Droplet generation and characterization using a piezoelectric droplet generator and high speed imaging techniques

Sofija Vulgarakis Minov a, b, *, Frédéric Cointault b, Jürgen Vangeyte a, Jan G. Pieters c, David Nuyttens a, *

* The Institute for Agricultural and Fisheries Research (ILVO), Technology and Food Science Unit, Agricultural Engineering, B.V. Gansberghelaan 115, bus 1, 9820 Merelbeke, Belgium
† Agrosup Dijon, UMR Agroécologie, 26 Bd Dr Petitjean, BP 87999, 21079 Dijon cedex, France
‡ Department of Biosystems Engineering, Faculty of Bioscience Engineering, Ghent University, Coupure Links 653, 9000 Ghent, Belgium

Article history:
Received 4 September 2014
Received in revised form 25 November 2014
Accepted 27 November 2014
Available online

Abstract
Accurate spray (droplet) characterization helps in the better understanding of the pesticide spray application process. The goal of this research was to evaluate the characteristics of a single droplet generated using a piezoelectric single droplet generator in 2 modes: Droplet-On-Demand (DOD) and continuous with 4 different orifice sizes. The droplet generator can produce a single droplet, or a continuous stream of uniformly sized droplets. Using a high speed imaging system and image processing algorithms, the effects of pulse width and pulse amplitude in DOD mode and of frequency and pulse amplitude in continuous mode on droplet characteristics (droplet size, droplet velocity and inter droplet spacing) were investigated for different orifice sizes. The system was able to produce droplet diameters within the range from 134.1 to 461.5 μm in DOD, and from 167.2 to 458.6 μm in continuous mode. In addition, droplet velocities ranged from 0.08 to 1.8 m/s in DOD mode and from 1.8 to 4.7 m/s in continuous mode. Validation using a droplet weighing method showed good agreement with the droplet image analysis results.

1. Introduction

The process of generating and controlling small droplets of constant size, form and velocity is necessary to study the behaviours of spray droplets before, during and after impact in a controlled and repeatable way (Reichard, 1990). A better understanding of spray droplet behaviour and of the complex spray application process can lead to more efficient pesticide usage and a reduction of the environmental impact. Poor accuracy and spray losses may reduce the effectiveness of the application and increase environmental contamination and operator risk (Matthews, 2000). More than 80% of the pesticide may be lost during spraying due to drift (up to 15%), rebound (up to 30%), and run-off (up to 20%) and other processes (up to 15%) including evaporation or photolysis and thus can affect public health as well as contaminate water, soil and the atmosphere of an ecosystem (Knowles, 2001; Pimentel, 1995; Pimentel and Burgess, 2012).

In general, spray droplet characteristics depend on nozzle type and orifice size (Nuyttens et al., 2007b), liquid properties (De Schampheleire et al., 2009) and spray pressure (Etheridge et al., 1999). In practice, a pesticide spray produced by hydraulic nozzles is characterised by a wide range of droplet sizes (–10–1000 μm) and velocities (–0–25 m/s). To evaluate the behaviour of such droplets in a realistic way, a droplet generation method that produces uniform droplets within these size and velocity ranges in a controlled and repeatable way is needed, while the combination with an imaging technique allows for the reliable and automated evaluation of droplet characteristics and behaviour.
Droplet generation can be accomplished by making one short duration fluid jet which condenses into a single droplet of desired diameter (Droplet-On-Demand (DOD) mode) or by breaking up a continuous fluid jet into uniform sized droplets with a source of acoustic energy (Continuous mode) as described in detail by Lee (2003). The first mode, DOD mode, has been used in many technical, industrial and scientific applications because only a small amount of fluid is needed to form droplets e.g.: inkjet printing (Li et al., 2010), calibration of particle sizing instruments (Ulmke et al., 1999, 2001), one-drop-fill technology (Kuang-Chao et al., 2008), biotechnology and medicine (Saunders et al., 2008). Continuous mode has also been used in applications like fabrication of metal parts (Luo et al., 2011) and inkjet printing (Castrejon-Pita et al., 2008). Basi et al. (2012) used a pneumatic droplet generator in DOD mode for pesticide applications because only a small amount of water droplets in the size range of a few μm over long time periods was developed by Riefler and Wriedt (2008).

The aim of this paper was to determine the range of droplet sizes and velocities that can be obtained and the corresponding settings using distilled water and a droplet generator in two modes, DOD and continuous mode, for different nozzle orifice sizes, using the image acquisition system developed in a previous study by Vulgarakis Minov et al. (submitted for publication), consisting of a high speed (HS) camera with microscope lens and xenon backlight. This droplet generation system may be useful for various fundamental researches using single and uniform size droplets such as droplet--target interactions (Reichard et al., 1998), droplet formation and ejection (Castrejon-Pita et al., 2008) and validation of droplet size measuring equipment (Nuyttens et al., 2007b).

2. Materials and methods

2.1. Droplet generator setup

The droplet generator (Université de Liège, Gembloux, Agro-Bio-Tech, Belgium) used in this study consisted of a liquid filled chamber with a piezoelectric element that can be driven with voltages up to 60 V (Fig. 1).

The design and working principle of the piezoelectric element are described in detail by Lee (2003). The piezoelectric setup consists of an electronic part, including an amplifier, a pulse generator (digital-to-analogue converter (DAC) (National Instruments, Austin, USA)), a pressure supplier (Furness Controls FCO 502, East Sussex, UK), and a software part (LabVIEW (National Instruments)) installed on a conventional PC (Fig. 2).

The pulse generator drives the piezoelectric element. The signal from the pulse generator was amplified 10 times before it was sent to the piezoelectric element via an RG-58 coaxial cable and the LabVIEW software enabled specific pulse forms to be generated.

Different glass nozzles (Université de Liège, Gembloux, Agro-Bio-Tech, Belgium) were placed on the outlet of the droplet generator (Fig. 2) in contrast with hydraulic spray nozzles, such nozzles can be used to produce single or a continuous stream of droplets with a uniform size sized in a controlled way.

Tests were done with 4 glass nozzles with orifice sizes of 261.6 ± 3.3 μm (nozzle 1), 123.4 ± 5.2 μm (nozzle 2), 87.2 ± 4.0 μm (nozzle 3) and 67.4 ± 3.3 μm (nozzle 4). Theses orifice diameters were determined by producing a continuous fluid jet through every nozzle which was filmed using the image acquisition setup described below. By measuring the jet diameters at the orifice exit (in number of pixels) and multiplying with the 8.23 μm pixel size (Vulgarakis Minov et al., submitted for publication), the actual orifice sizes were determined. The measurements were repeated 5 times.

The droplet generator is able to form uniform droplets in 2 modes: DOD, generating single droplets using double square—edged pressure pulses (Switzer, 1991) (Fig. 3a) and continuous, generating a continuous stream of uniformly spaced and sized droplets using a continuous square signal (Fig. 3b).

The following paragraphs contain a description of the steps involved in both modes.

2.1.1. Droplet on demand (DOD) generation

The principle of DOD mode is based on the acoustic wave theory in which two closely timed pulses (double pulse) are fed to the droplet generator to eject a single droplet (Hsuan-Chung and Huey-Juan, 2010; Lee, 2003; Switzer, 1991; Yang et al., 1997).

The single droplet breakup (Fig. 3a) is characterized by an ejection of a single droplet. A pulse width that is too large may lead to droplet ejection followed by satellite droplets of different sizes (jet on demand) (Li et al., 2010; Riefler and Wriedt, 2008). These satellite droplets and the settings at which they are formed were not desired and not analysed in this study.

Droplet formation in DOD-mode requires some conditions in order to generate uniform and single droplets in a repeatable way.
Air bubbles are detrimental to the operation of the droplet generation and should be removed. To prevent fluid from dripping out and air bubbles from entering the system via the nozzle orifice, the fluid pressure should be controlled until a meniscus is just visible on the tip of the nozzle. This can be achieved by changing the liquid column height in the fluid tank (Yang et al., 1997). After that, droplets can be generated by pressure pulses delivered by the actuator to the piezoelectric element (Castrejon-Pita et al., 2008).

During the positive pressure period of the double pulse or the absorption time ($t_a$) (Fig. 4a), the meniscus at the nozzle exit is formed and a droplet is created. Once the pressure reaches a negative value the droplet is ejected from the nozzle. This process occurs during the pulsation time ($t_p$). More information on the droplet formation and ejection can be found in the study of Li et al. (2010).

The effects of the following pressure pulse parameters on droplet formation and droplet diameter and velocity were tested: absorption time ($t_a$ (ms)), pulsation time ($t_p$ (ms)) and pulse amplitude ($\pm V_p$ (V)) (Fig. 4a).

In a first stage, determination of the appropriate pressure pulse settings resulting in single droplet breakup was done for each of the four nozzles. These preliminary tests were done at $t_a$ values of 0.01, 0.02, 0.05, 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 1, 2 and 5 ms, all combined with $t_p$ values of 0.01, 0.05, 0.1, 5, 10, 25 and 50 ms. All 135 combinations were tested at a $V_p$ value of $\pm 4.5$ V. The combinations of pulse width values resulting in a repeatable single droplet ejection were selected for the actual single droplet characterization (Table 1). These combinations differed considerably between the nozzles. In addition, the effect of the pulse height from 3.0 V to 6.0 V at incremental steps of 0.5 V using nozzle 1 at $t_a = 5$ ms and $t_p = 0.01$ ms was also evaluated.

The DOD measurements were repeated 5 times for every setting. After breakup from the nozzle exit, the falling droplet was recorded using an HS image acquisition system (2.2), and the droplet diameter and droplet velocity were determined using image analysis (2.3). All measurements were done using distilled water in a climate control room at an ambient temperature of 20 °C and a relative humidity of 47%.

2.1.2. Continuous mode droplet generation

In the continuous mode, a continuous stream of uniformly sized droplets is produced with the piezoelectric droplet generator. Using the LabVIEW software, a square acoustic signal was sent to the piezoelectric element causing instability and standing waves on the fluid stream as it emerges from the orifice (Lee, 2003) (Fig. 4b). In order to form uniform sized droplets (Fig. 4b), a suitable resonance frequency must be applied (Switzer, 1991). In contrast with the DOD mode where a liquid column was used, a pressure supplier was used to create a liquid pressure around 2 kPa in order to create a continuous jet.

Preliminary tests were done at frequency values from 7.5 to 8.5 kHz at incremental steps of 0.1 kHz and amplitudes of 1.0–9.0 V at steps of 1.0 V. All combinations were tested for the 4 nozzles resulting in 99 frequency/pulse amplitude combinations. These preliminary tests showed that 8 kHz was a suitable frequency for generating uniform sized droplets for every nozzle. At this frequency and for each nozzle, the effects of pulse amplitude on the
images were taken in full resolution (1280 × 1024 pixels) with a field of view (FOV) of 10.5 mm × 8.4 mm at 1000 fps. In continuous mode the frame rate was set to 10,000 fps due to the bigger droplet velocities with an image size of 480 × 96 pixels corresponding with an FOV of 3.95 mm × 0.79 mm.

An example of the captured droplet formation in DOD mode with the described image acquisition system is shown in Fig. 5.

2.4. Droplet(s) characterization with image analysis

Image processing algorithms were developed in Matlab (MathWorks Company, Massachusetts, USA) to characterize the single droplets (Vulgarakis Minov et al., 2013). Tracking and sizing of the droplet(s) were done in 3 steps:

1) Detection of the moving droplet(s) using edge detection based on local changes in the image brightness (Lecuona et al., 2000); 2) Tracking of the droplet between frames and 3) Measurement of the droplet characteristics (size, velocity, inter-droplet spacing (continuous mode)).

The ejection velocity of each droplet is calculated based on the distance travelled between two consecutive frames and the time between two frames (0.001 s). A detailed description of the image analysis is given by Vulgarakis Minov et al. (2013).

2.5. Validation

The droplet size measuring method was validated by a droplet weight method (Li et al., 2010) for DOD as well as for continuous mode. For the DOD mode, 100 droplets were collected and weighed for one test condition (nozzle 2 at \( t_a = 0.7 \text{ ms} \); \( t_p = 1.0 \text{ ms} \); \( V_p = \pm 4.5 \text{ V} \)). The total mass of droplets generated was determined using an analytic scale (Sartorius M-Pact AX224, S.A. Sartorius Mechatronics Belgium N.V., accuracy: 0.0001 g). Droplet diameters were calculated from the weight and density of the collected water and compared to the image analysis results. For the continuous mode, validation was done using nozzle 2 at a frequency of 8.0 kHz and a pulse amplitude of 8.0 V. The liquid emitted by the nozzle over a period of 30 s was collected in a Petri dish covered and completely closed with Parafilm, weighed and the total volume was calculated. The volume of one droplet was calculated by dividing the total volume by the number of droplets generated during the 30 s period based on the breaking frequency and compared with the droplet diameter resulting from the image analysis.

Finally, to test the effect of the measuring method (image analysis vs. droplet weight) on the droplet diameter (dependent variable) an ANOVA was performed. A p-value < 0.05 was considered statistically significant. The test was performed in SPSS Statistics 21 (IBM, USA). The significant differences were assessed using SNK (Student–Newman–Keuls) post hoc tests.

3. Results and discussions

3.1. Droplet on demand generation

3.1.1. Effects of pulse width and nozzle orifice size

The effect of the selected pulse width values (Fig. 2) on droplet diameter and droplet velocity were investigated by keeping the pulse amplitude constant at ± 4.5 V for all nozzles. The results are presented in Table 2.

![Image sequence showing the formation of a 461.5 μm droplet in DOD mode with nozzle 1 with a droplet velocity of 0.59 m/s. The different frames correspond with times of 0, 3, 6, 9, 12 ms after the first frame.](image-url)
Table 2
Effect of the pulse width values (ms) on the droplet diameter (µm) and droplet velocity (m/s) produced with nozzles 1 to 4 (mean ± std).

<table>
<thead>
<tr>
<th>Nozzle</th>
<th>Pulse width combination</th>
<th>Droplet diameter (µm)</th>
<th>Droplet velocity (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>5/0.01</td>
<td>389.2 ± 2.4 b</td>
<td>0.33 ± 0.02 e</td>
</tr>
<tr>
<td></td>
<td>5/0.05</td>
<td>360.9 ± 2.2 d</td>
<td>0.65 ± 0.05 b</td>
</tr>
<tr>
<td>2</td>
<td>5/0.1</td>
<td>351.2 ± 1.2 e</td>
<td>0.81 ± 0.03 a</td>
</tr>
<tr>
<td>3</td>
<td>5/0.7</td>
<td>383.4 ± 1.2 c</td>
<td>0.10 ± 0.01 f</td>
</tr>
<tr>
<td>4</td>
<td>5/0.9</td>
<td>385.7 ± 3.0 b</td>
<td>0.48 ± 0.02 d</td>
</tr>
<tr>
<td>1</td>
<td>0.4/5</td>
<td>458.7 ± 3.5 a</td>
<td>0.34 ± 0.01 e</td>
</tr>
<tr>
<td>2</td>
<td>0.5/50</td>
<td>461.5 ± 3.3 a</td>
<td>0.59 ± 0.01 c</td>
</tr>
</tbody>
</table>

For nozzle 1, pulse width values significantly affected the droplet diameter ($P < 0.001$). Of all tested combinations, these were the biggest droplets produced in DOD mode. Diameters ranged from 351.2 ± 1.2 µm up to 461.5 ± 3.3 µm corresponding with about 1.3 and 1.8 times the orifice size, respectively.

- For the other glass nozzles, the combination of pulse width values also significantly affected droplet diameters ($P < 0.001$). Droplet diameters ranged from 312.7 ± 1.5–416.5 ± 0.2 µm (nozzle 2), 242.9 ± 1.5–310.1 ± 0.3 µm (nozzle 3), 134.1 ± 3.7–207.2 ± 16.4 µm (nozzle 4), corresponding with 2.33–3.37 (nozzle 2), 2.78–3.55 (nozzle 3), 1.99–3.07 (nozzle 4) times the orifice size (Table 2).

- In general, an increase of both pulse widths ($t_a$ and $t_p$) tended to increase the droplet diameter (Reifler and Wriedt, 2008). This effect was most pronounced for larger nozzle orifices (nozzle 1 and nozzle 2).

Increasing the nozzle orifice increased the measured droplet diameter as it was also found by Kuang-Chao et al. (2008) and Basi et al. (2012). By selecting nozzle and pulse width values, droplets ranging from 134.1 ± 3.7 up to 461.5 ± 3.3 µm could be generated which is a realistic size range for real pesticide sprays (Nuyttens et al., 2007b).

The smaller the nozzle orifice size, the more difficult it was to produce droplets. This comes from the fact that if the pressure (pulse width and voltage amplitude) is not high enough to overcome surface tension, a droplet is not ejected. Therefore, only 3 different droplet sizes could be generated with nozzle 4 (Table 2 and Fig. 6).

Pulse width combinations significantly affected droplet velocities at nozzle 1 ($P < 0.001$), nozzle 2 ($P < 0.001$), nozzle 3 ($P < 0.001$) and nozzle 4 ($P < 0.001$).

Furthermore, it can be observed in Table 2 that the smallest droplet velocity ($0.08 ± 0.01$ m/s) was measured for nozzle 3 whilst the biggest droplet velocity of $1.78 ± 0.12$ (m/s) for the smallest nozzle orifice (nozzle 4). The data showed no clear relation between pulse width values on droplet velocity at constant pulse amplitude. Similarly, no clear correlation between droplet size and droplet velocity was detected for nozzle 1 and nozzle 3 (Fig. 7). However, a strong correlation ($R^2 = 0.96$) using nozzle 2 was observed i.e. increasing the droplet diameter led to decreasing the droplet velocity while the opposite effect was observed for nozzle 4 ($R^2 = 0.74$) (Fig. 7). The generated droplet velocities were lower than the ones of hydraulic spray nozzles used for pesticide applications in practice (Nuyttens et al., 2007b) indicating the difference in droplet formation mechanisms between DOD mode and hydraulic spray nozzles.

3.1.2. Effect of pulse amplitude

The effects of pulse amplitude ($V_p$) on droplet diameter and droplet velocities were investigated by keeping the pulse widths constant at $t_a = 5$ ms and $t_p = 0.01$ ms for nozzle 1. Pulse amplitude significantly affected droplet diameters ($P < 0.001$) as well as droplet velocity ($P < 0.001$) as shown in Fig. 8.

By increasing pulse amplitude from ±4.0 V up to ±4.5 V, both droplet diameter and velocity decreased, although not significantly for droplet velocity, and the minimum droplet diameter of 389.1 ± 2.4 µm and minimum velocity of 0.3 ± 0.0 m/s were obtained.

A further increase of $V_p$ resulted in a significant increase of both droplet diameter and velocity as previously found by Sadeghian et al. (2014), although with little change thereafter for droplet velocity, eventually reaching a maximum value of 438.1 ± 7.1 µm and 0.54 ± 0.0 m/s at $V_p$ of ±6.0 V, respectively. In contrast with the effect of pulse widths, there was a clear correlation between droplet

![Fig. 6](image-url) Mean droplet diameter results for the selected pulse width values for the 4 nozzles with $V_p = ±4.5$ V.
Further increasing $V_p$ above $\pm 6.0$ V resulted into ejection of satellite droplets. Decreasing pulse amplitudes below $\pm 4.0$ V resulted into no ejection of droplets.

### 3.1.3. Validation

The actual mean droplet diameter based on weighing 100 droplets was 346.4 ± 9.5 μm while a value of 339.5 ± 1.6 μm was found with image analysis. Hence, the overall accuracy of the measurement was satisfactory with a relative measurement error of about 2% and an absolute error of about 7 μm (~1 pixel). No significant differences in droplet diameter between the two techniques were observed ($P > 0.05$).

### 3.2. Continuous mode droplet generation

The effects of pulse amplitude on droplet diameter, droplet velocity and inter-droplet spacing at the optimal frequency of 8.0 kHz for the different nozzles is shown in Figs. 10–12.
For nozzle 1, the droplet diameter was significantly affected by the pulse amplitude values ($P < 0.001$) (Fig. 10). Generally larger droplet diameters were found for pulse amplitude values of 3.0, 4.0, 5.0, 6.0, 8.0 and 9.0 V followed by 7.0 V pulse amplitude. Smaller droplets were generated at 1.0 and 2.0 V pulse amplitude. Droplet diameters with nozzle 1 ranged from 358.3 ± 6.9 to 455.8 ± 4.8 μm corresponding with 1.37–1.75 times the orifice size. The biggest droplet diameter produced in continuous mode was 455.6 μm (at 5.0 V). Using nozzle 2 ($P < 0.001$), the droplet diameter ranged between 328.4 ± 6.2 and 353.5 ± 4.6 μm. The effect of pulse amplitude was limited but significant with biggest droplets at 5.0 V and smallest droplets at 1.0 V. For nozzle 3, no significant effect of pulse amplitude was observed within the range from 1.0 to 7.0 V, while significantly bigger droplets were produced at pulse amplitudes of 8.0 and 9.0 V ($P < 0.001$). With nozzle 4, smallest droplets were generated with a pulse amplitude of 6.0 V ($P < 0.001$). This was also the smallest droplet produced in continuous mode with a size of 167.2 ± 1.4 μm. With nozzle 4, the biggest droplets were produced at 7.0 up to 9.0 V. In general, no clear correlation between pulse amplitude and droplet diameter was found although there was a trend for bigger droplets at bigger pulse amplitudes.

The influence of the nozzle size and pulse amplitude on the droplet velocity is shown in Fig. 11 with velocities ranging from 2.42 ± 0.1 m/s up to 4.57 ± 0.0 m/s. These higher velocities relate much better with velocities of droplets generated with hydraulic spray nozzles at a distance of 0.50 m below the nozzle (Nuyttens et al., 2007b). A positive correlation was found between the droplet diameter and velocity generated with different nozzles and pulse amplitudes at a constant frequency of 8.0 kHz ($R^2 = 0.98$) (Fig. 12).

With nozzle 1 ($P < 0.001$), the lowest velocities were produced at amplitudes of 1.0 and 2.0 V. These velocities were comparable with droplet velocities produced with nozzle 2 ($P = 0.068$) at all amplitudes. With nozzle 2, no significant effect of amplitude on velocity was found, but the tendency of an increase in velocity with an increase in amplitude was confirmed. Considering nozzle 3 ($P < 0.001$) and nozzle 4 ($P < 0.001$), the highest velocities were obtained with the highest amplitudes of 8.0 and 9.0 V. For these nozzles, the effect of amplitude on velocity was limited within the range from 1.0 to 7.0 V.

A significant effect of pulse amplitude on inter-droplet spacing was found for every nozzle (Fig. 13). For nozzle 1 ($P < 0.001$) a significant increase in inter-droplet spacing was observed with increasing pulse amplitudes with the smallest inter-droplet spacing at 1.0 V and the biggest inter-droplet spacing at 9.0 V. Similar as for droplet velocities, the effect of amplitude on inter-droplet spacing in case of nozzle 2 was limited and in most cases not significant with nozzle 2 ($P < 0.001$). There was also a significant effect of the pulse amplitude on the inter-droplet spacing using nozzle 3 ($P < 0.001$) and nozzle 4 ($P < 0.001$). With nozzle 3, highest values were found at amplitudes of 5.0 and 6.0 V, with nozzle 4 at amplitudes from 7.0 up to 9.0 V. For these nozzles, the smallest inter-droplet spacing was found at 3.0 V and 6.0 V. respectively.

3.2.1. Validation

The actual droplet diameter based on weighing 100 droplets was 320.0 ± 9.4 μm while a value of 337.1 ± 5.8 μm was found using the image analysis. Hence, the overall accuracy of the measurement was satisfactory with a relative measurement error of 5.3%. No significant differences in droplet diameter between the two techniques were observed ($P > 0.05$).

3.3. Comparison between DOD and continuous mode

The presented experiments with the DOD and continuous mode have shown comparable values for the biggest and smallest droplet diameters achieved with these glass nozzles. The smallest droplet diameters measured with image analysis in DOD and continuous mode were 134.1 ± 3.7 μm and 167.2 ± 1.4 μm respectively. The biggest droplet diameters in DOD and continuous mode were 461.6 ± 3.3 μm and 458.6 ± 4.8 μm.

The smallest achieved droplet diameter ratio within both modes was found using nozzle 1, i.e. 1.34 for DOD and 1.37 for continuous mode. The biggest ratio between the droplet diameter and nozzle orifice size was measured with nozzle 3 in DOD (3.55) as well as in continuous mode (3.95) (Table 3). Previous studies were generally dealing with smaller droplets sizes and pulse widths. Riefler and Wriedt (2008) generated droplets in DOD mode ranging from 8 to 70 μm with a 40 μm orifice size. Kung et al. (1999) achieved a ratio up to 4 between droplet and orifice diameter using a very small 1 μm orifice size. Lee (2003) mentioned that droplet generators can produce droplets of half the nozzle diameters to twice the whole diameter.

On the contrary, a big difference in droplet velocity results between the modes was noticed, i.e. droplets fell faster in continuous mode than in DOD mode. The droplet generator developed droplet

![Fig. 10. Droplet diameter (μm, mean ± std.) in continuous mode for different nozzles and pulse amplitudes at a frequency of 8.0 kHz. Different letters indicate statistical differences within the same nozzle ($P < 0.05$).](image-url)
velocities in DOD and continuous mode in the range of $0.08 \pm 0.01 \div 1.78 \pm 0.12$ m/s and $1.84 \pm 0.08 \div 4.66 \pm 0.17$ m/s, respectively.

In conclusion, measurements using a single droplet generator in DOD and continuous mode were performed. The effects of the operating parameters, including voltage pulse width and pulse amplitude with 4 nozzle orifice sizes on droplet diameter and droplet velocity have been characterized. These different droplet sizes and velocities were successfully measured with an image acquisition and image processing system developed by Vulgarakis Minov (submitted for publication). The experiments in DOD mode have shown that the initial droplet characteristics from the droplet generator are a function of the double pulse width and the orifice size. By changing the pulse width, it was possible to control the droplet velocity and droplet size diameter. In general, increasing both pulse widths ($t_a$ and $t_b$) increased the droplet diameter. Similarly, increasing the nozzle orifice size increased the droplet diameter. With the DOD mode, droplet sizes ranged between 134.1 μm and 461.5 μm. Foremost, the smallest and the fastest droplets were measured with the smallest nozzle orifice. The measured droplet velocities ranged between 0.08 m/s and 1.78 m/s. Besides, we noticed an effect of the pulse amplitude on the droplet diameter and velocity.

The ratio of the droplet diameter and nozzle orifice in DOD mode was in-between 1.3 and 3.5.

The continuous mode for every nozzle was established for an optimal frequency. This frequency together with different pulse amplitudes were used to test the effect on the droplet diameter, inter-droplet spacing and velocity. As for the DOD mode, the droplet diameter was mainly controlled by the nozzle orifice. The droplet size here was between 167.2 μm and 455.8 μm. Furthermore, the nozzle orifice also influenced the droplet velocity i.e. the bigger the nozzle orifice was, the higher droplet velocity was measured. Obviously, there is a linear trend between the droplet diameter and velocity. Based on the results from the experiments, the effect of the pulse amplitude on the inter-droplet spacing was statistically significant. The ratios between the nozzle orifice and droplet diameter ranged from 1.3 to 3.9. In continuous mode, the slowest droplet velocity of 1.84 m/s was measured with the smallest nozzle orifice size while the fastest droplet velocity of 4.66 m/s was measured with the biggest nozzle orifice size.

Fig. 11. Droplet velocity (m/s, mean ± std.) in continuous mode for different nozzles and pulse amplitudes at a frequency of 8.0 kHz. Different letters indicate statistical differences within the same nozzle ($P < 0.05$).

Fig. 12. Correlation between droplet diameter and velocity in continuous mode for different nozzles and pulse amplitudes at a frequency of 8.0 kHz.
Based on the results in both modes, similar droplet diameter sizes were produced. However, in continuous mode it was possible to achieve faster droplets than those found in a real spray application.

In future, this droplet generation and imaging system can be used to study, among others, droplet–target interactions, droplet formation and ejection and the accuracy of droplet size measuring equipment.

References


