COMPARISON OF 1D PDA SAMPLING METHODS TO OBTAIN DROP SIZE AND VELOCITY DISTRIBUTIONS INSIDE A SPRAY CONE OF AGRICULTURAL NOZZLES

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Summary

In agriculture, spray drift research is carried out in field experiments and by computer simulation. Regarding the latter approach, accurate knowledge of the initial spray is required. Not only is the overall drop size distribution of the spray an important factor in the spraying process, but also its local variation within the spray cone below a nozzle. Furthermore, the velocity distribution of drops in the spray cone has to be considered, which is a function of drop size and location in the spray cone. A PDA system is well-suited to carry out measurements on drop size and velocity. This study compares four scanning methods using a 1D PDA system to characterize the spray cone of a flat fan nozzle. These methods differ in operator time and handlings during the measurement and data processing afterwards. Fortunately, all methods give similar results so one is free to choose one's preferred method. Although in some cases 2D or 3D PDA systems may be ideal, this study shows that a 1D system still offers possibilities for spray characterizations.

Introduction

For spray drift research regarding agricultural sprays, the drop size spectrum and droplet velocities inside the spray cone below the nozzle are measured. These measurements are carried out using Phase-Doppler anemometry (PDA), following a standardized procedure. The results are used for classification of nozzle types at certain liquid pressures into various drift reduction classes with respect to spray drift when using predefined reference nozzles. Drop size distributions and velocity profiles are used as input for the simulation model IDEFICS, which calculates downwind deposits of spray drift during application of chemicals using field sprayers (Holterman et al., 1997). Since the distribution of drop sizes and velocities varies with location in the spray cone one has to do PDA measurements at many locations inside the spray cone to get an overview of the distributions and their local variations.

Whereas 1D PDA can do drop sizing perfectly well, a 2D or 3D system is preferred for measuring droplet velocity profiles. Assuming circular symmetry in pressure-swirl nozzles or planar symmetry in flat fan nozzles, a 1D system may suffice for determining velocity distributions as well. The current study investigates a few methods using 1D PDA to derive the required information on drop size and velocity distributions. Pros and cons of the methods are discussed and results are compared.

Equipment

The equipment used is a one-dimensional Phase-Doppler Particle Analyzer (PDPA; Aerometrics, USA), connected to photo-detection module PDM1000 and size analysis hardware FSA3500 (both TSI, USA), and using FlowSizer software (TSI, USA) 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, in such a way that the principal direction of particle flow is straight downward.
All experiments were done with one flat fan nozzle type, the Delavan LF 110-01, at a liquid pressure of 450 kPa, which is the BCPC threshold nozzle between spray quality classes very-fine and fine (VF/F) (see Southcombe et al., 1997). Spray liquid was tap water at a temperature of 20°C. The spray chamber was controlled at a temperature of 20°C and a relative humidity of 70%.

Measuring methods

Four methods for measuring the distributions of drop sizes and velocities in the spray cone are compared. Below is a description of these methods.
The ‘parallel line scan method’ (PL) involves the continuous measurement in a horizontal plane below a spray nozzle (see Fig.1). The nozzle 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.

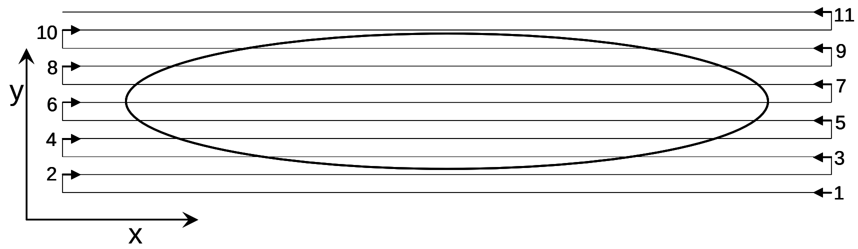

Fig. 1. Schematic plot of the parallel line scan method (PL) in a horizontal plane below a flat fan nozzle. The straight lines indicate the relative movement of the sampling point of the PDA. The ellipse roughly indicates the cross-section of the spray cone.

If the movement of the nozzle along its path is computer-controlled, the detection of individual drops can be synchronized easily with the location of the probe area along the parallel lines. 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).

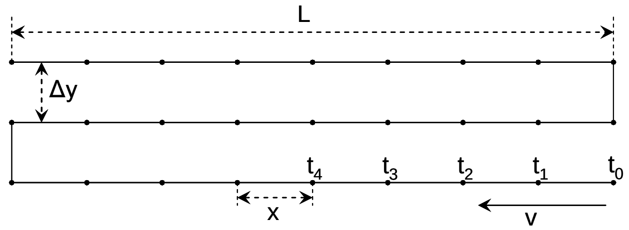

Fig. 2. Sequencing the scanned lines as a series of subsequent time intervals.

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. In this way all drops can be assigned to the predefined compartments. For each compartment spray characteristics can be determined, resulting in a 2D distribution of these characteristics (Holterman, 2008).
The 'cross line scan method' (CL) is similar to the previous method, but now the scan lines are parallel to the shorter axis of the spray pattern ellipse (Fig.3). Each cross line is scanned a few times to obtain a sufficient number of drops to characterize the average spray along that line. While the parallel line scan method in fact is a single measurement, the data obtained for each cross line are stored as separate measurements.

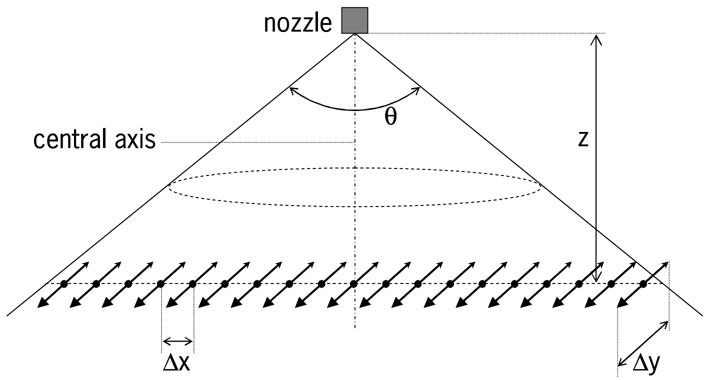

Fig. 3. Schematic plot of the cross line scan method (CL) in a horizontal plane below a flat fan nozzle. Arrows indicate the cross lines where separate measurements are done.

With the 'circular scan method' (CS) separate cross lines are measured as with the CL method. However, in this case the cross lines are located at constant distance to the nozzle outlet (Fig.4). This means that the midpoints of the cross lines are positioned at a circle around the nozzle. The nozzle itself remains oriented vertically downward.
The last method is the 'rotating nozzle scan method' (RN): it involves separate cross line measurements as before, yet the nozzle remains located straight above the probe area (Fig.5). The nozzle is rotated stepwise between separate cross line measurements. As the point of rotation is above the nozzle outlet, after each rotation the nozzle position has to be adjusted slightly to assure the nozzle outlet remains at its required location.

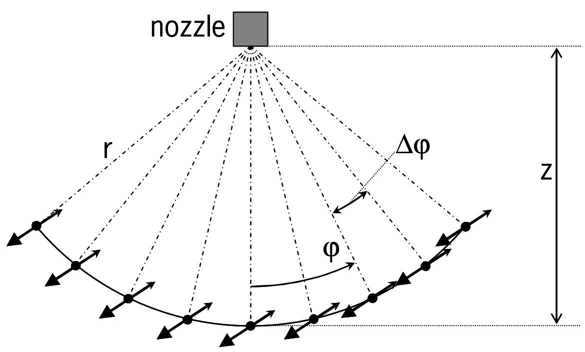

Fig. 4. Schematic plot of the circular line scan method (CS) below a flat fan nozzle. Arrows indicate the cross lines where separate measurements are done.

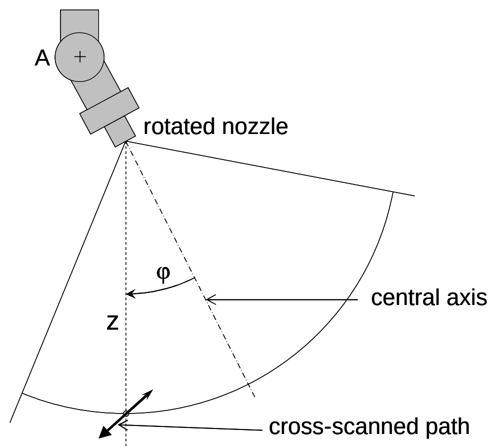

Fig. 5. Schematic plot of the rotating nozzle scan method (RN) below a flat fan nozzle. Nozzle is rotated around point A. The arrow indicates the cross line where measurements take place, straight below the nozzle outlet.

To obtain angular distributions, with the planar scan methods (PL and CL) a translation of planar data to angular data is required. The relation between horizontal position x and angular position φ is straightforward:

$$\varphi = \arctan\left(\frac{x}{z}\right) \qquad (1)$$

where z is the height of the nozzle above the plane of measurement. Each cross-line measurement is weighted by the average angle Δφ around φ, which can be derived by differentiating Eq.(1):

$$\Delta\varphi = \frac{z\,\Delta x}{z^2 + x^2} \qquad (2)$$

where Δx is the distance between adjacent cross-lines. The actual distance between nozzle outlet and cross-line is a function of x as well:

$$L(x) = \sqrt{z^2 + x^2} \qquad (3)$$

If it is assumed that the spray cone of a flat fan nozzle diverges radially, the spray density in a certain direction φ decreases with $1/L^2$. This assumption will hold if measurements take place at locations relatively close to the nozzle outlet, where deviations due to gravitational forces are negligible. In all methods the results actually represent an integration over the cross direction, therefore the measured spray densities (by droplet number or volume) will decrease with 1/L rather than $1/L^2$. Thus, if the cross-line at distance L(x) would have been placed at distance z (with the same direction φ) the local spray density would rise by a factor f_L given by:

$$f_L = \frac{L}{z} = \sqrt{1 + (x/z)^2} \qquad (4)$$

Therefore, with the PL and CL methods, to obtain spray density as an angular distribution one must multiply the measured (planar) density by the factor f_L.
Regarding droplet velocity, with the 1D PDA only one velocity component can be measured (i.e. the vertical component in the current setup). Therefore, if drops move radially outward from the nozzle outlet only their vertical velocity component is obtained. Their radial velocity can be computed by dividing the measured (vertical) velocity by the cosine of the direction of flight:

$$v_{rad} = \frac{v_{vert}}{\cos\varphi} \qquad (5)$$

Each of the described scan methods has its pros and cons, which are briefly summarized in Table 1.

Table 1. Pros and cons of the four scan methods in this study

Method	Pros	Cons
Parallel line (PL)	Fast measurement; single data file only	Laborious data handling afterwards; no direct interpretation possible without data processing
Cross line (CL)	Angular distribution easily interpreted	Measurement is more laborious; consumes more data files; some data handling required still
Circular scan (CS)	Angular distribution easily interpreted	Measurement is more laborious; consumes more data files
Rotating nozzle (RN)	Interpretation of data into angular distribution is straightforward; 1D PDA suffices completely	Manual nozzle rotation is laborious and not very accurate; consumes more data files

Measurements

The PL method involved 15 scan lines of 65 cm length, adjacent scan lines were separated by 0.7 cm, scan velocity was 5.0 cm/s. The plane of measurement was 15.0 cm below the nozzle outlet. In the data handling afterwards, the scan lines were divided in 20 imaginary pieces of 3.25 cm length each. The centre of each piece was taken as a reference for locating it with respect to the nozzle position.

In all cross-line methods (CL, CS, RN) the scanned path was one time back and forth the cross line of length 20 cm, with a scan velocity of 3.0 cm/s. In the CL method the plane of measurement was 15.0 cm below the nozzle outlet. Distance between adjacent cross lines was 2.0 or 4.0 cm. With CS and RN methods, the distance to the nozzle outlet remained constant at 15.0 cm. Nozzle positioning was computer-controlled with the CS method, and an accurate angular resolution of 5° was easily obtained. With the RN method, however, the nozzle was rotated manually and adjusting the angle of measurement was less precise, so using an angular resolution better than 10° was assumed not to be worthwhile.

All methods were done in two or three replications to check repeatability. As a rule of thumb, a sample of at least 10^4 drops is required to obtain an accuracy (CV) of 2.5% in D_{V50} (Holterman, 2000). This number of drops was obtained for measurements at all cross-lines, except for a few measurements at the outskirts of the spray cone. With the PL method the number of drops within each of the 20 'clips' was slightly below this rule of thumb (about 7000 drops in most clips apart form the outskirts).

Results

Fig. 6-left shows the angular distribution of droplet number density for each scan method for the flat fan Delavan LF 110-01 at a distance of 15 cm from the nozzle outlet. Curves represent averages over all replications per method. All scan methods appear to give a similar density profile. Fig. 6-right shows a similar comparison for the angular distribution of volume density. PL, CL and CS methods clearly show a rather flat central part, with increased volume density near the edges of the spray cone.

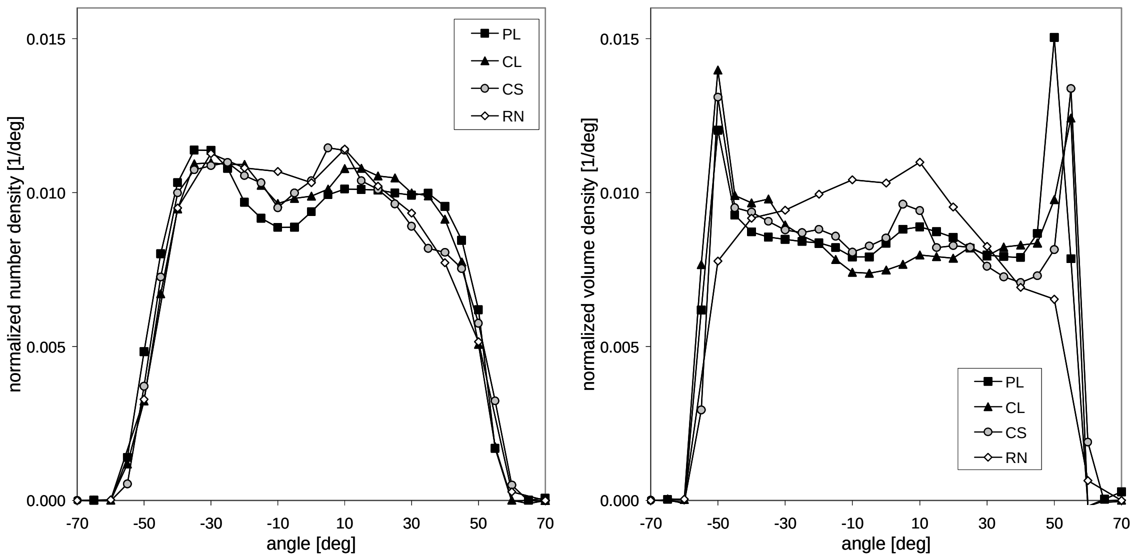

Fig. 6. Normalized angular spray densities by droplet number (left) and spray volume (right) for the four sampling methods. Nozzle: flat fan, Delavan LF 110-01, 450 kPa liquid pressure.

The RN method does not show this feature at the edges, probably due to the relatively large steps in sampled angles. The edge peaks in volume density are not seen in the number density curves. In fact at these angles the number density has decreased compared to that of the central part of the spray. This means that the edges contain relatively few but relatively large drops, as supported by the angular distribution of volume mean diameter D_{30} (Fig. 7).

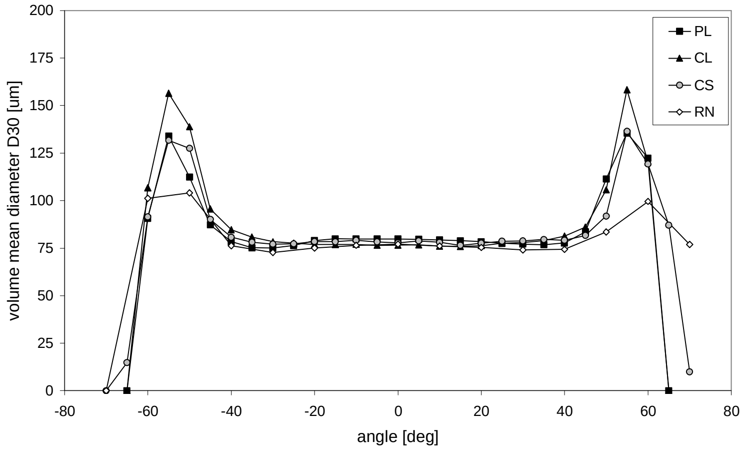

Fig. 7. Volume mean diameter (D_{30}) as a function of angle in the spray cone for the four sampling methods. Nozzle: flat fan, Delavan LF 110-01, 450 kPa liquid pressure.

By dividing the whole spray into several size classes, per size class the angular distribution of number density and volume density can be derived. Table 2 shows a division into four size classes for the Delavan LF110-01. Whereas most droplets are in the size range 50-100 μm (~50% by number), these represent only 14% of the spray volume. On the other hand, the upper 11% of drops by size represent almost 60% of spray volume. Fig. 8 shows the angular distributions of number density (left) and volume density (right) for each size class, compared with the overall density distributions. Both graphs show that between angles -40° through 40° the distributions are relatively flat, but at large angles smaller drops (<50 μm) are almost absent while larger drops (>150 μm) are abundant.

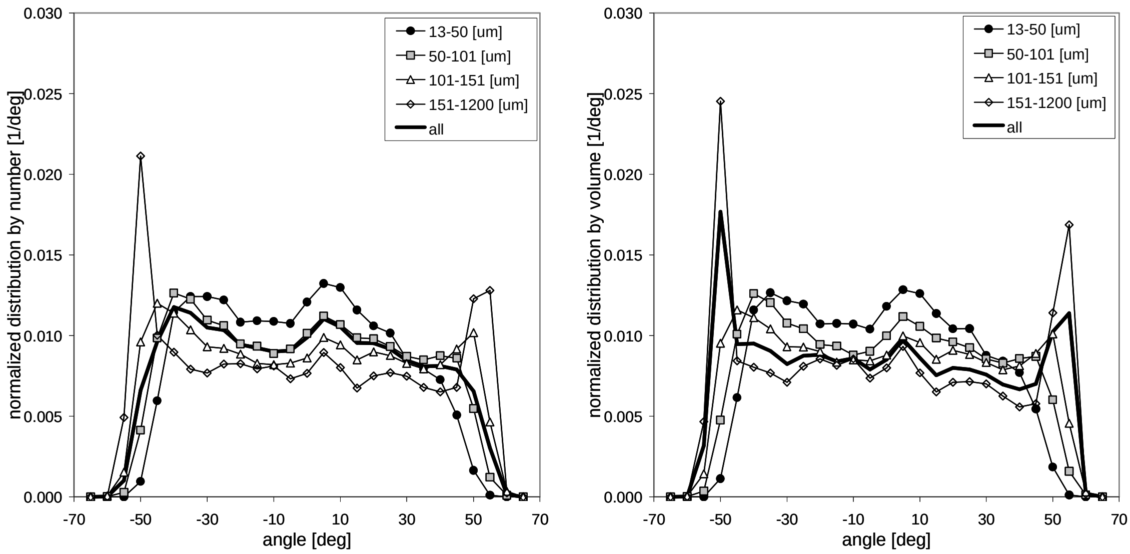

Fig. 8. Normalized angular spray density distributions by droplet number (left) and spray volume (right), for four drop size classes and the whole spray. Nozzle: flat fan, Delavan LF 110-01, 450 kPa liquid pressure; scan method: CS.

Table 2. Division of the spray into four size classes and its effect on number and volume fractions per size class (Delavan LF 110-01, 450 kPa).

Drop size classes [µm]	Fraction by number [%]	Fraction by volume [%]
13 – 50	18	1
50 – 101	50	14
101 – 151	21	26
> 151	11	59

It is expected that droplet velocities at a certain distance from the nozzle outlet depend on droplet size and on location in the spray cone. With the assumption of a radially diverging spray, Eq.(5) can be used to compute radial droplet velocity. Fig. 9-left shows the angular distribution of radial velocities for various drop sizes, as obtained with the CS method. Remarkably, the profiles are relatively flat, i.e. droplet velocities are almost independent of the direction of flight. At the spray edges the velocities are reduced. Fig. 9-right shows the relation between drop size and radial velocity at a large number of directional angles (between -50° and 50°). The curves are almost identical. Small drops (<70 µm) approach a constant (non-zero) velocity level (~5m/s), which can be interpreted as the velocity of entrained air inside the spray cone. Large drops approach a velocity of about 20 m/s, which is the initial velocity of liquid flowing out of the nozzle.

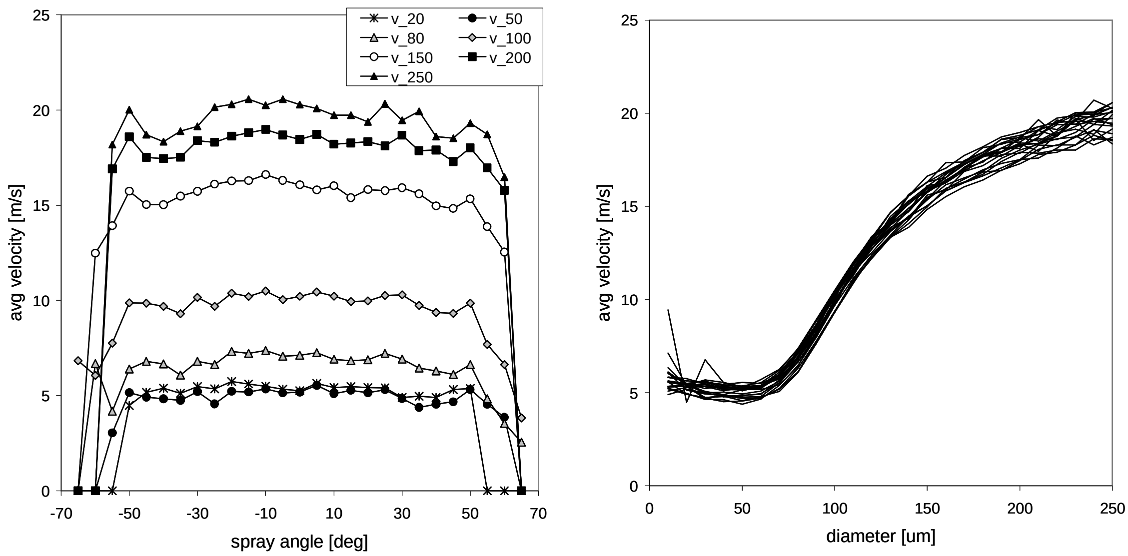

Fig. 9. Left: average droplet velocity as a function of spray angle for a few drop sizes. Right: average droplet velocity as a function of droplet size for all spray angles between -50 and 50 deg. All velocities are radial components (see text). Nozzle: Delavan LF 110-01, 450 kPa; scan method: CS.

Conclusion

In this study four methods were compared to compute angular distributions of spray densities for flat fan nozzles. All methods gave similar results for these distributions. Therefore, given the goals set and the boundary conditions (e.g. available equipment and operator time), one is free to choose the method best suited for one's purpose.

The PL method has a clear ease of operation, as the whole spray is measured in only one measurement. Using the imaginary piecewise clipping procedure 2D distribution patterns can be derived for various quantities in the plane of measurement. The large number of drops in a single measurement can be hard to handle, though. Each of the say 20 clipped pieces (apart from a few pieces at the outskirts) ideally should contain about 10^4 drops for accurate spectral characterization. As all pieces belong to a single measurement, the total number of drops in that single measurement will be about 150,000 to 200,000! By reducing the scan velocity or increasing the number of scan paths this large number of drops can be obtained easily, although data handling of such a large number of drops can become a problem.

With the CL method each cross-line measurement is stored as a separate data file, thus the number of drops per measurement is convenient yet sufficient (typically ~10^4). However, this procedure requires more handling by the operator who has to store the data and start a new measurement more often and keep track of all cross-line measurements. Besides, the CL method has the same important disadvantage as the PL method: since all measurements take place in a horizontal plane, those at large off-axis angles are done at relatively large distances from the nozzle outlet. Although correcting the results for this varying distance is easy, it implicitly assumes that gravitational forces can be neglected. This assumption has to be checked and even at measurements near to the nozzle outlet minor gravitational effects can be observed.

The CS method overcomes the above-mentioned disadvantage, as the distance to the nozzle outlet is kept constant for all cross-line measurements. However, to avoid errors due to misalignment, one must assure that the nozzle outlet is exactly in the centre of the circular path of cross-lines.

From the point of efficiency of using a 1D PDA technique the RN method seems ideal, as the dominant direction of flow is straight down for all cross-line measurements. Additionally, deviations from the radial direction of flow due to gravity can be neglected for such measurements. However, in our present setup the nozzle had to be rotated manually, which is not only laborious but also relatively inaccurate. Indeed the results for this method show that some typical features (such as the high volume densities at the spray edges) are lacking in the angular distributions.

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