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Analysis of Nigrosin and BSF Spot Sprays with PDPA drop size measurements

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Summary

Utilisation of plant protection products (PPP) in precision agriculture depends on sensing and application methods with a high spatial resolution. Nozzles are the common utensils for applying PPP but have the disadvantage that they are not switchable without affecting the spray pattern quality. Pulse Width Modulated (PWM) nozzles are a solution for switch ability without affecting the spray quality too much.

The aim of this research is to determine the spray distribution in the spot spray for a 20% and 50% flow rate PWM-setting for 2 and 3 bar liquid pressure. In three different experiments the spot spray is analysed. 1) Experiments with Nigrosin on a spray track. 2) Experiments with a fluorescent dye on a spray track and 3) Drop size measurements with a Phase Doppler Particle Analyser (PDPA). In the spray track the nozzle was moved at actual driving speeds. The PDPA measurements were done at a stationary nozzle.

Key words: Pulse Width Modulation, spot spray, drop size distribution, PDPA, PWM-settings

Introduction

Common application methods for crop protection products involve the whole crop being sprayed with a uniformly distributed dose. In practice the dose should depend on the pathogen distribution in the crop and diseases are mostly not homogeneously distributed over the crop. Or, for other crop protection products, applied doses may depend on the amount of biomass below the spray so that a young crop will receive a lower dose (van de Zande *et al*., 2008). With sensors, biomass and maybe in future pathogen stress can be detected and then there is the demand for variable dose application methods like PWM-nozzles.

A PWM-nozzle makes use of an electronic valve which can be switched with a PWM-frequency up to 60 Hz. Then the spray cone is build-up every 0.015 s, at a driving speed of 1 m s^{-1} (3.6 km h^{-1}) the displacement of the spray is 2 cm within that cycle time or 8 cm at a driving speed of 4 m s^{-1} (14.4 km h^{-1}). If the plant to be sprayed has 5 cm radius the possibilities of applying a PPP effectively appear to be slim. There are however two parameters which serve as a smoothing agent on this pattern, the spray cone depth and the drop inertia of mass.

The spray cone depth is the result of a forward or backward speed component the drop obtained in the braking up of the liquid sheet. The inertia of mass, dictates that small drops decelerate much faster than big drops (due to friction with air). The PWM-spray pattern is homogenised by both processes.

A pulse width modulation (PWM) nozzle can adjust its flow rate within milliseconds (Rometron, 2013; Giles *et al*., 1997) and should combine that with a good spray pattern. To analyse the spray pattern, spot sprays with *Nigrosin* and a fluorescent dye *Brilliant Sulfo Flavine* (BSF) were measured in the spray track. *Nigrosin* was used to visualise the spots sprayed, with BSF a quantified deposition within the spot was determined. Using a Phase Doppler Particle Analyser (PDPA) in a third experiment the drop distribution and the drop speed in the spray cloud was measured. In this paper the quality of the spot spray was quantified for driving speeds of 1, 2 and 4 m s^{-1} respectively 3.6, 7.2 and 14.4 km h^{-1}. No wind was applied to the spray.

Materials and Methods

The PWM nozzle

The PWM nozzle consists of a valve with nozzle head (Rometron, 2013), in these measurements a single nozzle was used. The nozzle type used is a Teejet4003E (E for even flow). The flow through the nozzle is adjusted by the frequency of opening and closing of the valve. In this way a flow of 50% and 20% of the full flow rate through the nozzle is realised using a cycle time of respectively 15 and 30 ms. Spot sprays of these two flow rates at 2 and 3 bar are generated. Each measurement was repeated three times.

Fig. 1. PWM-nozzle used in the experiments.

Spray track spot sprays of Nigrosin and BSF

Spot sprays are produced on a spray track moving the nozzle at a speed of 1, 2 and 4 m s^{-1}. The spray was activated by a light switch and sprayed a paper target 50 cm below the nozzle. *Nigrosin* sprays were collected on wallpaper and scanned in a set of overlapping scans by a commercial scanner. Afterwards the scans were combined to a complete scan using the picture combining software (*Hugin*).

BSF sprays were collected on strips of filter paper arranged parallel to each other. The strips are 2 cm wide (Whatman no. 2) and marked every 2 cm. The BSF concentration was determined for every 2 cm × 2 cm. Of the three repetitions of the BSF spot sprays only one (4 m s^{-1} spot sprays) or two (1 and 2 m s^{-1} spot sprays) are analysed.

Drop size measurements

To be able to assign spot structure to drop size Phase Doppler Particle Analyser (PDPA, TSI) measurements were performed. At different positions 50 cm below the nozzle the drop size and drop speed was measured. Each measurement was related to the time within the PWM-cycle, the

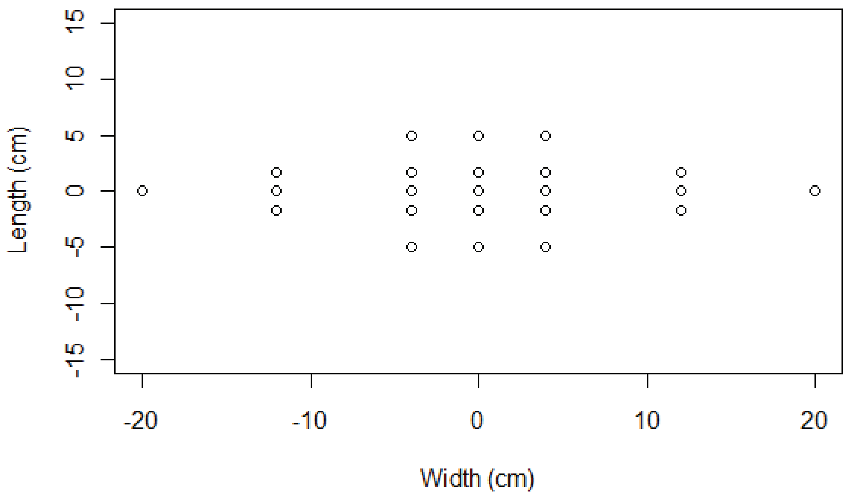

Fig. 2. Measure positions of the drop size measures by the PDPA in the horizontal plane of the spray fan at 50 cm below nozzle.

arrival time on the plane 50 cm below the nozzle. The pattern in the horizontal plane in which the drop size measurements are taken is displayed in Fig. 3.

The PDPA is a method where two horizontal laser beams cross each other under a small angle. At the point of crossing an interference pattern is formed, the measurement volume. A drop passing through this measuring volume scatters the interference pattern toward detectors in a collector. The detectors measure a fast modulated light intensity from which the size and vertical speed of the drop is determined. The height of the laser beam was 1.2 m above the floor.

The spray liquid used was tap water at a controlled temperature of 20^{o}C. The drop size measuring chamber in the laboratory was climate controlled at a temperature of 20^{o}C and a relative humidity of 70%. The liquid pressure was kept constant (3 bar) by a feedback flow regulator.

PDPA settings during measurements were:

• Laser power	700 mW
• Focus front lens transmitter	1000 mm
• Focus front lens detector	1000 mm
• Expander/contractor	contractor
• Detection angle	40^{o}
• Detector tension	450 V
• Signal threshold	75 mV
• Measurement size range	13–1250 µm
• Diameter resolution	2.0 µm
• Probe Volume Correction	yes

The Probe Volume Correction (PVC) was used to correct for an under estimation of small drops. As the laser intensity in the measurement volume is lower at the edges and the amount of light scattered by small drops is small, the signal of small drops moving through the side of the measurement volume produce a low intensity and therefore a lower chance of being detected than a larger drop. The computer program thereby generates a new drop spectrum in which the amount of small drops is corrected.

Reconstruction of a spot spray from the PDPA measurements

In total 23 positions are measured over an area of approximately 200 cm^2 in the PDPA measurements. In the measurements the nozzle was static unlike the measurement in the spray track and therefore a spot spray was generated using the arrival time of the drop in the “50 cm below the nozzle” plane. The nozzle forward speed effectively results in a repositioning of the measure location in the driving direction. The spray deposition was calculated as the sum of the drop volumes per surface area. Using interpolation the complete spot spray was approximated.

Results

Spot length and correction

In Fig. 3 the driving speed is 1, 2 and 4 m s^{-1} for a 20% flow rate spot spray at 2 bar liquid pressure. The spot length seems to have a linear relation with the driving speed.

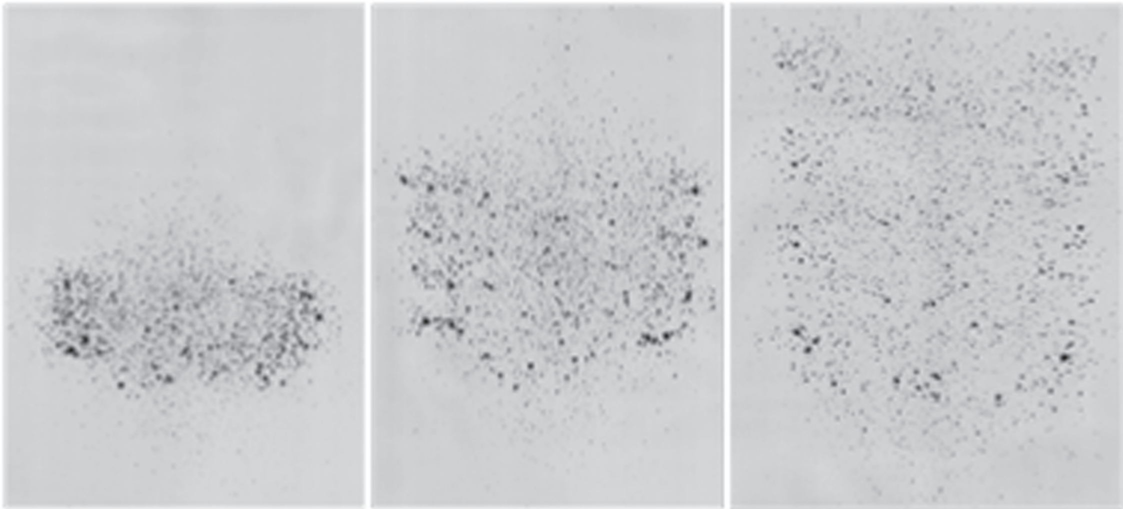

Fig. 3. *Nigrosin* footprint of spot sprays as function of driving speed, respectively 1, 2 and 4 m s^{-1} (left to right). For all spot sprays the flow rate was 20% of full flow rate at a pressure of 2 bar. In the pictures the nozzle moved from top to bottom.

The spot spray length, calculated from the integral of the measured dose (using 5% to 95% boundaries), for the *Nigrosin*, BSF and PDPA spot sprays are given in Fig. 4. The *Nigrosin* and *BSF* spot sprays have very much the same length while the spot sprays determined from the PDPA measurements are twice as long. For the *Nigrosin* and BSF spot sprays this was the result of forward movement of the drops through stationary air. Drops at the front of the spot spray are more decelerated than the drops at the back of the spot spray and therefore they end up closer to each other. In the rest of the paper the PDPA spot sprays are corrected for this effect by linearly compressing the spots in the driving direction. Using linear regression the spot length appears to depend on nozzle forward speed only.

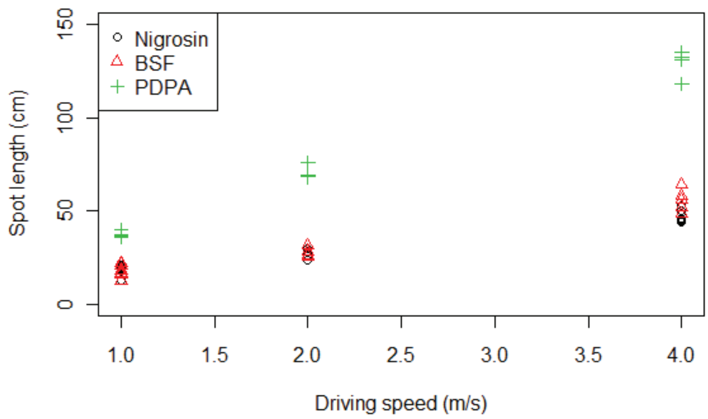

Fig. 4. Spot spray length of the *Nigrosin*, BSF measurements and the PDPA based calculations as function of nozzle forward speed. The spot spray length is calculated from 5% to 95% boundaries of the integral of the measured dose.

Spot spray profile

In Fig. 5 spot sprays with *Nigrosin* are given for 20% and 50% of the full flow rate and at 2 or 3 bar liquid pressure, the driving speed was 2 m s^{-1}. Apparently the most evenly sprayed spot was generated with a 50% flow rate at 3 bar. The spot spray of 20% flow rate at 3 bar has large drops at the front (bottom of figure) due to the inertia of mass of the drops. Large drops are less decelerated than small drops and therefore end up on front of the spot. At 2 bar the large drops are more located at the sides of the spot. In the 50% flow rate setting at 2 bar the large drops are more evenly distributed over the area. The spot length of all spots is very much the same.

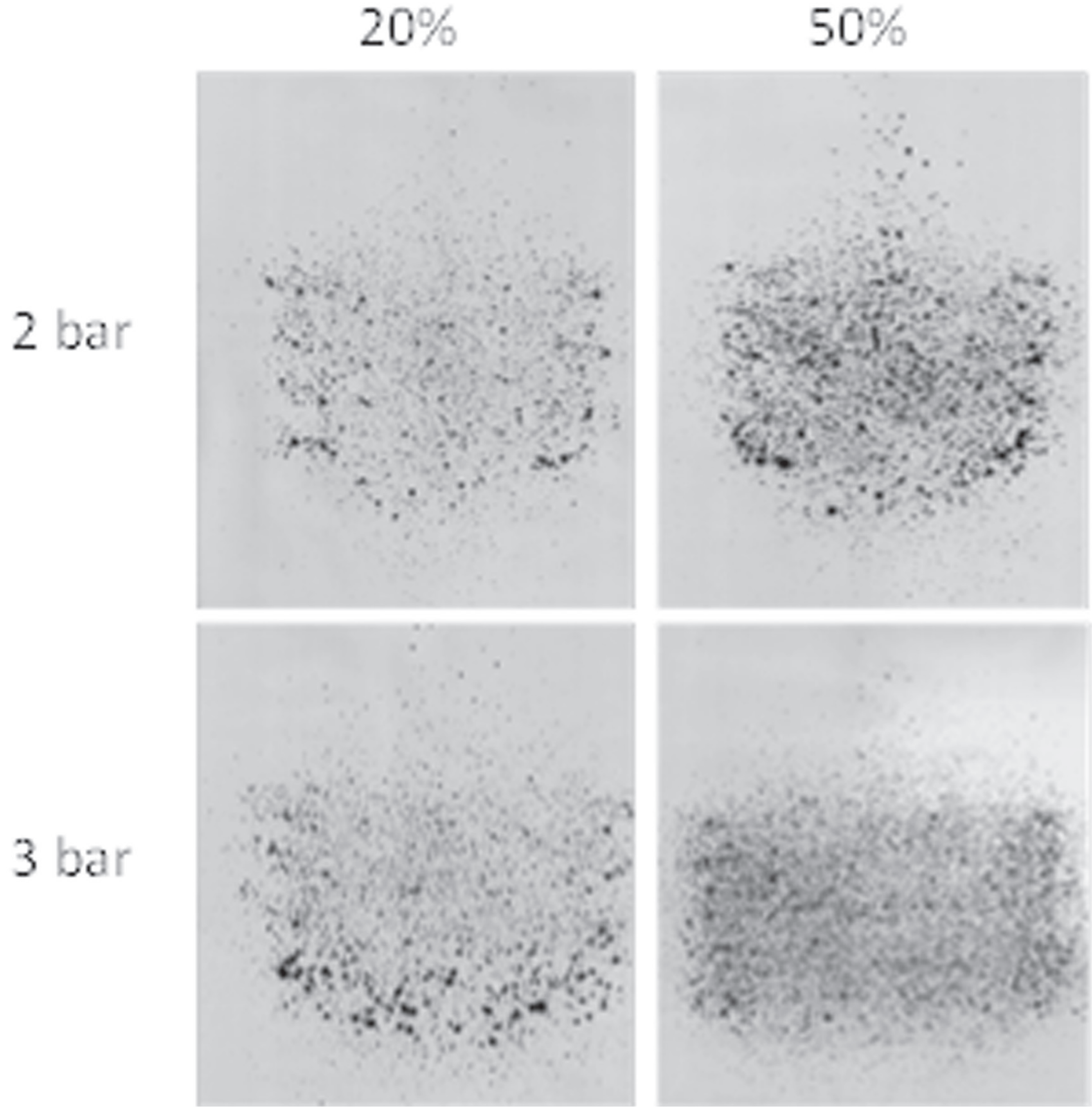

Fig. 5. *Nigrosin* footprints of spot sprays for 20% and 50% of the maximum flow rate and at 2 and 3 bar spray pressure. The forward speed for all spot sprays is 2 m s^{-1}. The driving direction was from top to bottom of the figure.

The integral volume of spray deposition for the four spray settings in the driving direction and perpendicular to the driving direction are given in Fig. 6, Fig. 7, Fig. 8 and Fig. 9. The driving speed was 2 m s^{-1}. The Nigrosin curves perpendicular to the driving direction all have similar shapes, a maximum in the centre and a peak at each side. The shape in the driving direction does not alter much for all spray types. The curves of the BSF sprays are triangular shaped for the 20% flow rate sprays and rectangular shaped for the 50% flow rate sprays. The PDPA sprays generally have a maximum at each side.

Spot integral

The integral of the complete spot spray for the three methods as a function of flow rate are given in Fig. 10. A clear relation with the flow rate is found, it did not show a relation with driving speed and liquid pressure (tested with linear regression).

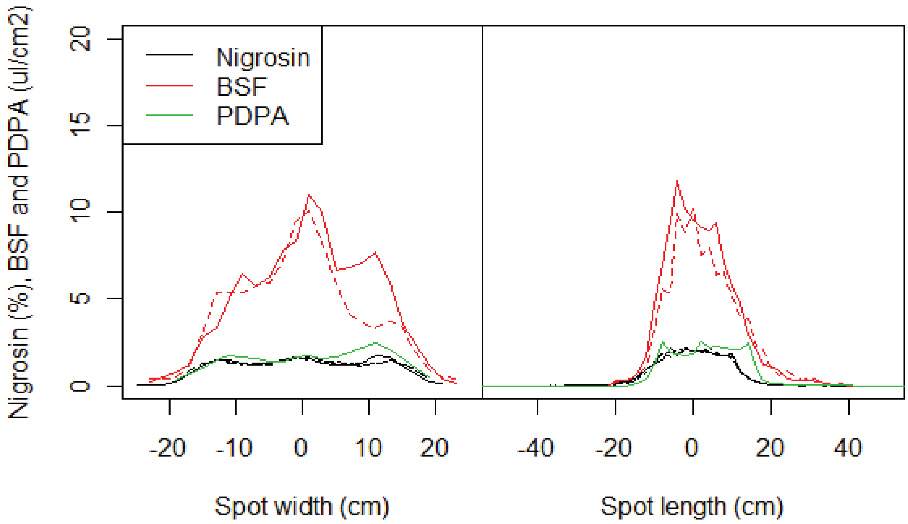

Fig. 6. Projection of the integral of the Nigrosin, BSF and PDPA spot sprays for the 20% flow rate spots at a pressure of 2 bar and forward speed of 2 m s^{-1}. Projections in the direction of driving (length) and in the perpendicular direction (width) are given. Lines of equal colour but different type are repetitions.

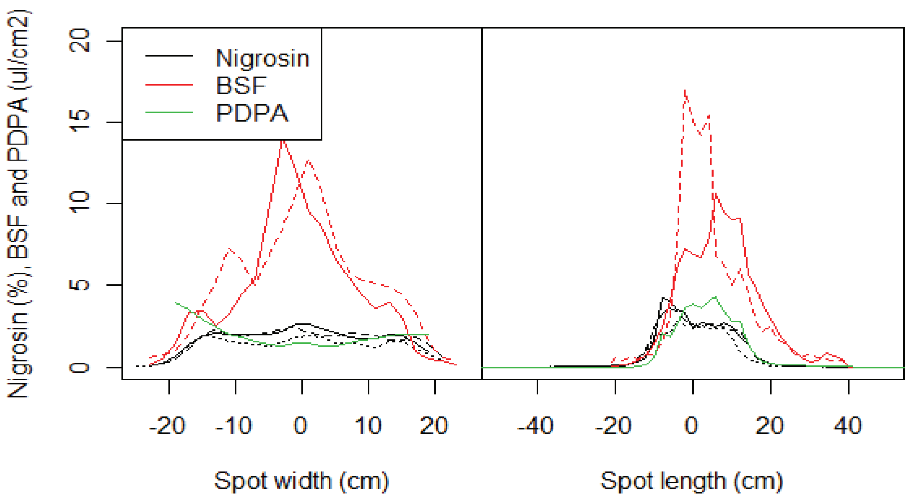

Fig. 7. Integral of the projections of the Nigrosin, BSF and PDPA spot sprays for the 20% flow rate spots at a pressure of 3 bar and forward speed of 2 m s^{-1}. Projections in the direction of driving (length) and in the perpendicular direction (width) are given. Lines of the same colour but different type are repetitions.

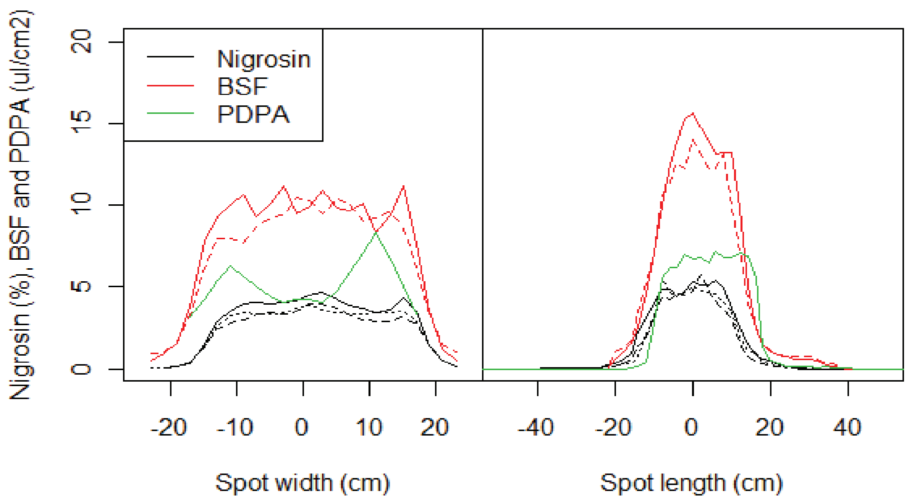

Fig. 8. Integral of the projections of the Nigrosin, BSF and PDPA spot sprays for the 50% flow rate spots at a pressure of 2 bar and forward speed of 2 m s^{-1}. Projections in the direction of driving (length) and in the perpendicular direction (width) are given. Lines of the same colour but different type are repetitions.

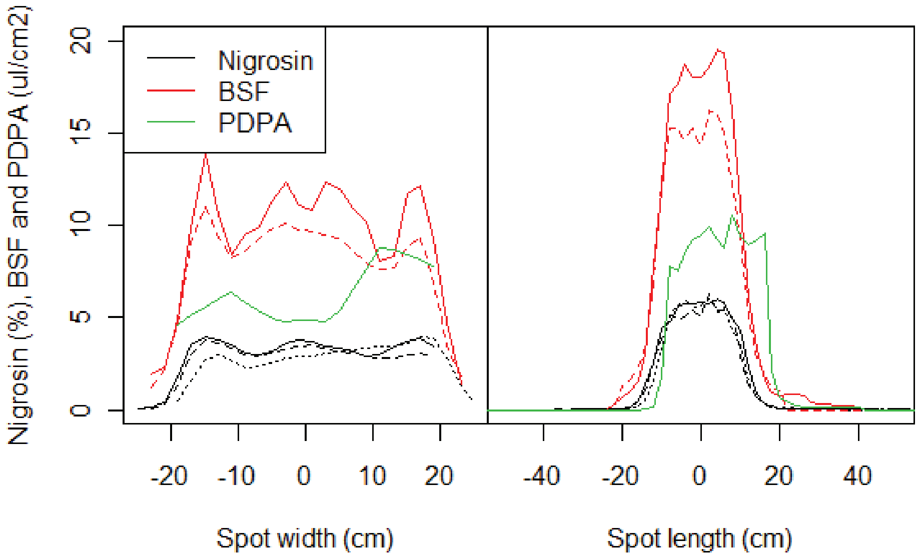

Fig. 9. Integral of the projections of the Nigrosin, BSF and PDPA spot sprays for the 50% flow rate spots at a pressure of 3 bar and forward speed of 2 m s^{-1}. Projections in the direction of driving (length) and in the perpendicular direction (width) are given. Lines of the same colour but different type are repetitions.

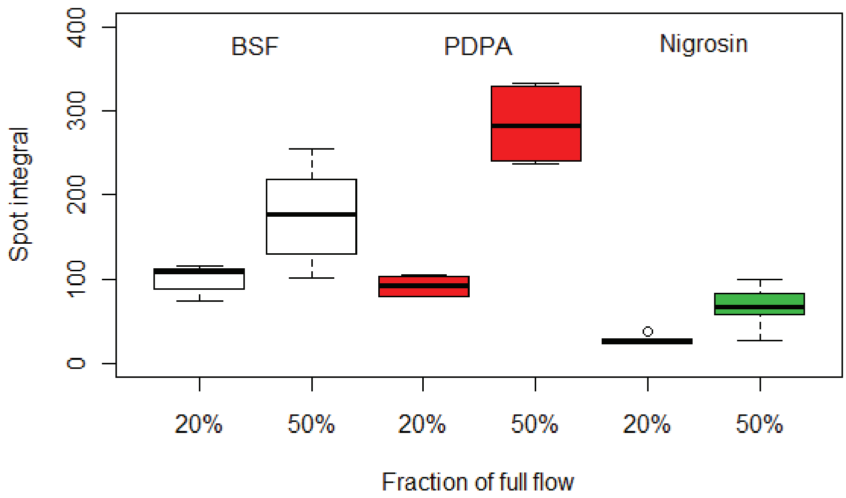

Fig. 10. Integral of the spray deposition for the three detection methods of the spot spray. All methods show a strong relation to flow rate.

Discussion

Proof for the mechanism that the length of the spot sprays is compressed by deceleration of the front drops can also be concluded from the shape of the spot sprays in Fig. 3. Comparing the spot sprays from a low to a higher forward speed a more pronounced "V" shape is visible. Due to friction with the air the sides of the spray encounter more resistance than the central part of the spray, resulting in a "V" shape.

The BSF detection method should give the most accurate estimate of the real deposition, therefore, the 50% flow rate setting, when compared to the 20% flow rate settings, should result in a 2.5 times higher integral. In fact the ratio results in a factor less than two times (Fig. 10). The origin of this loss is not yet resolved.

In Fig. 6, Fig. 7, Fig. 8 and Fig. 9 the PDPA integral is systematically lower than the BSF integral. There is, however, uncertainty about the cross section of the probe volume. This is taken as 1 mm^2 but was not measured and is depending on parameter settings of the laser.

Comparing the projections to the *Nigrosin* absolute values is meaningless because *Nigrosin* values determine covered area in % and BSF and PDPA in µL cm^{-2}. Another aspect of the PDPA spot is the lower volume in the centre of the spot spray compared to the centre of the BSF volume. Why the centre of the PDPA spot is underestimating the measured volume is also not clear.

The spot spray determined by the PDPA does not take into account the deceleration of the drops. Here, the spot length is adapted by rescaling the length of the spot while in fact the length is controlled by inertia of mass in the deceleration process of individual drops. For a better match between the PDPA measurements and the BSF measurements this process should also be taken into account.

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