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# A New Technique for Safe Pesticide Spraying in Greenhouses

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## 1. Introduction

Protection from parasites is an important factor in agricultural operations, and calls for continual monitoring and prompt action when needed. In many cases, the equipment, pesticides and manpower required for this purpose account for the majority of production expenses.

Though the use of chemicals has had a major influence on the development of agriculture in the twentieth century, bringing significant benefits, it has also had many side effects on human health, animals and the environment.

The ease with which these substances can be used, their initial low cost and the lack of knowledge on the part of growers has led to an overuse of pesticides, with dangerous consequences. Only in the last few years have agricultural techniques brought about improvements in the pesticides used (Hewitt, 2000).

There can be no doubt that advances in this field have provided a more effective range of choices, for growers and the environment in particular.

Parasites must thus be combated by producing a climate that is unfavourable for them, as well as by using a forceful, accurate and incisive spray technique.

To reduce pesticides by using more effective treatments, recent studies have investigated different spray techniques capable of reducing the pesticide dose with very low waste and outflow (Austerweil & Grinstein, 1997).

Efficacy of crop spraying depends on two main factors: coverage density and uniformity, and droplet size.

For the first factor, it should be emphasised that droplets should reach leaves without any overlapping.

The second factor is important because many studies have shown that coarse droplets reduce spraying treatment efficacy. In fact, smaller droplets penetrate the canopy better and, transported by air, can reach each part of the crop without dispersion. This is especially true in the greenhouse, where wind is not a problem.

These considerations have spurred interest in the idea of spraying pesticides in a defined volume, i.e., a confined area (Moltò et al, 2001) (Ebert et al, 2003).

The first step in designing an innovative pesticide sprayer is to study various spraying techniques.

In particular, investigating correct pesticide distribution entails considering the environment where the treatment is carried out, the crop growth rate and the characteristics of the chemical product used (Gil & Sinfort, 2005).

Standard atomizers are the most widely used equipment for crop treatments. They are based on three different designs: pneumatic atomizers, mechanical atomizers and mix atomizers (Cerreto & Failla, 2003) (Braekman et al, 2009).

These machines are employed both in the open field and in greenhouses, as they are highly reliable and easy to use, though their disadvantage is that the operator is directly exposed to chemicals. Consequently, the operator is forced to use eye protection, rubber gloves, and filter masks. All of this equipment is essential in order to avoid contact between pesticide and human skin or airways (Methner & Fenske, 1996) (Paul & Illing, 1997) (Nuyttens et al, 2004) (Nuyttens et al, 2009).

Another limitation of these machines consists in the absolute lack of control over the sprayed dose, which can be influenced by the nozzles' height from the ground and their orientation.

In addition, droplet size depends on operating pressure and nozzle type. Though a large number of models offering various levels of performance are available on the market, many growers base their choices more on economic considerations than on any knowledge of the nozzles' actual technical characteristics (Derksen & Sanderson, 1996) (Briand et al, 2002) (Ade et al, 2003).

## 2. Greenhouse spraying requirements

Spraying techniques used by many growers involve a number of significant problems.

Environment conditions in the greenhouse increase the incidence of plant diseases affecting common crops, because of intensive cultivation in an artificial ambient with heavy use of plant food. Consequently, the high value of the crops often grown in greenhouses can justify the use of more expensive protection treatments (Kondo et al, 1996) (Christensen et al, 2008). Moreover, pesticides are used weekly throughout the entire production cycle (Maertens et al, 2005) to prevent aphids, mites and fungi.

In such cases, pesticides are generally atomized by means of mechanical sprayers.

### 2.1 Requirements for the new greenhouse pesticide spraying system

An effective system for treating crops in greenhouses should satisfy the following requirements (Naoki et al, 1995) (Mandow et al, 1996) (Acaccia et al, 1998) (Tian et al, 1999) (Nuyttens et al, 2003) (Singh et al, 2005) (Solanelles et al, 2006) (Piccarolo, 2008).

- **Quantity and quality of spraying control:** the crop must receive the correct dose of pesticide, as excessive doses increase costs and can cause damage to the environment and the crop. Conversely, insufficient doses cannot provide protection against pathogens, especially on the underside of the leaves. Delivering the correct dose is a question of controlling droplet size.
- **Efficient treatment with low pesticide doses:** it is important to avoid excessive pesticide doses, both for the operator and for the environment. This can be achieved by reducing pesticide loss by confining the spray within a defined volume where crops can be treated.
- **Operator safety:** the danger involved in using pesticides is underscored by the fact that operators are required to pass an exam before handling these chemicals. Operator safety could be guaranteed by a higher level of automation in pesticide spraying.

- **Ease of use and reliability:** the sprayer must guarantee that the operator's work can be carried on correctly and without difficulty, avoiding overly complex technical procedures. As such systems are currently required, it is necessary to develop a new device capable of satisfying all of these characteristics.
- **Flexibility:** the crop's volumes, geometries, leaf density, etc., all influence pesticide distribution, as do the grower's specific needs. Accordingly, the new machine must feature a wide range of regulations (nozzle orientation and height from ground, coverage area, etc...) so that it can be adapted to various cultivars.
- **Economy:** using an automatic pneumatic system makes it possible to obtain easy, durable and economical technical solutions. Though the market now provides a wide range of choices, few spraying techniques can satisfy all of these requirements together.

### 3. Design of the new system

Development of a new defined-volume sprayer involved the following stages:

- theoretical and experimental study of very fine pesticide fog generation to cover all parts of the canopy;
- study of a textile cover sheet capable of enclosing the spray area;
- construction of preliminary prototypes;
- design and testing of the system used to move the textile cover sheet;
- final testing in both the laboratory and the greenhouse.

All of these steps will now be analyzed.

### 4. Fog generation

The first step in developing an innovative pesticide spraying technique is an efficient and reliable fog generation system (Ade & Fabbri, 2000). To this end, many nozzle models were tested. All tests used a mixture of water and air, because the viscosity and the surface tension properties of this mix are similar to those of pesticide solutions in water (Singh et al, 2006) (Singh & Kumar, 2007) (Singh, 2007).

#### 4.1 Atomizer nozzles

A pneumatic atomizer nozzle is a small mechanical component capable of generating a fine fog of droplets using a compressed gas. It has two inlet ports, one for gas and the other for liquid, as shown in Figure 1, and an outlet port where the mixture is produced (Teci, 2006). There are many models of atomizer nozzle.

##### a. *Internal mix model*

In this case, compressed air and liquid are mixed inside the component. It is suitable for fine fog generation (Figure 2a).

##### b. *External mix model*

In this model, compressed air and liquid are mixed outside the nozzle chamber (Figure 2b).

##### c. *Jet impact model*

An air stream mixes with the liquid outside the nozzle chamber. Using two nozzles makes it possible to reduce droplet dimensions by the impact of the two jets (Figure 2c).

Each nozzle is then characterized by its spray jet pattern. This pattern is the jet section at a plane orthogonal to the jet axis, in a defined outlet position. There are, generally, conical spray jets (full or hollow cone) and flat fan spray jets. The pattern which is best for the

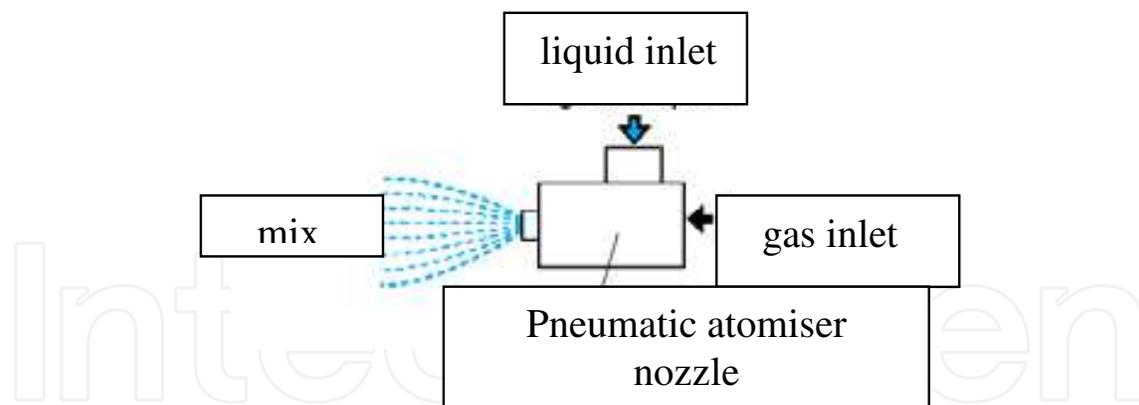


Fig. 1. Functional schematics of an atomizer nozzle

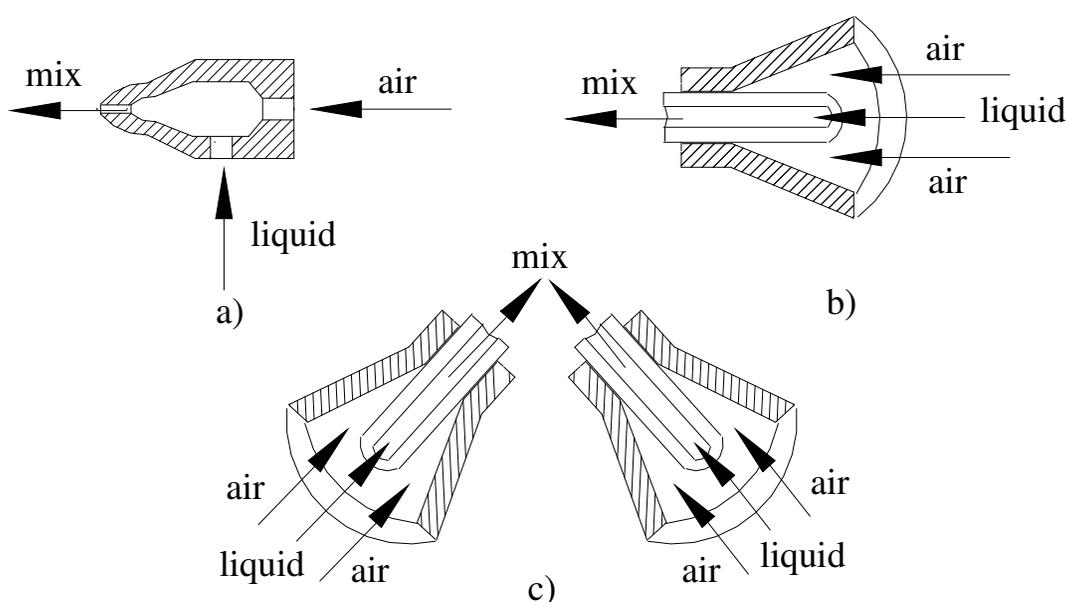


Fig. 2. a) internal mix; b) external mix; c) jet impact mix

specific application can be chosen. The nozzle spray pattern changes significantly with the distance between the target surface and the nozzle: increasing this distance also increases spray pattern diameter. In general, full cone jets have a smaller aperture angle than hollow cone jets. Atomizer nozzles are then classified by the operating pressure used for both air and water. Nozzle selection is also a question of droplet size, which is not an easy parameter to measure.

The basic thing is, obviously, to use the same method to compare droplets from different nozzles (Bouse, 1994) (Paice et al, 1995) (Nuyttens et al, 2007).

Droplets can be classified in three size groups. Droplets less than 10  $\mu\text{m}$  in diameter generate what is called “dry fog”, droplets whose diameter is between 10 and 100  $\mu\text{m}$  form “fine fog”, while diameters between 100 and 300  $\mu\text{m}$  form “semi-fine fog” .

In this investigation, several full cone nozzles were tested, finally choosing the nozzle shown in Figure 3. This internal mix model was assembled together with another nozzle to obtain a jet impact mix (Figure 4) generating very fine fog (less than 50  $\mu\text{m}$ ).

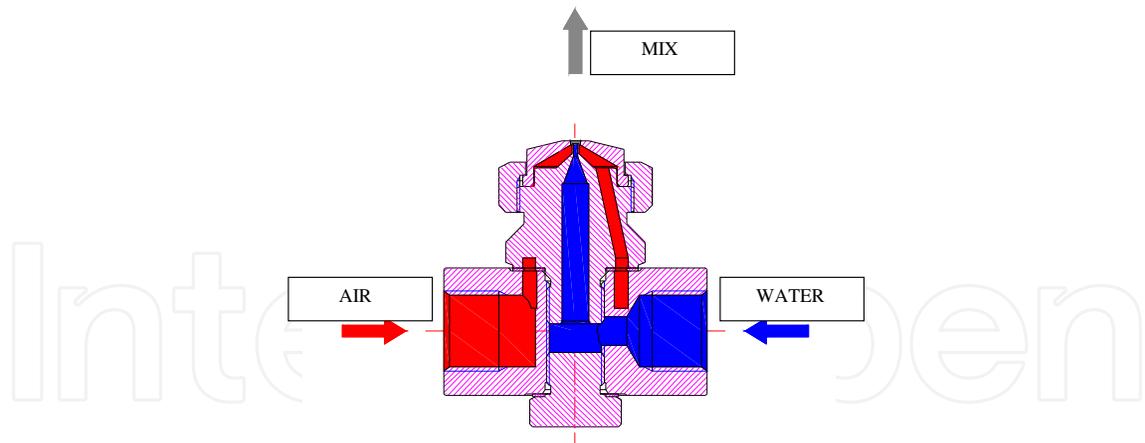


Fig. 3. Selected atomizer nozzle section



Fig. 4. Spraying technique with jet impact method

#### 4.2 Experimental tests on nozzles

On the basis of a method developed at the Politecnico di Torino Department of Mechanics to measure atomized oil droplets in pneumatic circuits (Belforte et al, 1996), a special test-bench was designed for measuring nozzle droplet diameters. The method entails projecting a water-air spray against water-sensitive cards (Salvarani, 2006). They have a coated, yellow surface that is stained blue through a chemical reaction when contacted by water droplets or moisture. The cards are attached to a fixed wall, while a perforated moveable plate is placed between the wall and the nozzle in order to regulate spraying time and the surface exposed to the spray. The exposed cards are then examined under a fiberoptic microscope at x200 magnification. To improve analysis, enlarged specimens were also analyzed using imaging software (Cruvinel et al, 1996) (Kashden et al, 2006) (Qing et al, 2006).

The test bench is shown in Figure 5. It consists of a metal frame supporting the nozzles and a receiving screen to which the cards to be exposed to the spray are attached.

A rodless pneumatic cylinder moves the interrupter plate with a central hole measuring 120-40-26 mm in diameter which cuts the spray jet and establishes the time period for which the cards are exposed to the spray.

Tests were carried out with different types of nozzle, projecting droplets both horizontally and vertically. In this case, spraying conditions are adversely affected by gravity, because the highest droplets reach all of the leaves.

Cards were analyzed to construct graphs as shown in Figure 6, which refer to two nozzles assembled as in Figure 4. This graph shows percentage droplet dimensions in five consecutive tests: as can be seen, most of the droplets are less 50  $\mu\text{m}$  in diameter, with a supply pressure of  $1.6 \cdot 10^5$  Pa for air and  $0.5 \cdot 10^5$  Pa for water.

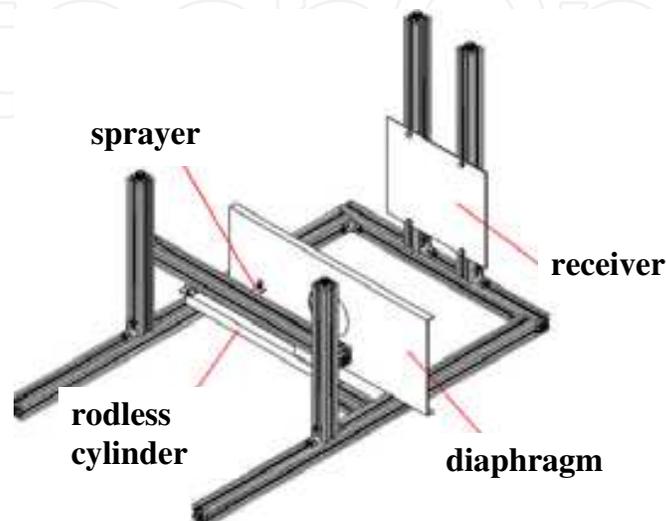


Fig. 5. Test-bench for experimental nozzle validation

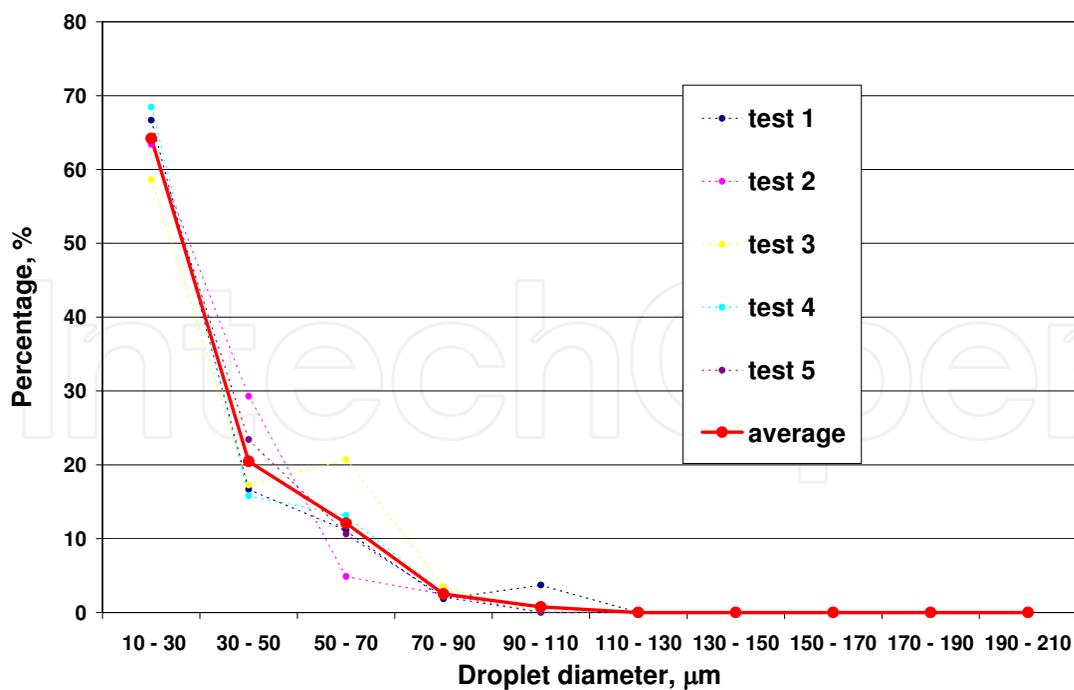


Fig. 6. Percentage dimensions of droplets

A Pitot tube was connected parallel to and in front of the spray jet (x axis) to measure spray profile and droplet velocity close to the leaf (Figure 7) (Belforte et al, 2009).

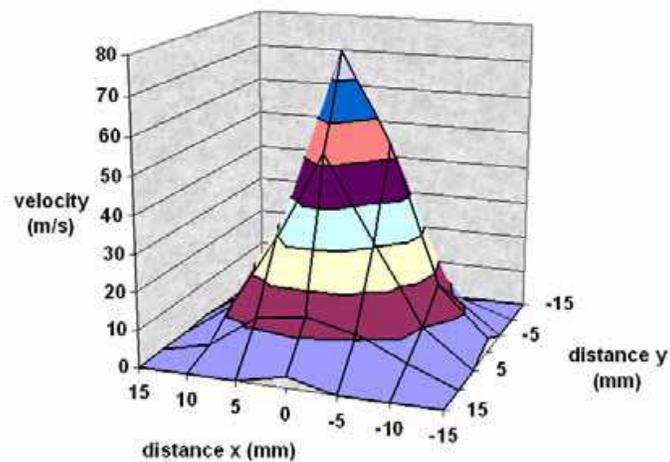


Fig. 7. Pitot tube results

#### 4.3 Numerical simulation of leaf spraying

To assess the efficacy of spraying crops with these nozzle configurations, a numerical simulation was conducted to investigate droplet trajectories close to the leaves, in the presence of gravity (Lebeau, 2004).

In addition, an axially symmetric scale model was constructed which reproduces the nozzle, a leaf and the confined volume around it which represents the chamber where spraying takes place. In this model the leaf is simulated by a rigid 20 mm radius disk placed facing the spray jet at a distance of 280 mm from the nozzle outlet port.

Simulation was carried out by establishing the mass flowrates and the supply pressures measured experimentally at the nozzle input port, viz., 0.00018 kg/ s and  $1.6 \times 10^5$  Pa for air, 0.00066 kg/ s and  $0.5 \times 10^5$  Pa for water, temperature 300 K, steady-state flow.

In particular, simulation used a bi-phasic air-water mixture as the operating fluid to provide a better approximation of the experimental results. Droplet velocities near nozzle and leaf are shown in Figure 8.

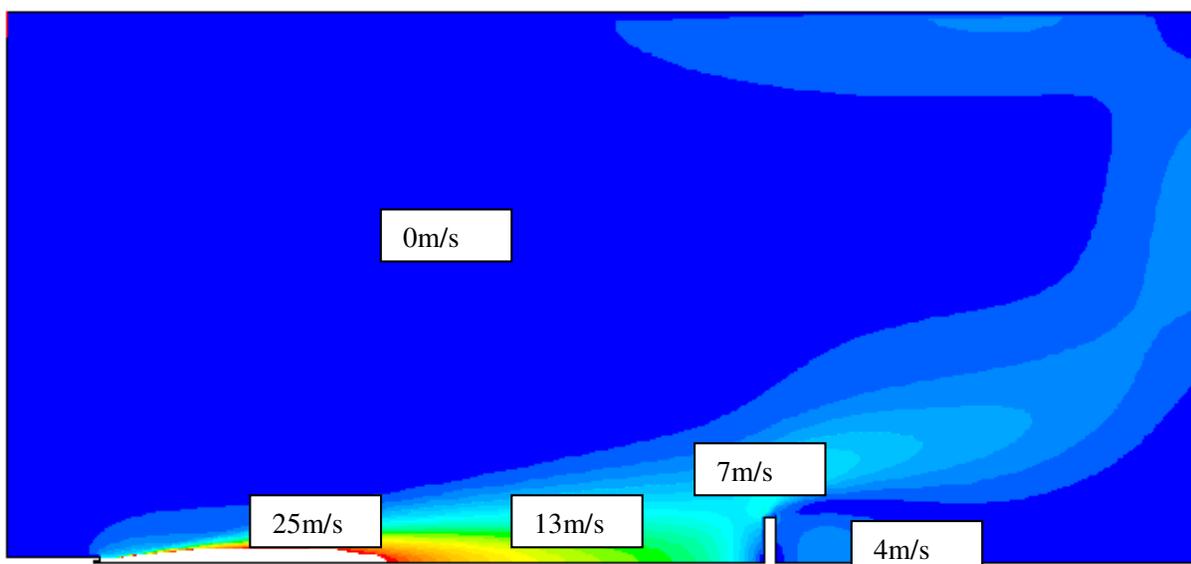


Fig. 8. Droplet velocities near leaf, with a bi-phasic air-water mixture

#### 4.4 Experimental tests with various crops

Experimental spraying tests were carried out to assess droplet rebound and the resulting pesticide deposition on the top surface and underside of the leaf.

The test bench used for this purpose is shown in Figure 9. It consists of a rigid chamber of defined volume in which both nozzles and leaves to be sprayed are placed.

Initially, one leaf suspended from a small bar parallel to the ground was placed in the chamber and exposed to spray. The spray contained a yellow UV phosphorescent dye.

After treatment, the leaf was viewed under a UV lamp, where areas covered by the spray appear yellow and those that remain uncovered appear violet.

Surfaces were photographed using a digital camera to compare different crops in various test conditions.

Test parameters included crop type, type of ground surface, distance between leaf and ground, exposure time, and spray jet orientation. Tests were carried on using the following three types of leaf: flat, oily leaf (Cyclamen); smooth, irregularly shaped leaf (Pelargonium domesticum – geranium); flat, velvety leaf (Saintpaulia jonatha – African violet).

Crops were chosen on the basis of observations of the leaf surface.

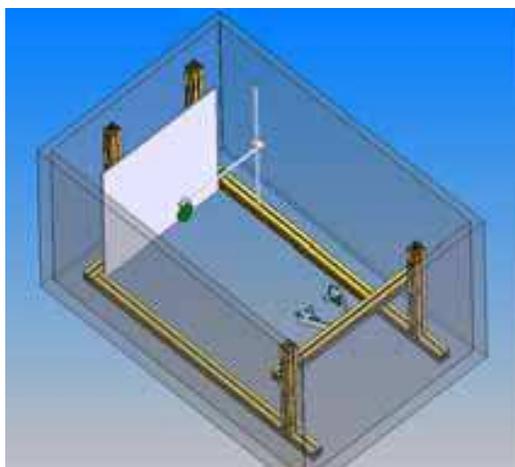


Fig. 9. Test bench for experimental tests on various crops

#### 4.5 Test parameters and results

As the type of material used to cover the greenhouse benches on which potted plants are generally placed can influence droplet rebound towards the leaves, four types of surface in common use were considered, viz., stainless steel, linoleum, kraft paper and clay.

The distance between leaf and rebound surface was then varied, with all other parameters remaining constant.

This was done in order to simulate actual exposure conditions, as plants may stand at various distances between nozzles and ground. Tests were carried out at distances of  $h = 120-180-240$  mm.

As an excessive dose of pesticide can damage leaves (causing spots and drying), it is necessary to stop spraying at the right time, before pooling and dripping take place. Spraying times used during test were approximately 5 and 10 s.

Test were carried out both horizontally and vertically. The test bench is shown in Figure 9.

Experimental results show that:

- the optimal distance between plant and ground is influenced by plant type, by exposure time and by the ground material;

- the underside of the leaf is difficult to reach unless vortexes around the leaf can be taken advantage of;
- droplets rebounding off the ground surface can reach the underside of the leaf more readily.

Figure 10 illustrates the results obtained with horizontal spray on various kinds of plant. Whether or not leaves are wrinkled affects spray coverage, while droplet rebound is affected by the type of ground surface.

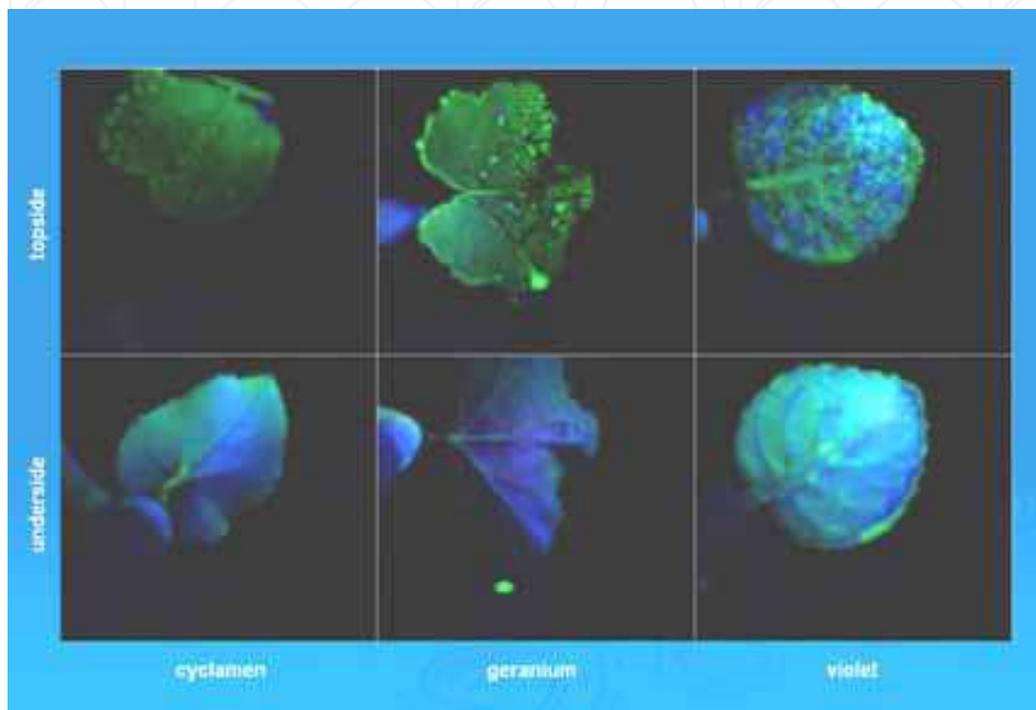


Fig. 10. Spraying tests on various plants

## 5. Defined volume

To spray pesticide in a confined area (Panneton et al, 2000) (Planas et al, 2002), a closed chamber with a metal top cover, pneumatic side walls, and a bottom surface consisting of soil or greenhouse bench covering was initially analyzed. Two atomizer nozzles were placed inside this chamber. Pneumatic walls are supplied with compressed air, thus producing a laminar fluidic layer. A large number of experimental tests were carried out to evaluate the behaviour of these pneumatic walls, especially as regards their interaction with the fine fog generated by the nozzles. Supplying pneumatic walls at a pressure of  $6 \cdot 10^5$  Pa proved unsuccessful, as vortexes generated on the ground interacted with the fog, spreading it all over the chamber. This is illustrated in Figure 11, where the arrows show the pesticide fog limited only in the upper part of the defined-volume chamber.

In addition, it was found necessary to supply pneumatic walls around the chamber at  $5 \cdot 10^5$  Pa for them to be effective. At this pressure, however, the pesticide fog, though limited to the chamber, caused too much ground and crop wetting for coalescent droplets to be produced.

Experimental tests thus indicated that pneumatic walls are not a good solution for this kind of fog application.

Consequently, a new chamber was designed with a rigid upper plate and retractable side walls consisting of an appropriate textile material: in this way, the chamber can be retracted when it is moved from one work position to the next, or when it is not in use.

The main requirement for this textile covering is absolute impermeability to air and to pesticide vapours, though it must also be lightweight and capable of resisting corrosive chemicals. For these reasons, various textile materials impermeable to liquid and to air were investigated, also attempting to find ways of guaranteeing these properties at the seams. Accordingly, seams were thermally bonded to prevent pesticide loss through needle holes. Results of air and water tightness tests on the chosen textile material were good.



Fig. 11. Pneumatic walls supplied at  $6 \cdot 10^5$  Pa and 700 mm from ground

## 6. Fixed covering prototypes

Two preliminary fixed covering prototypes were constructed to assess spraying efficacy with the selected nozzles.

### 6.1 First fixed-covering prototype

An initial test bench for assessing nozzle efficacy was assembled using a metal frame for the textile walls, two pneumatic nozzles, a pneumatic control circuit, water-sensitive cards, flowmeters and manometers (class 1). The first step in experimental testing was to perform a three-dimensional evaluation of the fog generated in the chamber. A metal tree structure with a central trunk and six lateral branches was constructed to support the water-sensitive cards. To check plant coverage by the sprayed pesticide, twelve card positions were established, at 300-200-100 mm from the ground, at the center and edges of the tree. Cards were also positioned to simulate leaf top surfaces and undersides as shown in Figure 12a. Card placement on a tree is illustrated in Figure 12b. Using this metal tree, several preliminary tests were carried out with different nozzle orientations, varying supply pressure and exposure time. In this way, the best spraying conditions were identified whereby a very fine and concentrated fog can be produced. Further experimental tests were performed using a yellow UV phosphorescent dye in the spray. In this case, tests were conducted using real flowers. Results are indicated in Figures 13 and 14, using two nozzles assembled as shown in figure 4.

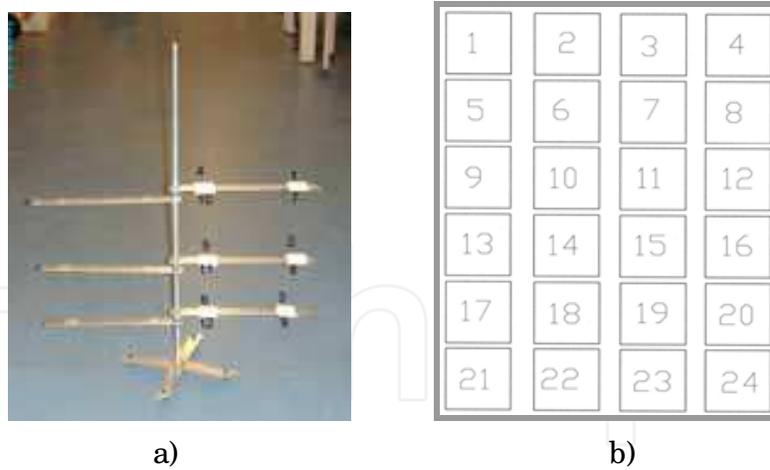


Fig. 12. a) Card placement on metal tree b) Card numbering on the metal tree

Test parameters are illustrated in Table 1, including air and water supply pressure and flowrate, exposure time  $t_s$ , and time following treatment  $t_e$  (time between spraying and off-target pesticide recovery).

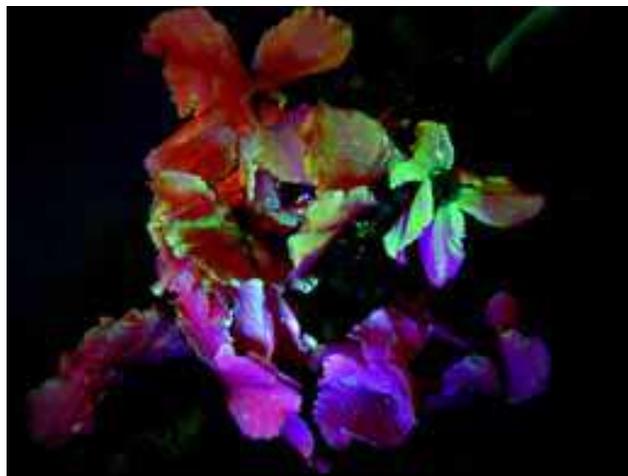


Fig. 13. Actual flower sprayed with phosphorescent dye

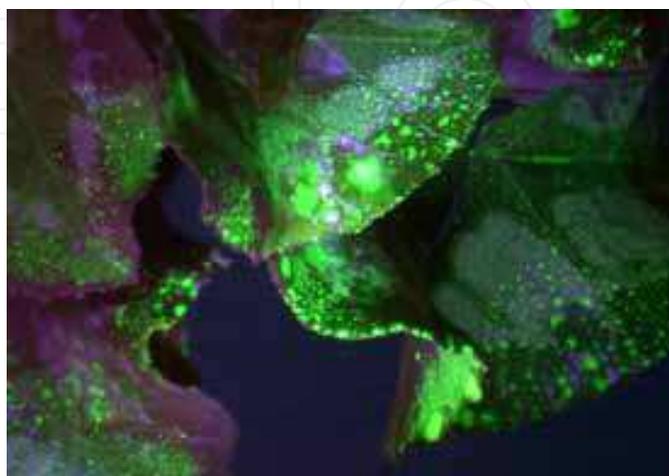


Fig. 14. Enlarged view of a treated crop

Air	Water
$p_a = 1,6 \cdot 10^{-5} \text{ Pa}$	$p_w = 0,5 \cdot 10^{-5} \text{ Pa}$
$Q_a = 844 \cdot 10^{-3} \text{ dm}^3/\text{s}(\text{ANR})$	$Q_w = 1,17 \cdot 10^{-3} \text{ dm}^3/\text{s}$
$t_s = 5\text{s}$ $t_e = 30\text{s}$	

Table 1. Parameters used during tests

Flowers were adequately sprayed and preliminary results were good.

### 6.2 Second prototype with a fixed covering

As the first prototype demonstrated that the new spraying treatment is effective, a second prototype was constructed to simulate a sprayed area similar to an actual greenhouse bench measuring around 1x1 m. This prototype is illustrated in figure 15.



Fig. 15. Second fixed-covering prototype

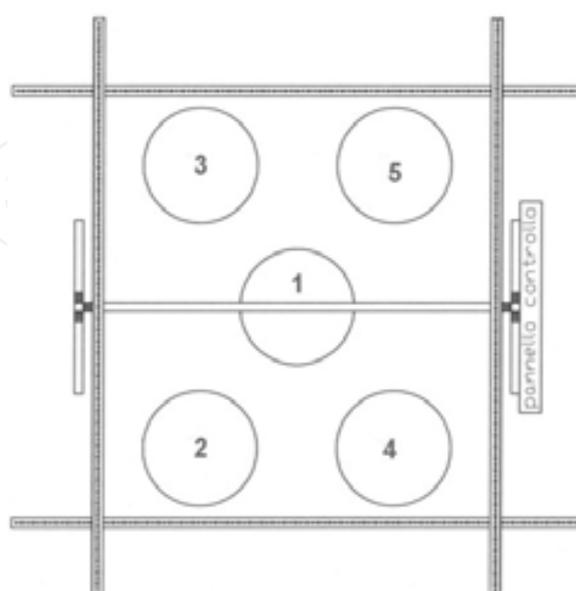


Fig. 16. Plant placement in the new spray area

The main goal is to achieve uniform pesticide deposition on the plants, thus maximizing treatment efficacy and reducing product wastage.

The first step in experimental tests was to perform a three-dimensional evaluation of deposition in the chamber, using five metal tree structures carrying water-sensitive cards as shown in Figure 16. During these tests, four nozzles were moved over the plants by means of a rodless pneumatic cylinder. This prevents excessive concentration of pesticide on flowers and produced a more uniform distribution. Spray patterns produced by these nozzles (two nozzles in the first tests and four movable nozzles in final tests) are shown in Figure 17. As the nozzles are full cone nozzles, their spray pattern is an ellipse with 500x600 mm axis. An area measuring around 1 m<sup>2</sup> can be covered by moving four nozzles over the plants. Operating parameters for the experimental tests carried out with this second prototype were as follows:  $h$  (distance between nozzles and ground);  $p_a$  (air supply pressure);  $p_w$  (water supply pressure);  $n_c$  (number of cylinder cycles on plants - two movements of the rodless cylinder);  $n_t$  (number of treatment cycles);  $t_{sp}$  (spraying time).

The experimental tests were performed with the test bench shown in Figure 15, using cards on the metal tree structure as well as UV phosphorescent dye with real plants. In particular, tests were carried out both with two and with four nozzles, moved over plants. The latter solution proved to be optimal.

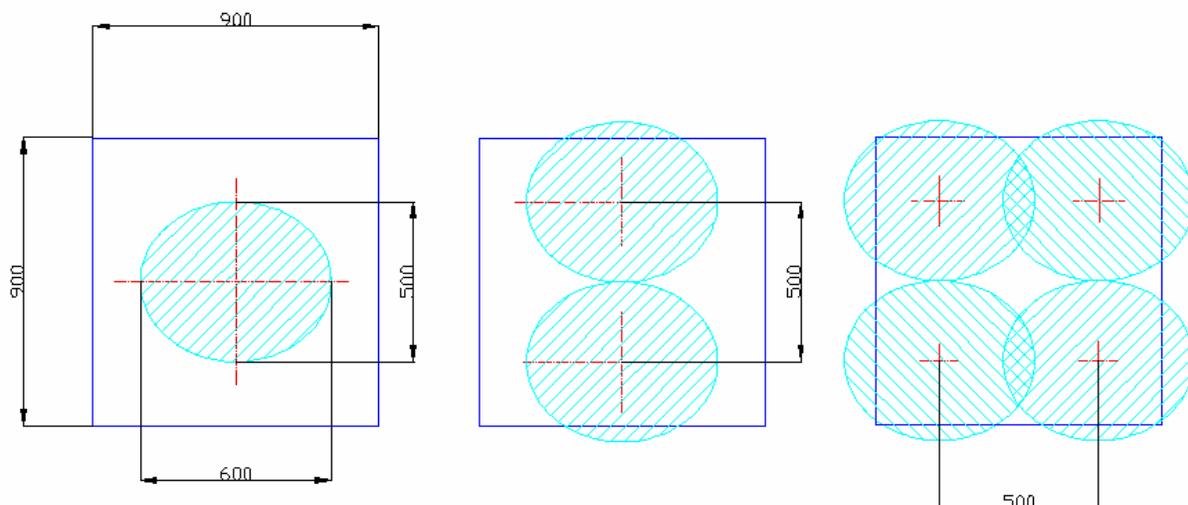


Fig. 17. Nozzle spray patterns: a) two fixed nozzles; b) four fixed nozzles; c) four nozzles moved over plants

Experimental results obtained with four nozzles moved in the chamber are shown in Figure 18. As can be seen, practically all of the cards are effectively reached by sprayed droplets.

As shown in figure 19, the dye on real flowers is also well distributed. Here, the test parameters are:  $h=0.8$  m;  $p_a = 1.9$  bar;  $p_w = 0.7$  bar;  $t_{sp} = 14.8$  s;  $n_c = 2$ ;  $n_t = 2$ .

In particular, the chamber reached saturation earlier with four atomizer nozzles, and parameters  $n_c$  and  $t_{sp}$  can be reduced. However, consumption of air and water increases in this case. As the figures show, coverage is higher on trees 3 and 5, while deposition on the undersides of the leaves is better when four nozzles are used.

Finally, a comparison of the results obtained from metal tree structures and real plants indicates that the more complex geometry of the latter makes it absolutely essential to use four movable nozzles.

With real plants, in fact, two atomizers are not sufficient to guarantee uniform deposition, because in this case only plant 1 is effectively sprayed. When four nozzles are used, very good results are obtained on all of the plants in the chamber.

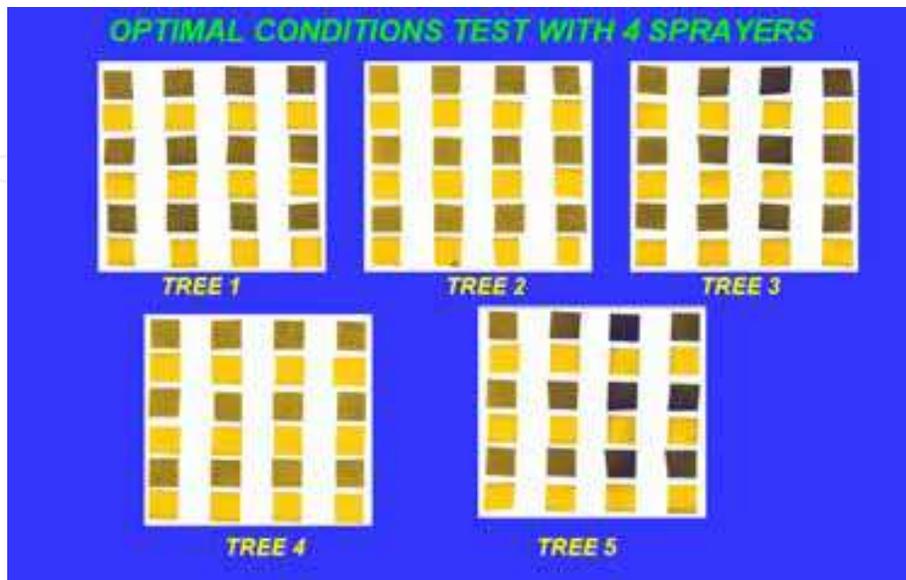


Fig. 18. Spraying results with five metal tree structures



Fig. 19. Spraying results with actual plants and phosphorescent yellow dye.

### 6.3 Analysis of results

These experimental results were evaluated by means of a statistical study.

The first step was to establish a rating scale, where each score is associated with a different color. This method makes it possible to compare card level and dye coverage obtained on plants, as well as to construct histograms with a readily interpreted chromatic scale as shown in Table 2.

The first group of histograms (figure 20) was constructed by analyzing quality of deposition for each test on various tree structures, distinguishing between upper and lower cards. A

score was assigned after calculating the arithmetic mean of results obtained from deposition evaluation.

The second series of histograms was constructed to assess the variation in deposition quality for each card on each tree structure. Twenty-four cards were analyzed for each tree.

The third and final group of histograms evaluated a comparison between the cards placed in the same position on a tree structure in different tests.

Pesticide deposition quality rating	Numerical score	Card color	Color name
Excessive	6		Blue
Excellent	5		Dark green
Good	4		Light green
Fair	3		White
Poor	2		Light yellow
Insufficient	1		Yellow

Table 2. Qualitative ratings and scores for pesticide deposition using cards

From this analysis, the mean  $m_x$ , the variance  $s_c^2$ , the standard deviation  $s_c$  and the probability density  $f(x)$  can be calculated using the following expressions:

$$m_x = \frac{1}{n} \sum_{i=1}^n x_i \quad (1)$$

$$s_c^2 = \frac{1}{n-1} \sum_{i=1}^n (x_i - m_x)^2 \quad (2)$$

$$s_c = \sqrt{\frac{1}{n-1} \sum_{i=1}^n (x_i - m_x)^2} \quad (3)$$

$$f(x) = \frac{1}{\sqrt{2\pi s_c}} e^{-\frac{1}{2} \left( \frac{x - m_x}{s_c} \right)^2} \quad (4)$$

where  $x_i$  is the sample and  $n$  is the sample number.

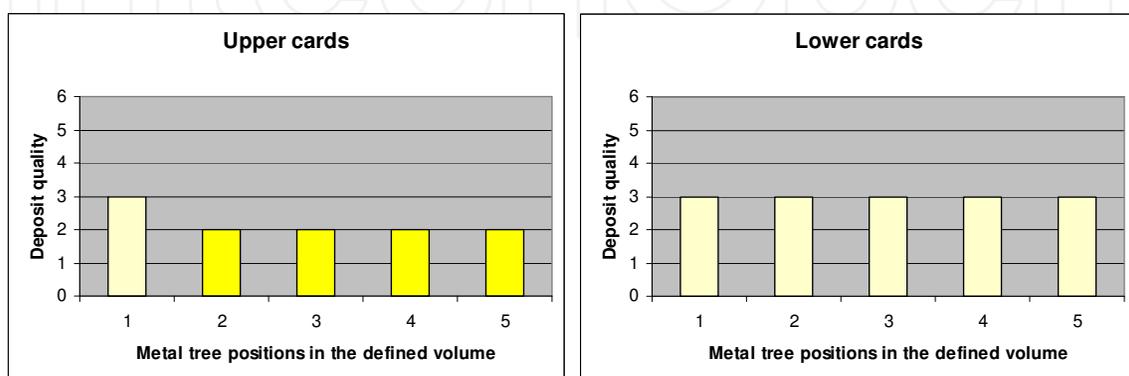


Fig. 20. Example of histograms from the first group

These statistic analyses yield the results shown in Table 3, which makes it possible to analyze the Gaussian distribution for these experimental results.

In this table, the mean value and other results refer to the score explained in Table 2. The optimum test condition is also indicated.

Tests	Mean value for upper cards in each metal tree	Mean value for lower cards in each metal tree
1	2.2	3
2	1.4	1
3	1.4	1
4	2.6	1.8
5	4.4	2.2
6	5.2	3
7	4.2	3
8	4	1.6
9	4.2	3
10	3.4	1.4
11	4.8	3.2
12	4.6	3.6
13	5	4
14	5	3.4
15	5	4
16	5.4	4.2
17	6	4.4
18	3.6	1
19	4.2	1
20	5	1
21	1.4	1
22	4.2	1
23	4.8	1

a)

Tests	Standard deviation value for upper cards in each metal tree	Standard deviation value for lower cards in each metal tree
1	0,45	0
2	0,89	0
3	0,89	0
4	1,34	0,45
5	0,89	0,45
6	0,45	0
7	0,45	0
8	0,71	0,89
9	0,45	0
10	1,52	0,89
11	0,84	1,1
12	0,89	0,89
13	0	0
14	0	0,55
15	0,71	0
16	0,55	0,45
17	0	0,55
18	0,89	0
19	1,1	0
20	0	0
21	0,55	0
22	1,3	0
23	0,45	0

b)

Table 3. a) Mean value for upper/ lower cards on a metal tree structure; b) Standard deviation for upper/ lower cards on a metal tree structure (first group)

## 7. Prototype with retractable covering (DeVoPeS)

As the new technique for spraying in a confined area was found to be effective, it was decided to design a retractable covering for the spray chamber.

Accordingly, a new prototype called the DeVoPeS (Defined Volume Pesticide Sprayer) was designed, constructed and tested (Belforte et al, 2008) (Belforte et al, doi 2010).

The prototype consists of:

- a retractable covering enclosing the defined-volume spray chamber and robot docking system;
- a pesticide spraying system;
- an off-target pesticide recovery system;
- a lower sealing system to ensure that the chamber is air tight during spraying.

These parts will now be described in detail.

- Retractable covering (pantograph and side curtains)

The DeVoPeS retractable covering system as shown in Figures 21 and 22 consists of:

- a structure delimiting the pesticide spray chamber;
- a series of devices for connecting DeVoPeS to the robot moving over the plants.

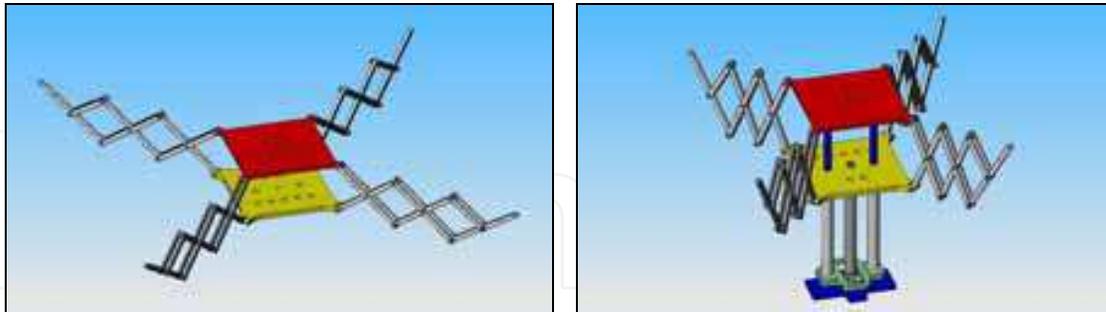


Fig. 21. Pantograph and plates with actuating cylinder

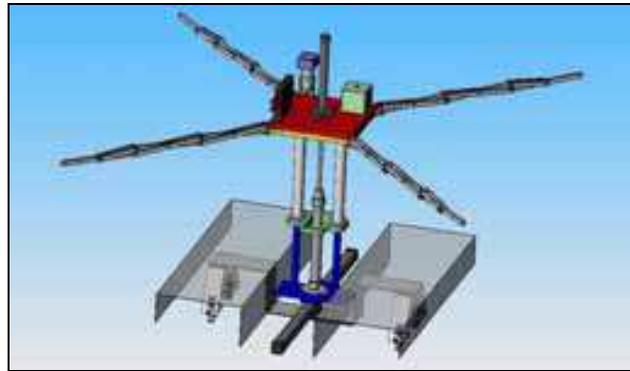


Fig. 22. DeVoPeS structure with robot docking system

The structure delimiting the DeVoPeS spray chamber consists of a textile cover sheet, four corrugating tubes which move the side curtains pneumatically, a pantograph mechanism which moves the cover sheet by means of two plates, a stationary plate connected to the robot docking system, a movable plate, a pneumatic actuator which moves the two plates and associated pantograph mechanism automatically, and metal guards that prevent the moving cover from catching on the nozzles (Figure 22).

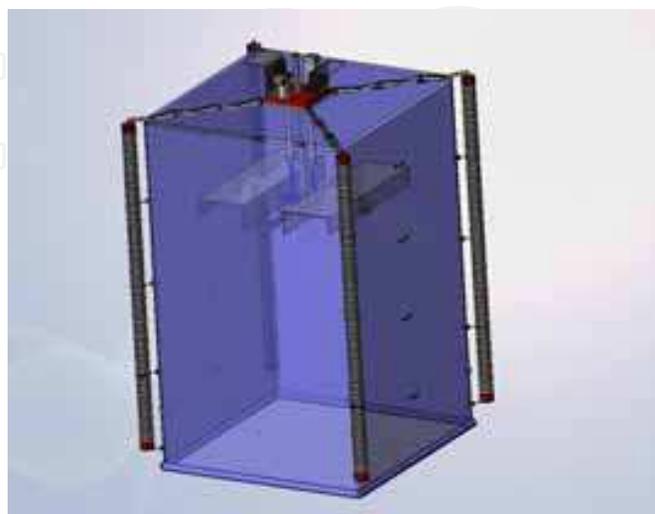


Fig. 23. Corrugating tubes for raising and lowering the side curtains



Fig. 24. Example of textile cover sheet retraction/ extension in the laboratory

Side curtains are moved by means of a pneumatic ejector that generates vacuum in the corrugating tubes, thus causing it to retract. When the ejector is switched off, the cloth drops under the effect of gravity (Figures 23 and 24). Textile characteristics are as described earlier.

b. *Pesticide spraying system*

Various tests were carried out with different nozzles as described above to evaluate product deposition. The optimal final configuration features a pair of nozzles tilted towards each other at a 130° angle mounted on a rodless cylinder for horizontal movement over the plants.

c. *Off-target pesticide recovery system*

This system operates after each treatment, when the spray chamber still contains air with pesticide droplets in suspension which have not been deposited on the plants. The system uses a tube for conveying air away from the closed chamber, an ejector that aspirates air from the chamber and projects it towards a target, and a filter on the ejector suction port.

It was necessary to study various kinds of filters and ejectors for separating pesticide from the air. Specifically, three types of filter were tested: centrifugal condensate separators, blade-type mist eliminators, and coalescing filters.

In view of its low bulk and suitability for the application in question, it was decided to use a coalescing filter for the DeVoPeS.

To evaluate performance of the different filters, the ejector output spray was projected onto a metal target carrying water-sensitive cards. A distance of around 420 mm between ejector and target was selected after several preliminary tests. In addition, tests were carried out on different ejectors with equivalent aspiration properties ( $Q_{asp}=700 \cdot 10^{-6} \text{ m}^3/\text{s}$  with  $4 \cdot 10^5 \text{ Pa}$  supply pressure).

The basic testing procedure was as follows. A spray treatment was first performed by opening the main solenoid valves. This creates a mist in the chamber mockup consisting of a mixture of air and finely dispersed water droplets. After treatment, these valves are closed and the mist is allowed to settle, as the pesticide must have time to act on the plants. In the final stage, the ejector inlet air circuit is opened by means of another valve to aspirate the excess mist. This mist passes through the filter to separate air and liquid (pesticide).

The air issuing from the filter, which should no longer contain liquid, passes to the ejector and is expelled onto the target, where the color assumed by the water-sensitive cards indicates whether air alone, or air mixed with liquid, has been aspirated.

Each test was performed twice, first with the filter as described above, and then again after removing the filter. In this way, it is possible to evaluate the amount of liquid aspirated: with the filter, the liquid drops to the bottom of the filter housing, while if there is no filter the liquid is collected on the target.

The parameters that vary from one test to another are the three time periods mentioned earlier: to improve the system's effectiveness, all of these times should be as low as possible. Spraying time  $t_1$  depends on the properties of the pesticide used and the type of plant it is intended to protect, but cannot drop below a certain minimum threshold. The same holds for mist settling time  $t_2$ , which also varies according to the type of plant and pesticide. Off-target pesticide recovery time  $t_3$  is the magnitude that provides the greatest scope for variation: as no data from previous tests are available, different times must be tested until the minimum value that optimizes system performance is found. A further parameter that can be varied during testing is air pressure at ejector inlet. By varying this parameter, it is possible to control the vacuum created by the ejector and thus its aspiration capacity. Mist was absorbed both with and without the filter. At this point, the water-sensitive cards placed on the target were examined to evaluate the extent of recovery. Depending on the type of pesticide treatment concerned, it may not be necessary to allow for a mist settling time  $t_2$ . Consequently, tests were also performed with zero settling time. Where no filter is used, it is clear that particles of pesticide are aspirated but not retained, as the color of the water-sensitive cards shows.

The final system used on DeVopeS to recover off-target pesticide consists of an ejector, a coalescing filter and tubes that, aspirating air from the confined area enclosed by the cover sheet and side curtains, carry the pesticide to the filter, where it is collected and recovered for later reuse. For the DeVopeS, aspiration time  $t_3$  has for the moment been reduced to 10 s, in accordance with the type of spray treatment performed ( $t_1=8$  s).

d. *Lower sealing system*

Pneumatic sealing is provided along the DeVopeS system's lower horizontal edges by means of inflatable chambers that can guarantee that the spray area is completely air tight. These air chambers inflate inside a metal frame as shown in Figure 25. Their efficacy was demonstrated in experimental tests.

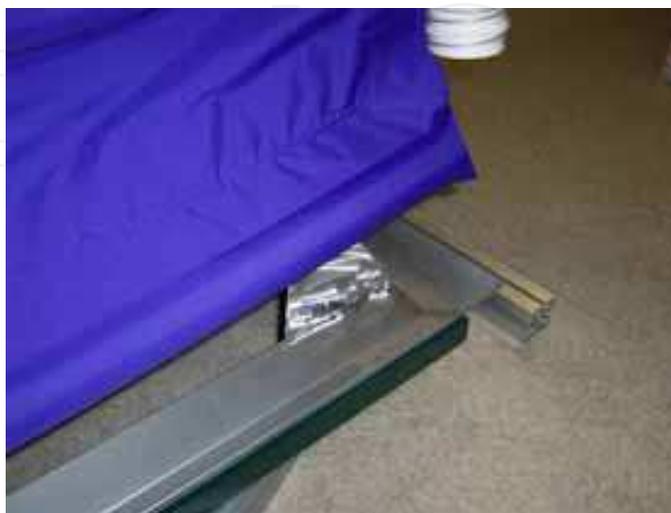


Fig. 25. Lower pneumatic sealing in DeVopeS

## 8. DeVoPeS work cycle

The DeVoPeS work cycle is as follows.

- The DeVoPeS is positioned over the area to be sprayed.
- The pantograph cylinder is actuated to spread the cover sheet.
- The corrugated tubing is extended to lower the side curtains.
- Pneumatic chambers are inflated at top and bottom. Top chambers stiffen the structure, while bottom chambers both stiffen the structure and create a seal.
- Air and pesticide are supplied to the atomizers.
- The rodless cylinder moves the atomizers to distribute pesticide uniformly on the plants.
- The atomizers are automatically shut off after a certain number of passes over the plants.
- The rodless cylinder stops.
- The aspiration system is activated to remove off-target pesticide, deflating the bottom sealing chambers.
- The corrugated tubing is retracted to raise the side curtains.
- The pantograph mechanism closes so that the system can be stowed or moved for a further spray cycle in another location.

The pneumatic control circuit used for DeVoPeS is shown in Figure 26. It consists of two pneumatic cylinders, one for the pantograph and the other for moving the nozzles over the plants; two ejectors, one for the corrugating tubes and the other for the pesticide recovery system; a number of solenoid valves for supplying actuators, ejectors, lower sealing chambers and nozzles for both air and water.

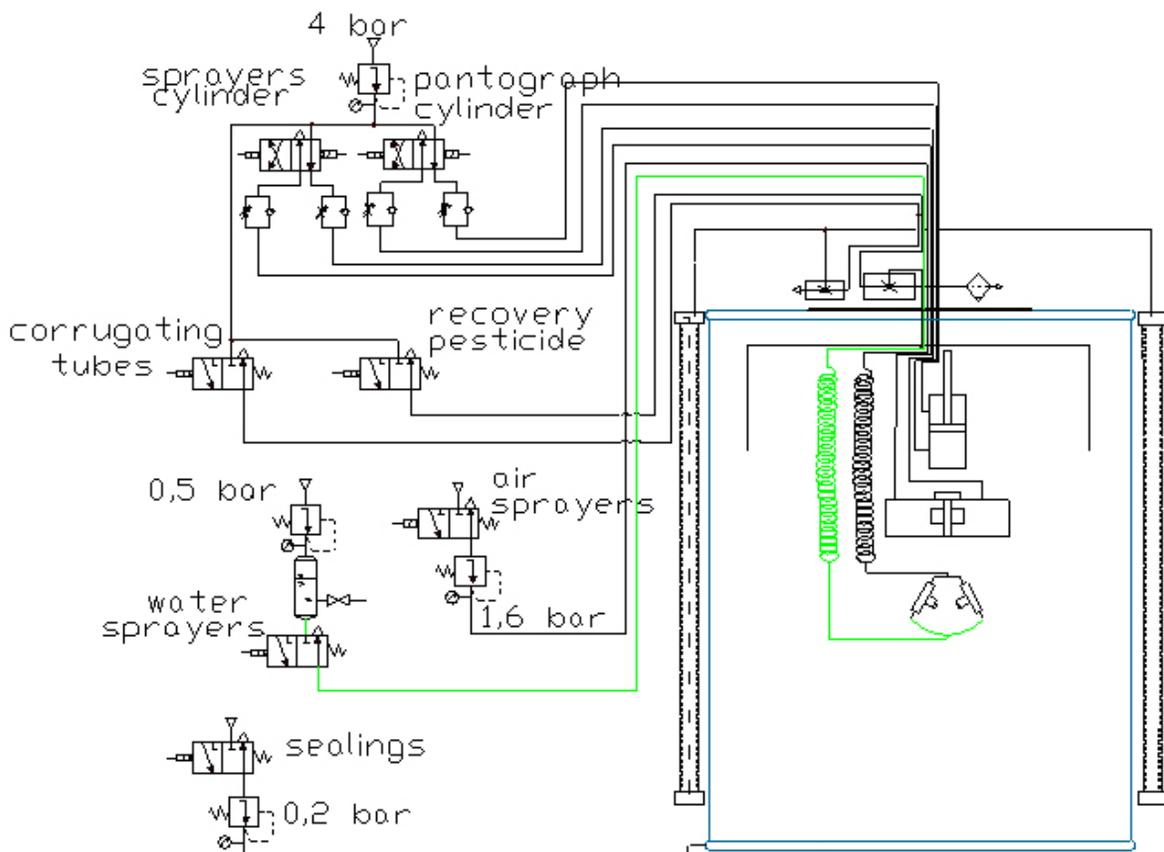


Fig. 26. DeVoPeS pneumatic control circuit

## 9. Laboratory testing

A large number of laboratory tests were conducted on the entire system to assess cycle times, air and water consumption, and retractable cover sheet movement.

The whole work cycle is accomplished in about 1.5 minutes.

Figure 27 shows overall DeVoPeS consumption during a work cycle. It should be emphasized that the largest consumption is due to the ejectors which, however, never work together. These ejectors generate a vacuum level of about  $-0.6 \cdot 10^5$  Pa when supplied at  $4 \cdot 10^5$  Pa as supply pressure, with a flowrate of  $0.0015 \text{ m}^3/\text{s}$  (ANR).

The cycle is automated by means of a PLC (Programmable Logic Controller) that receives a signal from end stroke actuators and sends commands to valves using timers. This PLC has 23 inputs and 15 outputs.

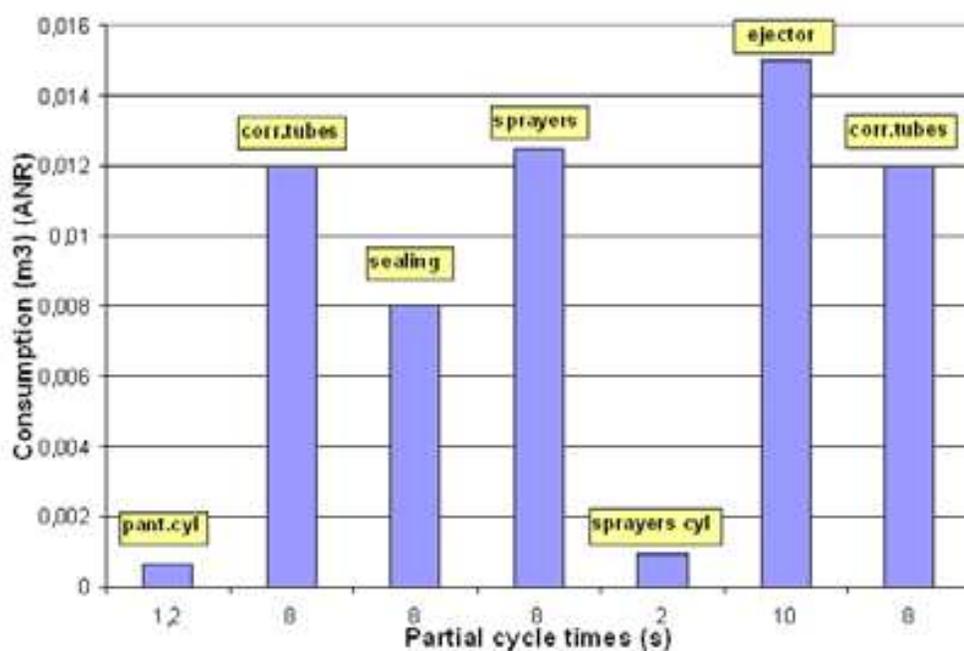


Fig. 27. DeVoPeS consumption in a work cycle

## 10. Greenhouse testing

For greenhouse testing, DeVoPeS was connected to a robot capable of moving it onto plants. The DeVoPeS work area on a greenhouse bench is shown in Figure 28, together with the robot and the bench dimensions. It should be noted that the DeVoPeS was constructed as a half-scale prototype for demonstration purposes. Figure 29 shows the DeVoPeS connected to the robot. The robot is controlled by special position control software with NI PXI electronic cards and has a maximum acceleration of about  $4 \text{ m/s}^2$  (Belforte et al, 2006) (Belforte et al, 2007) (Belforte et al, 2008). The DeVoPeS flow chart can be divided in two cycles:

- the first is used to move DeVoPeS by robot to the treatment area on the bench (the cover sheet is retracted in this phase);
- the second is used to carry out the treatment on plants with the work cycle described earlier.

Figure 30 shows DeVoPeS working in a greenhouse. Experimental tests yielded good results, demonstrating the usefulness of this new pesticide spraying technique.

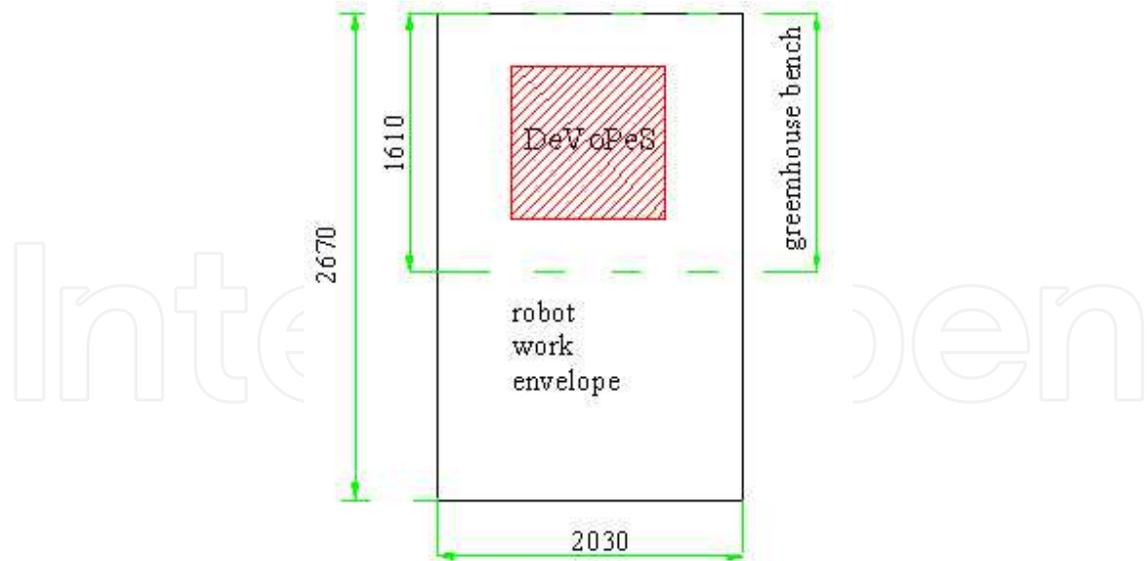


Fig. 28. DeVoPeS work area

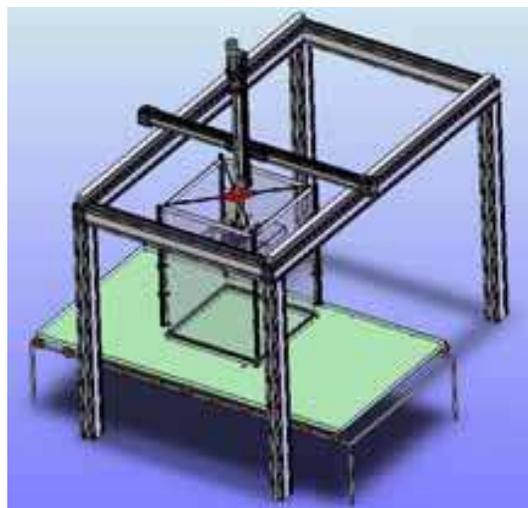


Fig. 29. DeVoPeS on robot



Fig. 30. DeVoPeS working in greenhouse

## 11. Conclusion

A new spraying technique for safely distributing pesticides was investigated.

The spraying technique was studied using both numerical and experimental methods.

Overall results are good and provide an understanding of the interaction between leaf and droplets.

In particular, experimental tests on atomizer nozzles indicated that nozzles must be moved over the crop in order to achieve uniform pesticide distribution.

A new prototype called the DeVoPeS which can spray pesticide inside an enclosed, airtight chamber was designed, constructed and tested.

This machine offers a number of advantages: treatment is fully confined so that it does not affect the outside environment; the operator can remain in the greenhouse during spraying; pesticide losses are sharply reduced, increasing safety for both growers and the environment; the off-target pesticide recovery system provides economic benefits. DeVoPeS is currently a half-scale prototype, though its dimensions could readily be increased in the future to cover an entire greenhouse bench.

## 12. Acknowledgments

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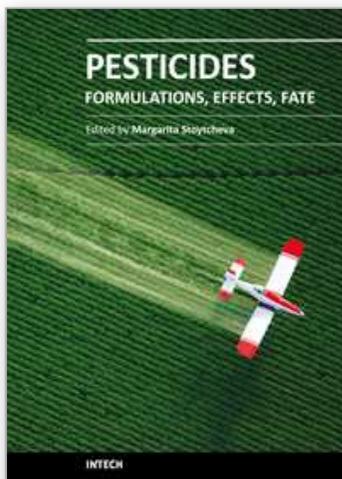
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## **Pesticides - Formulations, Effects, Fate**

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This book provides an overview on a large variety of pesticide-related topics, organized in three sections. The first part is dedicated to the "safer" pesticides derived from natural materials, the design and the optimization of pesticides formulations, and the techniques for pesticides application. The second part is intended to demonstrate the agricultural products, environmental and biota pesticides contamination and the impacts of the pesticides presence on the ecosystems. The third part presents current investigations of the naturally occurring pesticides degradation phenomena, the environmental effects of the break down products, and different approaches to pesticides residues treatment. Written by leading experts in their respective areas, the book is highly recommended to the professionals, interested in pesticides issues.

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