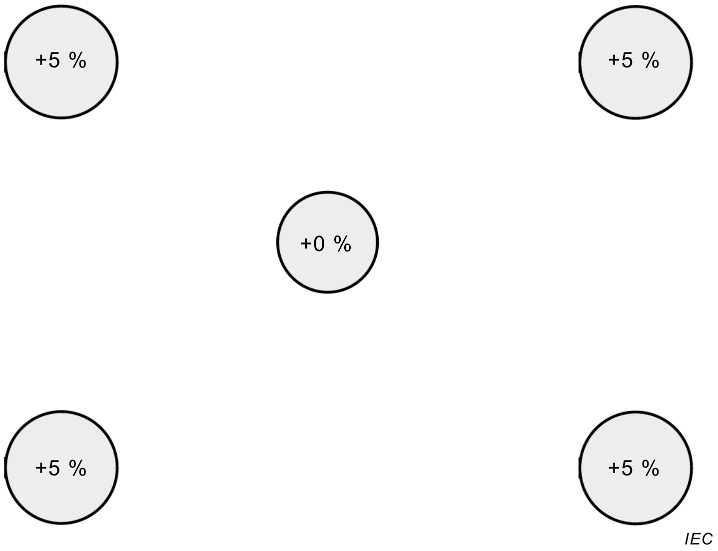


Figure A.4 – Example of percentage size distortion in image plane for a conventional lens

As an example, if a +2 % magnification distortion applies for an off-centre image, a volume discrepancy of +6 % occurs for droplets imaged there rather than in the (0 %) central region. Again, telecentric lenses usually have lower distortion than single fixed focal length lenses.

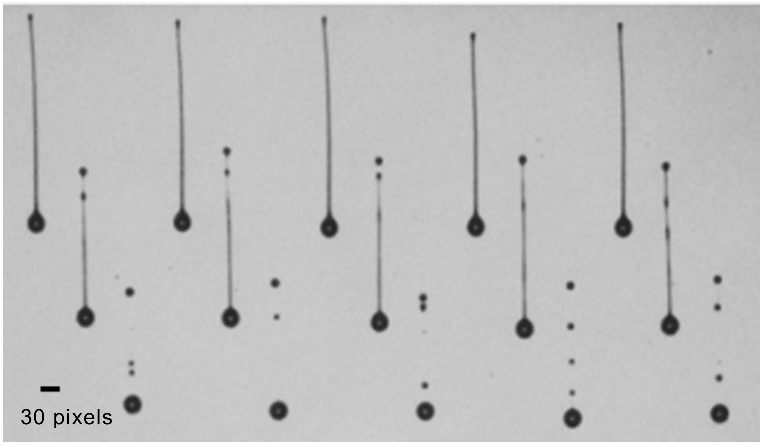
A.1.4 Absolute droplet volume

The droplet image shape is used to determine the droplet volume by assuming axial symmetry about the jetting axis [6, 7, 8, 9]. As a result of the critical optical conditions, results for inkjet droplet volume measurement may be drop-analysis system-dependent. As absolute standardization for measuring droplet volume is complex, and since a measurement error range is inevitable, it should be stated together with the measured droplet volume to ensure reliable absolute comparisons between different drop analysis systems. The absolute accuracy of inkjet droplet volume measurements by direct weighing is reported as approximately ± 0,1 pl (picolitre) [2].

By weighing the collected liquid corresponding to known (counted or computed) numbers of inkjet droplets (or trigger pulses), an average jetted drop volume can be deduced by assuming the density of the ink is well known at the relevant temperatures (of jetting and weighing). Any evaporation occurring during the collection period will adversely affect this calibration [10]. National laboratories are researching new micro-balance weighing techniques for individual inkjet droplets, and have deduced that inkjet drop volumes may be traceable to ± 0,1 pl, i.e. ± 3 % for 3,3 pl droplets [2]. The most accurate size measurements require spherical droplets. Holographic measurements are accurate to radii < 100 nm [1, 11].

Relative droplet diameters (pixels) can be calibrated for many purposes by measuring the horizontal separation between focused droplets corresponding to different nozzles of vertically jetting print-heads using the known separation of these nozzles. Such linear calibration factors, even in the absence of aerodynamic and optical effects, have uncertainties of typically > 1 % and the droplet volume is thus uncertain to > 3 %.

Figure A.5 is part of a shadowgraph of inkjet-printed droplets, ligaments and satellites jetted at 5 m/s from an industrial inkjet print-head. For low magnification distortions, an approximate linear calibration of the image pixel size can be found from the average horizontal separation of the drops and the nominal nozzle pitch. In this example the presence of trailing ligaments and satellites prevented the accurate determination of jetted droplet volume because the satellites do not merge with the leading drop into a single droplet as required in this document; furthermore the pixel width of even the largest drop visible is not sufficient for high accuracy.



IEC

Figure A.5 – Shadowgraph of inkjet-printed droplets, ligaments and satellites in-flight

A.2 Formulae for inkjet droplet volume

Given droplet diameter D in pixels and calibration conversion factor k to convert pixels to micron (10^{-6} m), droplet volume $V = \pi(kD)^3/6\,000$ pl (10^{-9} l = 10^{-12} m^3). For droplet volume determination using image-based drop analysis systems, sub-pixel analysis of a drop image diameter is required for reaching volume accuracies better than ± 3 %.

One-pixel analysis techniques introduce further uncertainties in droplet centroid locations. Droplet diameter D should exceed approximately 30 pixels to reduce total volume error below ± 5 %.

The formulae given below for images in one-pixel height slices can be modified for other heights. An implicit assumption in volume determination is that the boundary should be axisymmetric.

Given the analysed boundary, the droplet volume (V) may be computed from the summation of the pixel volumes for all the consecutive conical slices with one-pixel height containing the droplet boundary. For N slices, with the j^{th} slice between the neighbouring diameters of D_j and D_{j+1} pixels:

$$V = \frac{\pi k^3}{12} \sum_{j=1}^{N} \left(D_j{}^2 + D_j D_{j+1} + D_{j+1}{}^2 \right)$$

This conical slice summation usually improves on the more commonly used circular drum slice resulting in:

$$V = \frac{\pi k^3}{4} \sum_{j=1}^{N} \left(D_j^{\,2} \right)$$

A.3 Results

Results should include, but are not restricted to:

- the manufacturer, model type and serial number of the drop measurement system;
- which optical calibration reference standard has been used, including its traceability (if any);
- which image types are analysed for the drop volume quoted (single or multi-event);
- the number of droplets used in evaluating the average droplet volume quoted;
- the average droplet volume and uncertainties at the specified print frequency;
- the nominal droplet speed at the specified print frequency;
- the ink type used and relevant operating conditions for the inkjet print-head used;
- the manufacturer, model type and serial numbers of the inkjet print-head used;
- the nozzle pitch along a nozzle row, number of nozzle rows and row spacing; and
- the nozzle row and array location identifier(s) for the droplet volume measurement.

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