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Printed electronics – Part 302-1: Equipment – Inkjet – Imaging based measurement of jetting speed

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The text of this standard is based on the following documents:

FDIS	Report on voting
119/168/FDIS	119/183/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.

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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

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- withdrawn,
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INTRODUCTION

Inkjet technology uses micro nozzles to precisely eject droplets. For printing, these droplets are patterned on a substrate. Inkjet is a mature technology that has been used widely in home, commercial, and industrial applications. When using inkjet technology, the volume of a droplet can be controlled down to the tenth of a picoliter (pl). Furthermore, the droplet can be placed onto the substrate with an accuracy of micrometers (μm). Because of these features and others, inkjet technology has emerged as one of the most powerful tools for patterning electronic devices, medical dispensing, high precision industrial applications, and more. Inkjet patterning for electronics is an additive process wherein the addition of multiple layers of the pattern does not require the removal of any previously deposited material, unlike the conventional photolithography process. Inkjet also reduces waste when used in more traditional printing applications and when it is used for dispensing. As a result, inkjet technology significantly reduces waste of what are often very expensive materials and is also more environmentally friendly.

As applications for inkjet broaden, a wider variety of jetting materials should be dispensed precisely from inkjet heads. For both new and traditional applications, droplet behaviour from the inkjet head should be measured properly to evaluate and control jetting behaviour. Vision-based measurement techniques are widely used in inkjet-based manufacturing systems, since physical insight into jetting behaviour can be obtained from visual images. The droplet jetting speed and droplet volume are the most frequently measured jetting performance parameters obtained from droplet images.

Using information obtained from vision-based measurement systems about inkjet droplet formation and characteristics, developers can adjust ink formulations and jetting parameters, in order to improve performance.

Note, however, that the measured jet performance and evaluation may vary considerably according to the measurement method since there is no standard measurement procedure available. It may be difficult for process engineers to judge the data sheets of jet performance provided by ink and inkjet head manufacturers since there are no fair test methods, thus causing potentially untrustworthy results. Therefore, the purpose of this document is to provide a standard inkjet measurement method.

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Part 302-1: Equipment – Inkjet – Imaging based measurement of jetting speed

1 Scope

This part of IEC 62899 specifies the method for determining inkjet drop speed based on visualized droplet images obtained by a drop analysis system. This measurement standardization is limited to drop-on-demand-type of inkjet and is not applicable to continuous inkjet. This document includes the test process, image processing software algorithm, and analysis of jetting behavior.

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
inkjet printing
type of printing in which a digital image is created by propelling droplets of ink onto a substrate

3.2
drop analysis system
vision-based equipment that can both image and measure inkjet droplets

3.3
drop speed
distance divided by the time it takes the drop to traverse the distance

3.4
drop delivery speed
total distance between the inkjet print-head nozzle plate and the substrate, divided by the time interval between jet triggering and drop arrival

3.5
drop trajectory
drop's direction of travel, often characterised as an angle relative to the nozzle plate

3.6
drop repeatability
droplet jetting behaviour whereby each drop ejected from the nozzle is the same as every other

Note 1 to entry: Drop repeatability is often visualized by displaying individual drops, one per frame, so the characteristics of each can be compared and contrasted. It is quantified by measuring the standard deviation of the drops.

3.7
drop trace
plot of droplet locations from sequential images to understand jetting behaviour including ligament and satellites

3.8
single event imaging
method of capturing each drop image that represents a single jetting event

Note 1 to entry: Raw images of individual drops are in no way added or averaged to produce the final image.

3.9
multiple event imaging
method of capturing each drop image that represents an average or sum of multiple jetting events

Note 1 to entry: Raw images of individual drops are added or averaged to produce the final image.

3.10
single flash mode
LED or high power light that is flashed once per jetting event

Note 1 to entry: Single flash mode may be used with single- or multiple-event imaging.

3.11
double flash mode
LED or high power light that is quickly flashed twice per jetting event, thereby capturing the same individual drop in two different locations within the camera field of view

Note 1 to entry: Double flash mode may be used with single or multiple event imaging.

3.12
sequential image
series of jetting images starting from the jetting trigger signal to the time of interest

Note 1 to entry: Sequential images can be obtained from the drop analysis system by increasing the trigger delay of the flash with respect to jetting signal.

3.13
jetting speed curve
jetting speed plot with respect to time, which is calculated from the drop trace

Note 1 to entry: The information includes the relative jetting speed of the main droplet with respect to satellites.

4 Inkjet jetting speed measurement

4.1 General

Inkjet jetting speed shall be measured by using one of the following methods, unless there is a user and supplier agreement. See Annex A for additional information on inkjet measurement methods.

4.2 Process for measurement of drop delivery speed (method 1)

This process describes the measurement method for drop delivery speed from the time of the jetting trigger to the time the drop reaches the target location.

1) Commence printing with the desired specifications (frequency, ink selection, waveform, etc.). It is recommended to record the jetting conditions, in addition to those described in Clause A.6.
2) Specify the target stand-off distance S from the nozzle surface, which usually corresponds to the distance between the nozzle surface and the substrate.

   NOTE Stand-off distances between 0,3 mm and 2,5 mm are typical.
3) Determine the time (T) for the leading edge of the droplet to reach the target stand-off distance by increasing the delay time of the strobe light flash. This process may be performed automatically, or manually. 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 image.
4) The drop delivery speed V can be calculated as:

$$V = \frac{S}{T} \tag{1}$$

5) The calibration factor F (µm/pixel) should be determined at the optical magnification used by the drop analysis system to determine drop delivery speed (m/s) from Formula (1). The bottom locations of the droplet are used for the droplet location if the droplet has a long ligament.

4.3 Process for measuring instantaneous jetting speed using single flash mode (method 2)

This process describes the measurement method based on a single flash for instantaneous jetting speed when the droplet reaches the target location.

1) Commence printing with the desired specifications (frequency, ink selection, waveform, etc.). It is recommended to record jetting conditions, as described in Clause A.6.
2) Specify the target location. The target location (stand-off distance) usually corresponds to the location of the substrate media.

   NOTE Stand-off distances between 0,3 mm and 2,5 mm are typical.
3) Determine a starting trigger delay time (t_1) of the strobe light flash, at which the drop is slightly above the target location. The smaller the distance of the drop above the target location, the smaller the distance over which the average drop velocity will be calculated.
4) An image is captured and analysed at trigger delay t_1 to determine P_{x1} and P_{y1}, the position of the droplet (center or leading edge) in the x and y directions, respectively.
5) Determine the ending trigger delay time (t_2) of the strobe light flash, at which the drop is slightly below the target location. The smaller the distance of the drop below the target location, the smaller the distance over which the average drop velocity will be calculated.
6) An image is captured and analysed at trigger delay t_2 to determine P_{x2} and P_{y2}, the position of the droplet (center or leading edge) in the x and y directions, respectively.
7) The drop speed V is calculated as:

$$V = \frac{\sqrt{(P_{y2} - P_{y1})^2 + (P_{x2} - P_{x1})^2}}{t_2 - t_1} \tag{2}$$

8) The calibration factor F (µm/pixel) should be determined at the optical magnification used by the drop analysis system to determine the instantaneous jetting speed (m/s) from Formula (2). The bottom locations of the droplet are used for the droplet location if the droplet has a long ligament. If Δt is too short, the jetting speed error due to image quality will be amplified. If Δt becomes large, a long-term average jetting speed is obtained instead of the instantaneous jetting speed at the target location.

4.4 Process for instantaneous jetting speed curve (method 3)

This process describes the measurement method for jetting speed curve.

1) Commence printing with desired specifications (frequency, ink selection, waveform, etc.). It is recommended to record the jetting conditions, in addition to those described in Clause A.6.
2) Specify the target location. The target location (stand-off distance) usually corresponds to the location of the substrate media.

   NOTE Stand-off distances between 0,3 mm and 2,5 mm are typical.
3) Determine the final trigger delay time (T_f) of the strobe light flash to identify the time when the droplet is at the target location. If there are ligament and satellites, the final trigger time should be long enough such that the ligament and satellites can reach the target location.
4) Increase the trigger delay of the strobe light flash from zero to the pre-determined time (T_f) to obtain the sequential image. The appropriate trigger delay increment can be adjusted to accommodate faster or slower drops, but 20 μs is typical.
5) Each sequential image is processed to measure drop trajectory and instantaneous jetting speed. Automatic image processing is recommended. From a binary image converted from a grey image, the maximum and minimum locations of the k^{th} droplet in the y direction, denoted as $P_k^{\max}(t\text{d})$ and $P_k^{\min}(t\text{d})$, can be obtained (see Figure A.5 and refer to Clause A.4). The superscripts max and min denote the maximum and minimum locations in the jetting direction, respectively. The drop trajectory was updated by adding the calculated maximum and minimum locations of each droplet, $P_k^{\max}(t\text{d})$ and $P_k^{\min}(t\text{d})$, respectively, to the graph before acquiring the next sequential image.
6) The instantaneous jetting speeds of each droplet, $V_k^{\max}(t\text{d})$ of the k^{th} droplet, can be obtained using the following relation:

$$V_k^{\max}(t\text{d}) = \frac{P_k^{\max}(t\text{d}) - P_k^{\max}(t\text{d} - \Delta t\text{d})}{\Delta t\text{d}} \tag{3}$$

   where $\Delta t\text{d}$ is the incremental time of trigger delay between the two consecutive images, and $P_k^{\max}(t\text{d}) - P_k^{\max}(t\text{d} - \Delta t\text{d})$ are the travel distance from the nozzle of the maximum locations of the k^{th} droplet during time duration $\Delta t\text{d}$.
7) The calibration factor F (μm/pixel) should be determined at the optical magnification used by the drop analysis system to determine jetting speed (m/s) from Formula (3). The bottom locations of the droplet are used for the droplet location if the droplet has a long ligament. If $\Delta t\text{d}$ is too short, the jetting speed error due to image quality will be amplified. If Δt becomes large, a long-term average jetting speed is obtained instead of the instantaneous jetting speed at the target location.

4.5 Process for measurement of instantaneous jetting speed using double flash (method 4)

This process describes the measurement method for instantaneous jetting speed using the centroid of a single drop.

1) Commence printing with the desired specifications (frequency, ink selection, waveform, etc.). It is recommended to record the jetting conditions, as described in Clause A.6.
2) Specify the target location. The target location (stand-off distance) usually corresponds to the location S where the substrate media is located.
3) Switch to “double flash mode”, in which the LED is flashed twice for each droplet, showing the single drop in two different locations on the camera field of view.

4) Determine the delay time (T_D) between the two flashes of the LED, thereby moving the two images of the same droplet closer and farther apart. The smaller the distance between the images of the drop, the smaller the distance over which the average drop velocity will be calculated. Commonly, this delay is determined so as to allow approximately the width of one drop between the two images.
5) Determine a trigger delay time for the first strobe light flash, so that the two images of the drop straddle the target location.
6) An image is captured and the centers of each of the two images of the single drop are determined using automatic image processing (P_{x1}, P_{y1} and P_{x2}, P_{y2}).
7) The drop speed V is given by:

$$V = \frac{\sqrt{(P_{y2} - P_{y1})^2 + (P_{x2} - P_{x1})^2}}{t_2 - t_1} \tag{4}$$

8) Calibration factor F (μm/pixel) should be determined at the optical magnification used by the drop analysis system to determine jetting speed (m/s) from Formula (4). If Δt is too short, the jetting speed error due to image quality will be amplified. If Δt becomes large, a long-term average jetting speed is obtained instead of the instantaneous jetting speed at the target location.

Annex A
(informative)

Additional information on inkjet measurement methods

A.1 Vision-based measurement hardware

Figure A.1 shows an example drop analysis system that is typical of what is used in inkjet-based manufacturing systems. By using a strobe light source (e.g. LED) synchronized with the firing signal, droplet images appear to be frozen in the acquired CCD camera image. As a result, the image processing used to measure the ink droplet location and size can be relatively straightforward.

Vision measurement systems have primarily been used to evaluate inkjet system performance, including droplet speed and volume, drop repeatability, drop formation, and more. Even when using similar hardware and basic measurement concepts, however, the measurement results will differ significantly if the standard procedures are not used. These measurement issues will be discussed in detail for better understanding of the need for standardization.

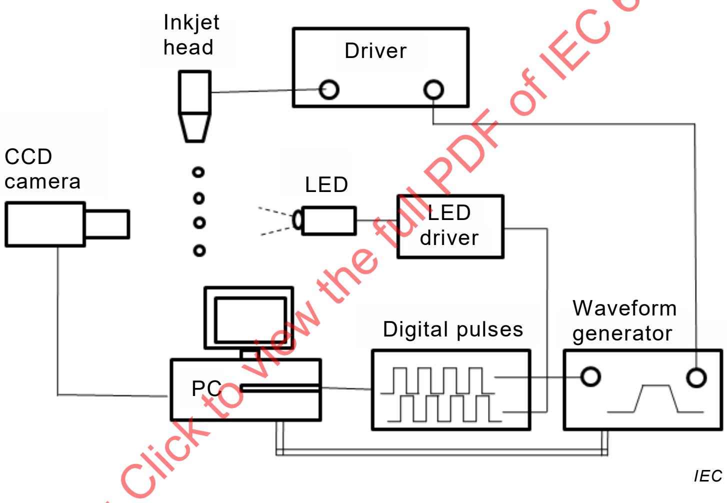


Figure A.1 – Vision measurement method

A.2 Flash imaging

A.2.1 General

There are two major types of strobe (flash) imaging: single event imaging and multiple event imaging.

A.2.2 Single event imaging

Single event imaging means that any displayed or analysed image is captured based on a single firing pulse, with a single flash of the LED. Images are not formed by summing or averaging multiple individual frames. In other words, any drop shown in an image is a single individual drop, and not a compilation.

A.2.3 Multiple event imaging

Multiple event imaging means that any displayed or analysed image is captured using multiple firing pulses, with several flashes of the LED. Images are formed by summing or averaging multiple individual frames. In other words, any drop shown in an image is actually a compilation of several drops.

A.3 Analysis method 2 (instantaneous jetting speed using single flash)

Method 2 describes the measurement of the instantaneous jetting speed using a single flash. For method 2, two images are captured of different droplets, triggered at delay times t_1 and t_2 with respect to the jetting trigger signal (see Figure A.2).

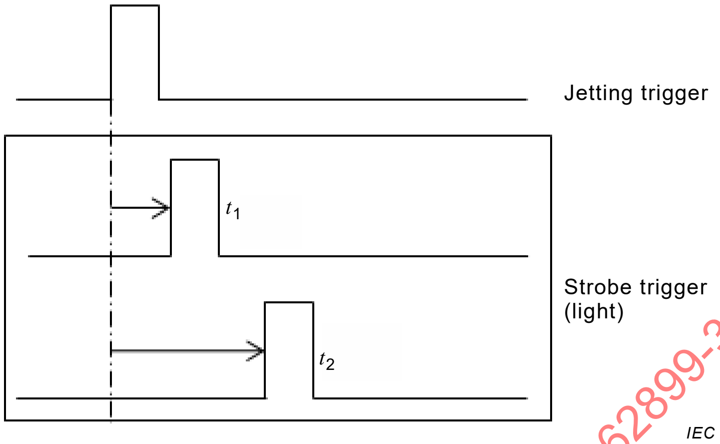
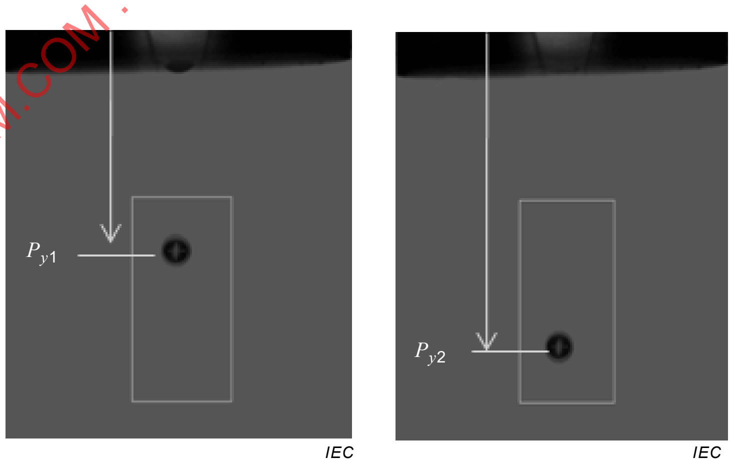


Figure A.2 – Two different trigger delays for two images

Jetting speed V (m/s) can be calculated as:

$$V = \frac{\sqrt{\left(P_{y2} - P_{y1}\right)^2 + \left(P_{x2} - P_{x1}\right)^2}}{t_2 - t_1} \qquad \text{(A.1)}$$

where P_{y1} and P_{y2} give the identified droplet center location in the y direction at t_1 and t_2, respectively, and P_{x1} and P_{x2} give the identified droplet center location in the x direction at t_1 and t_2, as shown in Figure A.3.



a) **Image at t_1** b) **Image at t_2**

Figure A.3 – Jetting speed measurements using two images

A.4 Analysis method 3 (instantaneous jetting speed curve)

Method 3 describes the measurement of the drop trajectory and instantaneous jetting speed curve to measure jetting speed variation during drop formation.

For this purpose, each sequential image in Figure A.4 will be analysed to obtain the bottom and top locations of droplets.

From a binary image converted from a grey image, the maximum and minimum locations of the k^{th} droplet in the y direction, denoted as $P_k^{\max}(t\mathrm{d})$ and $P_k^{\min}(t\mathrm{d})$, can be obtained as shown in Figure A.4. The superscripts max and min denote the maximum and minimum locations in the jetting direction, respectively. The drop trajectory was updated by adding the calculated maximum and minimum locations of each droplet, $P_k^{\max}(t\mathrm{d})$ and $P_k^{\min}(t\mathrm{d})$, respectively, to the graph before acquiring the next sequential image as shown in Figure A.5 a). From the drop formation curve, the instantaneous jetting speed curve can be obtained as shown in Figure A.5 b) [1][1].

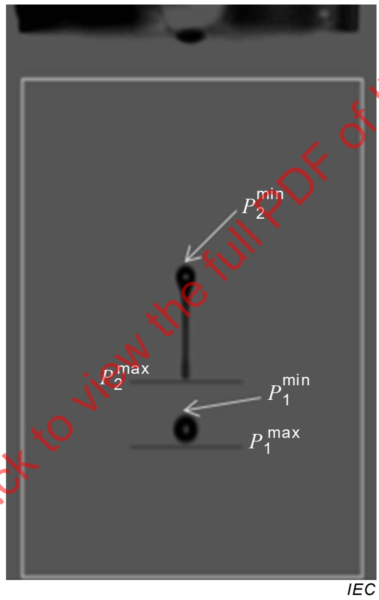
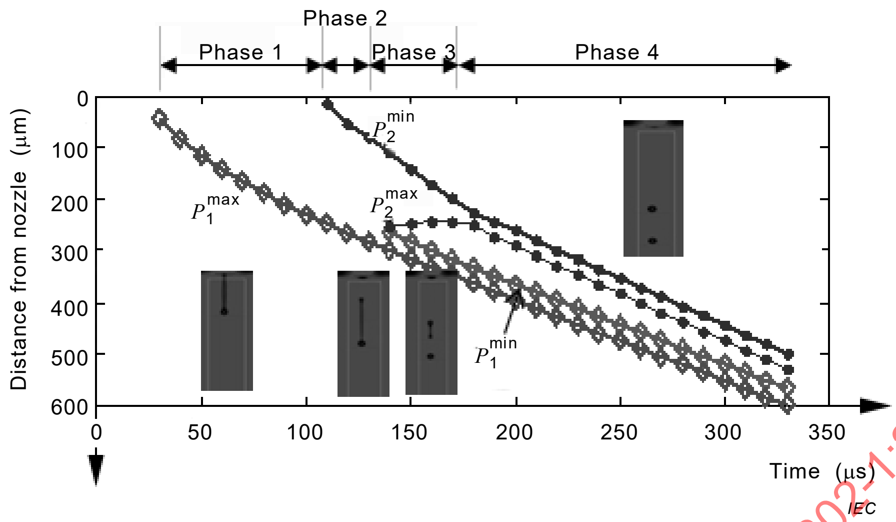
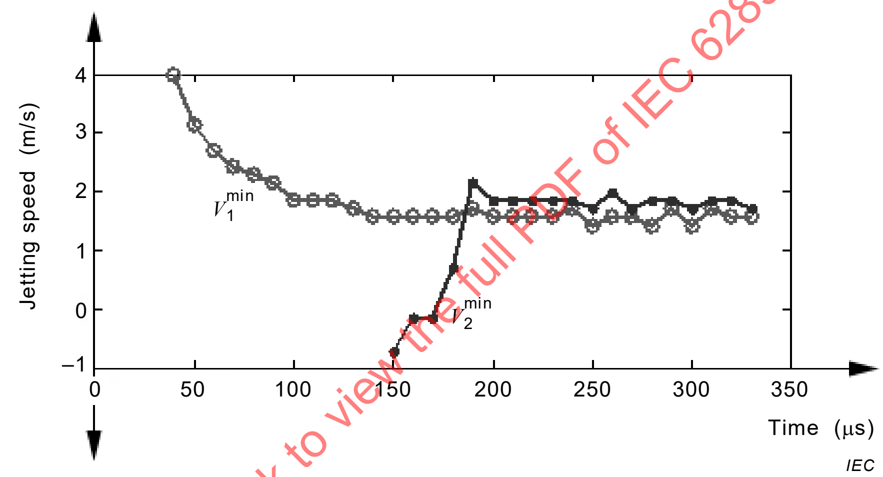


Figure A.4 – Droplet locations in a droplet image

1 Numbers in square brackets refer to the Bibliography.



a) **Drop trajectory**



b) **instantaneous jetting speed curve**

Figure A.5 – Drop formation measurement

From the measured curves shown in Figure A.5, the drop formation can be analysed as follows:

1) Initial extrusion (from 30 µs to 110 µs): In phase 1, part of the droplet is extruded from the nozzle. During the jetting process of phase 1, the instantaneous jetting speed of the extruded part, $V_k^{\max}(td)$, is significantly reduced from 4,0 m/s to 1,9 m/s. This effect may be due to the viscoelasticity of the fluids, that is, the still-attached fluid at the nozzle may pull back the extruded fluid from the nozzle before the fluid is pinched off from the nozzle. Here, the time required for the pinch-off and the velocity profile prior to the pinch-off can be used to evaluate the viscoelastic effect of ink on jetting.
2) Ink pinch-off and free flying of droplet (from 110 µs to 130 µs): In phase 2, after pinch-off at 110 µs, the ink droplet is in a free-flying jetting state but still has a ligament. The instantaneous jetting speed of the leading end, $V_k^{\max}(td)$, was about 1,6 m/s to 1,8 m/s as shown in Figure A.5 (b). The jetting speed variation in free-flying state was small compared to the jetting speed variation in phase 1.
3) Satellite forming (from 130 µs to 180 µs): In phase 3, the single droplet is separated into a spherical main droplet and a lengthy satellite with a ligament length of 120 µm at 130 µs. From the instantaneous jetting speed, the jetting speed of the satellite droplet was slightly

negative (-0,8 m/s) during the breakup process as shown in Figure A.5 b). Note that the negative jetting speed resulted from the speed measurement at the leading end of the droplet. If the speed is measured at the centroid of the droplet in the jetting direction, the jetting speed could be positive. The jetting speed variation of the satellites during the breakup is also related to jetting conditions such as jetting material properties and driving waveform. The satellite ligament length can be determined from the difference in distance between $P_2^{\max}(td)$ and $P_2^{\min}(td)$. The length of the satellite ligament decreased since the tail end of the satellite ligament was faster than the leading end.

4) Drop formation finish (from 180 µs): In phase 4, at 180 µs, the satellite droplet became spherical, whereupon the jetting speed of the satellite increased significantly (from –0,8 m/s to 2 m/s). Then, the jetting speeds of both spherical droplets tended to be constant until the two droplets merged into a single droplet.

In this example, slow jetting speed was used for the easy explanation. However, the method is extended to higher jetting speed of more than 6 m/s because most printed electronics applications require higher jetting speed where there are more satellites in practice. For more information on the measurement techniques and the analysis, a published paper [2] can be referred to.

A.5 Analysis method 4 (instantaneous jetting speed using double flash)

Method 4 describes the measurement of instantaneous jetting speed using a double flash. For method 4, two images (see Figure A.7) are captured of the same individual droplet, triggered at delay times t_1 and t_2 with respect to the jetting trigger signal (see Figure A.6) [3] [2].

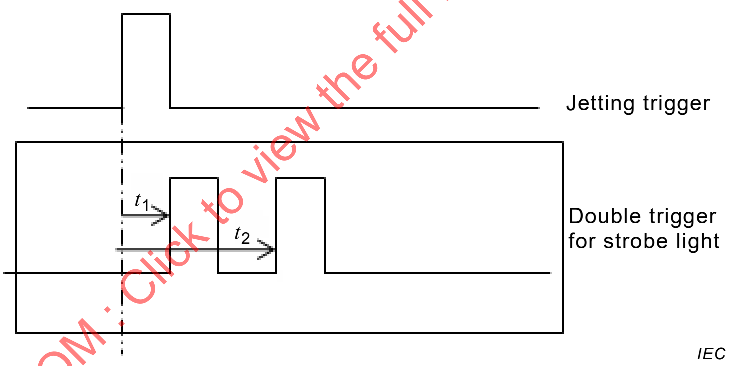


Figure A.6 – Double flash using single jetting trigger

Jetting speed V (m/s) can be calculated as:

$$V = \frac{\sqrt{(P_{y2} - P_{y1})^2 + (P_{x2} - P_{x1})^2}}{t_2 - t_1} \quad \text{(A.2)}$$

where P_{y1} and P_{y2} give the identified droplet center location in the y direction at t_1 and t_2, respectively, and P_{x1} and P_{x2} give the identified droplet center location in the x direction at t_1 and t_2.