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EFFECTS OF PDA SAMPLING TECHNIQUES ON SPECTRAL CHARACTERISTICS OF AGRICULTURAL SPRAYS

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Summary

Using PDA, a convenient method to measure the spectral characteristics of the spray below a nozzle is to scan that spray along a set of parallel lines in a horizontal plane. Data of such a measurement are processed in order to determine the 2D distribution of spectral characteristics in the plane of measurement. Essential parameters of the measuring method include nozzle height above the plane of measurement, distance between scan lines, rotation of the nozzle in the plane of measurement and lateral offset of scan lines. The effects of varying these parameters on spectral characteristics of the spray are quantified in model calculations. Such effects appear to be highly dependent on the actual 2D distributions (depending on nozzle type and the liquid pressure) and on the number of relevant scan lines. It is demonstrated that deviations can be significant, but these can be minimized easily by reducing the distance between neighbouring scan lines.

Introduction

For spray drift research regarding agricultural sprays, drop size spectrum and droplet velocities inside the spray cone below the nozzle are measured. These measurements are carried out using a PDA system, following a standardized procedure. Results are used for classification of nozzle types at certain liquid pressures into various drift reduction classes with respect to a reference nozzle. The reference nozzle used is the BCPC threshold nozzle between size classes fine (F) and medium (M) (see Southcombe et al 1997). Drop size distributions and velocity profiles are used as input for the simulation model IDEFICS as well, which calculates downwind deposits of spray drift during application of chemicals using field sprayers (Holterman et al 1997).
The PDA measurement procedure involves the continuous scanning along several parallel lines in a horizontal plane at fixed distance below the nozzle. This procedure gives the averaged drop size spectrum in that plane. However, in the standardized procedure the number of parallel scan lines, the distance between them, and the height of the nozzle above the plane of measurement have been selected without proper research. For instance, it is not known if and how changing these parameters will affect the resulting drop size distribution and the spectral characteristics of the spray. The current study investigates the effects of changing the number of scan lines, the distance between those lines, and the height of the nozzle above the measurement plane.
In order to study these effects, a 2D spectral characterization of the spray is modelled, derived on data from standard measurements. For this purpose the droplet data from a

measurement, which includes the exact time a droplet passes the PDA probe area, are synchronized with the timing of the sequence of parallel scan lines, resulting in a 2D distribution of all data.

Equipment

The equipment used is a one-dimensional Phase-Doppler Particle Analyzer (PDPA; Aerometrics), connected to photo-detection module PDM1000 and size analysis hardware FSA3500 (both TSI), and using FlowSizer software (TSI) for data acquisition and analysis. The light source is a 1 W Argon-ion laser (Lexel 85-1), of which only the green light (514.5 nm) is used. The optical transmitter and receiver are positioned in the 40° forward scattering setup, with 1000 mm front lenses. The spray chamber climate is controlled at a temperature of 20°C and relative humidity of 70%.

The parallel line scan method

Since measurement times should be limited to acceptable durations, and due to the fact that the probe area of PDA-systems is small, global spray characteristics in fact are estimated by taking a specific sample of the spray. A convenient way to do this is the 'standard' parallel line scan method (see Fig.1). The nozzle to be tested is moved along a set of equidistant parallel lines, while the PDA measures the droplets passing through the probe area. Provided that the number of lines is sufficient, their length is adequate and the whole spray 'fits' well in the circumferential rectangle of the scanned area, the method is expected to give representative results. Parameters to be adjusted for optimal performance are the number of parallel lines, their lengths, the distance between neighbouring lines ('line distance') and the scan velocity at which the nozzle moves along its path ('scan velocity').

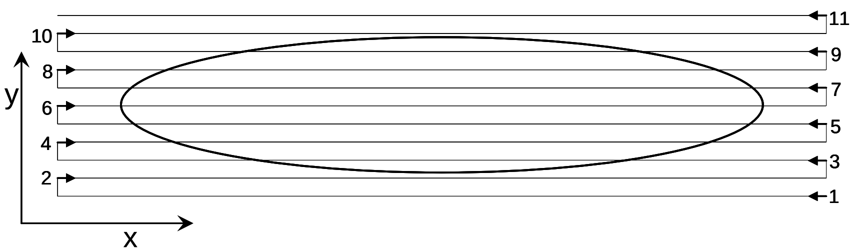

Fig. 1. Schematic plot of the standard scan method in a horizontal plane below a flat fan nozzle. The straight lines indicate the relative movement of the sampling point of the PDA. The ellipse roughly indicates the cross-section of the spray cone.

If local (vertical) volume flux is defined by $\rho_{x,y}$ [$m^3 \cdot m^{-2} \cdot s^{-1}$], and PDA probe area is A_{pr}, the measured volume along a single scan line is given by the following integral along the line:

$$V_{line} = \int_{line} \rho_{x,y} A_{pr}\, dt = \frac{A_{pr}}{v_s} \int_{line} \rho_{x,y}\, dx \qquad (1)$$

where the latter equality is formed by identifying that passing along a piece dx of the scan line takes a time interval $dt = dx/v_s$, where v_s is the scan velocity. The total length of the line does not affect V_{line}, as long as the line is longer than the length of the spray cone, since outside the spray cone the flux density is zero and obviously does not contribute to the integral. The total volume of spray measured in the standard scan method is the sum of V_{line} over all lines.
Apart from volume flux, drop size spectrum too is a function of location in the spray cone. Assume the normalized volumetric spectral density at location (x,y) is given by $\beta_{x,y,D}$ [m^{-1}],

then the fraction of spray volume containing droplets of diameters between D and D+dD is given by $\beta_{x,y,D}\cdot dD$. It can be derived that the overall volumetric spectral density B_D of the spray is given by:

$$B_D = \sum_{\text{all lines}} \left(\int_{\text{line}} \rho_{x,y}\, \beta_{x,y,D}\, dx \right) \Big/ \sum_{\text{all lines}} \left(\int_{\text{line}} \rho_{x,y}\, dx \right) \qquad (2)$$

This spectral density distribution B_D as obtained from the measurement is an estimation of the 'real' spectral density distribution. In practice the estimated distribution may differ from the real distribution due to (a) finite measuring time, (b) limited sampling area by the line scan method.

Regarding (a): in a finite measuring time obviously only a finite number of drops can be measured, which corresponds to taking a finite sample out of an almost infinite number of drops. Clearly the actual number of sampled droplets is stochastic, and consequently the size distribution of this sample is stochastic as well. As a rule of thumb, a sample of 10^4 drops is required to obtain an accuracy (CV) of 2.5% in D_{V50} (Holterman 2000).

Regarding (b): scanning only a limited number of thin lines and leaving the areas in between untouched, is likely to be the more important factor affecting the accuracy of the estimated spectral density distribution. Two aspects are to be considered: (1) the line distance between neighbouring lines; (2) the possible lateral offset of the central scan line with respect to the centre of the spray. The effects of these aspects on the estimated spectral density distribution are related to the rate of change of the real distribution in the plane of measurements. In other words: significant changes in the real spectral density that are spatially small with respect to the line distance may give rise to significant changes in measurement results, when parameters such as line distance and lateral offset are varied.

Resolving a 2D spray pattern from a parallel line scan measurement

If the movement of the nozzle along the parallel scan lines is computer-controlled, the standard scan method can be synchronized easily with the PDA results. Dividing the longitudinal lines into a series of small imaginary compartments, each compartment corresponds to a time interval from t_k to t_{k+1}, that is completely determined by the parameters defining the scan lines (see Fig.2). So if a certain droplet is measured at a time t between t_k and t_{k+1}, then it must belong to the corresponding compartment.

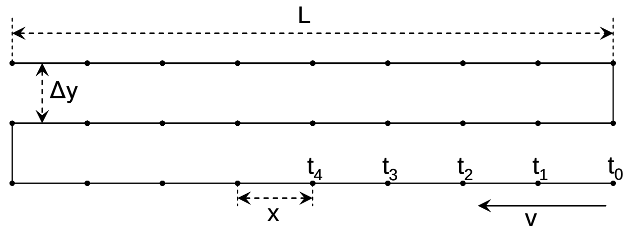

Fig. 2. Sequencing the scanned lines as a series of subsequent time intervals.

In this way all drops can be categorized into the predefined compartments. For each compartment spray characteristics can be determined, resulting in a 2D distribution of these characteristics, based on line index and compartment index. Currently 20 compartments per scan line are defined.

It turned out that synchronization was not as straightforward as one would expect. Since scan line length L and line distance Δy are easily checked, these parameters will not cause any problems. However, small deviations in scanning velocity v and small but non-zero turning times at the corners can give rise to linearly increasing errors in the timing of each following line, particularly when the number of scan lines is relatively large and total scanning time is relatively low. Fortunately, manual adjustments of the time intervals of the small tracks connecting two neighbouring scan lines can solve synchronization errors.

Measurements

A Delavan LF 110-01 nozzle at a liquid pressure of 450 kPa was characterized using the standard line scan method. This is the BCPC threshold nozzle between spray quality classes very-fine (VF) and fine (F) (see Southcombe et al 1997). Spray liquid was tap water at a temperature of 20°C. The spray was measured in horizontal planes at 5 distances below the nozzle. The corresponding settings of the scanned path are given in Table 1. For most nozzle heights two separate measurements were done; only for nozzle height 50 cm three measurements were done.

Table 1. Overview of settings used with the standard line scan method to investigate the effect of nozzle height on spray characteristics.

Nozzle height [cm]	Line length [cm]	# lines	Distance between lines [cm]	Scan velocity [cm/s]
10	45	15	0.5	6.0
15	65	15	0.7	5.0
20	90	15	1.0	4.0
25	110	15	1.3	4.0
50	200	11	2.0	4.0

Effect of nozzle height

Fig.3 shows the overall volume mean diameter D_{30} (left) and volume median diameter D_{V50} (right) as a function of nozzle height. Whereas D_{30} is constant for all height, apart from an elevated value at 10 cm, D_{V50} shows a decreasing trend with increasing nozzle height.

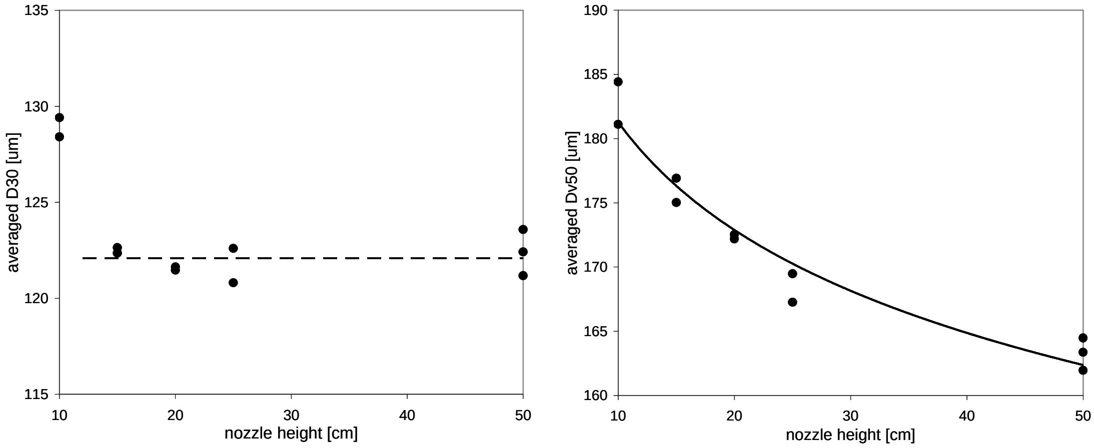

Fig. 3. Overall volume mean diameter D_{30} (left graph) and volume median diameter D_{V50} (right graph) of a flat fan spray (Delavan LF 110-01, 450 kPa) as a function of nozzle height above the measurement plane. Each dot represents the result of a standard scan method. Dotted line (left) represents averaged value for heights 15-50 cm; fitted power-law (right) roughly indicates trend.

The measurement data were processed using the 2D compartment method described above. This resulted in planar distributions like those of Fig.4 for the volume mean diameter. Compartments near the surroundings of the spray appear to be slightly jagged, due to the fact that the number of droplets in those compartments is relatively low. For all nozzle heights the central part of the spray is relative homogeneous and constant with respect to volume mean diameter. In contrast, both edges at the longer axis of the flat fan spray cone appear to be relatively coarse. For increasing nozzle height the differences become more pronounced. At nozzle height 50 cm, the volume mean diameter of the tested nozzle at the edges of the spray cone is about twice as large as that in the centre of the spray.

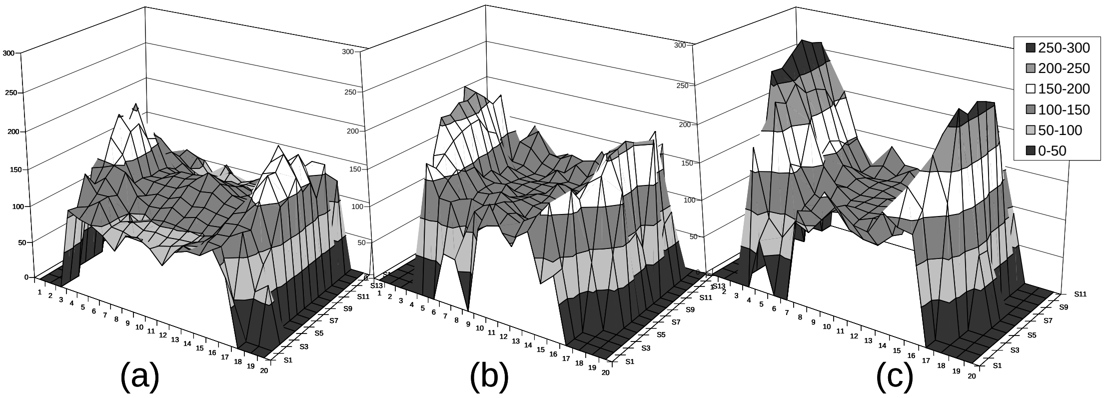

Fig. 4. Volume mean diameter (D_{30}) in horizontal planes below a flat fan nozzle (Delavan LF 110-01, 450 kPa); distance below the nozzle: (a) 10 cm; (b) 20 cm; (c) 50 cm.

After averaging over corresponding compartments at all scan lines, and identifying each compartment by its angle with respect to the vertical central axis of the spray cone, distributions along the longer axis of the flat fan spray can be compared easily for different nozzle heights. Fig. 5 shows such a comparison, indicating that the volume mean diameter in the central part of the spray cone remains almost constant at a level of about 115 µm. Only for nozzle height of 10 cm D_{30} is slightly larger in the central part. The edges, however, show a clear trend. D_{30} values at the edges increase with increasing nozzle height. At nozzle height 50 cm the spray cone appears to be less wide: due to gravity and the effects of entrained air flow, droplets in the edges of the spray tend to bend downward slightly. Apparently this effect is still insignificant between 10 and 25 cm nozzle height.

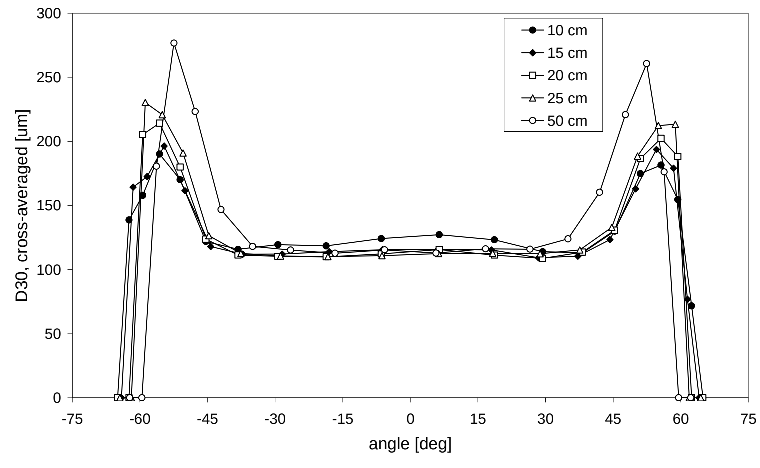

Fig. 5. Volume mean diameter (D_{30}) of a flat fan spray (Delavan LF 110-01, 450 kPa) as a function of angle along the longitudinal axis; measurements took place in a horizontal plane at 5 heights below the nozzle.

Fig. 6 shows the relative 2D distribution of liquid volume flux of the spray at various nozzle heights. In all cases three peaks are clearly visible and directed along the longer axis of the flat fan spray cone. The peaks at the edges of the spray cone are very high at low nozzle heights, but shrink gradually with increasing nozzle height. Though these peaks coincide with the peaks in the D_{30} distribution of Fig.4, these show a different trend. While the relative volume flux in the edge peaks decreases with increasing nozzle height, the mean droplet size in those peaks appears to increase.

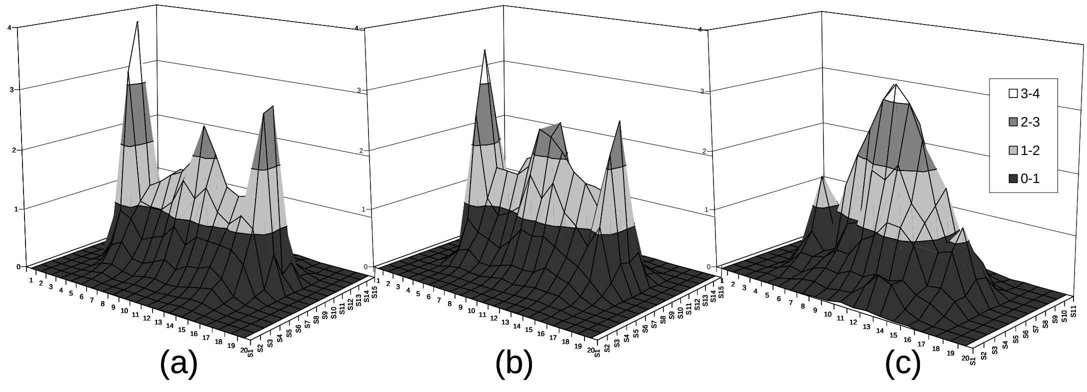

Fig. 6. Relative volume flux [% of total] in three horizontal planes below a flat fan nozzle (Delavan LF 110-01, 450 kPa); distance below the nozzle: (a) 10 cm; (b) 20 cm; (c) 50 cm.

Effect of changes in the pattern of parallel scan lines

The results from PDA measurements described above were modelled into imaginary 2D drop size distribution patterns. For instance the modelling of the patterns at nozzle height of 10 cm of Fig.4a and Fig.6a resulted in the idealized patterns of Fig.7 for volume flux (left) en volume mean diameter (right). Local drop size spectra were modelled using the Nukiyama-Tanasawa distribution (see Lefebvre 1989):

$$dN / dD = a\, D^{p}\, \exp\left\{-\left(b\, D\right)^{q}\right\} \qquad (3)$$

with parameters p=2 and q=1.2. Parameter b is adjusted to obtain the required D_{30} of the spray, while parameter a is adjusted for normalization. The 2D patterns of Fig.7 were modelled using the sum of three Gaussian functions, adjusting their peak values and their widths along the two main directions of the spray cone to obtain the desired shape.

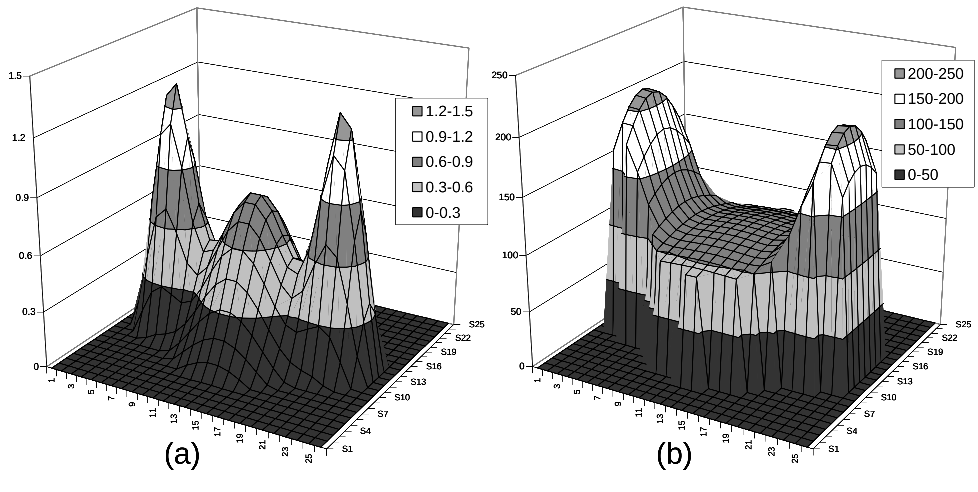

Fig. 7. Model of 2D distribution of relative volume flux [%] (a) and volume mean diameter D_{30} [µm] (b), as idealized estimates of the measured distributions for a Delavan LF 110-01 nozzle at a nozzle height of 10 cm.

These idealized 2D patterns of volume flux and drop size distributions were used as input in a simulation program to evaluate the parallel line scan method. The line distance Δy, relative to half the width of the spray cone, was varied between 0.1 and 0.5. The number of relevant scan lines, i.e. lines that actually cross the spray cone somewhere, varied subsequently from 3 lines for Δy=0.5 to 17 lines for Δy=0.1 (see Fig.8). Scan lines were distributed symmetrically, always keeping the central scan line through the centre of the spray cone. A small rotation of the spray cone in the plane of measurement could be added (to simulate improper placement of the nozzle in a real measurement). Nozzle rotation was varied between 0° and 6° giving 7 curves of D_{30} as a function of Δy (see Fig.8). As the relative line distance decreases, the number of relevant scan lines increases and the resulting value of D_{30} tends to approximate its actual value. Particularly for cases with only a few scan lines (n=3 or 5) the effect of Δy on D_{30} gets stronger. Fig.8 also shows that for n=3 even a small rotation of the nozzle can have a large and almost quasi-random effect on D_{30}.

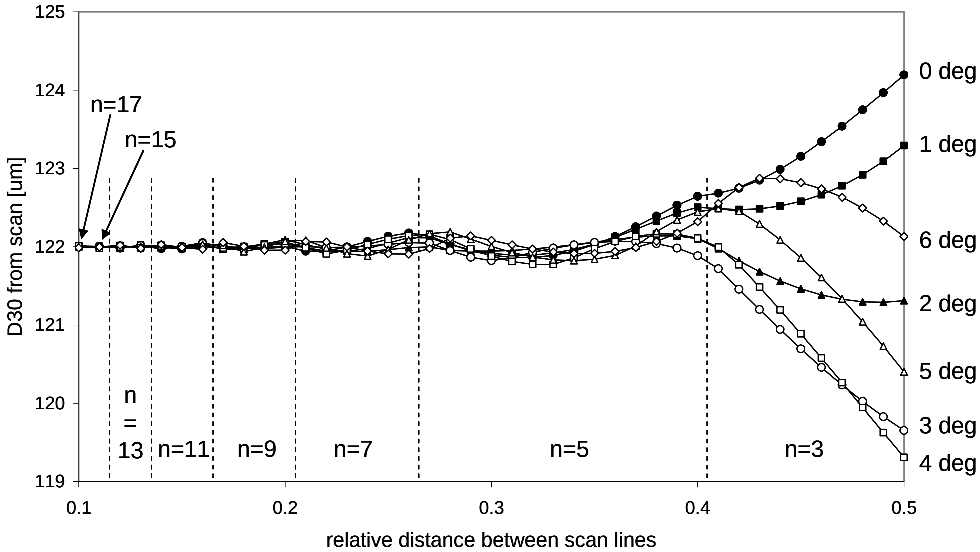

Fig. 8. Estimated effect of relative line distance on D_{30}, for nozzle rotations 0°-6° in the horizontal plane. Regions 'n=3', 'n=5', etc. indicate the number of relevant scan lines (i.e. with non-zero spray flux) for the non-rotated nozzle (0 deg). Based on the modelled distributions shown in Fig 7.

So far the central scan line was placed through the centre point of the spray pattern. In practice there may be a small lateral offset. This offset can range from -0.5 to +0.5 times the line distance. For larger offsets another scan line takes over the role of 'central' scan line, and no new situation occurs. Besides, for elliptically symmetric sprays, a certain negative offset has exactly the same effect as a positive offset of the same size. So only relative offsets between 0 and +0.5 times the line distance have to be considered. Fig.9a shows the effect of relative lateral offset on D_{30} for the cases Δy=0.25 (relevant scan lines: n=7), Δy=0.30 (n=5) and Δy=0.45 (n=3). When the number of relevant scan lines decreases, the effect of lateral offset gets more pronounced. Fig.9b shows the effect on D_{30} for Δy=0.45 (n=3), while the nozzle is rotated between 0° and 6°. Remarkably, both Fig.9a and Fig.9b seem to indicate that at a lateral offset of about 0.25 times the line distance, there is hardly any change in D_{30}.

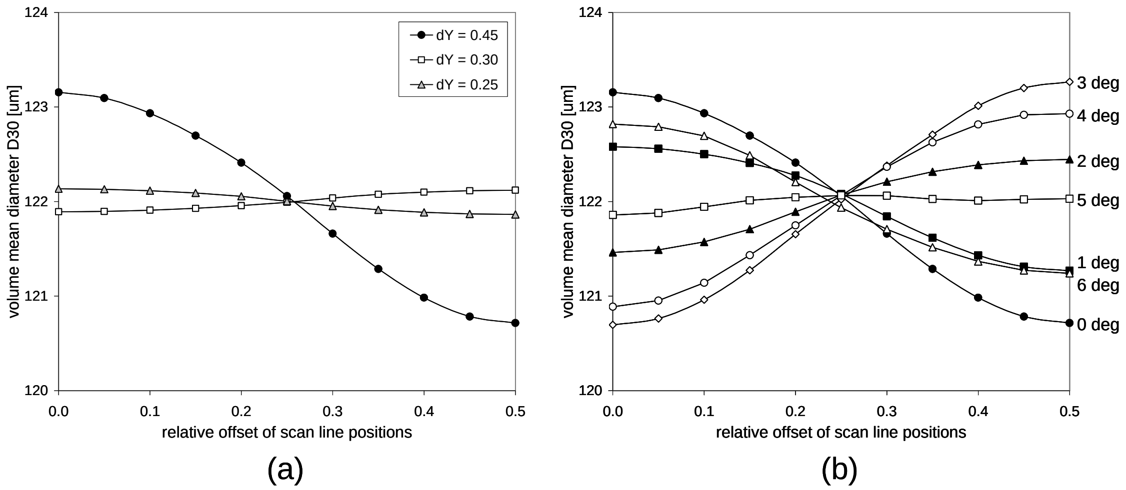

Fig. 9. Effect of relative lateral offset of the scan lines on D_{30} values. (a): for three values of Δy (0.25, 0.30 and 0.45), corresponding to 7, 5 and 3 relevant scan lines, respectively; without nozzle rotation. (b): for nozzle rotation between 0° and 6°, and $\Delta y=0.45$ (n=3).

Conclusion

Standardized PDA measurements involving a set of parallel scan lines can be processed into 2D distributions of spectral characteristics by proper compartmentalization of the measured data. As compartments near the surroundings of the spray pattern contain only a limited number of drops, spectral characterization of those compartments is less accurate.
Fitting 2D distribution models to the results of the above-mentioned data processing, such models can help to evaluate the effects of variations in the parallel line scan method on spectral characteristics of the measured spray. For instance, changing the distance between neighbouring scan lines can significantly affect volume mean diameter, particularly if the number of relevant scan lines is low. Small rotations of the nozzle in the plane of measurement and lateral offset of the scan lines can have relatively large effects on spectral characteristics as well. However, all such effects are highly dependent on the actual 2D spray pattern in the plane of measurement.
Although this study deals with only one nozzle type at one liquid pressure, it demonstrates that the parallel line scan method may affect spectral results, if the parameters involved are not properly selected. Fortunately, deviations appear to decrease below significant level if the number of relevant scan lines is large enough. For instance 11 scan lines appear to be sufficient to suppress the effects discussed in this study to a very low level.

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