Improved Uniformity of Spray Deposition in a Dense Plant Canopy: Methods and Equipment

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The global trend to shift from highly toxic pesticides to environmentally safe and less toxic chemicals requires, generally, very high spatial uniformity of the spray deposition. Effective penetration of the spray into a dense canopy can be achieved by utilizing fast air-streams. In contrast, slow and turbulent flow near the leaves and the stems is required for good deposition of the spray. A new sprayer was designed to achieve a sharp decline in air velocity to meet the two – seemingly contradictory – constraints, and thereby obtain effective penetration and coverage of dense canopy. In the present work, air ducts with several shapes of air outlets were developed and tested in an attmept to meet these requirements. Generally, a short and wide air slit created a moderate decline in air velocity; a longer and narrower air slit improved the uniformity of the air velocity along the slit outlet, and brought about a sharper decline in speed of the air-streams. Installing air deflectors at the air outlets added a slight upward motion to the air-streams and enhanced spray deposition on the underside of leaves. Preliminary field tests with the long and narrow air slit showed uniform spray deposition on all plant parts.
KEY WORDS: Drop-tube; sprayer; dense canopy; leaf-underside; air characteristics; spray deposit; pesticide application.

INTRODUCTION

Contact action of a pesticide on insects and mites depends, to a large extent, on the pest's behavior, *i.e.*, its mobility and 'pick-up' characteristics (8). A mobile pest has a higher probability of coming into contact with a given quantity of deposited pesticide than does a stationary one. There are cases where a cover density of only three or four droplets per cm^2 is adequate for control of some leaf-consuming larvae, but as many as 100 droplets are required for sucking insects, or even 300 droplets for sessile armored scales. The distribution of the pesticide on the plant host is also of special importance, since the shading effect of the leaves and other plant parts may provide shelter for certain pests (5).

Modern agriculture calls for reduction in both the dosage applied and the toxicity of the pesticide. Therefore, less toxic and more 'environmentally safe' pesticides are favored. Their use requires uniform coverage and high cover density of all parts of the foliage, to achieve direct contact of the pesticide residue with the pest (5). The use of air-streams for transport and penetration of spray droplets into plant canopies can improve the efficiency and uniformity of spray deposition and facilitate the use of much lower volumes (5,8). In

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the optimal case, the discharged material would reach the desired target, thereby avoiding the release of any spray material into the surroundings.

Agricultural spray systems operate in an adverse environment, with complex and variable target geometry (1-4; 12). The development of an 'ideal' spraying system, with minimal use of chemicals and optimal deposit for all of the existing canopies, is therefore very complicated.

Pesticide application in arable agriculture is generally done by boom sprayers. Since farmers apply pesticides on a large scale in cotton fields, the present work was focused on improving deposition of spray in the cotton crop-canopy.

Preliminary experiments to apply detergents and oil-based compounds at 70–200 *l*/ha (such as LQ-215, Zohar-Dalia, Israel) showed that efficient control of whitefly was achieved only when more than 80% of the plant surface area was covered with 200 drops/cm^2 or more (6). Such a level of area coverage was not attainable by the commercially available sprayers (air sleeve and hydraulic boom) that were tested.

Boom-sprayers are the most common method of applying pesticides to field crops in the more developed agricultural regions of the world (11). Sprayers with drop-legs to place nozzles within the crop canopy can be of help in achieving improved deposition in dense canopies (5,11). The nozzles may by positioned to release the spray and direct it through the foliage to the underside of the leaves or, preferably, utilize an air-stream carrier to deliver the droplets to the plant parts (8,11). Moving in the canopy may involve the use of protective shields, inhibiting direct contact of the nozzle with the canopy (8).

Prototype sprayers utilizing pulsed-air-streams to carry the droplets were tested in a tomato greenhouse and in cotton fields (13). The pulsed-air technology, developed for tomato pollination, achieved good coverage of both sides of the leaf due to the alternation of air velocity in an upward and a downward direction (7,9). The sprayers were operating as drop-tube sprayers, with the air outlets located between the rows. Use of these sprayers resulted in leaf coverage (200 droplets/cm^2 or more) of more than 80% on both sides of the lower leaves of the plant and of close to 100% on the higher leaves. However, high energy consumption (at least 4 HP was required for creating the air-streams needed per cotton row) and the large number of moving parts represented obstacles to the commercial application of this sprayer.

Low-volume sprayers with an air-sleeve boom sprayer, achieved leaf coverage of approximately 30% when operated in the same field (6).

A droplet will be deposited on the target only if an approaching motion exists prior to the contact, *i.e.*, if it has a velocity component aiming at the surface. In an air-assisted spray deposition, the air velocity should have the component aiming at the desired surface. If the surface is facing down – which is the usual situation in regard to the lower sides of leaves – despite partial moving by the air-stream, the air velocity should have an upward component. The contribution of the upward and downward air velocity components in the above mentioned pulsed-air-stream sprayer has yet to be investigated.

To meet the requirements for uniform deposition and to overcome the deficiencies of the previous prototypes, the present work was aimed at developing a sprayer for uniform spray deposition on all plant parts, even when the canopy is very dense. To enable a large span, the specific objective of the design was to develop an energy-efficient and reliable drop-tube with an air outlet that operates close to and under the canopy of a dense crop such as cotton.

MATERIALS AND METHODS

In the development of the prototype sprayer, the first laboratory stage comprised tests of various configurations of air slit-outlets. Subsequently, those configurations that gave the best results in the laboratory were tested in the field. The laboratory stage was also divided into two phases: measurements of air velocity, followed by tests of spray deposition.

General

Three versions of drop-tubes were designed and tested: (*a*) short slits with pulsed air-streams, released at a rate of 1200 air pulses per minute through alternating 20 x 100 mm openings (9); (*b*) a short slit with an 8 x 220 mm opening and steady air-streams; and (*c*) a long slit, 8 x 1400 mm, with or without deflectors (Israel patent pending no. 112599). Each of these versions had a few variations, which will be referred to along with the relevant results (Table 1).

An air blower with a variable speed and maximum air flow of 300 m^3/h and an air velocity of 70 m/s at 6000 rpm, was used for testing the short slits in the laboratory. Another air blower, with variable speed but a maximal air flow of 2500 m^3/h and an air velocity of 40 m/s at 2300 rpm, was used for all the other tests.

Air velocity

A pitot tube was mounted to an arm of a coordinate table in order to measure the air velocity at each spatial point in front of the tested drop-tube.

Air direction and spraying system

Optimal location of the nozzle: A coordinate table for the short slit and a modified coordinate table for the long one, were used for positioning the nozzles in front of the air slit, to define its optimal location and angles in order to achieve a wide and even distribution pattern of the sprayed droplets in the air stream. The hydraulic spray nozzle used in all experiments was Conejet x3 (Spraying Systems, Wheaton, IL, USA) operated at 2 bars (200 kPa). Tests were repeated five times for each type of air outlet.

Spray direction: A moving cart, simulating the forward speed of a field sprayer ($\sim$1.5 m/sec) was used to catch the emitted spray cloud on a narrow (1-cm-wide) target. Water-sensitive papers (WSP, Ciba-Geigy, Basle, Switzerland, for droplets $\geq$50 μm) were mounted on a wooden pole to form a 1.5-m-high and 1-cm-wide sampling rod, which was advanced across the sprayer. The pole was mounted on an electric cart moving at a predetermined speed to ensure control of the crossing speed and quantity of the applied spray. The resulting cover density of the deposited droplets was measured by direct counting.

Field tests

In the field tests, the pulsed air-stream sprayer was compared wtih models IV and V (shown in Table 1) and later model V was compared with (*a*) an over-the-canopy boom sprayer assisted by an air curtain (air-sleeve sprayer, Dagan, Deganya Sprayers, Deganya Bet, Israel); and (*b*) an over-the-top hydraulic boom sprayer. All the sprayers in this experiment worked at rates of 200 or 500 *l*/ha.

TABLE 1. Triangular air drop-tube: cross-section of the models, and the outlet air-jet angles.

The various drop-tubes tested were mounted on a horizontal boom, so that two cotton rows were treated simultaneously. The distance between the centers of the two rows was 97 cm. The tests were performed in a cotton field (approximate height 110–120 cm, LAI 6), 15–19 weeks after germination. A spray suspension with 1% fluorescent tracer (Saturn Yellow, Swada Ltd., Stratford, UK), at 200 *l*/ha or 500 *l*/ha, was used to monitor visually the covered area (the proportion of the area covered with droplets at a predetermined cover density) and the cover density (no. of droplets/cm^2), which was analyzed under ultraviolet light (5). Coalescing of drops to form a film was determined as runoff.

RESULTS AND DISCUSSION

Design characteristics

Farmers' efforts to shift to safe and less toxic materials, *e.g.* repellents, demands a higher deposit of the material for pest control. The pulsed-air-streams prototype tested in the past released air-streams at a rate of 1200 pulses per minute, provided good penetration into the cotton canopy and, as reported earlier, uniform spray deposition (6,13). This prototype was energy-inefficient and, due to the large number of valves (7,9) – 36 on a sprayer for six rows – created operational problems.

The new design assumed that while high velocity air-streams are required to deflect the leaves away from the nozzles, prevent runoff and improve the penetration into the canopy, a rapid drop to low velocity inside the canopy is desired to facilitate the settling of drops on leaves and stems (6).

Fig. 1. The laboratory device for measuring the air-streams released by the short slit – a schematic view and the axis directions. (The left edge of the slit is assigned the 0 point in Figure 3.)

A short triangular body, with a narrow slit (22 cm long x 0.8 cm wide, with a 1-cm-wide support at the center of the long side) and no moving parts (Fig. 1) was designed and tested in the laboratory. The field tests were conducted with a box-shaped (18 x 18 x 120 cm) drop-tube, with three slits which were located one above the other along the tube. Thus, the slits were facing the cotton row from each side. The droplet shearing was achieved, as previously, by hydraulic pressure nozzles. Six nozzles were mounted on each side of the drop-tube (one at each end of each slit). The nozzle location was selected to provide optimal deposition uniformity in accordance with the laboratory findings. Foliage deflectors at each side of the drop-tube assured free operation of the nozzles, resulting in a relatively large total width (*ca* 40 cm). When spray application is required for mature cotton plants, a wide drop-tube causes severe damage and therefore a narrow cross-section is required.

The improved design utilized the tube body for the purpose of deflecting the foliage, as shown in Figure 2a. The nozzles' location behind the tube enabled the total width of the system to be reduced considerably. The cross-section was narrowed toward the front, resulting in a triangular shape, to open up a path between the cotton rows. An upward-air-velocity component was added by mounting deflectors (Table 1 and Fig. 2b), to improve spray deposition at hidden sites such as leaf sides which are facing the ground (underside of the leaf).

As shown in Figure 2, the air enters the tube at the wide end. This side is mounted to the main air channel of the sprayer. The narrow end is closed, and kept a few centimeters

Fig. 2. A drop-tube with a triangular cross-section and the air-streams directions: (*a*) General view and a cross-section in the A-A plane. (*b*) Nozzle location in relation to the air outlets in the A-A plane of model V, and the air flow directions as affected by the deflectors installed in this model, shown in the B-B view.

above the ground when the sprayer is operating. The nozzles' location in relation to the air outlet is of great importance and was determined experimentally (see below). This mounting ensures a gap between the nozzles and the canopy, to enable complete opening of the hollow cone.

Laboratory results

The laboratory tests of spray deposition determined the optimal parameters of the outgoing air-streams and the optimal position of the spray nozzles. The laboratory simulator was used to catch the emitted spray cloud on a narrow target, avoiding possible interference of the impaction by air turbulence (8). Air velocity measurements concentrated at finding an air outlet with uniform air-streams along it, as well as one with a sharper velocity-drop with distance from the outlet. The air speed profiles and directions of the air-streams released by the various drop-tubes were measured. Typical results for the short-slit version are shown in Figure 3. The air velocities along the outlet are generally uniform and decrease from 75 to 5 m/s within a distance of 0.5 m. Figure 4 shows that the air velocities along a drop-tube with three consecutive short slits provide gaps and a non-uniform air profile along the tube. This might cause uneven distribution, due to the effect of air velocity on collection efficiency (8). This phenomenon can also be the reason for the relatively high rate of runoff that was recorded in a preliminary field test at 200 *l*/ha (6). However, the long-slit version, either with or without deflectors, provides a relatively uniform air velocity profile along the outlet.

Fig. 3. Air-streams profiles of the short slit device as measured along the outlet at various distances from the slit. The left edge of the slit is the 0 point of the distance along the outlet. −20 indicates a measurement point located 20 mm before the slit. 230 indicates a measurement point located 10 mm beyond the right end of the slit. The mid-point reduction indicates interference of the central support.

Table 1 shows schematic cross-sections of selected long-slit models (shown above, Figure 2). Considerable change in the departure angle of the air-streams is observed for variation in the cross-section and air outlet geometry. The first and simplest model comprised a clear passage within the tube and a flat cover at the rear side of the tube. The air-stream was released at an angle of 109° from the travel direction and 26° downward. A curvature inward or outward on the rear cover reduced or increased, respectively, the angle of the air stream to the travel direction (models II and III). Construction of a slotted partition as shown for model IV did not change the stream direction considerably. However, the partition enabled construction of air deflectors at the outlet, as shown in model V, and caused an upward component for the air velocity.

Fig. 4. Air velocities along the outlet of a short slit and long slits with and without deflectors.

Inclination of the tube by rotating the whole tube backward, caused an additional increase in the upward component of the air velocity. It also reduced the plant damage, by enabling the branches to slide along the tube. The angles shown in Table 1 are an average of the angles measured at various locations along the tube.

Field test results

Operation of the new drop-tube sprayer (model V, Table 1) in 16–19-week-old cotton, showed that the triangular-shaped drop-tubes could move inside a fairly dense canopy with no noticeable damage to the plants. Detailed measurements of such damage – if any – should be conducted in the future during every stage of crop growth. The nozzles were protected by the wide side of the drop-tube so there was no nozzle damage.

The deposition of fluorescent tracer on cotton plants for the various sprayers described above was very high, as shown by the number of fluorescent stains per area (Fig. 5). The covered area (with 200 droplets/cm^2 or more) of leaves at various plant heights for the pulsed-air-stream and the slit versions with deflectors was similar. The uniformity of coverage for drop-tubes with slits without deflectors was slightly lower on the underside of the leaves. The observed runoff caused by the pulsed-air-stream sprayer was very high on all parts of the plant (50–90%). This indicates uneven distribution of the deposit, and ineffective prevention of leaves from touching the nozzle. Runoff is considered a reduction in efficacy of the spray process. It causes waste of material, and may result in leaf burns and soil pollution (5).

The upward air-streams of the slit version produced good coverage of the underside of leaves. The dense and even coverage on the leaf (500–700 droplets/cm^2) indicates slow air-streams near the target and good conditions for deposition (with runoff of less than 10%). The applied volume in this experiment was 500 *l*/ha.

Fig. 5. Covered area on the upper (U) and lower (L) surface of leaves located at the top (T), middle (M) and bottom (B) of the plant, as found in field tests of drop-tube sprayers with pulsed-air-streams and long slits, with and without deflectors.

Fig. 6. Covered area on the upper (U) and lower (L) surface of leaves located at the top (T), middle (M) and bottom (B) of the plant, as found in field tests of a long-slits drop-tube with deflectors, a hydraulic boom sprayer and a vertical air-sleeve sprayer.

The air-sleeve sprayer, the regular hydraulic boom sprayer and the drop-tube sprayer with a long slit and deflectors, were tested under the same field conditions. The forward speed of the air-sleeve and the hydraulic boom sprayers was reduced to apply volumes of 200 *l*/ha, as applied by the drop-tube sprayer at a higher speed. The air energy for these sprayers was 10×10^6, 0 and 6×10^6 joule/ha, respectively. Despite the fact that the reduced speed improved the cover density, the two control sprayers gave poorer results (Fig. 6). The control sprayers exhibited the well known distribution of spray deposition, with poor coverage of the lower leaves and almost no coverage of leaf undersides, even in the upper leaves (5). Although Figure 6 confirms that the air-sleeve sprayer gave a slight improvement over a boom sprayer, the drop-tube sprayer gave much better coverage on all parts of the plant. The cover density for the drop-tube sprayer ranged from 540–560 droplets/cm^2 at the top of the plant to 430–450 droplets/cm^2 near the ground, for both sides of the leaf. Values for the air-sleeve sprayer and for the regular spray boom were 248 and 328 droplets/cm^2 and 103 and 38 droplets/cm^2, respectively, for the upperside of the leaves at the top of the plant and of the leaf near the ground. The respective values for the underside of these leaves were 63 and 55 droplets/cm^2 (at the top) and 15 and 0 droplets/cm^2 (near the ground). The runoff values were 16%, 13% and 1% for the air-sleeve, hydraulic boom and drop-tube sprayers, respectively. The very low runoff can be related to the good protection of the nozzles from the canopy, achieved by locating them behind the drop-tube. The difference in performance of the drop-tubes (Figs. 5 and 6) is related to the higher spray volumes in Figure 6.

It may be concluded that drop-tube sprayers with long and narrow slits, and an upward air velocity, provide even deposition and dense coverage of all parts of the cotton plant. The questions of whether the uniform deposition achieved by this sprayer is more efficacious also in the application of less toxic materials, and if the uniform deposition enables dosage reduction for routinely used materials, are presently under investigation.

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