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Test Method for Boom Suspension Influence on Spray Distribution, Part I: Experimental Study of Pesticide Application under a Moving Boom

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Abstract

The quality of pesticide spraying depends on boom movement. A conveyor with a shaking platform was built to analyse the influence of boom movements on spray distribution. It is able to generate uniform translations and rotational movements of a small boom under laboratory conditions. The overall ground spray distributions were studied using image analysis. Suitable representations and mathematical tools were considered to analyse the unevenness of ground spray distributions and to compare accurately spray patterns. The effects of boom height, boom speed and nozzle type on dynamic spray distributions were analysed and compared with stationary distributions. The effects of yaw and roll movements were also considered. Measurements of droplet size and velocity made with a phase Doppler analyser were added to complete the dynamic effect study. Tests were repeatable but some fluctuations were obtained when boom height increased. Static and dynamic distributions have the same overall unevenness but this unevenness is more important in dynamic conditions due to turbulence effects. Roll and yaw increase unevenness. For roll movements, changes in nozzle heights explain the variations. For yaw movements, over-dosed areas are observed where the nozzles have a small horizontal velocity.

Keywords: boom, ground distribution, image analysis, nozzle, pesticide, sprayer

1. Introduction

Optimising the evenness on the ground of spray application from field crop sprayers is important in order to reduce the chemical doses used in field while maintaining the required biological effect (Enfält *et al.*, 1997a). An even spray liquid distribution is obtained when the nozzles are correctly chosen, when the calibration of the sprayer is effective and when the boom remains stable. Moreover, with a stable boom, the distance between the nozzles and the target can be reduced and then, drift losses are less important. Boom movements are due to soil irregularities that are transformed and more or less amplified depending on the mechanics features of the machine (including tyres and boom suspension). In this study it is proposed to adopt an experimental approach to the effects of the boom movements on the distribution pattern. This study was a part of a European project (SPECS, 1998) to develop a boom test method at the farm level. The objective was to analyse which phenomena were predominant in order to select adequate tools for the design of the test method. A second part describes how the selected tools were implemented to develop the test method.

Several authors already tried to understand boom influence on spray distribution. During static spraying (without movement) boom height, combined with evaporation phenomena, influence fall speed of the droplets (Reichard *et al.*,1992) modifying drift importance. Stains due to the droplets are also depending on their impact velocity and thus, on the discharge height. When the sprayer is moving, Richards *et al.* (1997) hypothesised that the two major influences upon dynamic spray distribution, were spray interaction and air turbulence. They stated that spray interaction depended on nozzle angle, spacing and height and that air turbulence depended on droplet size, flow rate, height and boom speed.

Boom movements were measured by Pochi and Vannucci (2001, 2002) using linear and angular potentiometers. Ooms *et al.* (2002) equipped the boom with ultrasonic sensors and accelerometers to measure horizontal movements, the sprayer being equipped with a radar speed sensor and a three-axis dynamic measurement unit. The effects of nozzle height, forward speed and nozzle type on spray pattern were studied in field conditions by Womac *et al.* (2001). The coefficient of variation (CV) of spray distribution ranged from 5 to 17% for static booms and from 6 to 37% for moving (at 6 to 26 km/h) booms. Using a bump, Jeon *et al.* (2003) studied the influence of a sprayer boom dynamics on spray coverage. The maximum vertical displacement was 1.05 m for both 27.4 m boom tips. The maximum CV of spray coverage was 53.45% and 39.42% for two nozzle types. Dynamic movements of the boom can be analysed as a combination of horizontal (roll) and vertical (yaw) movements. Simulations made by Clijmans *et al.* (2000) clearly indicated that both rolling motion and horizontal vibrations of the boom can severely disturb the spray deposition pattern. Dose percentages of 0%, which indicates a null volume, and up to 700% were found from simulations, with the extreme values situated under the tips of the boom.

Due to boom rolling, the distance between the nozzles and the ground is different from the desired distance. Nozzle cone overlaps are disturbed and a redistribution of the spray liquid takes place along the boom (Kennes *et al.*, 1996). The effect of vertical boom movements on the uniformity of spray distribution was studied by Langenakens *et al.* (1999). The effect of translations was low, while rolling and vertical flexible deformations had larger influences on spray distribution, especially at the extremities of the boom where the amplitude is more important. Maximum deposits reached 760% and minimum 0% in the case of the largest sprayer boom motions.

Horizontal boom movements cause an unequal velocity of the nozzles, resulting in variable spray deposition in the driving direction (Kennes *et al.*, 1996). Lebeau *et al.* (2004) studied the effect of nozzle speed on spray coverage and try to compensate the speed effect by acting on nozzle flow. They observed that longitudinal spray distribution was mainly affected by the horizontal speed variations of the nozzles. Using their vibration test bench, Herbst and Wolf (2001) measured the distributions under seven tractor mounted sprayers (15 m and 24 m boom width) and 10 trailed sprayers (27 m), at 6 and 10 km/h, with a mean spray dose of 200 *l*/ha. A correlation was observed between the coefficient of variation of the spray deposit and the coefficient of variation of the horizontal boom speed. For a mounted sprayer, it was shown that it was possible to improve the dynamic spray distribution at the boom tip by an optimal adjustment of springs and dampers.

Thus, it was clearly stated that ground spray distribution is influenced by the driving speed and by angular movements. Results on distributions were published for bump and field tests. The effects of roll and yaw were studied by simulation. To a better understanding of the occurring phenomena, the objective of this study was to design a device to reproduce the main movements (translation, translation with roll, translation with yaw) in a controlled way to measure their effect on ground distribution on a large continuous area (half boom width and similar scale length) and with a good accuracy (50 mm x 50 mm). In this paper, the shaking device is described and the measurement method is discussed. Then, results of tests with translations at several driving speed and with translations combined with roll and yaw movements are presented. Finally, the methodology is discussed as well as the consequences of the observed results for the development of a simulation model.

2. Materials and methods

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2.1. *Moving device*

To analyse sprayer boom movements, different systems have been developed to shake the tractor-boom system with controlled excitations as, for instance, bench with four jacks bearing rollers with transverse bars (Lines, 1987), track simulator (Sinfort *et al.*, 1994), vibration test bench (Herbst *et al.*, 2001), mobile low power test rig for experimental modal analysis (Kennes *et al.*, 1999).

To analyse in a more accurate way the influence of velocity and of rotational movements, a testing device including a conveyor bearing a shaking platform was built. Its maximum velocity is 4.17 m/s (*i.e.* 15 km/h) with a maximum acceleration of 4 m/s^2. The conveyor has a 16 m useful length, allowing up to a 12 m test ride length in normal velocity conditions. The command is hydraulic with feed back on position and velocity. Movement is controlled by an encoder. The servo-control board [proportional integrated derivative (PID) type] was developed in Cemagref. It is connected to a computer which generates speed orders and controls the position of the wagon. The connection between the personal computer and the servo-control board is a control area network (CAN) communication bus. The maximum carried mass is 120 kg and a frame can hold the boom from 300 to 900 mm height. The shaking platform includes 10 pneumatic jacks with a maximum frequency of 2 Hz allowing rotational movements of +/- 5 degrees (for roll, pitch and yaw) and vertical translations of +/- 50 mm. The actuators are controlled by logic output modules connected to the CAN bus. The electronics of control consists of a digital servo control system piloted by a software developed in C ++ on a PC. The rotational movements of the shaking platform are recorded by means of potentiometers delivering analogical information which is converted by modules connected with the control area network.

2.2. *Distribution measurements*

To measure ground spray pattern under the moving boom, two set of methods are usually considered: chemical methods and image analysis. Chemical methods include colorimetry, fluororimetry (Salyani & Whitney, 1988) and chromatography (Sundaram, 1994). These methods provide reliable results and have been commonly used in the agricultural research field for several years but they are too time-consuming and expensive to analyse a large area with the chosen accuracy (50 mm x 50 mm) and with numerous repetitions. The use of machine vision combined with image analysis was considered to increase speed and ease of use and to reduce the cost of spray deposition assessment (Evans *et al.*, 1994), but Salyani and Fox (1994) observed that image analysis had intrinsic limitations which can result in wrong measurements. Nevertheless, Evans *et al.* (1994) found a strong correlation between the spray coverage determined from image analysis and the mass deposition measured by chemical analysis as long as the spray coverage is fairly uniform. Image analysis method using this correlation could therefore be a good compromise. To calibrate such method Enfält *et al.* (1997b) obtained calibration samples by spraying manually Nigrosine with one nozzle. Three different nozzles were used to obtain a large calibration range. During each spray, the operator tried to change manually the nozzle speed and height to have a large range of volumes. Each sample was weighted quickly with an accurate balance (1 mg) after spraying Nigrosine above a Petri box to limit the evaporation phenomena. In 2003, Ooms *et al.* used this method and studied the influence of boom movements while spraying on a band of wallpaper. To measure spray distribution by image analysis, the dried papers were scanned to obtain a grey scale image. A threshold was applied to measure the spray coverage.

The chosen method was then the one of Enfält *et al.* (1997b). The basis of this method is to spray a black dye (Nigrosine water soluble) on large pre-pasted wallpaper sheets (*Fig. 1*). Nigrosine is a powder, a sulphonated phenazine dyestuff. Its boiling-point is greater than the water boiling-point. Nigrosine mixed on water would not increase the evaporation phenomena of water nor drift phenomena. Several concentrations were analysed to optimise these factors. The deposit was measured with image analysis. The average grey values observed on 50 mm × 50 mm cells were observed relatively to the mass deposits measured on the same surfaces to give a correlation chart. Such calibration curves were established for each test by spraying Nigrosine mixture on 50 mm x 50 mm square papers with a small manual sprayer and weighting them immediately. Height of spraying was 0.5 m.

2.3. *Description of the tests*

2.3.1. *Dynamic effect*

Dynamic spray distributions were obtained for a boom equipped with eight nozzles spaced by 0.5 m. The average temperature was 30° and the relative humidity varied from 64 to 73%. The first set of tests was made without rotational movements. The varying parameters were forward speeds (6, 10 km/h) and heights (0.3, 0.5, 0.7 m). Two sets of flat fan nozzles were tested: Teejet XR 11002VS and Teejet XR 11004VS; they will be denoted as XR02 and XR04. The horizontal angle between the nozzles and the boom was 10° and the pressure was 2 bar. For the XR02 and XR04 nozzles, the theoretical flow rates were then 0.65 *l*/min and 1.29 *l*/min respectively. The corresponding spray doses were 130 and 258 *l*/ha at 6 km/h, and 78 and 155 at 10 km/h. Each test was repeated three times thus 36 distributions were obtained. Three tests were added to analyse the influence of nozzle angle (0°, 10°, 20°). These three tests were made at 0.5 m boom height, using the XR04 nozzles with a 6 km/h boom speed. Distributions were analysed on the area above which the conveyor speed was constant. This area was 3.25 m long in the driving direction and 4.20 m in the boom direction. The first roller of wallpaper was placed at 4 m from the conveyor starting point. The static pattern under the boom was measured on a patternator with the same nozzles, height and pressure. The patternator is made of 60 tubes which are spaced at 50 mm giving a total width of 3m.

Diameter and speed distributions of the droplet cloud under a single nozzle were measured with a phase Doppler analyser equipped with a bi-color laser generator (wavelengths of 488 and 514.5 nm) and a receiver with two standard and two planar detectors. The beams had perpendicular polarisation and the receiver was placed to analyse the refraction scattering mode (scattering angle of 45°). The nozzle was placed on a traverse system (two axes), to move the measurement point in a horizontal plane at a given height (from 150 to 250 points in a given plane). These tests were realised in static conditions with the same height and pressure conditions than dynamic spray tests.

2.3.2. *Rotational movements*

Yaw movements (horizontal plane) and roll movements (vertical plane) were reproduced on the conveyor. Thirty-six tests were organised for the XR04 nozzle: +/-5° roll and yaw, frequencies of 1.08, 0.77 and 0.49 Hz, 6 and 10 km/h boom speed, with three replicates for each test. Boom height was 0.5 m and the horizontal angle between the nozzle and the boom was 10°. The most important frequencies for both horizontal and vertical boom movements are between 0.5 and 1 Hz (Kennes, 1999). Frequencies of 1.08, 0.77 and 0.49 Hz were chosen to be within this range and to use periods multiple of 186 ms as imposed by the shaking-platform command. The angles of +/-5° for roll and yaw were measured by Kennes (1999) on the tips of a 24 m boom. The analysed area for this second set of tests was 4.5 m in the forward direction and 4.45 m wide.

2.4. *Distribution patterns and analysis*

Measured distributions are described with volumes collected on 50 mm ×50 mm adjacent squared areas. Static distributions were computed from the one dimensional distributions of each nozzle, measured on the patternator, knowing the travel velocity. The comparison between measured and static distributions is expected to provide an evaluation of the dynamic spraying effect.

Some ways for the analysis of ground distributions were already proposed by Sinfort *et al.* (1997) and Lardoux *et al.* (1998): grey level representations, over and under-sprayed areas representations, estimation of the surface percentage of several areas (area with correct spraying [V_m-15%, V_m+15%], under sprayed area [<V_m-15%], over sprayed area [>V_m+15%], where V_m is the average sprayed dose on the squares), analysis of dose variations (minimum dose, maximum dose, mean dose). The value of 15% is commonly used as acceptable deviation from the ideal dose. The mean value V_m could also be the chosen dose for the application but it causes worse results.

Several statistical tools such as tendency and dispersion measurements are also available (Blard–Laboderie, 1994; Lethielleux, 1998). The coefficient of variation C_v is commonly used to indicate the volume dispersion around the mean value. It is defined as:

$$C_v = \frac{1}{x_m}\sqrt{\frac{\sum (x_i - x_m)^2}{n-1}} \quad (1),$$

$$x_m = \frac{\sum x_i}{n} \quad (2)$$

where: n is the number of values; x_i is the volume measured on the analysed area i; and x_m is the average of the measured volumes.

Roughness indices and frequency analysis are other indicators to analyse the evenness of the distributions. Scalar product of histograms and arithmetic differences provide a way to compare measured and static distributions.

Roughness indices:

Usually, roughness is described by the mean deviation, M_D, defined as the mean absolute deviation divided by the median value, where the mean absolute deviation is the dispersal value around the median.

Others indices are used to evaluate roughness. For example, Currence and Lovely (1970) proposed:

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$$I_R = \frac{1}{n.x_m} \times \sum_{i=1}^{n} \left(x_i - x_{i-1} \right) \quad (3)$$

where I_R is the mean roughness.

Arithmetic difference

Applied to distribution patterns, histograms represents the number N_i of squared areas for each class i of volume X_i. When comparisons are intended, normalised histograms are preferred: instead of using the number k_i of analysed areas from a class i, the ratio $m_i=k_i/k$, where k is the total number of analysed areas, is considered. Afterwards, $m(X_i,i)$ will stand for the fraction corresponding of the analysed area number (frequency) from a class i of mean volume X_i. For normalised histograms, the sum of the $m(X_i,i)$ values defined above is always equal to 1. Intuitively, it is clear that histograms are better differentiated when their overlap is not important, *i.e.*, when the number of common elements is close to 0. The overlap is given by the arithmetic difference D_A :

$$D_A\left(X_i, X_i'\right) = \sum_i \min\left[m_i ; m_i'\right] \quad (6)$$

If X_i and X_i' are equal, $D_A(X_i, X_i')$ is equal to 1 and, if X_i and X_i' are totally dissociated, $D_A(X_i, X_i')$*)* is null. The arithmetic difference is a normalised coefficient.

Scalar product of histograms

Each distribution can be represented by a vector in a space of C dimensions where C is the number of histogram classes. In this space, two histograms will be well differentiated if the angle between their vectors is close to 90°. This optimal angle is obtained when its cosine is null, that can be evaluated with a scalar product (Rabatel, 1991). The scalar product of histograms S_P is a two-dimensional correlation coefficient :

$$S_P = X_i X_i' = \frac{\sum_i m_i m_i'}{\sqrt{\sum_i m_i^2 m_i'^2}} \quad (5)$$

This scalar product can then be considered as a similitude coefficient. Scalar product of histograms can also be used to evaluate the homogeneity of a given distribution: an ideal distribution is logically a ground spray distribution without unevenness. Therefore, the scalar product with this ideal distribution gives globally the regularity of the ground spray distribution.

Frequency analysis

Spray unevenness can be then considered as signal variations at high frequencies. Two dimensional Fourier transforms can analyse signal harmonics and give the frequencies of spray unevenness.

3. Results

3.1. *Dynamic effect*

3.1.1. *Stationary and dynamic spray distribution*

Representations of over-sprayed (black), under sprayed (white) and correctly sprayed (grey) areas are presented in *Fig. 2* both for static and dynamic conditions. The overlap of individual nozzle patterns [*Fig. 2(a)*] is not homogeneous and is responsible of spray unevenness observed on static and dynamic distributions [*Fig. 2(b) and Fig. 2(c)*]. The periods of spray unevenness obtained with 2D Fourier transform *T(m)* are similar in static and in dynamic conditions (Table 1). Generally, the period of spray unevenness fits with the distance between nozzles (0.5 m), except for the tests made at 6 and 10 km/h with the XR02 nozzles at 0.3 m height where the period is divided by 2. The values obtained for the scalar product of histograms S_p confirm that static and dynamic spray distributions are globally similar.
Mean doses obtained for the dynamic spray tests are lower than mean doses obtained for static spray tests. In dynamic conditions, they also decrease when boom height increases. The over and under sprayed are higher in dynamic than in static conditions, except for the tests made with the XR02 at 10 km/h with a 0.7 m boom height. The coefficient of variation results

confirm the same behaviour. The CV is approximately constant in dynamic conditions but not in static conditions. For the latter, CV values decrease when the boom height increases for the tests with the XR04 nozzles. With the XR02, the trend is more difficult to analyse. The lowest values for the CV and the standard deviation (STD) are obtained at 0.5 m boom height. The CV values are between 10 and 14% in dynamic conditions and between 5 and 13%, in static conditions. The STD values show that dispersion of volumes decreases in dynamic conditions when boom speed and boom height both increase and when the nozzle gauge decreases. The scalar product of the histograms of the measured and simulated ground spray distributions S_p was always close to 1, showing that the static approach considers correctly spray unevenness due to nozzle overlap.

The relative difference between mean doses in static (theoretical value) and dynamic conditions is not influenced by the velocity but mainly depends on boom height. The influence of nozzle angle was observed too (Table 2): the mean dose obtained with a nozzle angle of 10° (191 *l*/ha) is higher than the ones obtained with 0° and 20° (respectively 166 and 168 *l*/ha). The values for the STD show that the highest dispersion of volumes is obtained for a 20° nozzle angle.

Figure 3 shows the results obtained for dynamic conditions at 6 km/h. Satisfactory repetitive results are obtained for each configuration. It can be considered that both boom height and nozzle type have an important influence on spray coverage. Fluctuations increase with height, mainly for the XR04 nozzles. It can be considered that interactions and turbulence between nozzles are mainly responsible of the observed unevenness.

3.1.2. Phase Doppler analyser measurements

Figures 4 and 5 show results obtained with phase Doppler analyser measurements. Falling droplet speed depends on boom height (*Fig. 4*). When height increases, deceleration is

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observed: the percentage of droplets in the class [0, 5 m/s] increases when it decreases in the higher classes. This deceleration is more important for the XR02 nozzle. As observed in *Fig. 5*, the cumulative volume percentage of droplets smaller than 150 µm is equivalent for both nozzle series. The volume percentage of droplets with diameters between 150 µm and 400 µm is greater for the XR02 nozzle. The measure confirms that the XR02 nozzle generates smaller droplets than the XR04, except for droplets smaller than 150 µm.

3.2. *Rotational movements*

Good similarity is observed for each repetition. The mean values obtained in the tested configurations are shown in Table 3. Mean values, standard deviation, coefficient of variation do not depend on movement frequency. Without any roll or yaw movement, the distributions are more homogeneous and the obtained dose is more important. Spray due to yaw movement seems to give less even distributions than spray due to roll movement (CV is more important). Volumetric losses (relative difference between mean doses in static and dynamic conditions) are a little bit more important for roll (between 44 and 50%) than for yaw tests (between 43 and 48%) which are also higher than those obtained for tests without any rotational movement (between 23 and 26%). Examples of the effect of rotational movements on distributions are shown in *Fig. 6*. For yaw movement, over-sprayed areas occurred when the direction of boom tip changes, where the nozzle velocity is near zero. These areas stand in front of under-sprayed areas, corresponding with high velocity of the nozzles. For roll movements, unevenness is mainly due to nozzle overlap and rotational angle variations of the nozzle.

4. Discussion

4.1. *Method*

The measurement method for the distributions give quick and accurate results but the obtained dose in *l*/ha decreases when boom height increases. Losses should be due to evaporation, drift and dispersal of droplets. Measured doses did not depend on boom velocity, except for the test made with the XR04 nozzles, a 0.7 m boom height. Turbulence intensity generated between sprays is then not responsible. The granulometry measurements showed that the droplet velocity at the impact point decreases with the nozzle height. It can be hypothesised that this velocity influences the sizes of the stains and then modifies the image analysis results. The observed differences could also be due to evaporation but the losses of dose between tests are generally different and the granulometry shows that the nozzles have the same amount of droplets prone to evaporate (0-150 µm). It is then necessary to improve the image analysis method, particularly the calibration part, for instance, by comparison with other methods, such as colorimetry or fluorimetry.

Indicators proposed for the analysis of distributions are in good agreement. The values for the roughness indices give the same indications as the coefficients of variation. For the comparison of distributions, the arithmetic difference and the scalar product of histograms can be used in a similar way. In the second part of this work, which is aimed at the comparison of simulated and measured distributions, the roughness indices and the arithmetic difference are not used.

4.2. *Dynamic tests*

Longitudinal spray unevenness is due to nozzle overlap and velocities (and turbulence) of both droplets and air. Variations of nozzle overlap are mainly due to boom height and nozzle angle (overlap is more important when the boom is high). Velocities of droplets and air are influenced by boom height, nozzle angle, boom speed, droplet diameters and nozzle flow rate. These influences can be observed on the variations of the CV in the experimental results when it stays constant in static computations. Nevertheless, the position of the over-sprayed areas in dynamic conditions is globally the same as in static conditions and the correlation coefficients are near to one. Then, it can be hypothesised than static measurements on patternators are able

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to provide enough information to predict ground spray unevenness due to nozzle overlap according to boom height and nozzle type.

4.3. *Rotational movements*

Yaw movements are characterised by longitudinal variations of the nozzle speed and roll movements, by vertical modifications of the nozzle position. During roll movements, the nozzle height is modified. As the losses increase with boom height, the volumes are under-estimated for the higher nozzles and over-estimated for the lower ones. Then, when the height of the boom is varying, the method does not allow to quantify with accuracy the amount of sprayed liquid but it depicts correctly the zones of unevenness.

Dispersion of volumes is more important for yaw than for roll movements. This observation is important for boom manufacturers for the design of boom suspensions.

Over-sprayed areas correctly tally with yaw movements of the boom. Then, a static geometric model that would allocate volumes on small ground areas should correctly represent the influence of yaw movements on the distribution. However, such static approach would not be convenient to account for non-linear dynamic phenomena.

5. Conclusion

The methodology developed in this study allowed to observe the influence of boom movements on the ground distribution. The use of a conveyor combined with image analysis method provided quick and acceptable results. It was observed that the weighting step of the calibration procedure could introduce some errors: this point should be checked with another method such as colorimetry. Nevertheless, the estimated errors are not important enough to affect the observed global tendencies.

The spray tests were realised with a small boom bearing height nozzles spaced by 0.5 m. Uniform translations and rotational movements were established with a conveyor and a shaking platform. The obtained results correctly explain the different phenomena affecting ground spray distribution evenness. The main effects of the uncoupled movements (roll and yaw) can be simulated with a geometric approach even if this does not provide information about drift or other dynamic effects. Testing the influence of the boom behaviour on the distribution can then be made through the use of appropriate mechanical excitation of the boom, measurement of boom displacements and simulation of the distribution with such model.

The obtained results are useful to boom and nozzle manufacturers, pesticide firms or pesticide users, all associated with spraying operations.

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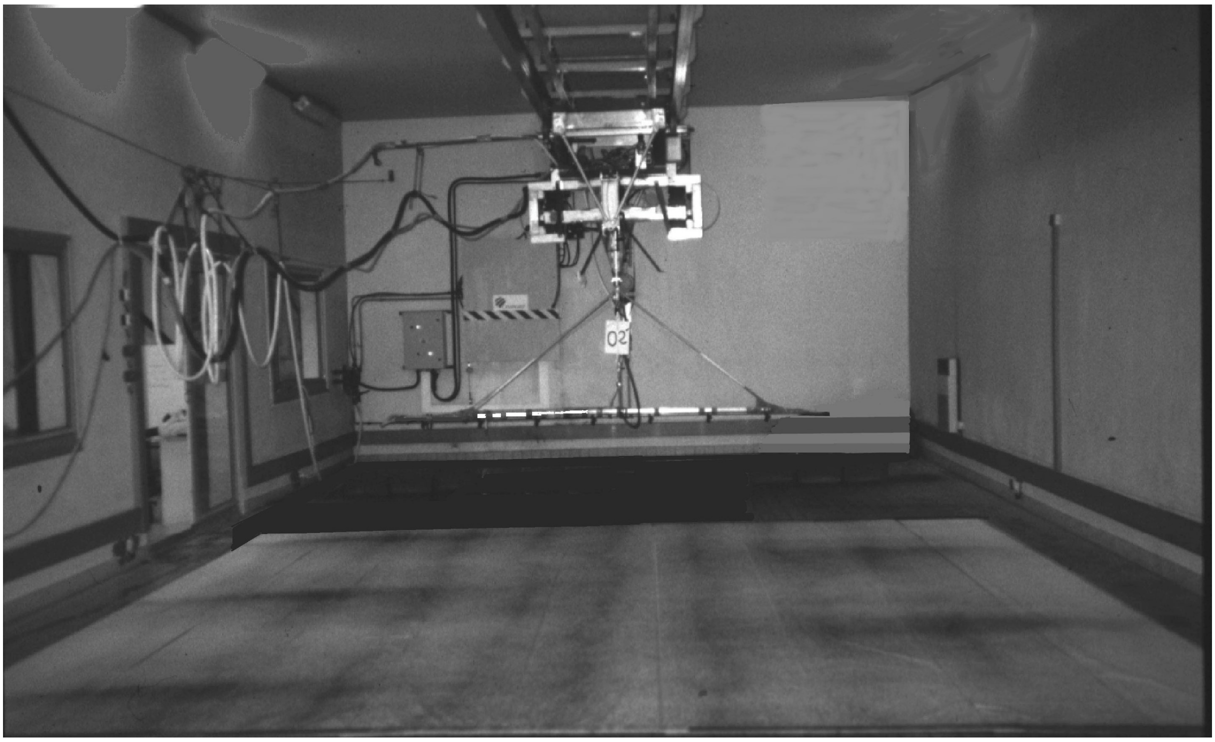

Fig. 1. Laboratory tests (Nigrosin sprayed on pre-pasted wallpaper)

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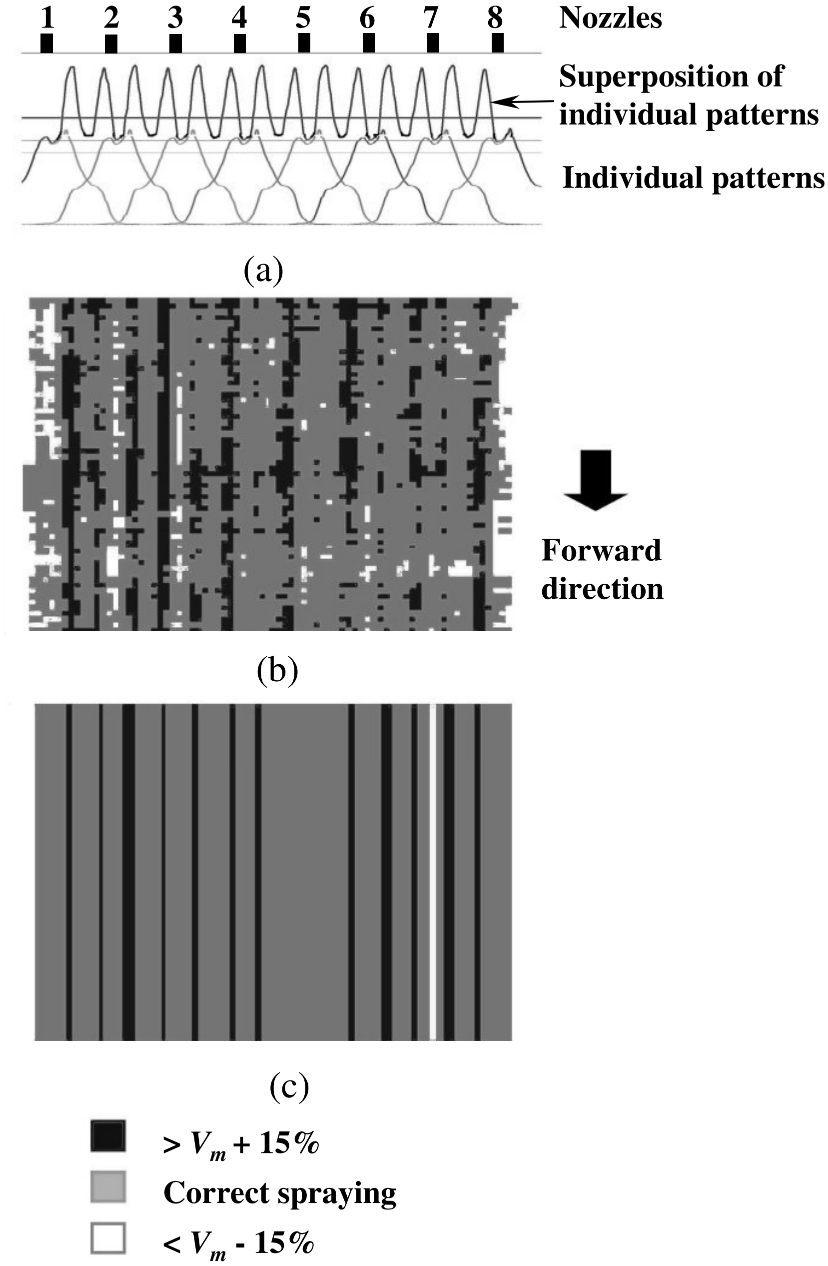

Fig. 2. Comparison between (a) individual nozzle pattern superposition, (b) dynamic and (c) static distributions (Teejet XR 110 02VS, nozzle height of 0.3m, nozzle angle of 10°) ; V_m, mean volume

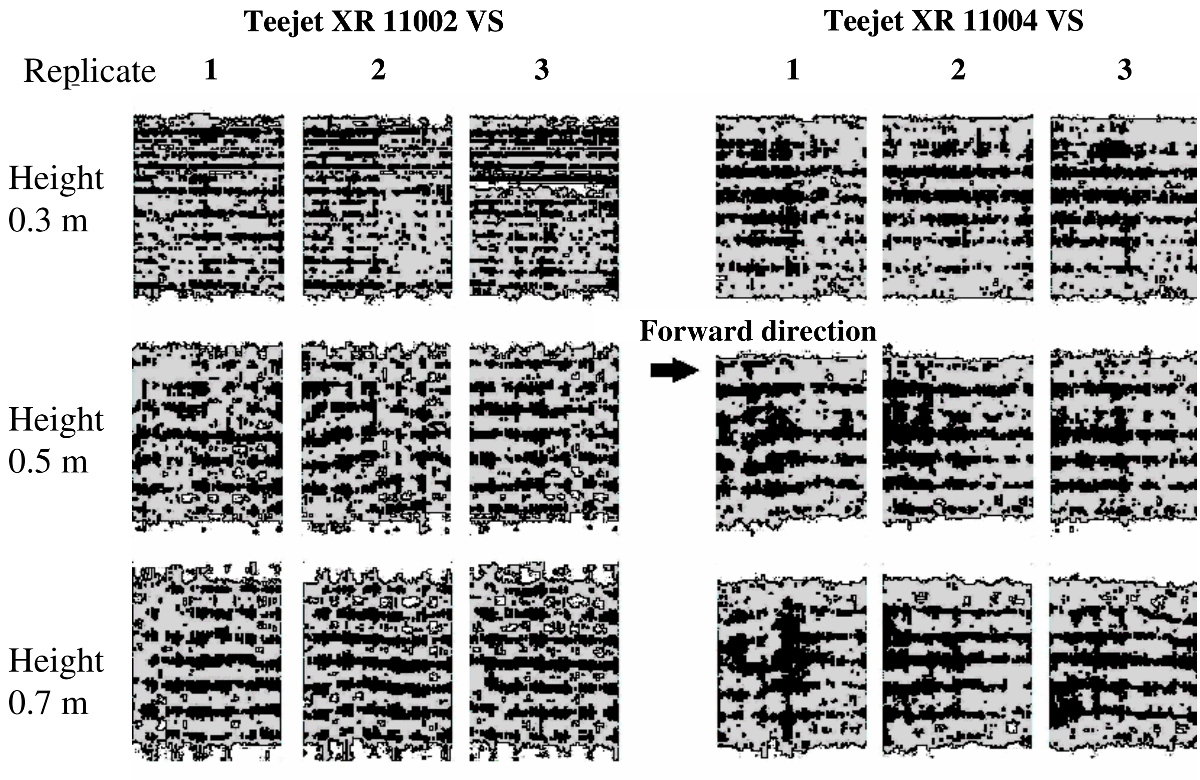

Fig. 3. Dynamic distributions at travel speed of 6 km/h, pressure of 2 bar, nozzle angle of 10°): black, dose higher than mean volume + 15%; white, dose lower than mean volume -15%; grey, correct dose (higher than mean volume -15% and lower than mean volume +15%)

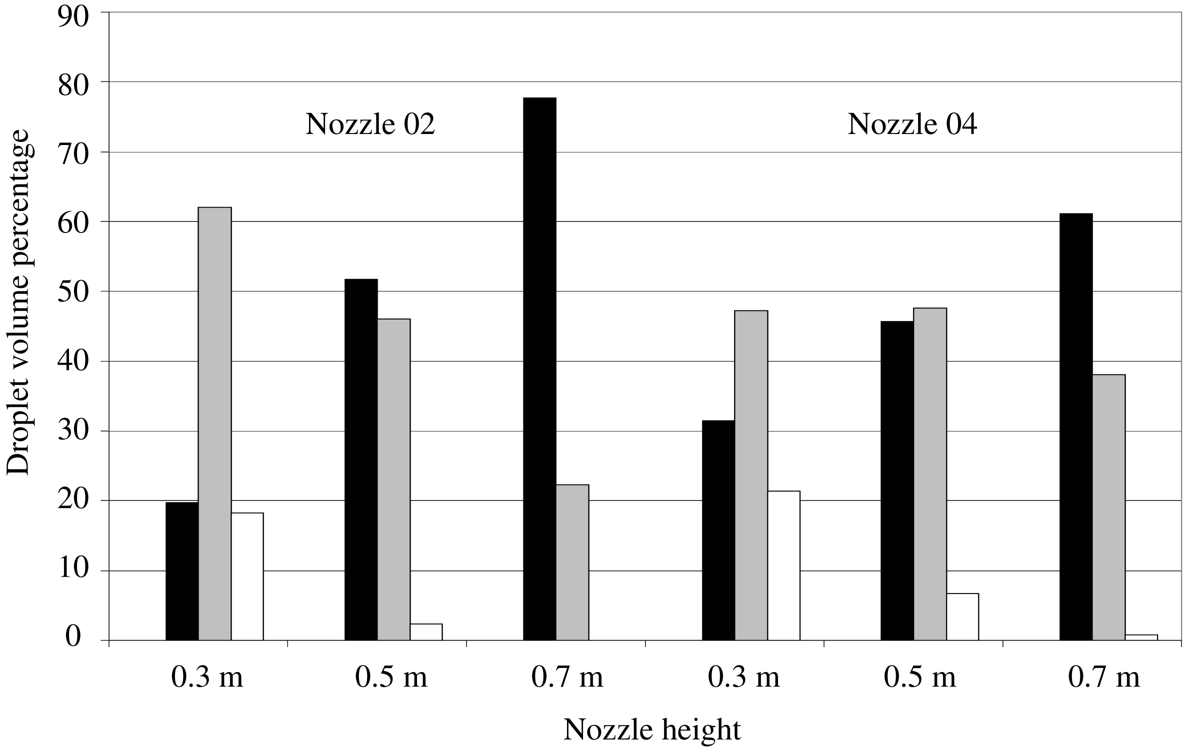

Fig. 4. Droplet speed at different heights: black, 0-5 m/s; grey, 5-10 m/s; white, 10-15 m/s

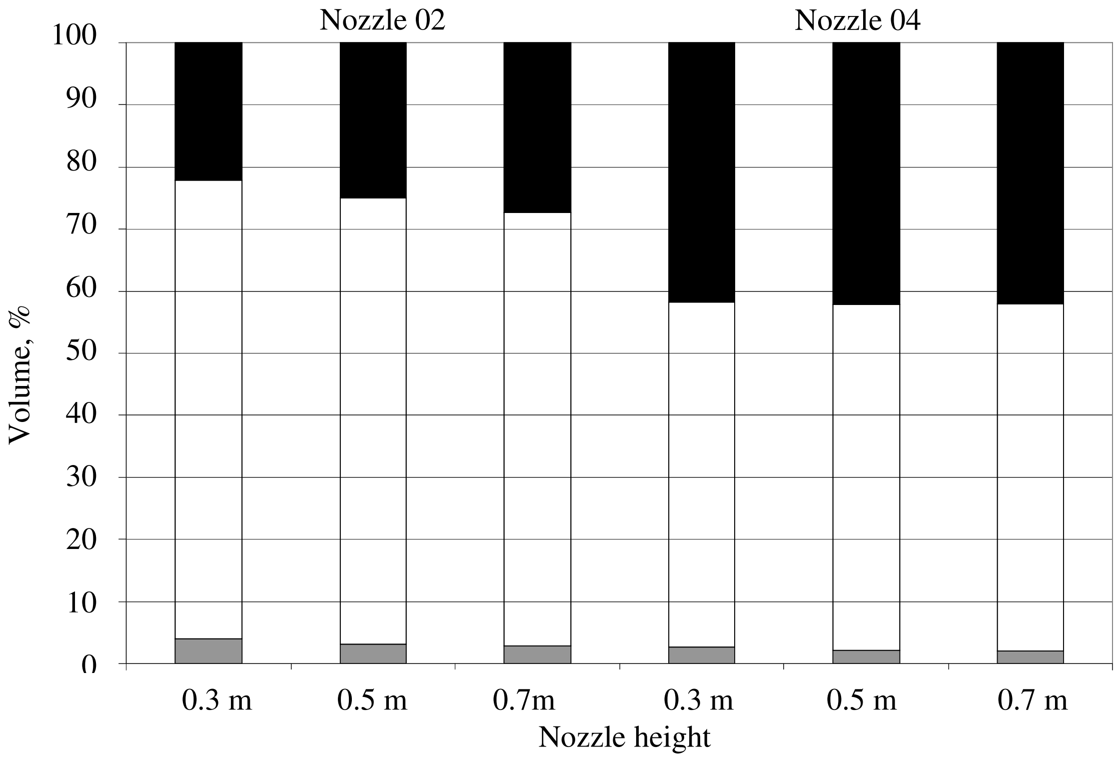

Fig. 5. Granulometry of the nozzles at several heights: grey, 0-150 µm; white, 150-400 µm; black, >400 µm

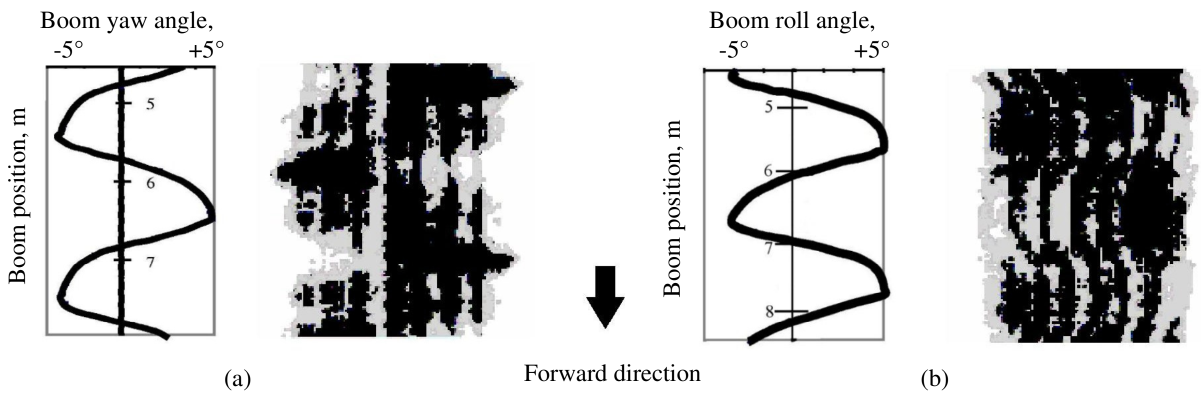

Fig. 6. Effect of (a) yaw and (b) roll movements on spray distribution: grey level scale, black is maximum volume; XR04 nozzle, movement frequency of 0.77 Hz, boom height of 0.5 m, speed of 6 km/h, nozzle angle of 10°