Converging Air Jets in Orchard Spraying

Influence on Deposition, Air Velocities and Forces on Trees

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Abstract

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To provide necessary plant protection in orchards, spray drops are transported to and into the apple tree canopy with an air jet from a fan sprayer. The interaction between the spray air jet and the canopy is central to effective droplet transport, spray coverage and pest control. Converging air jets were introduced as a way of improving the spray application. In this study, a two unit cross-flow fan orchard sprayer, configured as converging or plane (vertical fan units) air jets, were compared in several experiments. Inclining the top or bottom fans towards the tree created different types of converging air jets. The influence of these air jets on spray deposition, on air velocities and on forces acting on apple trees was measured.

Deposition was measured throughout the season with fluorescent tracer on leaf sized filterpaper targets inside canopies.

Different types of air velocity measurements were made with the fan sprayer passing the tree. Peak velocities were recorded at positions throughout apple tree canopies, and in-depth measurements of several air velocity parameters were made inside, above and beyond an apple tree canopy. Velocity pulse values were integrated over time. Air velocity profiles were measured in stationary situations and compared to existing mathematical models.

Forces and moments caused by the air jet striking the tree were measured with a new method, utilizing a multicomponent force transducer, placed between the tree trunk and the ground.

Compared to plane air jets, converging air jets resulted in significantly higher deposition values, more uniformly distributed through the canopy. The converging air jets increased the air velocity parameters in the denser parts of the canopy, and resulted in higher air power and energy at those positions. Converging air jets transferred greater forces to the canopy. This could be explained by the ability of the converging air jets to reduce the air flow directed above the trees, thereby concentrate and increase the amount of spray liquid, penetrating into the densest part of the canopy. Finally, an increased air velocity improved deposition prerequisites. The new method for measuring forces and moments has a potential to extend and complement other application technology measuring methods.

Keywords: air jets, air velocity measurements, anemometer, apple, application technology, canopy, converging air jet, cross-flow fan, fan sprayer, fluorescent tracer, force measurements, force transducer, orchard spraying, pest control, plant protection.

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To

International cooperation between researchers

Contents

Appendix

Papers I – IV

This thesis is based on the following papers, which will be referred to by their Roman numerals:

I Svensson, S.A. 1994. Orchard spraying - deposition and air velocities as affected by air jet qualities. *Acta Horticulturae*, 372, pp 83-92.

(Mainly based on: Svensson, S.A. 1991. Besprutning av frukträd – avsättning och lufthastigheter vid olika karaktär på luftströmmen (Orchard spraying - deposition and air velocities as affected by air jet qualities). Department of Agricultural Engineering, Report no 149, Swedish University of Agricultural Sciences, Alnarp. 79 p (in Swedish). This report was presented and defended for receiving the Swedish academic grade 'Licentiate in Technology'.

II Fox, R.D., Brazee, R.D., Svensson, S.A. & Reichard, D.L. 1992. Air jet velocities from a cross-flow fan sprayer. *Transactions of the ASAE* 35(5), 1381-1384.

III Svensson, S.A., Brazee, R.D., Fox, R.D. & Williams, K.A. 2001. Air jet velocities in and beyond apple trees from a two cross-flow fan sprayer. (Submitted to *Transactions of the ASAE*)

IV Svensson, S.A., Fox, R.D. & Hansson P-A. 2001. Forces on apple trees sprayed with a cross-flow fan air-jet. (Submitted to *Transactions of the ASAE*)

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Introduction

Application technology in orchard plant protection

The objective of application technology as used in plant protection with chemical as well as with biological agents is to put a uniform distribution of the desired amount of active ingredient on the intended target area with the smallest possible losses. This will achieve the greatest biological effect with the minimum of pest control agents and carrying liquid and, in addition, have the least possible impact on the environment.

Contact-active pest control agents require the most uniformly applied distribution. Because these agents do not penetrate the plant and translocate, they must be applied to every position where the pest resides. However, the three-dimensional structure of trees and shrubs makes it difficult to obtain the desired result. It would be logical to deposit the spray exactly where the pest is, but not enough information about pest habitat is available to target defined, nonuniform distributions throughout the canopy (Cross et al., 1997). To get the optimum biological effect, the grower should instead aim at a maximum amount of deposited spray liquid, uniformly distributed through the canopy and with a minimum of losses. The most difficult part of the canopy to achieve desired deposition is normally the center part (Hall et al., 1975, Kümmel & Göhlich, 1993, Svensson, 1991).

Air assisted sprayers for agricultural crops were introduced in several different designs during the beginning of the 20th century. Air blast sprayers, as we recognize them for use in orchards, came on the American market in the beginning of the 1940's. They were imported to Sweden beginning about 1950 and became more commonly used after domestic production began in the mid 1950's (Brann, 1956, Hislop, 1991, Göhlich, 1993, Persson, 2001, Svensson, 2001). There are many air blast sprayers in use throughout the world, in all types of three dimensional crops; fruit, vineyards, nuts, citrus, hops, nursery plants, etc. An approximation of the number of sprayers in some countries is summarized in table 1.

Applying spray with air blast sprayers is still the only commercial method used to control insects and diseases in orchards, although totally different methods like confusion with pheromones and other biocontrol approaches have been introduced. In principle, spray from an air blast sprayer is generated in a high power air jet, which carries the spray drops to the target, i.e. the tree canopy. Experience shows that this method of application results in relatively effective plant protection with the doses and equipment used today, but that it also has obvious disadvantages.

Table 1. Examples of number of orchard sprayers in some countries, (Rietz et al., 1998, Svensson & Hagenvall[1], 1997, Doruchowski[2], 2001, Fox, 2001[3])

Country	Approximate number of orchard sprayers	Country	Approximate number of orchard sprayers
Austria	26 000	Norway	1 000
Belgium	5 000	Poland[2]	25 000
Finland	< 100	Spain	28 000
France	60 000	Sweden[1]	200
Italy	400 000	Switzerland	28 000
Netherlands	7 500	USA[3]	175 000

The interaction between the air jet and canopy is critical to achieving uniform deposits, but it is difficult to describe because the canopy is a complex and irregular target. In addition the canopy changes from being open and thin in the springtime to a dense body that is difficult to penetrate later in the growing season. To get enough coverage on positions most difficult to spray, today's equipment will typically overdose portions of the tree near the sprayer by 3 - 4 times. Depending on the measured deposition area, local overdoses up to much more than 8 times the amount required for control have been reported (Nordby, 1959, Hall et al., 1975, Kaul et al., 1996).

Losses owing to wind drift or wasted on the ground can comprise between one third and two thirds of the applied spray, depending on the external conditions (i.e. Morgan, 1981). Spray that misses the intended target causes the most troublesome disadvantage in orchard spraying. Careful German studies have shown that you could expect about ten times greater wind drift amounts from orchard sprayers than from boom sprayers (Ganzelmeier & Rautmann, 2000). Special care must be taken when spraying in locations and situations where spray may drift over and deposit on surface water or wetland conservation areas, thereby creating serious environmental problems. Swedish fruit production is located in areas that are also used for recreation, and/or are close to urban areas. Risks to the environment in general, through wind drift, should influence the choice of equipment and methods for application. The above mentioned German investigations show possible technical ways to reduce orchard sprayer wind drift by 90% (Ganzelmeier & Rautmann, 2000). Wind drift may also result in pollution of the working environment, whereby the operator may drive into the spray cloud.

To reduce the wind drift risks, night-time spraying is often chosen in Sweden, because wind velocity is usually less than during the day. However, work at night introduces other types of accident risks.

"Integrated Fruit Production" (IFP) is a production method, based on ecological and other scientifically tested methods, for economic production of quality fruit with a minimum of pesticides and nutrients. IFP has been introduced on a large scale in Europe, including Sweden. Increased precision in application of chemicals and increased knowledge of application technology are important tools in successfully applying these production principles.

The cost of controlling insects and diseases is significant. Pesticides account for about 5000 SEK/ha; a large portion of the costs in producing Swedish fruit (Trulsson, 2001). In 1999, tree fruit production acreage was around 2100 ha of which apple acreage was about 1600 ha (production 1999: 18000 tons apple) (SCB, 1999). This means that more than 10 million SEK is spent for chemicals for Swedish fruit production each year. Roughly half of the chemical never reaches the correct location in trees.

Therefore, for several reasons, it is important to intensify research that will develop knowledge on application methods that reduce wind drift and other losses, that will increase the possibility of getting less variation in coverage with less chemical and that, finally, contribute to effective pest control without real or apparent hazards, either for the operator, or for those living near orchards. Development of these methods must be based on scientific knowledge of the basic phenomenon that occurs in the canopy when spraying with air blast sprayers.

Basic relationships in deposition

In orchard airblast spraying, liquid drops are injected into an air jet produced by a blower. The air jet carries the spray to and into the canopy, where drops are deposited. The main objective is to create conditions such that a maximum portion of the spray deposits on the different parts of the canopy. The basic theory for spray droplet deposit is common to spray technology in agriculture and to collection of particles by technical air filters in industry and is described in literature (Strauss, 1975, Little, 1979, Spillmann, 1979, Uk, 1979, May & Clifford, 1967, Metz, 1986, Dullien, 1989, and others). The theory of air filters refers to "aerodynamic capture", where conditions are created so that the airborne particles are separated onto special targets.

The deposition is theoretically modeled according to the following principles: inertial impaction, interception, sedimentation, and diffusion. The models' conditions reflect idealized assumptions. In complex reality all principles are acting together.

Inertial impaction implies that the mass and/or velocity of the drop is so high that its inertia causes the drop to deviate from the streamlines of the surrounding gas and to impact on a collector. In the mathematical model for describing impaction, the size of the drop is not considered.

For interception it is assumed that the drop has no mass, just volume. This means that it will move without inertia and will follow the streamlines of the surrounding gas. Depending on its size it can get close enough to touch a target and adhere.

Sedimentation can be visualized as a special case of the earlier mentioned deposition. Sedimentation means deposition, where the movement of the drop results only from the force of gravity.

Diffusion results from the influence of molecular or turbulent forces. Applying an electric charge to spray drops (electrostatic spraying) is another principle of deposition. Both diffusion and electrostatic forces are neglected in the following discussion.

Mathematical models have been developed for the different principles of deposition and empirical solutions have been obtained by experiments. Some of the major relationships are recorded in Table 2 below (from mainly Strauss, 1975, Spillman, 1979 and May & Clifford, 1967).

Table 2. Basic relations in deposition

Relations	Symbols	
Sedimentation (terminal) velocity	V_S	Sedimentation velocity, the terminal velocity of a drop, falling in still air
$V_s = \frac{\rho_d \, g \, d^2}{18 \mu}$ (1)	ρ_d	Drop density
	g	Gravitational constant
	d	Drop diameter
Stopping distance	s	Stopping distance, the distance the drop travels before it reaches the velocity of the surrounding fluid
$s = \frac{V_s V_0}{g}$ (2)	V_0	Initial velocity of the drop, relative to the surrounding fluid
Capture parameter (for inertial impaction)	P	Parameter in the case of inertial impact; the parameter that determines the probability of capture
$P = \frac{s}{D} = \frac{V_s V_0}{g D} = \frac{\rho_d \, d^2 \, V_0}{18 \mu D}$ (3)	D	Size of the target, width or diameter
	μ	Dynamic viscosity of the fluid

Several researchers have investigated these relationships and for a number of regular bodies it is possible to calculate (or we have empirical data for) capture efficiency. The relationships between capture efficiency for inertial impact and capture parameter vary with the shape of the bodies, but show the same trend (May & Clifford, 1967). Further more, the models for capture by inertia and by interception are not independent of each other.

These relationships also reveal that the sedimentation velocity decreases rapidly with decreasing drop size, since it is directly proportional to drop size squared. The stopping distance and the catch parameter are directly proportional to, among other things, the sedimentation velocity. This implies that the smaller the drop size, the more quickly the drop reaches the velocity of the surrounding fluid and follows the stream lines around an object. Another mass force acting on the drops is gravity. Low sedimentation velocity essentially explains why small drops, in general, involve risk from wind drift.

From the previous displayed equations it is clear that the probability for capture of a drop on a target increases with increasing drop size, decreasing target size and increasing flow velocity (within practical/reasonable limitations). These facts or relations are, of course, valid in reality and describe instantaneous deposition on the targets. However, execution problems lie in the difficulty in identifying the ideal and detailed model requirements. In the real world situation we have a changing drop size distribution, turbulent air flow, fluttering and wobbling objects of non-uniform size and shape, in combination with a rapidly changing situation. Leaves as targets could to some extent be regarded as ribbons or discs. Unfortunately, the situation is not stationary because they will turn, bend and rotate around their stems. Furthermore, especially with turbulence involved, we have a situation where random factors are not negligible.

In spite of the calculation problems and the detail required to describe the course of events, the relation is to the highest degree still valid and describes the capture efficiency on a general plane. We should base our actions on the essence of the mentioned relation, but do it during real world conditions, where compromise with economical, technological and environmental concerns is unavoidable.

Drop size

Air blast sprayers normally use hydraulic nozzles (swirl chambers), but in some cases twin fluid nozzles with supplemental compressed air or rotary atomizers are used. Traditionally, the nozzles are put within the air outlet, although there are examples where nozzles are placed outside the outlet and the spray is directed into the air jet.

In a discussion of what drop size should be chosen for spraying orchards, Allen et al. (1978) stated that there are so many different factors influencing application that it was impossible to isolate any specific drop size as being ideal for the full range of applications. Morgan (1981) reported similar opinions. Generally, drop sizes for air blast sprayers are smaller than for field sprayers, but are also related to the liquid application rate. Grower trends toward using lower liquid rates are accompanied by smaller drop sizes ("mist-blowers"). Standard nozzles of today's sprayers imply VMDs[1] of around 70 to 115 µm, but drop size ultimately depends on system operating pressure and nozzle size.

Wind drift, one of the main disadvantages in spraying, is strongly affected by drop size and has today grown to become a limiting factor in orchard spraying. Several papers report on drift research and recommend increased drop size as one of the measures to reduce drift (see, for example, Ganzelmeier & Rautmann, 2000, van de Zande et al., 2000, Holownicki et al., 2001, Koch, 2001).

Air-inclusion (AI) nozzles, as well as other drift reducing nozzles, were introduced during the 1990's. Use of AI nozzles reduces the number of small drops and winddrift to a considerable extent. These nozzles have been mostly used in field crops. Their use in orchard situations has been limited, as advisers and growers have been concerned about reduced foliage coverage. Field studies have indeed verified the reduced wind drift (Ganzelmeier & Rautmann, 2000), but new research also shows that the expected decrease in both deposition and biological effect was not observed (Knewitz & Lehn, 1997, Koch, 2001). The reason for this is the subject of ongoing research.

In air blast sprayers, spray drops are created in the high velocity air jet, which affects the drop size distribution. According to Reichard et al. (1979), the VMD decreased with increased air velocity due to an increasing number of small drops. Yates et al. (1985) reported the same observation.

Drop size decreases on the way to the target, as a result of evaporation which, in turn, depends on temperature, relative humidity and travel distance, as reported by, for example, Hosseinipour (1978), Nordby (1979) and Göhlich (1983). Spraying during favorable conditions, i.e. at night with low temperature and high relative humidity, the evaporation effect on drop size influence is insignificant, especially when the drop travel time from sprayer to tree is kept short due to a high air velocity and a proper air outlet geometry.

Targets

The size of the target or object is the second factor that influences deposition. Targets are defined here as single parts of the tree; leaves, buds and branches, but this chapter will also deal with the canopy as one unit. In laboratory experiments, Rosswag (1985) studied how deposition was influenced by the size and shape of leaf-like objects. In those experiments, the objects were fixed with

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[1] VMD: Volume median diameter; the dropsize of the drop that has half the liquid volume of the total spray in drops larger than itself.

their largest surfaces perpendicular to the flow direction. For small drops it was found that the narrower the object, the greater the deposit on the upper side, but this effect decreased for large drops. Deposition, in general, increased with flow velocity, but this relationship was more evident for small drops, especially with narrow targets. The lower side of the objects received mainly small drops; this effect increased with increasing flow velocity, but narrow objects were less sensitive to this effect. The fact that the objects were fixed, implies that they did not exhibit the same behavior as real leaves and reflects only an effect of size and shape.

The properties of the apple leaf surface have been studied in different contexts. It has been proven that the upper smooth surface could be considered easy to wet and that the lower hairy side absorbs drops. Metz (1986) confirmed these observations by measuring leaf properties; he also references, for example, Walker (1979). Reichard (1988) verified the phenomena by high speed photography.

Air velocity

The third important factor that influences deposition is air flow velocity. Normally, it is assumed that the velocity of the drops is equivalent to the air velocity, a statement that is more accurate for small drops than for big drops. As mentioned earlier, deposition increased with increased flow velocity. However, when an actual air blast sprayer is used to spray a crop canopy, many factors can not be controlled, and furthermore, technical and environmental facts limit the size of fans and air velocity. Even so, an increased air velocity generally increases deposition. It remains important to discuss how to efficiently use the air jet to penetrate into and expand throughout the canopy, thereby maintaining a high level of velocity close to targets and allowing greater deposition.

As far back as 1956, Brann remarked:

> *"We cannot go on solving the problems by building larger machines with more air blast. Progress lies in the direction of more efficient application of the power we are now using through a better understanding of the factors involved in getting the toxicant from the tank to the plants."* (Brann, 1956)

The airflow in orchard fan sprayers is produced by using different types of fans. However, even if there is, in practice, a close connection between the producing fan and the resulting air jet, it is more scientifically correct to discuss the different air jet types and their characteristics, on the basis of the fan outlet geometry. Rosswag (1985) showed a very illustrative presentation of the three main jet types (Figure 1):

a. Axis-symmetric jet, normally originating from a circular outlet (expanding in two planes).
b. Flat free jet, plane jet or parallel jet, normally originating from a long rectangular slot (expanding in one plane).

c. Flat fan jet or polar jet, normally issuing from a circumferential slot or annular nozzle (expanding in two planes)

During the 1980's German researchers and institutes investigated the construction of fans and their influence on air jet characteristics (see for example Göhlich et al, 1979, Lüders & Ganzelmeier, 1982, Bäcker, 1984, Moser, 1985, Rosswag, 1985, Metz, 1986, von Oheimb, 1986, etc). Figure 2 presents orchard sprayer and fan types, more like those actually used in orchards. The most common sprayers in use are equipped with axial fans; today these sprayers are equipped with many different types of deflectors or air directing attachments.

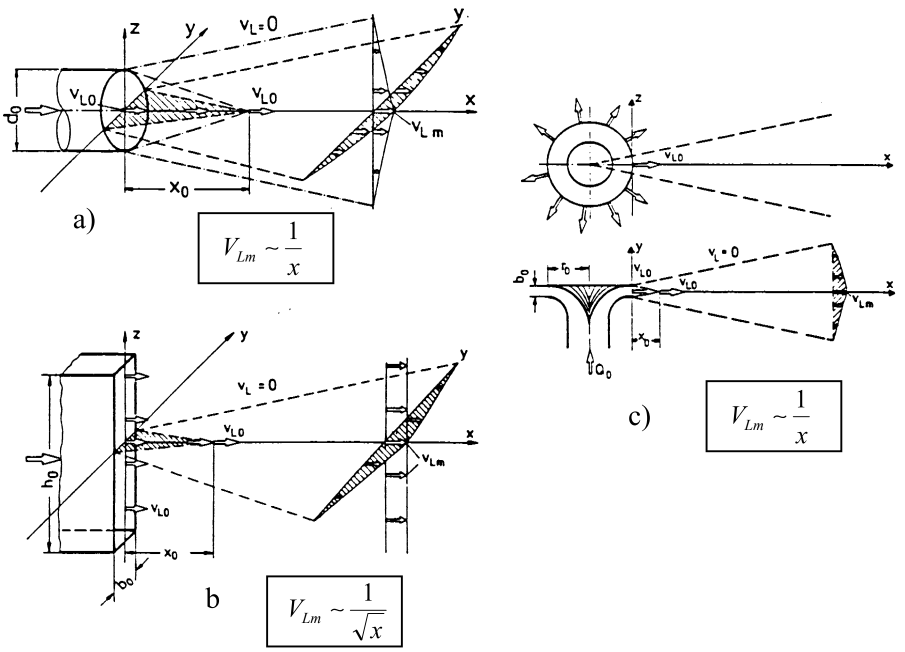

Figure 1. Air outlets with different geometry and the influence on the quality of the air jets (Rosswag, 1985).

In Rosswag's figure we find notes on the relation between maximum air velocity (in the jet center and beyond the core) and distance from the outlet. The basis for this goes back mainly to the modern turbulent jet theory by Abramowich (1963). Brazee et al. (1981) and Brazee et al. (1984a) further developed and extended the theory of air velocity fields produced by jets from the plane jet theory to a theory for a diverging 'fan-shaped' jet typical of axial-fan orchard sprayers (c in Figure 1). They also measured air velocity profiles produced by two stationary axial-fan orchard sprayers, compared normalized measured velocity fields with the fan-jet theory and found good agreement.

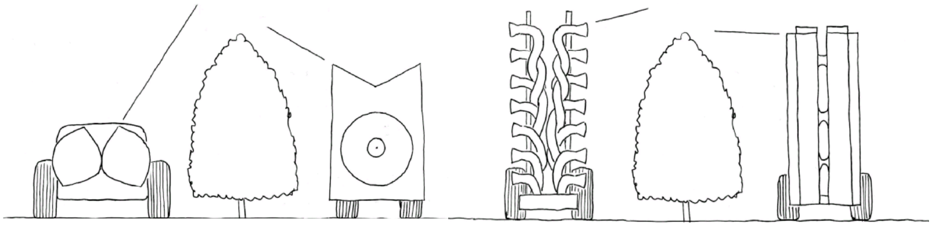

Figure 2. Different common sprayer types used in orchards.

Jet type a) and c): The velocity distribution for both the axis-symmetric and the flat fan jet could be described with the equation (4) For these types of fan outlets, the air velocity along the flow direction is inversely proportional to distance from the outlet (Brazee et al. 1981).

$$U_{\max} = \frac{U_0 \sqrt{R\, b_0}}{\sqrt{(c_m A_2)(r+R)(r-r_0)}} \tag{4}$$

U_{max} denote maximum air velocity in the main part of the jet; U_0 the uniform outlet velocity; 2 b_0 the outlet width; R is the radius of fan outlet; r the distance from outlet in the flow direction; r_0 the distance from the outlet to the pole, or apparent origin, of the main region; c_m an empirical dimensionless constant for the main region and A_2 an integral parameter depending on the velocity profile chosen for the main region of the jet.

Jet type b): The velocity distribution for the plane jet could be described with the following equation (5) (paper II). For the plane jet, the maximum air velocity is inversely proportional to the square root of distance. The latter relation is valid when the ratio of height (h_0) to width (2 b_0) is large enough. Rosswag (1985) showed that height has to be around 10 times greater than width to fulfil the condition. Figure 3 shows the principal difference between the two air velocity distributions from equation (4) and (5).

$$U_{\max} = \frac{U_0 \sqrt{b_0}}{\sqrt{A_2 c_m (r-r_0)}} \tag{5}$$

The power in the air jet is described by the equation (6), where P is the power, ρ air density, U air velocity and dA a unit area (Fox et al., 1982).

$$P = \frac{\rho}{2} \int U^3 \, dA \tag{6}$$

The fact, that air velocity varies in different ways with distance, depending on the shape of the outlet, is reflected in measurements of air velocity reported in a great number of references.

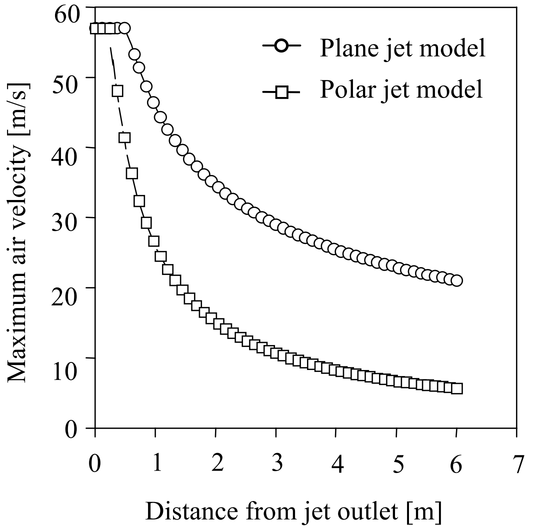

Figure 3. Axial air velocities for a diverging fan-shaped or polar jet (equation 4) and plane jet (equation 5) (Paper II).

Already in his basic work, Randall (1971) used and expressed the air jet conditions in energy or power relations. He pointed out that for a certain input of energy, the best spray distribution was obtained when the ratio of airflow to velocity was as large as possible (within practical/reasonable limitations). The relationship between power and velocity distribution was further defined and illustrated by measurements made by Fox et al. (1982), presented in equation (6) and table 3 and by Reichard et al. (1979) (Figure 4). Equation (6), together with equations (4) and (5) could describe differences in power along the jet flow direction for different air jet types. Rosswag (1985) related these facts to outlet conditions by stating that a jet with a large outlet area and a low air velocity at the outlet is more effective from the energy point of view compared to a jet with a narrower outlet and higher velocity. Through his measurements (of a scale model) he further illustrated clearly how different conditions affect the possibility of maintaining high air velocity with increasing distance from the outlet (Figure 5). The flat free jet from a long, narrow, rectangular column-like outlet has the best qualities. Cross flow fans normally have this type of outlet and flow and therefore, from this point of view, produce more favorable air jets than other fan types.

Table 3. Comparison between the air velocities at the outlet and the power required to produce an air velocity of 4.5 m/s at a distance 5 m from the outlet (Fox et al., 1982).
S1 - S3: Sprayer with the same fan, but with different width of the outlet
b_0: Half width of the outlet V_{L0}: Air velocity at the outlet P: Power at the outlet

Sprayer	b_0 [m]	V_{L0} [m/s]	P [kW]
S1	0.25	38.0	5.5
S2	0.125	47.6	5.9
S3	0.0625	62.3	7.3

The USDA research group (Brazee et al.) emphasized that the power at the outlet is only a measure of the power required to operate the sprayer. The power in the air jet at a given distance from the outlet, however, is a measure of the capacity of the air jet to transport droplets, to deflect (open) the canopy and to maintain its integrity in spite of wind.

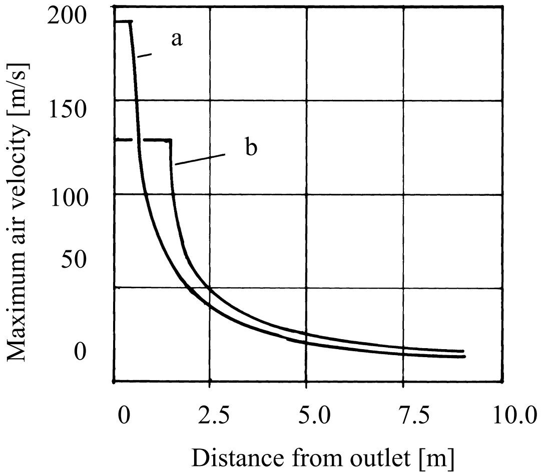

Figure 4. Comparison of air velocities as a function of distance from outlet, delivered by two sprayers with the same air horsepower at outlet but different discharge velocity and airflow rate. Fan-shaped outlets (after Reichard et al., 1979).
a: fan with high air velocity at the outlet and a lower ratio of airflow to velocity
b: fan with lower air velocity at the outlet and a higher ratio of airflow to velocity.

Figure 5 and the previous statement on power introduce another factor; travel velocity and/or wind. Equations (4) and (5) are valid only for the static situation, i.e. with a parked sprayer, no influence of outside wind, and air velocity measured in the center of the air jet.

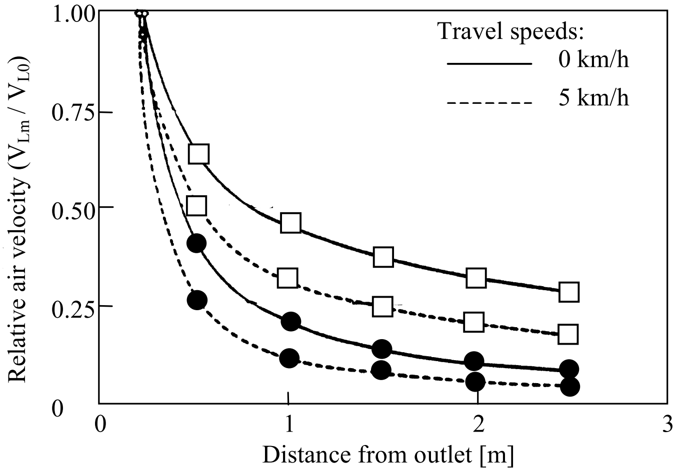

Figure 5. Relative air velocity (V_{Lm} / V_{L0}) as a function of the distance from outlet, at different outlet geometries and travel speeds. □ = rectangular outlet, ● = circular outlet. The air velocity at the outlet, width or diameter and length of the core are the same for the two outlets (after Rosswag, 1985).

Fox et al. (1985) and Brazee et al. (1984b) have studied how the air jet is influenced by travel speed and wind conditions. In Figure 6 is shown how the air jet is deflected backwards as a result of the travel wind. This effect is a result of the jet maintaining its integrity and continuously having to penetrate and to push away new volumes of stationary air. It is difficult to illustrate this phenomenon because of its dynamic structure. It should be noted that the theory as presented for the case of travel wind only, is valid as long as the target and ground are not involved.

The influence of the direction of the air jet in the horizontal plane (in relation to the travel direction) has been studied by German researchers, especially with respect to vineyard spraying. Von Oheimb (1986) showed that deposition increased, particularly on the lower side of the leaves, if the air outlets were directed 45° backward. Because the path of the air jet crossed the canopy at an angle, the travel distance of the drops inside the canopy and, in turn, the probability for deposition increased.

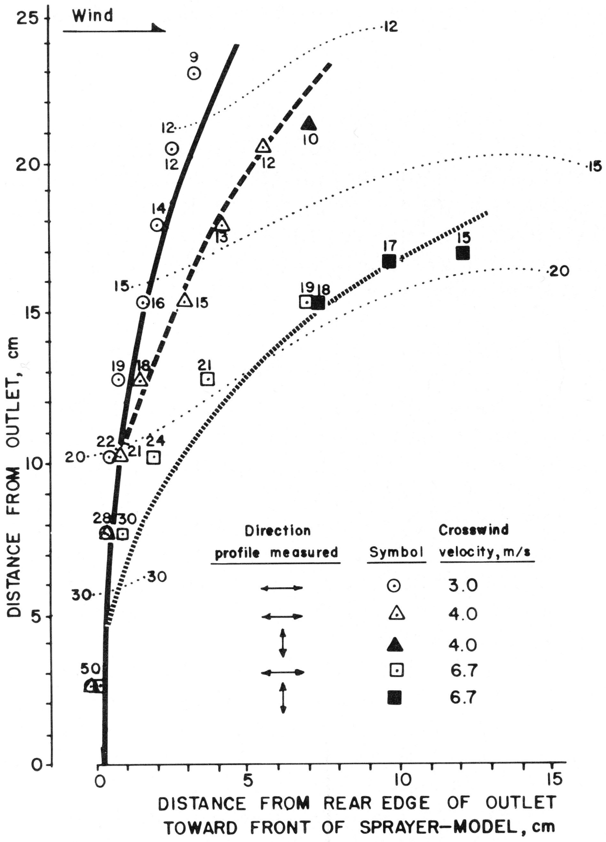

Figure 6. Effect of crosswind or travelspeed (90° angle in relation to direction of air jet at outlet) on the deflection. Dotted lines represent loci of equal-centerline air velocities (model prediction) (Fox et al., 1985).

When considering the influence of travel speed on air velocity, the effect of elapsed time must also be considered. Locher & Moser (1981) show in Figure 7 how air velocity, as a function of time, changed with travel speed. At a constant travel speed, the time during which the tree is acted on is extended in the same way, according to Hale (1978), as when air flow is increased at the expense of outlet air velocity (constant power at the outlet). The dynamics of the canopy should be affected in both cases.

Bukovac et al. (1986) point out that the problem of maintaining a high air velocity and an adequate deposition in the top and far side of the tree depends, to a great extent, on the fact that traditional sprayers have a low placed, almost point-source outlet (as jet type c in Figure 1, Figure 9 and a in Figure 10). The air jet and the spray will, for geometric reasons, diverge, resulting in a rapid decrease in air velocity and, at the same time, the spray content must be distributed over a larger area.

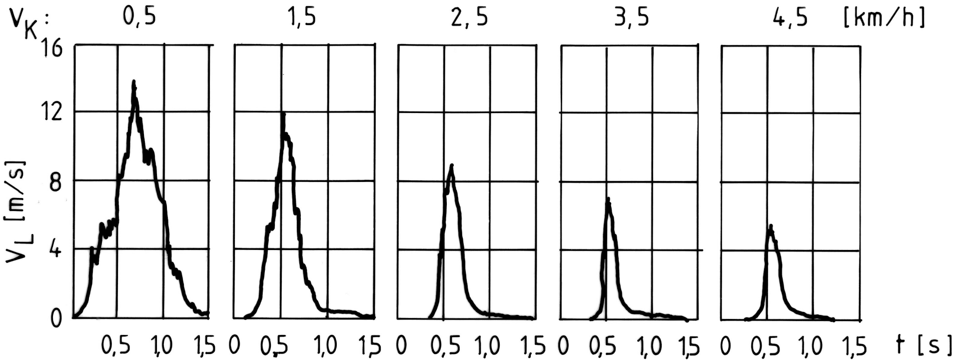

Figure 7. Air velocity (V_L) as a function of time (t) for different travel speeds (V_K) (after Locher & Moser, 1981).

Van Ee et al. (1984) pointed out that the combination of air velocity and drop size is important. They were of the opinion that, based on their experience in the development of sprayers, when using traditional nozzles, air velocities less than about 7 m/s had insufficient energy to carry the big drops into a dense canopy. The risk of sedimentation on the ground was therefore increased. For small drops they considered this effect not to be critical.

Hale (Hale, 1975, Hale et al., 1976, Hale, 1978) conducted air flow research with model experiments and also developed and investigated a sprayer prototype. Among other things, he showed that the distance an air jet reaches depends partly on the power at the outlet and partly on the airflow per unit length in the travel direction (m^3/m). Furthermore, it was shown that the deposition from a sprayer was improved if the air volume was increased and the air velocity was decreased for a fixed amount of power at the output. By using that type of sprayer, it was possible to maintain a higher travel speed and to use the sprayer during windy conditions and still achieve satisfactory results. In a similar way, Balsari & Tamagnone (1998) used m^3/ha as a treatment parameter and showed the importance of relating air volume to canopy characteristics.

Deposition in real tree canopies

Canopy as a filter or a body in the jet

Most of what has been related above about air velocities and jets, do not concern interaction with the fruit tree canopy. This is certainly an important part in the application process and it is also important to distinguish between effects that depend on properties of the single leaf and effects that result from the denseness and shape of the canopy. The canopy as a whole changes radically during the period of foliage development. The bare branches in springtime provide only a small resistance to the air jet and, at the same time, the objects (the branches and buds) are small; this leads to good deposition. On the other hand, the canopy has a very small total area, and most of the spray passes uneffected through the tree.

Spray cloud development and penetration into the canopy has been difficult to describe theoretically, as available analytical methods are more suitable for the free jets. Ras (1991) assembled most available data from earlier published research and presented a number of polynomials, where he also, based on the model results of Hale (1978) developed an analytical expression for “penetration into and propagation through foliage”. He used the air power losses and air velocity losses as expressions for the penetration. Walklate et al. (1993a), continued by Walklate et al. (1996b), presented theories for penetration, or air velocity decay through the canopy. In summary, they showed the velocity and turbulent kinetic energy to decay exponentially with penetration distance. They studied the exponent and found it to be proportional to the inverse of the jet width, the square of the ratio of sprayer speed to initial air-jet velocity and the crop density. The latter factor contained the mean gap between elemental surfaces of the crop. The theories were further developed and validated through measurements in an artificial and rigid (steel) canopy. Results showed a surprising local “channeling” effect, where air jets were guided through the canopy. This was noted as a contradiction in earlier measurements of air velocities in canopies (for example Reichard et al., 1979).

One measure of canopy density is the Leaf Area Index (LAI). Metz (1986) and Ganzelmeier (1984) presented values of LAI for apple trees. Trees used in their investigations exhibited LAI between 1.5 and 2.0 during most of the growing season. Walklate (1989), Richardson et al. (2000) and Walklate et al. (2000) used a laser based method (LIght Detection And Range system - LIDAR) in real plantations to measure the presence of canopy and thereby expressions for crop area densities. They also showed that canopy density had a great influence on deposition values. Jaeken (2001) used image analysis methods, which could be correlated to LAI, to produce more information on how canopy properties influenced deposition.

Walklate et al. (1993b), Walklate & Weiner (1994), Weiner & Parkin (1993) and da Silva et al. (2001) introduced and used Computational Fluid Dynamics (CFD) into the modeling work as a way to go further in the understanding of the interaction between air jet and canopy. In most cases artificial canopies were used for validation.

There has been some uncertainty about if and how deposition on leaves was affected by their fluttering parallel to the air flow. Metz (1986) argued that this effect assured more uniform deposition on both sides of the leaf, while the decreased projected area leads to decreased total deposition. Van Ee et al. (1984) pointed out that excessively high air velocities could make the leaves move to a position parallel to the air jet, decreasing their frontal area and thus making uniform deposition difficult. Byass (1965) measured the change in projected area of the canopy caused by the air velocity. He did not, on the other hand, draw any substantiated conclusions from the effect. However, Randall

(1971) used this result to state that a minimum air velocity to get a successful deposition was about 12 m/s.

When the cloud of drops reaches the part of the canopy closest to the sprayer, the drops have about the same size distribution as when they left the sprayer. They have a high velocity and conditions for deposition are good, especially for large drops. Deposition on leaves will selectively deposit drop sizes from the spray cloud as it moves through the entire canopy. Finally the combination of drop size, velocity and leaf size are such that all remaining drops pass through the canopy. The foliage acts as a filter; it gradually sorts out and collects the bigger drops. The effect is documented, for example, by Metz (1986) and is likely stronger in more dense foliage. Deposit filtering will change drop size distribution so drops will be smaller in the part of the canopy that is furthest away from the sprayer. Metz's measurements show that the VMD in the far side of the tree decreased to 190 µm from 280 µm in the canopy close to the sprayer. This phenomenon probably will also be reinforced due to some of the bigger drops being shattered at impact with the foliage and forming smaller drops.

It is possible to use a filter as an analogy for a canopy. This does not imply that filter equations apply directly to canopy deposits, but the analogy provides a basis for understanding. Jaeken (2001) characterized the "canopy filter" as a) a heterogeneous filter in time and space, b) a half open system with fluctuating porosity and filter depth and c) with varying boundary conditions.

On the other hand, through visual studies of orchard spraying, it is obvious that canopies also act as more or less solid bodies, reflecting and deflecting the air jet (Figure 8).

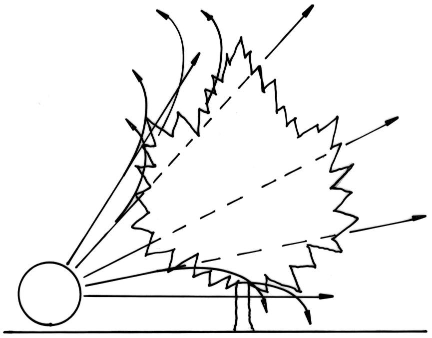

Figure 8. The tree as a filter and/or a body in the air jet.

Fan orientation and the influence on air-jet interaction with canopies

Determining the proper match between an air-jet/sprayer system and a tree canopy has been a subject for study for many years. Other research have compared deposits in tree canopies when using air-blast sprayers with several air jet characteristics.

The Australian researchers Furness & Pinczewski (1985) measured spray deposits in citrus and vineyard canopies from spraying with several sprayers with unusual fan arrangements for a range of travel speeds and application rates. A prototype, multi-head sprayer was used with both converging and diverging jet configurations. They found that the converging jet arrangement gave significant improvement in the uniformity of spray coverage on plant foliage compared to coverage when using diverging air-jets.

Examples of fan orientation, such as those first described by van Ee et al. (1984) and van Ee & Ledebuhr (1988, 1989) can be regarded as attempts to control the air velocity within the tree. Likewise, we can see efforts toward the same goals in the Danish and Dutch sprayers that have attached supplemental, high positioned outlets. However, the latter are afflicted with the disadvantage of having each outlet producing a divergent air jet (de Moor et al., 2000). As illustrated in the figure of principle below (Figure 9), the fan orientation for the sprayer developed by van Ee and Ledebuhr (henceforth called the Curtec-sprayer) is based on using a number of cross-flow fan units aiming at the far side of the canopy. They expected this convergence of the jets inside the canopy would increase air velocity.

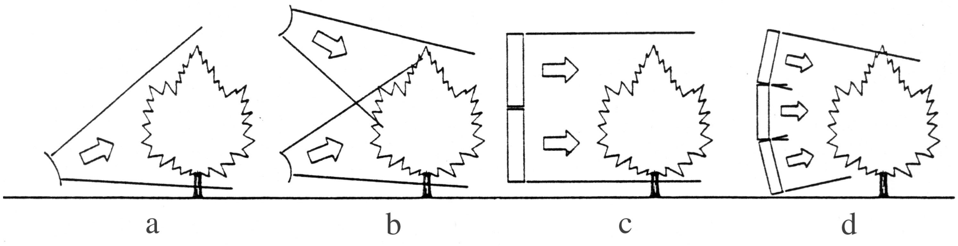

Figure 9. Fan outlets and air jet directions for commercial sprayers

a) Low positioned outlet, diverging air jets
b) Two outlets, each with diverging air jets
c) Parallel air jets (cross flow fans)
d) The Curtec sprayer (converging air jets, produced by cross flow fans, van Ee & Ledebuhr, 1988).

In Figure 10 are shown results of experiments with the Curtec sprayer. A higher and much more uniformly distributed deposition of spray liquid in the tree was obtained, by using several outlets directed toward the tree center (converging air jets), as compared to traditional technology with one low positioned outlet (diverging air jet).

Compared to a Swedish or North European fruit production system, both the American and Australian experiments utilized a totally different production system; i.e., they used larger trees, and higher liquid application rates. This is one of the important reasons why the attained experience could not easily be transferred and utilized here.

Technically, van Ee and Ledebuhr compared the Curtec sprayer with a conventional sprayer, where many other factors beside air jet directions were different. The Curtec sprayer used, for example, rotating wire cage nozzles of a special design. This makes it difficult to isolate the effects of the air jet factors from the effects of other factors in the results.

No published in-depth studies were found where in air flow, air velocities or canopy interaction were studied to give a statistically rigorous, physically based explanation of the converging air jet influences. On the other hand, from what is presented so far above, we know that air jet properties in the canopy and close to targets have a great influence on penetration and deposition.

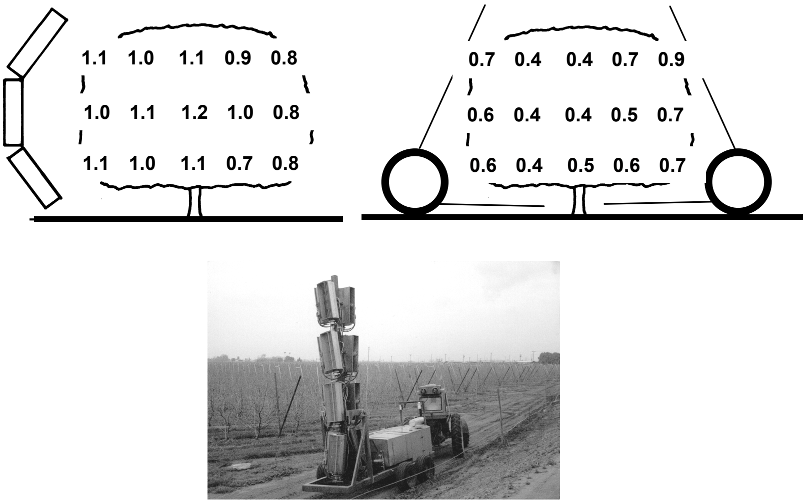

Figure 10. Relative deposition in different positions in the tree. To the left: sprayed from one side with a sprayer with converging air jets. To the right: sprayed from both sides with a traditional sprayer (polar air jets) (after van Ee & Ledebuhr, 1988). Below: the Curtec sprayer (courtesy Richard Ledebuhr)

In summary, results from orchard sprayers with converging air jets were presented during the 1980's (Furness & Pinczewski, 1985 and van Ee & Ledebuhr, 1988). They showed an exceedingly positive picture of deposition as well as distribution through the canopy – combined with lack of physically-based profound explanations. This underscores a need for a better understanding and scientific explanations, especially of the air jet properties, the interaction of the jet with canopy and then, how this interaction influences deposition, distribution and losses of spray liquid. In other words, would it be possible to obtain the same good results under North European fruit production systems, based on conventional equipment used here, and how are air jet properties, especially the converging jets, related to deposition?

Purpose of the thesis

The objectives of this work are to compare the properties of converging air jets with those of plane air jets with reference to orchard application technology.

This includes a documentation of the results through different application technology parameters, as well as developing a greater depth of knowledge on how converging air jets and canopies interact, and how this affects the application results.

Finally, the objectives comprise an effort to develop measuring methods to analyze the action of the jets on the canopy and thus complement existing methods.

The studies were limited to technical measurements of air velocity properties, of deposition and of other physical parameters. This implies that liquid deposition and distribution measurements were made without any pesticides and no measurements of biological effects were carried out. Sprayers and fans used were the same through the whole series of experiments. Two commercially available units of cross-flow fans, reconstructed to make it possible to change their vertical position angle (inclination), and in this way, to create plane jets as well as converging air jets. Consequently no axial fans or polar jets with diverging properties were used. The liquid distribution sections of the original sprayer were not modified. Almost all experiments were made in a dynamic situation, i.e. the sprayer with the fans was passing the apple tree where measurements were made.

All studies, with one exception, were made outside laboratories, in field situations. The studies utilized apple trees of a dwarf type, representing common North European apple production. Most of the studies were made on apple tree canopies in full leaf, but some studies cover the season from nearly bare branches to full leaf stage.

Objectives, methods and materials for studies carried out

Relations between the studies

This chapter was included to describe the work as a whole. The intention is to demonstrate how the results from one experiment gave rise to the purpose of the next. Materials, methods and results are summarized, and will be further presented and discussed in the following chapters.

As was concluded from the background discussion, results from orchard sprayers with converging air jets were presented during the 1980's by American and Australian researchers. They showed an exceedingly positive picture of deposition as well as distribution through the canopy.

The purpose of the first experiments, presented in Paper I, was to study the effects of converging air jets on deposition. First, were the good results really an effect of the converging air jet properties or were they an effect of other significant parameters? Secondly, were these effects valid only for typically large citrus trees or could they also be expected for the conditions of Swedish or North European fruit production? Already at this point, the hypothesis included air jet conditions as important factors for explaining deposition results. Therefore, air velocity measurements inside the canopies were also planned, at exactly the same positions as the deposition targets, i.e. at different depth of the canopy and in several trees. Fan positions were as in a) and c) in Figure 11.

Measurements of deposition confirmed clearly the earlier presented American and Australian research, also showing that the results were valid in the conditions of Swedish fruit production. The influence of the season (i.e. changing canopy density) was distinctly illustrated. The measurement of air velocities provided new and important knowledge. Basically, there was agreement between deposition and air velocity, but furthermore, the research identified inherent principle problems in measuring and analyzing air velocities. There was a need for high sampling rate equipment, with the possibility of determining flow direction. The air velocity (during a fan passage) was not represented by one single value that could be treated statistically, but by a pulse, that contained a lot of information components. Furthermore, if the velocity pulse values were sampled and computed in a appropriate way, they could be connected to parameters of application technology (as velocity cubed – mechanical power of the air jet; integrated velocity over time – air flow; integrated velocity cubed over time – air jet energy).

During the work with Paper I, we discussed the hypotheses that the apple tree canopy may behave both as a nearly solid body and as a leaking filter to the impacting air jet. These models are necessary to explain both the spreading of the jet above the canopy and penetration and deposition inside the canopy.

An in depth series of air velocity measurement inside, above and beyond an apple tree canopy was made in order to study the penetration ability of the converging air jets. The experiments were made in USA, utilizing measuring devices of good quality. The experiment included three different degrees of converging air jets, as in a), b) and c) shown in Figure 11. In addition, travel speed and fan rpm, parameters known to influence air velocity distribution and penetration, were also incorporated in the study.

The results were presented in Paper III and display a confirmation of the limited measurements presented in Paper I, but furthermore, made it possible to study more parameters and relations within the framework of the interaction between air jets and canopies.

In connection with this study, a stationary documentation of the air jets was made, with the intention of a thorough verification of the velocity distribution fields. This result was presented in Paper II and confirmed that the plane air jet used in the experiments could be described by the models earlier developed by Brazee et al. (1984a). It was also obvious that the converging air jets could not be described by a simple modification of the available models.

When experience from Papers I, II and III were combined with other research presented in literature, it was evident that air velocity characteristics were important to the deposition process. However, another outcome, equally important, was that measurement of air velocities in a dynamic situation (when the fan was passing the sensor) was certainly a complicated operation. Most of all, it was made clear that the results were influenced not only by the local position of the sensor in relation to the surrounding canopy parts, but also by movements by leaves and branches, as well as by the so called 'channeling-effect' (Walklate et al., 1996b). These factors produce many random events which lead to great variation in measured velocities and a need for many replicates.

To manage these shortcomings, a new method of measuring air jet/canopy interaction was developed. The method made it possible to measure the forces and moments caused by the air jets transferring energy to the tree. As presented in Paper IV, the results were certainly promising, showing agreement between the force- and air velocity-results. Furthermore measured signals were more stable as they showed less fluctuations and a very high repeatability.

Paper I (Orchard spraying - deposition and air velocities as affected by air jet qualities)

The main purpose of the first experiments was to study the influence of converging air jets on spray liquid deposition and air velocity distribution inside the canopies of common North European apple trees. This study was expected to confirm preliminary experiments in other countries that obtained positive deposition results when using converging jets, and trying to confirm international good results and to provide information about how air flow influences canopy deposition.

Four deposition measurements were made in apple trees during the growing season, from April 25 to September 27, 1990 in Alnarp (55 39N, 13 05E), southern Sweden. Leaf sized filter papers were put in seven positions in each of five trees (four papers in each position). The same positions were used in all experiments. Row distance was 5 m, tree spacing 3 m and tree height 2.3 m. Travel speed was 6 km/h. The comparable spray rate was 200 l/ha, but the trees were sprayed from one side only, to get a clearer distribution pattern. A fluorescent tracer (Helios 010 EC) was used and deposition was analyzed with a fluorimeter (Ciba Geigy PFM2).

The sprayer had two cross flow fan units (Holder), reconstructed to permit the angle of the fans to be changed. Figure 12 shows the two fan arrangements used as treatments in the experiment; straight fans producing a plane jet and angled fans producing a converging air jet.

On two occasions during the season air velocities were measured at the same seven positions used for deposition targets. Air velocities were sampled by two pin shaped hot film anemometers at two positions per sprayer pass. The sensors were moved from position to position during the repetitions (four set-ups per tree). An air velocity pulse was recorded for each passage and sensor. After low-pass filtering of the signal, a value of the maximum air velocity of each pulse was computed.

Paper II (Air jet velocities from a cross-flow fan sprayer)

The objective of this study was to test the hypotheses that the air velocity field produced by a two-fan, cross-flow sprayer can be represented by a plane-jet mathematical model and that inclining the top fan increases air flow at elevations typical of dwarf apple tree canopies.

The measurements represented a static situation, as the sprayer was parked inside a large fabrication shop. The sprayer fan units used in Paper I above were also used for this study. However, the fan positions were changed; positions used were: both units vertical and the top unit inclined 20° and the lower vertical, as shown in Figure 11 a) and b). Two outlet power levels (fan speeds) were studied; 1080 and 1476 rpm[2].

The air velocities were determined with a transversing hot-film sensor. The sensor measured the horizontal traverse velocity profiles at distances up to 6.0 m from the outlet (Figure 13). The maximum velocities were compiled for two heights; at the center of the lower fan unit and at the height of the joining point between the two fan units.

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[2] rpm: revolutions per minute

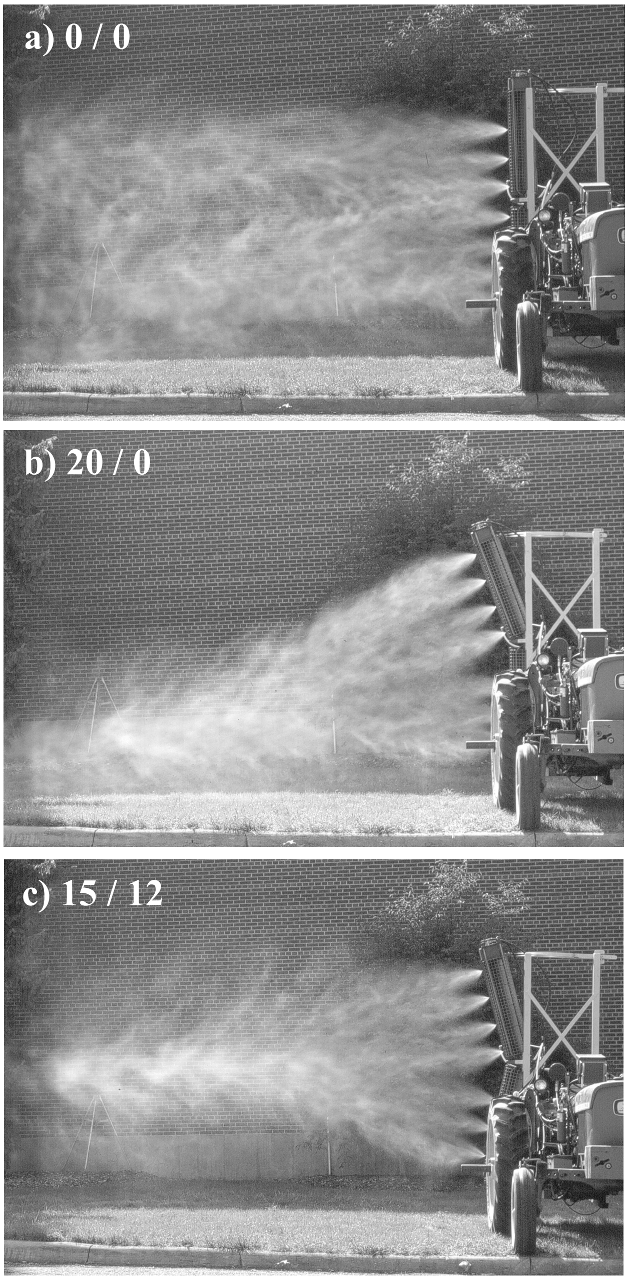

Figure 11. The three fan angle settings or ‘fan positions’, used in the experiments.

a) Both fan units vertical, resulting in a plane air jet, used in all experiments.

b) Top fan unit inclined 20º and the lower unit vertical, resulting in a converging air jet, used in experiments for Paper II, III and IV.

c) Top fan unit inclined 15º and the lower unit 12º, resulting in a converging air jet, used in experiments for Paper I and III.

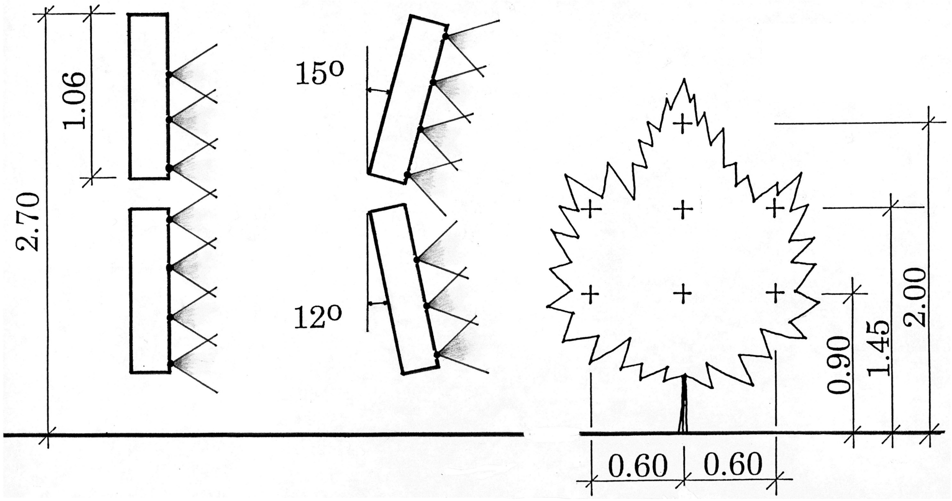

Figure 12. Fan arrangements with plane and converging air jets in Paper I, together with measurement positions in trees (four leaf sized filterpapers in each position). Measurements in meter.

The air velocity field was compared with two air jet models; the polar or "fan-shaped" air jet, as described by Brazee et al. (1981) and the plane jet (Abramovich, 1963). Empirical constants for the plane jet model were based on the actual cross flow fan properties and calculations for the polar jet used the same outlet width and outlet air velocities.

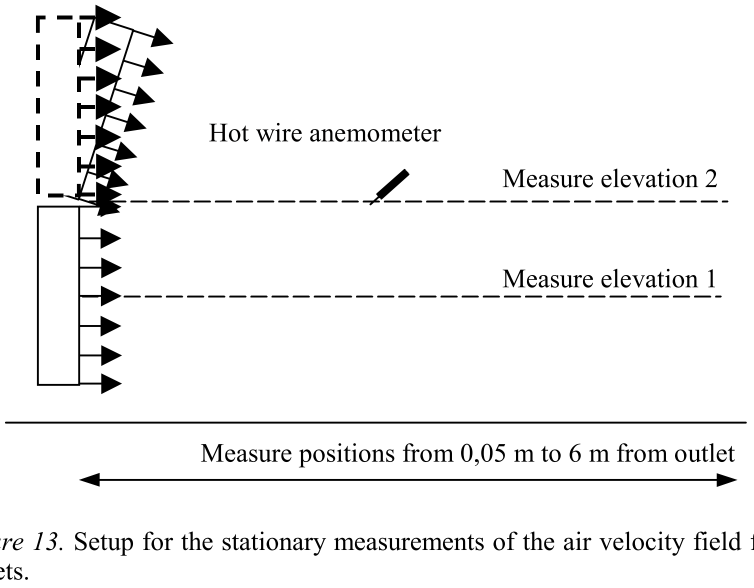

Figure 13. Setup for the stationary measurements of the air velocity field for converging air jets.

Paper III (Air jet velocities in and beyond apple trees from a two cross-flow fan sprayer)

The objectives of these experiments were 1) to determine if converging air jets penetrated an apple tree canopy better than a plane air jets, 2) to study the effects of sprayer travel speed, fan outlet air velocity and fan jet characteristics on the air velocity inside and around the apple tree canopy.

The measurements were made in a dwarf apple orchard in Wooster, Ohio, USA (40 46N, 81 54 W). Row distance was 4 m, spacing between trees in the row was 2 m and tree height was about 2.4 m.

Two vertical profiles of air velocity distributions were measured; tower one was near the center of the tree and tower two was in the drive path behind the tree. The hot film anemometer sensors at the two lowest levels on tower one were x-probes. Sensors at levels three and four were triple sensors. The sensor at level 3 was within the canopy and level four was above the canopy. A single-sensor probe was used at the top position (4.2 m above the ground) on this profile. Four (single sensor) anemometers were located on tower two, at about the same heights as the sensors on tower one. Air velocities were recorded as the sprayer was passing the sensor equipped apple tree. The original sampling rate was 2300 Hz, later computed and averaged to represent a velocity pulse with 30 values per second.

Three experiments were carried out, using three treatment factors: three fan positions (different degree of converging air jets), three travel speeds, and two fan speeds. In the first experiment, the air jets were acting on the west side of the tree. In the second the sensors were moved and the air jets were acting on the east side of the tree. In a third experiment the towers with the sensors were set-up in a way that air velocities were measured as the sprayer moved past the towers with no tree foliage to deflect or absorb air flow. Figure 11 shows the three fan positions used and Figure 14 below describes the sensor positions and the setup for air velocity measurements.

During the analysis of each pulse we calculated maximum velocity, velocity integrated over time, maximum velocity cubed and velocity cubed, integrated over time. These expressions can be associated with traditional physical parameters important for the spray application situation. Figure 15 shows a representative pulse as presented by Svensson (1991). Randall (1971) and Hetherington et al. (1995) present similar shapes. In general, the air velocity increases rather rapidly when the jet initially strikes the canopy, whereafter it damps out slowly and returns to its initial level.

One of the characteristics of the air velocity pulse is the maximum velocity. It could be regarded as an expression for how well the air jet was able to penetrate the canopy. As will be demonstrated further on, the instantaneous maximum exhibits great variation and is sensitive to random influence, and should be used with care. The velocity integrated over time is an expression of the volume of air passing a unit area at the measuring point. If we assume that the air from the jet contains drops of the spray liquid, this integral will also express a potential prerequisite for deposition. Calculated as an integral, it represents a more stable result, balancing out the signal fluctuations. A few large values are somewhat smoothed by the width of the pulse, and it also includes how well velocities are sustained across the total pulse width. High frequency variations will be suppressed and the integral represents a more reliable result.

The cubed velocity value is proportional to the mechanical power of the air jet and is by that also an expression for the power acting at the measuring position. As earlier mentioned, maximum values of such a fluctuating nature need many replicates to be reliable. A more stable expression is therefore the integral of the cubed velocity over time, logically proportional to the air jet energy in the position during a passage of the sprayer.

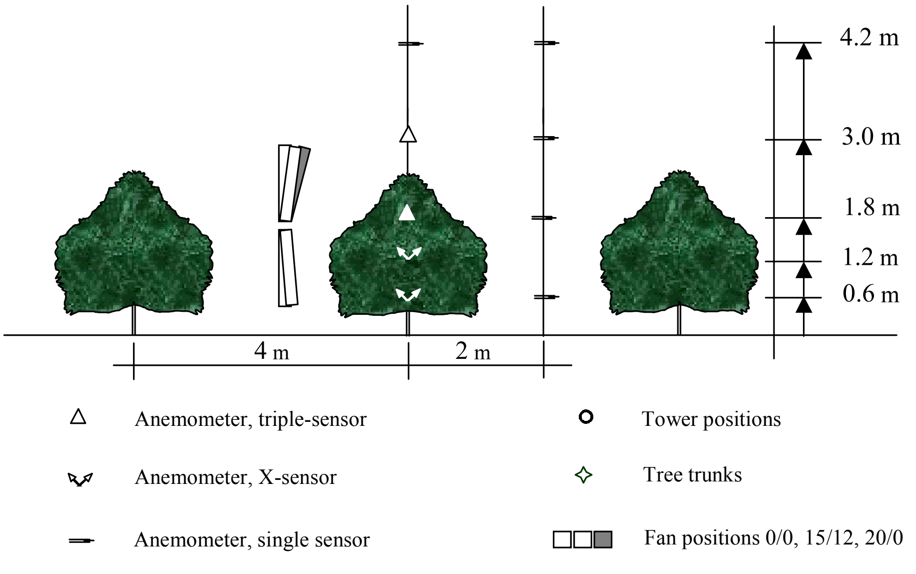

Figure 14. Arrangements for air velocity measurements presented in Paper III.

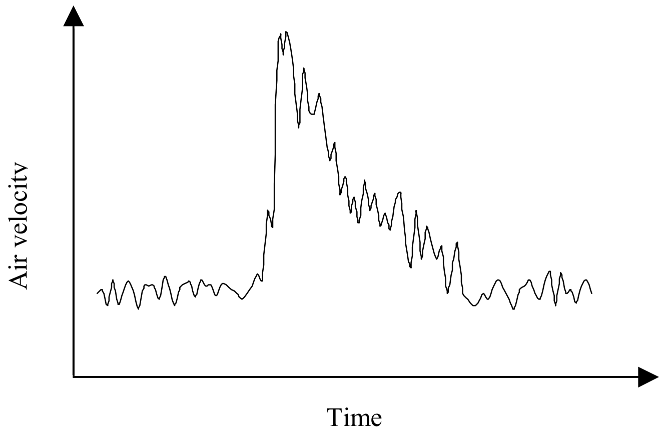

Figure 15. Air velocity pulse as a function of time. The figure shows a representative pulse appearance.

Paper IV (Forces on apple trees sprayed with a cross-flow fan air-jet)

The objective of this study was to develop an alternative to air velocity measurements for describing air-jet/tree canopy interaction and to test this new method by measuring forces applied to trees by sprayer jets during spray passes.

The experiment was conducted in Alnarp, Sweden. The apple trees used were dwarf trees of height 2.4 - 2.6 m. Figure 16 shows how a force-sensing dynamometer was mounted between the ground and the trunk of a cut-off apple tree. The multicomponent force transducer provided force measurements in the X-, Y-, and Z-directions and a measurement of the moment about the Y-axis. The X-direction was in the nominal direction of the sprayer air-jet, Y-direction was in the travel direction, and the Z-direction was vertical.

For each measurement sequence, three apple trees were cut in a neighboring orchard and placed 1.75 m apart in a row. The center tree was equipped with the measuring device. The sprayer drive path was parallel to the tree row and aligned to simulate a row spacing of 4 m. The dynamometer was connected to a data logger system and for each sprayer pass of the tree, the three force signals and the moment signal were sampled at a rate of 250 samples/s.

The sprayer with two cross flow fan units was the same as earlier described, but with two fan positions (both units vertical, and top fan inclined 19°, bottom fan vertical). Treatment combinations in this experiment were the two fan positions and two fan speeds. Travel speed was 4.7 km/h. The experiments were repeated with three different trees. After 20 passes for each tree, the tree with the force sensor was rotated about 180 degrees and a new series of experiments conducted. Each side of the test trees was considered a different tree.

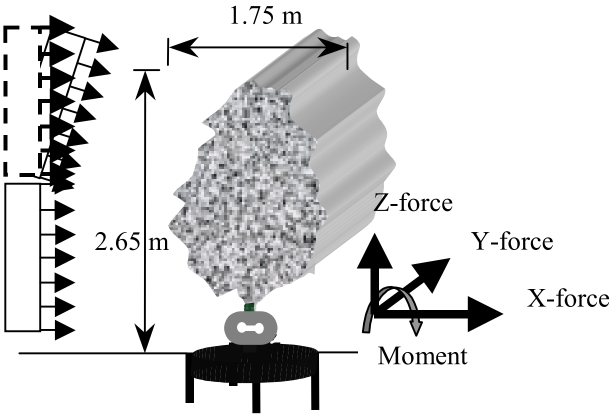

Figure 16. An apple tree attached in the multicomponent force transducer.

Results and discussion

Deposition measurements

Spray deposit amounts were measured by using a fluorescent tracer in the spray liquid. Results were to be compared with earlier research in other countries that showed improved coverage with converging air jets. However, the earlier studies were conducted in large trees and with greater liquid application rates than typically used by Swedish growers.

Deposit result, as summarized in Figure 17, showed that converging air jets resulted in a general deposition level that was about 50% higher than comparable plane jets. For the converging air jets, the deposition displays as an "arrow-like" trace through the densest part of the canopy, resulting in increased deposition at the height of the junction between fan units. The plane jet demonstrated a reduced deposition at the same height. The season, i.e. canopy density, played an important role for spray penetration, as illustrated in the cross section of the canopies. The shape of the "arrow" became more diffuse as canopy became more fully leafed.

Uniformity in deposition over the apple tree canopy was studied. Converging air jets were found to give a more uniform distribution than plane air jets. During the first spring spraying, the canopy was very thin and the deposition distribution for the angled fans was nearly the same as the distribution without trees. By the next spraying, at the end of May, the canopy had already developed so much that a clear change had taken place. For both sprayer configurations deposition displacement towards the sprayer could be noted. This is a result of the difficulties inherent in forcing a spray cloud to penetrate the denser canopy, and a typical example of increased filter-density and more “solid-body” behavior. Furthermore, statistical analysis showed that both position in the trees and the trees themselves influenced the results.

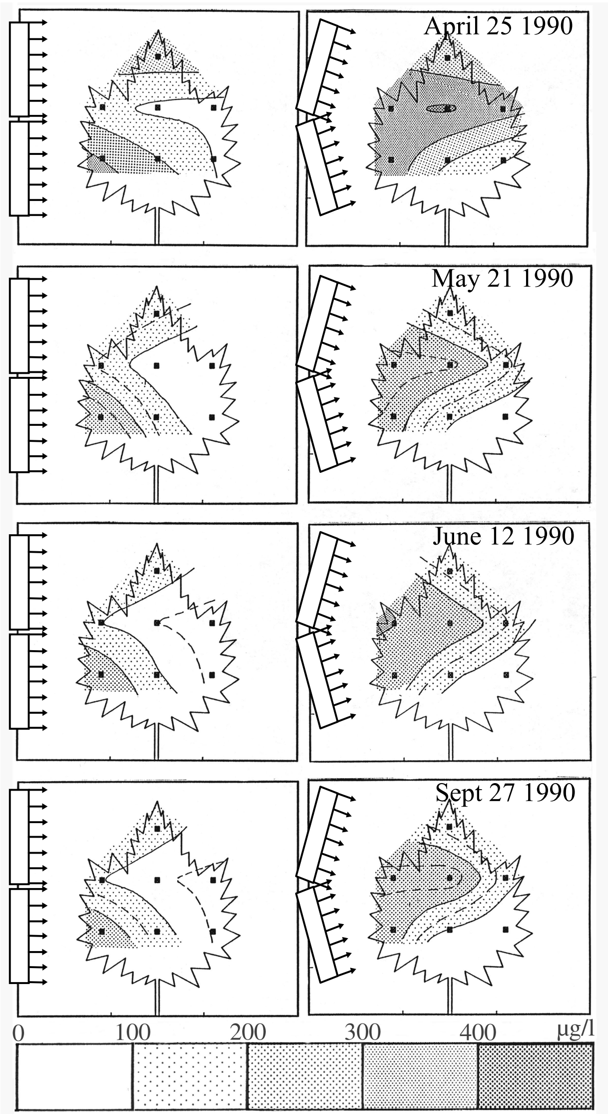

Figure 17. Deposition distribution in trees for plane jets and for converging jets. Trees are sprayed from left side only. Deposition levels are shown with contour lines and shading, indicating tracer concentration in wash liquid.

Air velocity measurements

From the introductory chapters, we know that air velocity parameters have a great influence on the effectiveness of results in orchard spraying. In general, the air jet should transport the spray cloud to the canopy, open the canopy, penetrate and disperse the drops inside the canopy, set the canopy parts in motion, and finally deposit the drops on the plant parts. We also know that the central phenomena in the detailed impact process partly depends on the air jet factors giving the drops a velocity that makes them leave the air streamline and impact leaves and twigs through inertial phenomena. These facts have been emphasized through many years of research.

The basic air velocity distribution from the orchard fan sprayer was documented through stationary measurements of the air velocity and without trees disturbing the flow. The results showed that the air jet axial velocity from the cross flow fan with both units vertical, agreed well with the traditional plane jet model (Abramowich, 1963). The maximum air velocity from this type of jet is expressed by the model to be proportional to $1/r^{1/2}$, where r is the distance from the fan outlet in the direction of the flow. This should be compared with the polar or 'fan-shaped' jet, where the air velocity is proportional to 1/r (Brazee at al., 1981). For equations and diagrams, see page 15).

The air velocity distribution from the converging jets did not agree with any of the current models, but showed other interesting qualities. With the top fan unit inclined 20° downwards, a very clear increase in air velocity was observed at lower elevations, at a distance of 1 – 2 m from the outlet. Far out, at distances > 4 m, and higher elevations (at about 2 m height) the air velocity was lower than for the plane jet.

This indicates that the converging of the air jets will give increased air velocities at distances where the apple tree canopies appear and reduced velocities with a downward-directed air flow far away from the sprayer. This is a result of the inclined upper fan unit supporting and strengthening the velocity profile of the lower unit.

Two other experiments with air velocity measurements inside and around canopies in the dynamic state are presented in this thesis. The results support each other, even if the experiments were carried out under different conditions and principles. The first result, presented in Paper I, describes the velocity distribution (expressed as peak velocities) over the tree row cross section, showing the converging air jets penetrates the canopy better than the plane jets. Maximum values should be used with care, and the air velocity experiment in Paper I is characterized as 'limited' with respect to sample rate and analysis. However, with the number of replicates and the number of trees, positions and times used, the measurements could certainly not be disregarded. A limited number of measurements made at elevations above the tree, showed here a reduced air velocity for the converging air jets (Svensson, 1991).

In Paper III, air velocities along a vertical centerline inside and above the tree were presented. In addition, the same types of measurements were made along a vertical line behind the tree. Several air velocity parameters were computed. In general, the converging air jets increased the air velocity inside the canopy, reduced the air velocity above the tree and conveyed a larger volume of air into the canopy. Power and energy levels were higher for the converging air jets than for the plane jets. The only position showing a different picture was the lowest position in the tree. It was located at the same level as the lowest part of the fans and when the lower fan unit was angled up, this velocity sensor was outside the air jet.

In both air velocity measurements for Paper I and III, great differences were observed between sensor positions, trees and replicates.

Force measurements

A method was developed to measure the forces and moments that the air jet exerted on the tree parts, that is, to measure how the air jet transferred kinetic energy to the tree. The force measurements were carried out as a new way to view how the canopy was influenced by the air jet. Apple trees were mounted in a multicomponent force transducer to determine the total effect of the moving air jet on the tree. The power transfer from air jet to canopy takes place as number of summations over the separate parts of the canopy. Short-time variations depending on turbulence, leaf positions, etc were balanced out, resulting in a very high repeatability. Furthermore it was the canopy itself acting as a part of the sensor. Influence from outside factors was limited. By this global tree approach, we expected to bypass some of the problems encountered with air velocity measures, i.e., the great variability in replications, sensor position effect, etc, that had such a strong influence on earlier studies.

For converging air jets, both forces and moments were significantly greater than forces caused by the plane jets. An increased output power (increased fan rpm) resulted also in significantly higher forces and moments. The time, during which the forces/moments were acting on the tree, was significantly longer for converging jets than for plane jets. Even though the difference was just 0.2 s, it represented about 10% of the total interaction time. Force and moment measurements confirmed air velocity results that converging air jets have a stronger influence on the canopy than plane jets.

Earlier we discussed different ways to compute sampled air velocity results. The computed values, maximum air velocity, velocity cubed, as well as their integrals can be used to constitute conditions or parameters for deposition. The force acting on separate tree parts is proportional to essentially the squared air velocity, a characteristic area and the drag coefficient (Wood, 1995). The force results presented in Paper IV therefore imply another evident physical relation to air velocity (v). The information could most of all be related to the power (proportional to v^3) or energy (proportional to $\int v^3\, dt$).

The mechanism that governs drag forces probably is closely related to the mechanisms that control the transfer of power or energy, or the transfer of drops to the leaves.

Drag forces are proportional to leaf size and shape, frontal area, local flow streamlines and therefore, necessarily, depend on leaf dimensions and position with respect to flow direction, etc. As the sum of air energy at the outlet was the same for the two fan positions, and a greater force was transferred by the converging air jets, the remaining power from the plane air jet simply missed the canopy or to a greater extent hit the less dense part of the canopy.

A synchronous recording of force and moment made it possible to calculate the elevation in the canopy where an apparent resulting force would be applied to produce measured moments. During the main time when the air jet acted on the tree, the computed averaged signals were rather stable and showed high repeatability within trees, but no significant differences between the moment elevation for converging and vertical fans were noted.

A representation of the force pulse was obtained in the same way as for the air velocity measurements. The pulse provided a picture yielding both maximal values and later calculated integrated values. However, the method did not give a detailed picture of how the air jets were deflected above and below the canopy (either as to direction or size).

Physical fragility of hot-wire or hot-film anemometers normally prevent a simultaneous measurement of air velocity and deposition of spray liquid. Preliminary experiments have shown that that it was possible to combine measurements of both forces and deposition, a fact that in future will gain more understanding of the interaction of canopies and air jets.

General comments

As described in the introduction chapter, deposition depends not only on the air velocity, but that the liquid phase parameters also have a great influence. Deposition measurements were made for experiments in Paper I, and throughout all of these experiments, liquid rates and drop sizes were kept constant. Figure 12 shows how the positions of open nozzles were changed to keep the vertical liquid distribution as uniform as possible even when the inclination of the fan units changed. However, it was still not possible to completely avoid effecting the vertical liquid distribution, as inclining the fans resulted in a more concentrated vertical liquid distribution, closer to the tree.

More concern should be addressed to the vertical space between the fan units. The distance between the fan units could not be made less than 18 cm due to technical and practical reasons. This blank space was reflected in deposition (Paper I) as well as in air velocity distribution (Papers II and III). Hetherington et al. (1995) illustrate the same effect on the vertical air distribution profile from similar fan units. A continuous vertical fan (if mechanically possible) would probably not exhibit this ‘gap-effect’ to the same extent.

The influence of the vertical liquid distribution on the deposit pattern in trees should not be exaggerated. Thorough research have shown that the relation between the spray distribution in real canopies and the statically measured vertical liquid distribution was not confident and unequivocal (Schmidt & Koch, 1995, Kaul et al., 1996). At least, a vertical distribution, statically adjusted to canopy shape (as, for example, measured with a vertical patternator), did not seem to show any better result than a uniform vertical distribution.

The influence from outside air movements in relation to the sprayer air jet, whether due to natural wind or travel induced wind, have been studied by Fox et al. (1985). The air jet is not only bent backwards, as seen from the sprayer and shown in figure 6, but its reach is also reduced. For polar jets with a diverging spread profile, the vertical plume width at a distance will be reduced (compared to the stationary situation) and, in the same time, more concentrated.

Walklate et al. (1996a) have noted higher deposition values and reduced drift with increasing travel speed for axial fan sprayers. They could be an effect of plume concentration (reduced width), due to travel-induced wind. With converging air jets, a similar factor/effect is built in by inclining the fan units, resulting in the higher deposition values reported. Expressed in other words, converging air jets redirected the spray from probable losses above and below the canopy to potential deposition in the densest parts of the tree.

We should also discuss the reduced uniform deposition distribution due to increased travel speed that was noted by Walklate et al. (1996a). As was shown in Paper III, the integrated velocity values increased when travel speed decreased. An increase in integrated velocities could be correlated to an increase in air flow and in the number spray drops reaching a canopy site. In Paper IV, the converging factor itself was shown to have a small but significant positive influence on the action time. These effects together would imply that an increase in travel speed reduces the penetration ability and the time during which the jet acts on the canopy. A prolonged action time would mean increased chances for leaves to flip another time in the turbulent flow and increased chances to collect drops on both sides.

Hetherington (1997) discussed the scale of turbulence important to orchard spray applications with air jets. He notes that turbulent flow is created by unstable velocity gradients, due to shear layers. Away from the sprayer outlet, the shear layer between the jet boundaries and ambient air mainly control the development of turbulence. When a jet penetrates a tree canopy, branches and leaves create shear layers that support turbulence on a smaller scale. Turbulent size scales that affect spray drop transport and deposition include undulations in leaf surfaces, leaf size and position, air jet dimensions, and wind speed, direction and interaction with the tree canopy. According to Wood (1995), the drag force transfer is affected by the properties of the targets and the air jet. Thus, there seems to be room for a speculation that if converging air jets produce an increased turbulence, this could have a positive influence on both force transfer and on drop deposition through greater and higher frequency air movements in the canopy.

There is an important difference between measurements of air velocity and deposition. Deposition is a result of an accumulation during the whole passage, while air velocity is presented as a function of time. Consequently, to compare deposition and air velocity correctly, the integrated velocity values should be used, or deposition result should be displayed as a function of time. The latter demands a complicated measuring system and Randall (1971) seems to be the only researcher describing such a system. Unfortunately, no results were presented.

Accumulation or integration across sample pulses also results in more stable signals. In our experiments this was evident from the great variations for maximum air velocities while integrated velocity values displayed less variation.

As pointed out in Paper III, air velocity variations are derived from the original turbulence in the air jet, influenced by more random factors during the interaction with the tree. Random tree effects include random location, size, and movements of leaves and plant parts. In addition, the effect of developing temporary, stable local “channels” through the canopy, as described by Reichard et al. (1979) and Walklate et al. (1996b), are often superimposed on the random flow field. These random actions certainly influence air velocity values and call for many repetitions, measurements in several different trees, and high quality measurement equipment with a high sampling rate.

We also noted differences in variability between deposition values and peak velocity values. Four leaf-sized filter papers, positioned in different directions and angles, constituted one sample for deposition, while a 11 mm long, hair-thin hot film sensor was used for velocity measurements. Thus deposition values represented an integral volume compared to a point air velocities measured by the hot film sensors. The results in Paper IV, where integration over all parts of the canopy resulted in stable force measurement signals with high repeatability, provide another example of the same effect. Without a great number of point measurements inside dense canopies, it is difficult to decide if we are measuring the characteristics of the measurement position or the general properties of the air jet.

Practical consideration of air velocity measurement systems are illustrated in the differences between systems used Paper I and III. In Paper I, two rather simple hot-film sensors, connected to a PC-logger, were easily moved between measuring positions, within the canopies and from tree to tree. In Paper III a more sophisticated system was used, with a great number of sensors, a much higher sampling rate, giving flow direction information. However, this sensor system needed regular calibration, demanded great manpower to operate and was also difficult to move.

The high repeatability in the force measurements made it possible to study differences in interaction time (pulse width). The difference is small; about 0.2 s (2.1 – 1.9 s), but significant. A general effect of this was also noted in Paper III, where the integrated values (containing the time factor) caused clearer differences between treatments than the air velocity maximum values, with an advantage for the converging air jets over the plane jet. Another example of the same effect was noted when the slower travel speeds resulted in greater integrated values than faster travel speeds.

Application of results in practice

The results are of most interest to other researchers, developers and manufacturers of orchard sprayers. First of all, the study would strengthen the arguments for and illustrate how air velocity properties could be utilized to improve the performance of orchard sprayers, both for increasing deposition efficiency and for reducing losses. For example, it should be possible to combine the results of this study with the results from Holownicki et al. (2000) who suggested developing a sprayer system to control the air jets in response to outside wind, travel speed, etc. With such technical remote control possibilities, the air jets could be directed to create converging air jets appropriate to canopy conditions.

When designing sprayers, major emphasis should be focused on the air jet properties and the outlet characteristics and less on the fan type itself. Furthermore, there are certainly other ways to construct converging air jets than demonstrated in this study. For growers, the results underline the necessity to always also carefully direct the air jets and adjust the air flow, in addition to the normal adjustment of liquid rate and distribution, for varying canopy conditions. These adjustments will provide better utilized spray liquid with reduced losses and will lower chemical costs and reduce wind drift.

The converging effect presented here was achieved by just changing directions of the fan units, and the fan outlet power was unaffected. Thus, it is important to note that the positive effects are obtained without any additional fuel consumption.

One disadvantage connected with the converging air jets of the kind used in these experiments is the fact that their vertical coverage is reduced. These converging air jet sprayers can not treat trees as tall as comparable plane jet sprayers, and certainly not reach tree heights attained by the polar jet sprayers (axial fan sprayers). However, in the latter case the reach is made at the expense of a larger portion of the spray missing foliage and being transported out of the orchard as wind drift. Solving the practical and technical problems of spraying tall trees with converging air jets have been shown by manufacturers (i.e., BEI Incorporated, 2001).

It should also be noted that the type of cross flow fans used in this study has an advantage in small tree plantations, where they are very easily adjusted to fit changing tree sizes and shapes.

Future research

The method of measuring forces reveals relevant information on the influence of the air jet on the tree canopy. At the same time, it has to be stressed that this method is not a replacement for other measuring principles, but augments and complements them. It gives information on the total air jet impact as a function of time, with high repeatability and low disturbance from outside factors. However, force measurement will not reveal any detailed information on air jet penetration or velocity distribution. It would be interesting to combine this with other research on, on one hand the jet penetration and deflection process and, on the other hand, spray deposition within the canopy.

The analogy of the canopy as a filter and/or a solid body was mentioned in the introduction (Svensson, 1991, Jaeken, 2001). Efforts to apply these concepts should be strengthened and further studied, in association with measurements in real or artificial canopies. Weiner & Parkin (1993) and Walklate et al. (1993a) presented interesting results where CFD[3] was introduced as tools in modeling and providing a different prospective for understanding air jet interaction or spray deposition.

Walklate (2000) showed that tree density is the most relevant factor in relating tree or canopy properties to dose calculation. Walklate measured the canopy

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[3] Computational Fluid Dynamics

density with LIDAR -equipment[4]. Jaeken (2001) and his colleagues worked with methods of photography/image-analysis to determine expressions of the canopy density. These methods could benefit by added information on how passage of different air jets – in the dynamic situation – could be related to canopy characteristics. Including force measurements during the sprayer jet passage will incorporate the time-aspect.

There are other interesting possibilities for connecting the force measurement method to other research methods. Van de Zande (2001) used artificial apple trees, constructed as copies of real trees. These gave, in the case of deposition, interesting correspondence with real trees. It would be interesting if this also was true for air velocity conditions and forces. If so, "instrumented trees" with different properties would be used for research, as well as for testing and development of sprayer equipment.

As early as 1971, Randall described experiments with time-related deposition measurements. This challenging research subject would provide basic knowledge by combining in detail (and in reality) deposition and air velocity parameters.

Conclusions

In this study, converging air jets are compared to plane air jets, produced by the same fan units, with the same outlet velocities, and other operating parameters.

The main conclusions are as follows:

- ➢ Converging air jets increased the air velocity parameters in the denser parts of the fruit tree canopy
- ➢ Converging air jets resulted in significantly higher deposition values, more uniformly distributed through the canopy of the studied trees
- ➢ Converging air jets showed higher power and energy values inside the canopy
- ➢ Converging air jets transferred greater forces to the canopy

An explanation for this result could be split in the following steps:

- ■ Converging air jets reduced the air directed above and below the canopy, and exhibited better angles for penetration into the canopy
- ■ For the same reasons, the converging jet also concentrated and increased the amount of spray liquid reaching the canopy

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[4] LIght Detection And Range system (LIDAR)

- Finally, concentration of the air jets increased air velocity, which improved deposition prerequisites inside the canopy.

When the air velocity results in Papers I and III are compared with the deposition maps in Paper I, there is a clear correspondence. These are confirming answers to the questions that were basal for the executed research. We can expect increased deposition through converging air jets, just as presented by American and Australian researchers, but with the use of Swedish or North European fruit tree conditions and with commercial available technical sprayer components available here.

Furthermore, we presented a new method for measuring forces and moments caused by the air jets striking the tree. This method has the potential to extend and complement other application technology measuring methods.

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ORCHARD SPRAYING - DEPOSITION AND AIR VELOCITIES AS AFFECTED BY AIR JET QUALITIES

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Keywords

Air blast sprayer, application technology, cross-flow fan, fluorescent dye, plant protection

Abstract

Apple trees were sprayed four times during the growing season with air blast sprayers with two different cross-flow fan configurations, producing converging air jets and horizontal, parallel jets, respectively. When converging air jets were used, deposition, measured on artificial targets with fluorescent dye, was 50 % higher and the distribution pattern in the canopy was more uniform. Maximum air velocities were measured in the same positions and correlated with the deposition results. Losses, detected as spray liquid behind the trees, appeared lower down (beneath the tree top level) when converging air jets were used.

1 Introduction

The objective of application technology as used in chemical plant protection is uniform distribution of the desired amount of active ingredient on the intended target area with the smallest possible losses. However, the three-dimensional structure of trees and shrubs makes it difficult to obtain the desired result.

In Swedish orchards, spraying with air blast sprayers is the common method of application. The sprayers and doses used today result in relatively effective plant protection, but have also obvious disadvantages.

The air jet and the canopy interact, where the canopy is a complex and irregular target. In addition, the canopy changes from being open and sparse in the spring time to a dense body that is difficult to penetrate later in the growing season. To get enough coverage on tree positions most difficult to spray, today's equipment will overdose portions of the tree near the sprayer by 3 - 4 times. Local overdoses up to 8 times the amount required for control have been reported (Hall et al., 1975). Losses due to wind drift or wasted on the ground can be between one third and two thirds, depending on external conditions.

During the last ten years, sprayers with new fan types and great changes in the outlet design and outlet positioning have been introduced (figure 1). Common to these sprayer designs are efforts to reduce the upward directed air jets and to increase canopy penetration and uniformity in deposition. These design changes also produce changes in the air jet conditions. The air jets shown in figure 1 a) and b) are typical of those produced by axial fan units, while the parallel air flow shown in c) is normally produced by cross-flow fans. These fans also could be positioned with different angles as shown in d), which creates converging air jets.

Sprayers with converging air jets, in most cases gave improved chemical deposition or at least more uniform distribution, compared to axial fan sprayers (Van Ee et al., 1984, Furness et al., 1985, Whitney et al., 1991).

The main purpose of this work was to study the influence of air movements on deposition in trees and air velocity distribution, especially when air jets were directed towards the centre of the tree (Svensson, 1991, Fox et al., 1992).

2 Methods and materials

2.1 Deposition measurements

Four deposition measurements were made in apple trees during the growing season, from 25 April to 27 September 1990. The variety used was Katja on A2, pruned between 'slender' and 'free' spindle. Row distance was 5 m, tree spacing in the row 3 m and tree height 2.2 - 2.3 m. The trees were sprayed from one side to get a clearer distribution pattern. Travel speed was 6 km/h.

Artificial targets (filter papers, 25 mm x 60 mm) were put in seven positions in each of five trees (figure 2). The targets were concentrated in a plane through the widest part of the tree, perpendicular to the sprayer travel direction. The target holders were left in the same position during the entire year. To reduce the effect of target orientation, four papers were attached in different directions in each position. This technique should provide samples more representative of a volume in the canopy instead of a single point.

The spray rate was 200 l/ha, calculated on spraying every row. The chosen nozzles were Albuz APT 212 (yellow) with a pressure of 0.47 MPa. The spray liquid was water containing a fluorescent tracer, Helios 010 EC (A 710 2A, Ciba Geigy). Deposition was measured with a Ciba Geigy Fluorimeter PFM2. Isopropanol was used as the solvent for washing the dye from the filter paper.

The sprayer had two cross flow fan units (Holder). To permit the angle of the fans to be changed, a hinge was installed between the two units. Two fan arrangements were used; straight fans where the outlet creates a straight, vertical line (parallel air jets) and angled fans where both fan units have an angle to the vertical line (converging air jets) (figure 2). Fan rpm was 1470.

Based on deposition measurements, the vertical liquid distribution without trees and behind the tree row was also calculated. The same spray parameters and methods as mentioned earlier were used.

2.2 Measurements of air velocities

Air velocities were measured at the same positions as used for deposition targets. However, measurements were made only two times during the growing season. Air velocities were collected by two pin shaped hot film anemometers (TSI Air velocity transducer 8640) controlled by a personal computer. With the sensors orientated parallel to the travel direction of the sprayer (perpendicular to the expected main velocity direction), angle errors were minimized. A representative value of maximum air velocity was computed by low-pass filtering of the signal.

The undisturbed velocity distribution (i.e. without trees) from different fan arrangements were measured in an experiment where the sprayer was driven past the stationary sensors. Another experiment was conducted to make a more detailed analysis of the velocity distribution. The sprayer was stationary and the sensors were moved across the air jet.

3 Results

3.1 Deposition

There was a clear difference in deposition between the two fan configurations (figure 3 and table 1). For the straight fans (parallel air jets) there was a clear decrease in deposition at the height of the gap between the fan units (this will be called 'fan junction height'), while for the angled fans (converging air jets) there was a clear increase at the same position.

In all cases the treatments (straight and angled fans respectively) were significantly ($P \leq 0.001$) different. There was a significant difference for the interaction between treatment and position, which means that the treatments produced different deposition distributions in the trees.

The difference between the deposition values for each position were calculated, as well as the coefficients of variation (CV). The difference between the two fan configurations was great and significant ($P \leq 0.001$) at the positions 1, 4 and 6 (figure 2), i.e. the fan junction height. In the other positions, the result was influenced by the different treatments only to a lesser degree. The CV were in all cases greater for straight fans than for angled fans and the CV increased with increasing canopy density.

The deposition measurements behind the tree showed that the vertical liquid distribution had its maximum over tree top level for straight fans, while for angled fans, the maximum was at fan junction height.

3.2 Air velocities

The maximum air velocities at different positions are presented in figure 4. During the analysis great variation between trees, positions and replications was noticed. The maximum air velocity was considerably higher in the tree centre for angled fans. When the total values (averages over all positions for each fan configuration) were compared, the air velocities from angled fans were about 1.7 times higher than from straight fans. The coefficients of variation for the velocity distribution were approximately 60 % for straight fans and 40 % for angled fans.

Measurements behind the tree showed that the air velocity was at maximum at a higher level (over tree top level) for straight fans compared to angled fans.

In the first (field) measurements of undisturbed (without trees) velocity distributions the angled fans concentrate the air jet in such a way that it will be more convergent, i.e. will produce a higher maximum value and will have less spread in the vertical direction. In the second (stationary) measurements velocity distributions were compared when both fan units were vertical and when the lower unit was vertical and the upper fan unit was inclined 20° from the vertical. The velocity fields from the two fan configurations showed great differences, where inclining the upper fan decreased the region of low velocity near the fan at fan junction height and greatly reduced the height of the combined jets from the two fans (figure 5). Also, when the upper fan was inclined, air velocities at the midline of the lower fan unit increased about 10 % at 3 m from the fan outlet.

4 Discussion

The deposition values for angled fans were about 50 % higher than for straight fans, and, at the same time, the distribution was more uniform. The difference in total deposition value was due to the big difference at the fan junction height. The increasing density of the canopy during the season resulted in changes of the distribution shape and increasing uniformity of the deposition. The greatest changes took place during the first three measurements (April - June), while the difference between the last two measurements (June - September) was small. The changes seem to be unaffected by the different treatments. For both sprayer configurations, deposition displacement towards the sprayer could be noted.

The results support the hypothesis (and results from the literature mentioned earlier) that converging air jets produce greater deposition and more uniform distribution in the foliage. From the penetration results compared with the additional measurements of liquid and air velocity distribution without trees, behind trees and over tree top level, it may be concluded that the good deposition result from spraying with the angled fans depends on a combination of different positive factors.

One main factor is the increased air velocity, directed to the widest and most dense part of the tree, which improves the collecting conditions at a greater depth into the foliage.

Another factor is how the tree, regarded as a more or less solid body, influences the air jets. The liquid distribution collected behind the tree and the velocity distribution at the same positions show that with parallel air jets, a greater part of the liquid passes over the tree. This could, to some extent, be explained by an unfavourable angle between the air jet and the canopy, which causes the air jet to be deflected over the trees.

Another factor of possible influence is that converging jets concentrate the vertical liquid distribution more than parallel jets. This phenomena is highly disrupted by the canopy interaction and can not be proved by the experiments made. However, the opposite expression of this factor could be observed clearly with polar-jets (axial flow sprayer), where both liquid and air velocity are radially spread.

The analysis of air velocity measurements reveals areas where understanding is limited. Some recordings had large variations in amplitude, and, at the same time, the velocity pulse occurs over a longer time interval. This may be one indication that the maximum velocity value alone is not sufficient to specify the effect of air velocity.

A final conclusion could be made on how the result would be implemented in practice. Even if the deposition results from converging air jets are better and more uniform, the distribution is not perfect. A more uniform distribution would be expected if the fans were positioned as presented in Fox et al. (1992), with the lower fan unit almost vertical and the top fan unit inclined 15 - 25°, depending on tree size.

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Table 1 - Summary of deposition values [µg/l] for different dates, fan configurations and positions. The values represent tracer concentration in the wash liquid. Tracer concentration 100 µg/l is equivalent to a deposition of 19 µl spray liquid in one position (= 4 filterpapers). The trees are sprayed from one side only (from left, according to figure 2, which also shows position numbers). Coefficients of variation (CV) for different dates and fan configurations are also presented.
Str. fans = Straight fans Angl. fans = Angled fans

	Before blossom 25 Apr 1990		After blossom 21 May 1990		After blossom 12 June 1990		After harvest 27 sept 1990	
Position	Str. fans	Angl. fans	Str. fans	Angl. fans	Str. fans	Angl. fans	Str. fans	Angl. fans
1	82	348	38	170	29	157	32	128
2	97	104	47	53	37	49	45	43
3	258	235	156	116	131	133	123	117
4	77	411	64	263	50	265	60	293
5	205	209	133	114	107	116	125	96
6	135	382	138	277	99	302	103	256
7	295	363	290	233	270	251	253	238
Average	164	293	124	175	103	182	106	167
CV %	54	38	71	49	80	51	71	56

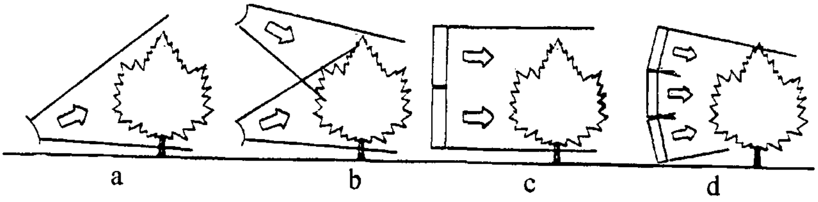

Figure 1 - Examples of fan outlet types and air jet directions for orchard sprayers.
a) Axial fan; diverging air jet
b) Axial fans; two diverging air jets, converging into the tree
c) Cross flow fans; parallel air jets
d) Cross flow fans; three parallel jets, converging into the tree.

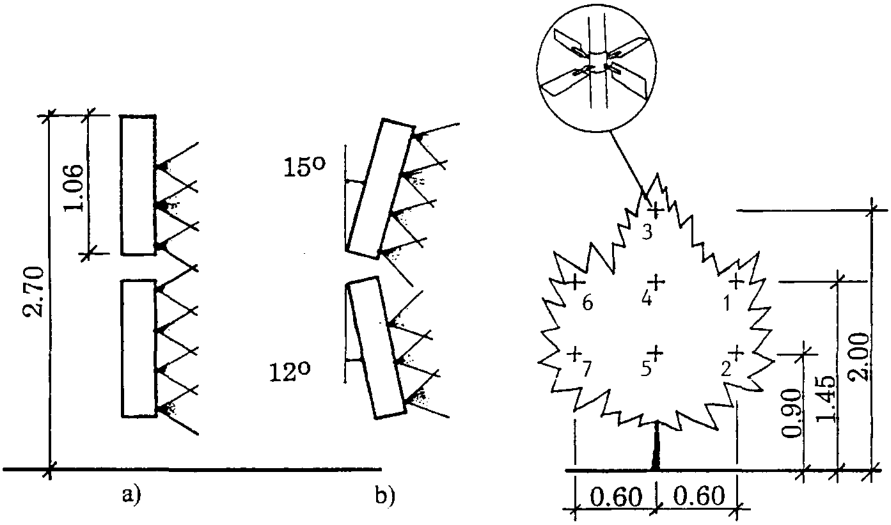

Figure 2 - Cross section of apple tree row, showing target positions, object orientations, fan unit configurations and nozzle positions. Measure in metre.
a) Straight fans, producing parallel air jets
b) Angled fans, producing converging air jets

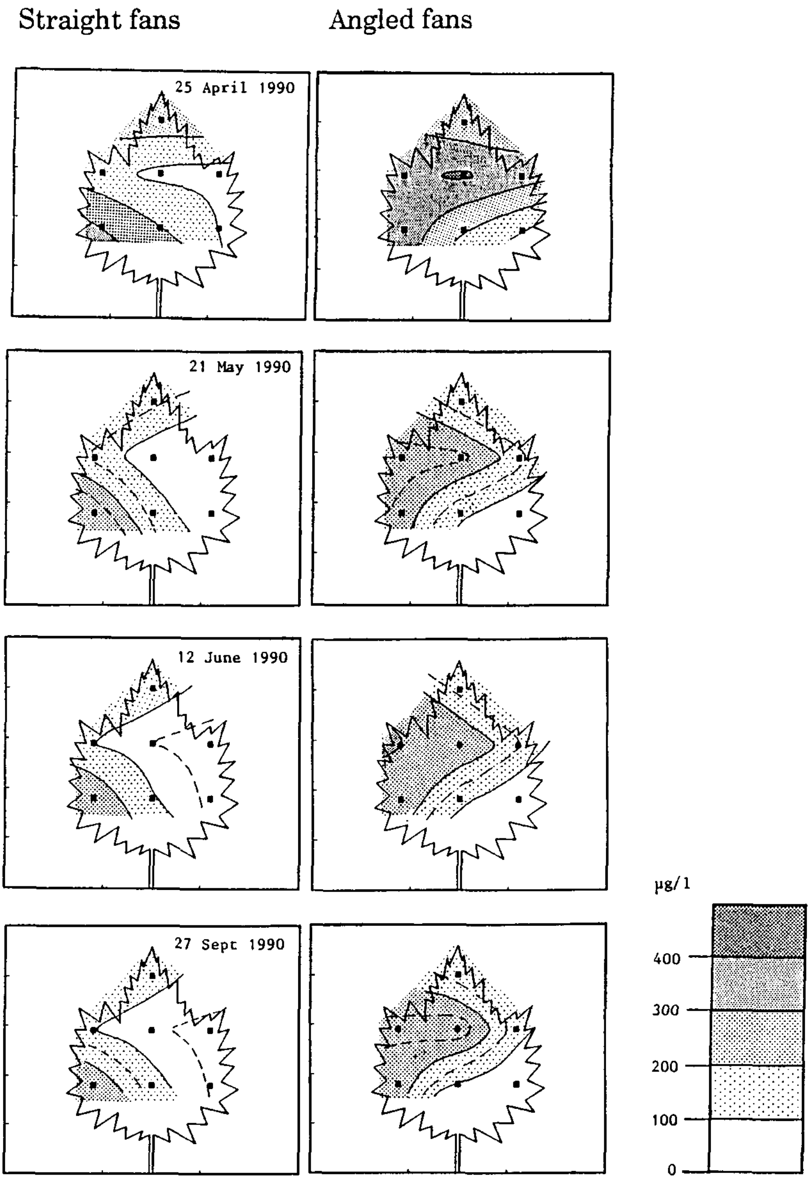

Figure 3 - Deposition distribution in trees for two different fan configurations. The trees are sprayed from left side only. Deposition levels are shown with contour lines and shading. The figures are based on the results from seven positions in each of five trees. A computer program for linear interpolation was used to construct the contour lines. The values represent tracer concentration in the wash liquid. Tracer concentration 100 µg/l is equivalent to a deposition of 19 µl spray liquid in one position (= 4 filterpapers).

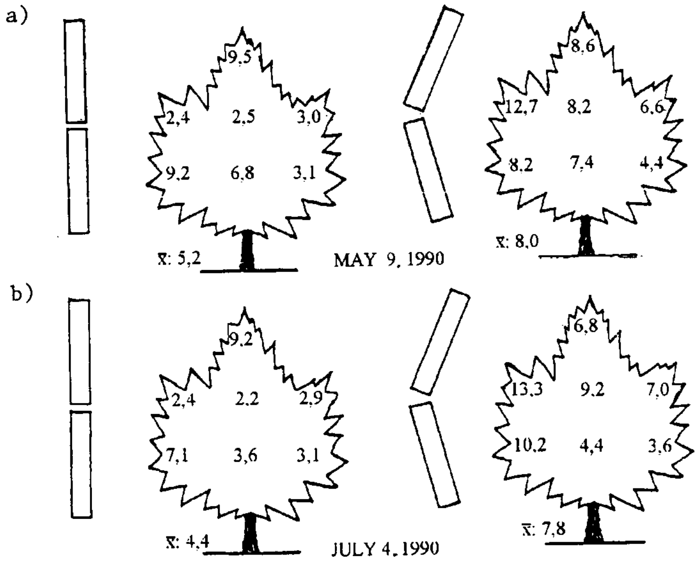

Figure 4 - Results of air velocity measurements in different positions in trees. The presented values represent maximum air velocity (in m/s).
a) without leaves during blossom
b) with leaves after blossom

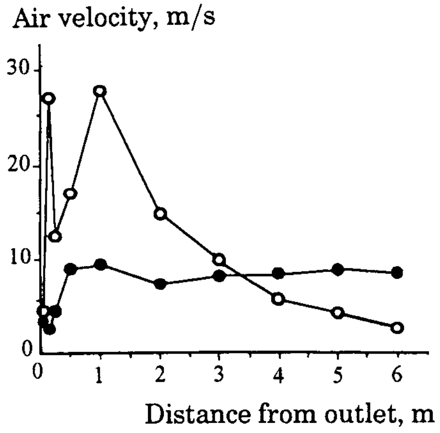

Figure 5 - Maximum measured velocities along the axial centerline at an elevation of 1.9 m (fan junction height) for two cross-flow fan units. Fan rpm: 1470. After Fox et al., 1992.

○ top fan unit inclined 20°, lower fan unit vertical

● both fan units vertical

AIR JET VELOCITIES IN AND BEYOND APPLE TREES FROM A TWO–FAN CROSS–FLOW SPRAYER

S. A. Svensson, R. D. Brazee, R. D. Fox, K. A. Williams

ABSTRACT. *The penetration of a sprayer air jet into an apple tree canopy was measured. An air–assisted sprayer with two vertical, cross–flow fan units, moving past the tree (without spraying liquid) provided the air jet. Treatments included three fan positions (fans vertical [0/0], top fan inclined 20° [20/0], and top fan inclined 15° with bottom fan inclined 12° [15/12]), three travel speeds (4.8, 6.4, and 8 km/h), two fan speeds (18 and 24.5 r/s), and three canopy conditions (south to north [SNT], north to south [NST], and north to south without a tree [NSO]). Vertical air velocities profiles were measured with hot–film anemometers in the center of the tree row and in the drive lane beyond the tree row. Maximum measured velocity, velocity integrated over the time of the air velocity pulse, air power (velocity cubed), and integrated power over the velocity pulse were measured or computed. The passing air jet produced distinct velocity pulses at elevations of 0.6 (except for [15/12]), 1.2, and 1.8 m within the tree and at elevations 0.6 and 1.8 m in the center of the drive row beyond the tree. Only fan position [0/0] produced distinct velocity pulses at the 3.0 m elevation, and no treatment produced visible pulses at the 4.2 m elevation. Fan positions had great and significant influence on air velocities inside tree canopies. At the 1.8 m elevation in the tree center, converging air jets [15/12] produced the highest velocities, followed by the [20/0] treatment. The plane jet [0/0] produced the lowest velocities at this position. Fan position had little significant difference on air velocities at the 1.2 m elevation in the tree. Fan speed had great and significant influence on air velocities. Travel speed produced little difference among treatments when maximum velocities were considered; however, there were greater differences when integrated velocities were considered. For the canopy conditions, greater velocities were measured for the treatments without canopy; however, velocities for the SNT treatment were nearly as great. Velocities for NST treatments were significantly less. This illustrates the effect of velocity sensor position (local canopy differences) on measured velocities. In general, converging air jets, low travel speed, and high fan output power improved penetration velocity and power into the tree canopy.*

Keywords. *Air jets, Air velocity measurements, Application technology, Cross–flow fan, Converging air jet, Fan sprayer, Orchard spraying, Plant protection.*

Orchard sprayers commonly use air jets to transport spray droplets into tree canopies. The air jet characteristics as well as the liquid part of the spray cloud influence deposition (Hislop, 1991). Air velocities in the sprayer jets are critical to how effectively the droplets are transported into the canopy and deposited on the leaves. Typical sprayers use an axial fan to produce the air jet. Air velocities in these jets have been shown to decrease rapidly as distance from the jet increases (Randall, 1971; Brazee et al., 1981). Due to the distance from the sprayer outlet to the tops of trees and the attenuation of air jets by the diverging air jet and by tree canopy interaction, spray deposits in the top–center of trees are usually much less than deposits near the sprayer outlet (Hall et al., 1975; Vang–Petersen, 1982; Juste et al., 1990).

The measured air velocity, integrated over time of the sprayer pass, expresses the flow of air through a position, thus indicating how much of the available flow has penetrated the canopy. Because the air contains spray droplets, airflow volume during a pass is one of the factors influencing the deposition result. The power of an air jet is proportional to the velocity value cubed (Fox et al., 1982). Thus, integrating the cubed velocity values over the time interval of a sprayer pass produces a result that is related to the available energy in this position of the tree.

Randall (1971) measured air velocities in and between apple tree canopies as produced by three sizes of axial–fan sprayers. He calculated the air power values from the air velocity pulse, measured at each sample position, and used that as an expression for the air jet penetration ability. He found that sprayer jets with greater air volumes at lower air velocities penetrated trees better than jets with lower air volumes and greater air velocities, given that all sprayers produced the same air power. This was confirmed in deposition measurements.

Planas et al. (1998) observed what initially might seem to be contradictory results. By reducing the flow rate from 8.2 to 4.5 m^3/s (or increasing travel speed), they gained deposition but found reduced uniformity within the canopy. However, this change in deposition could be explained by

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reduced air penetration into the canopy, as expected from Randall's (1971) results.

One of a sprayer's operating properties is a combination of the fan output flow and forward travel speed. It is expressed as the available flow per m in travel direction, or "machine output" stated in m^3/m forward travel (Hale, 1978). Hale (1978) conducted a study of model sprayers in a wind tunnel to determine the optimum sprayer outlet size to effectively penetrate model trees. He concluded that it would require an air output of 3.7 m^3/m in calm winds and 5.6 m^3/m in windy conditions to penetrate trees that were 5 m tall. For hedgerow plantings (about 2 m tall), 2.8 m^3/m would be sufficient to penetrate the trees at forward speeds up to 11 km/h.

Reichard et al. (1979) measured air velocities from two axial–fan sprayers that were driven past a vertical array of anemometers at several speeds and at several distances from the anemometer sensors. They found that measured air velocities decreased as distance between the sprayer fan and the anemometers increased, and that air velocities decreased as travel speed of the sprayer increased.

Derksen and Gray (1995) found no significant difference among air velocities within apple trees when an axial–fan sprayer drove past at 0.9 and 1.3 m/s or when the fan air–volume output was 652 or 822 m^3/min. There was also no significant difference between total deposits on trees sprayed with these sprayer treatments.

Several commercial sprayers have been introduced that use cross–flow fans (Van Ee et al., 1985; Bäcker, 1984; Svensson, 1994; Derksen et al., 1999). Air jets from cross–flow fans are "plane jets" and produce velocity fields that decrease less with increasing distance from the outlet than velocity fields from axial fans (Fox et al., 1992). Cross–flow fans are usually mounted in a vertical array for spraying trees. This reduces the distance from the fan outlet (spray atomizers) to the intended target in the tree. Vertically inclining cross–flow fan units to create converging air jets in most cases gave improved chemical deposition, or at least more uniform distribution, compared to axial–fan sprayers (Van Ee et al., 1985; Furness and Pinczewski, 1985; Whitney and Salyani, 1991).

Svensson (1994) used a two–fan cross–flow sprayer in which the fan units were vertically inclined to produce a converging air jet. He found that, in general, this increased the spray deposit and improved deposit uniformity through the tree canopy. He also made limited measurements of air velocities inside canopies of the same apple trees and found higher air velocities for the converging air jets.

Objectives

The objectives of this study were: (1) to determine if a converging air velocity pattern from two cross–flow fan jets penetrated a dwarf apple tree canopy better than a plane jet pattern, and (2) to measure the effects of sprayer speed, fan outlet air velocity, and fan jet characteristics on the air velocity of the sprayer jet in the center and beyond a typical small, dwarf (European–style) apple tree.

Materials and Methods

Orchard Site

Experiments were conducted in August 1991 at the Ohio State University/Ohio Agricultural Research and Development Center (OSU/OARDC) Horticulture Unit 2 orchards in Wooster, Ohio. Treatment trees were selected because they were similar in shape to trees being grown in Europe. The trees were Smoothee Golden Delicious planted on Mark rootstock in 1987 and trained as slender spindles. Tree spacing was 4 m between rows and 2 m between trees in each row. Tree height was about 2.4 m, and row width was about 2.4 m. Row direction was north–south. A tree with uniform density and characteristic shape was chosen for the study.

Anemometer System

Figure 1 displays the locations and type of sensor–probes used for measuring air velocities. All sensors were anemometers of 6–mil constant temperature hot–film type; the probes used were: two triple–sensor, two dual–sensor, and five single–sensor probes (models 1294–60, 1240–60, and 1244–60, respectively, TSI, Inc., St. Paul, Minn.). The triple–sensor probes were controlled by TSI model 1054b linearized servoamplifiers, and the output signals were resolved by an analog resolver and combined with flow directional data (Fox et al., 1980) to produce three velocity components along the sensor axes at the sensing points. The resultant signals were recorded on FM analog tape recorders (model 3500, Sangamo, Inc., Indianapolis, Ind., and model 3900, Hewlett–Packard). The dual–sensor probes were controlled by servoamplifiers (model 700, Flow Corp., Watertown, Mass.), and the output signals were connected to sum and difference correlators (model 1015C, TSI, Inc.) for

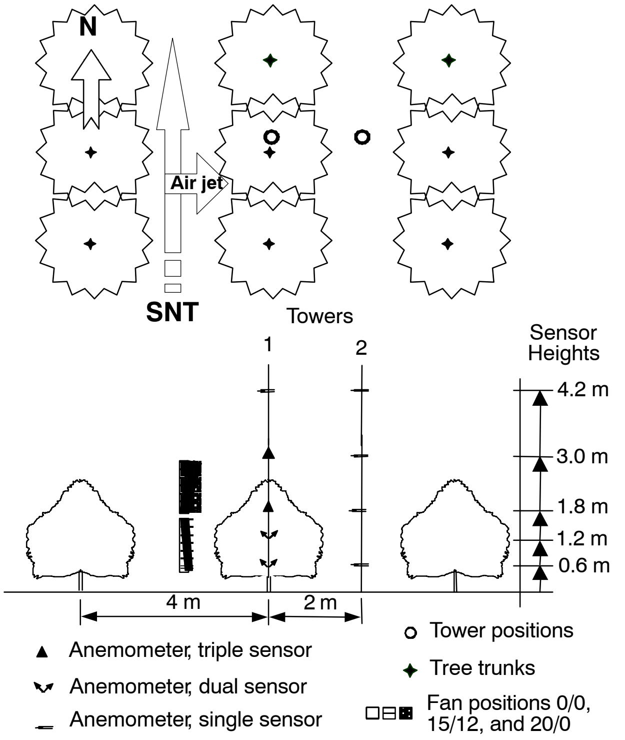

Figure 1. Plan and section showing anemometer positions and types. The figure displays the SNT experimental setup (from south to north with trees).

separating the signals into longitudinal and transverse components.

The sensors were mounted on two vertical towers: tower 1 was located north of and near the center of the tree, and tower 2 was in the middle of the drive path beyond the sprayed tree. The dual–sensor and triple–sensor probes were mounted facing south for all experiments. The cross–flow fan sprayer was pulled northwards past the west side of the tree with the fans operating but without spraying liquid (south to north with trees, SNT). For a second series of experiments, tower 2 was moved into the west drive path and the sprayer was moved along the east drive path (NST). A third experiment was conducted with the towers set up in an east–west drive path; air velocities were measured as the sprayer moved past the towers with no tree foliage to deflect or absorb airflow (NSO). During the SNT experiments, the sprayer air jet traveled through a different section of the canopy to reach the anemometer sensors than the jet produced by the NST experiments. We assumed that variations in the canopy density would produce a different flow regime in the SNT trials, compared to the NST trials, and would be similar to spraying two different trees.

Sensor Calibration

All anemometer units were calibrated each day with a portable calibration system (Fox et al., 1991), which had been calibrated using a standard hot–film sensor calibrated in a TSI model 1125 calibrator.

Multi–sensor probes were mounted so that airflow from the air jets was near 90° to the probe axis. Response of the triple–sensor probes and dual–sensor probes to flow near 90° to the probe axis was measured in the portable calibrator.

Two switch plates were used to mark the beginning and end of each sprayer pass. When the tractor tire crossed each plate, a 5 V signal (positive = start, negative = stop) was recorded on channel one of each recorder. These signals and a voice track were used to identify the 160 sprayer passes.

Meteorological Measurements

Background wind directions were measured with a three–propeller anemometer (Gill UVW Anemometer, model 27004, R.M. Young Co., Traverse City, Mich.) mounted at 5.9 m elevation in an open area north of the orchard. Temperatures were measured with a vertical array of thermocouples.

The experiments were conducted during times of low wind velocities. When one–minute averaged wind velocities were consistently greater than 1 m/s, experiments were postponed until wind velocity decreased. Meteorological conditions for all experiments are shown in table 1. For most spray passes (135 of 162), wind speed was less than 1.1 m/s. Maximum wind speed for any pass was 1.65 m/s. As expected for such low wind speeds, wind direction was somewhat variable.

Sprayer Air Jets

The air jet for the sprayer used in the experiments was produced by two cross–flow fans (Gebr. Holder GmbH, Metzinger, Germany) and were mounted on a three–point hitch chassis built in the laboratory. Each fan had an outlet of 1.1 by 0.086 m; they were powered by hydraulic motors and hinged at the common support between the fans so that the top and bottom could be inclined from the vertical. The fans were inclined to produce a converging jet. Airflow per fan unit was 7 700 m^3/h (at 18 r/s) and 11 600 m^3/h (at 24.5 r/s). See Fox et al. (1992) and Svensson (1994) for more details on the fans.

Experimental Treatments

The treatments were:

- Three travel speeds (4.8, 6.4, and 8.0 km/h)
- Three fan positions: both fans vertical (0/0), top fan inclined 20° from vertical and bottom fan vertical (20/0), and top fan inclined 15° from the vertical and bottom fan inclined 12° from the nadir (15/12)
- Two fan speeds: 18 and 24.5 r/s

Two in–canopy conditions were used and in the analysis regarded as blocks: from south to north with trees (SNT), and from north to south with trees (NST). In one comparison, the canopy condition from north to south in the open (NSO) was used together with NST as treatments. Measurements of each treatment were repeated three times.

Data Analysis

Each pass of the sprayer jet past the air velocity sensors produced velocity pulses. Careful consideration was given to the selection of the air velocity attributes to best represent the velocity pulses and to present parameters related to spray penetration into the tree and spray deposit within the tree canopy. For this study, we selected maximum velocity, maximum velocity integrated over the action time of the velocity pulse, velocity cubed, and velocity cubed integrated over the action time. The maximum velocity in the air jet pulse can be regarded as an expression for how well the air jet is able to penetrate the canopy. The velocity integrated over time is an expression of the volume of air passing a unit area at the measuring point. If we assume that the air from the jet contains drops of the spray liquid, then this integral will also express a potential prerequisite for deposition. Calculated as an integral, it represents a more stable result than maximum velocity, balancing out some of the signal fluctuations.

The cubed velocity value is proportional to the mechanical power of the air jet and is by that also an expression for the power acting at the measuring position. The integral of the cubed velocity over time (the velocity pulse) is proportional to the air jet energy in the measurement position during a passage of the sprayer. The detailed procedure for these measurements is given below.

Table 1. Meteorological conditions during experiments.

Date	Treatment	Maximum Wind Speed (m/s)	Temp (°C)	RH (%)	Wind Direction	Number of Passes in which Wind Speed was <1.1 m/s	Sprayer Air Jet Direction
5 August	SNT	1.65	21 to 24	68	NNW – NNE	42 of 54	East
6 August	NST	1.6	20 to 24	60	NW – NE	39 of 54	West
24 August	NSO	1.1	14 to 16	75	SE – W	54 of 54	West

The velocity signals were played back from the tape recorder and sampled using a measurement and control system (model 500A, Keithley, Inc., Cleveland, Ohio). An analysis program was written to sample the signals, to convert from voltages to velocities, to make necessary corrective computations, and to store the results in computer files on disks.

For the triple–sensor and dual–sensor signals, about 15,000 values were sampled for each sensor at each elevation. Samples were recorded during the time interval between the start and stop pulses, approximately 6.5 s. Concurrent values for the triple–sensor probes were multiplied by a transformation matrix to change the velocity vectors from the recorded coordinate system (along the sensors) to the cardinal direction coordinate system. The resulting velocity component in the x–z plane (perpendicular to the tree row direction) was also calculated. At this stage, with a sample rate of about 2,300 Hz, each value was also cubed. The resolved samples were then averaged in groups of 75 to produce 200 velocity values in each direction for each sprayer pass, resulting in a final sampling frequency of about 30 Hz. The x–z plane components and the cubed values for the dual–sensor probes were computed in the same way. The single–sensor probes were sampled in a similar way, but with a lower original sampling frequency.

A second analysis program was written to read the files of 200 velocity points stored by the previous program, to correct for background wind by adjusting the background air velocity level (the velocity level preceding the jet pulse) to zero, and to record the greatest single sample for v, v^3, and the sample number at which these maximums occurred. The program also computed the start and end of the velocity pulse from the sprayer pass and plotted the result. The operator then could adjust the pulse start and stop sample number, and the total area under the velocity curve was calculated. The integrated values of v and v^3, together with locations and maximum velocities, were stored in a file.

The program SPSS, vers. 10.0.5, (SPSS Inc., Chicago, Ill.) was used to compute the analyses of variance (ANOVA) of the various treatments and result parameters at each elevation, for south to north with trees and north to south with trees (SNT + NST). ANOVA were also computed for treatments including north to south with trees and north to south without trees (NST + NSO).

Results

Air Velocity Pulses

Sprayer passes produced obvious air velocity pulses at the 1.2 and 1.8 m elevations on tower 1. At the 0.6 m elevation, the fan arrangement with the bottom fan inclined 12° did not produce pulses for all passes. Both fan arrangements with the top fan inclined did not produce air pulses for all passes at the 3.0 m elevation. None of the three fan arrangements produced a noticeable pulse at the 4.2 m elevation; however, sprayer passage was noticeable for many passes at this elevation because the anemometer signal became more active. Velocity pulses on tower 2 were similar in that the only consistently visible pulses for all treatments occurred at the 0.6 and 1.8 m elevations. Only passes with both fans vertical produced visible pulses at the top two elevations.

Fox et al. (1992) found that airflow was turbulent in the air jet at the fan outlet, and that turbulent intensity increased as distance from the sprayer increased. When an air jet strikes a canopy composed of many leaves and twigs, the random air motion increases and creates random movement in these elements also. Movement of the local tree elements (leaves and twigs) near the sensors can channel airflow and change the flow at a particular sensor from pass to pass, even with the same jet operating conditions. The entire air jet pulse passed the sensors during about one second (depending on travel speed). These facts, despite the high sampling frequency, explain the great variation shown by the velocity maximum values. Integrated velocities were more stable and also included the time factor related to travel speed.

Table 2. Fan position influence on measured air velocities at tower 1 (tree center) and tower 2 (behind trees).

Parameter Studied	Treatment Combinations[a]	Tower 1 Sensors (heights in m)[b]					Tower 2 Sensors (heights in m)[b]			
		0.6 m	1.2 m	1.8 m	3.0 m	4.2 m	0.6 m	1.8 m	3.0 m	4.2 m
Maximum velocity (m/s)	Fan pos. 0/0	3.6 b	12.5 a	4.1 b	5.6 a	3.5 a	2.2 b	3.1 c	4.1 a	2.0 a
	Fan pos. 15/12	1.0 c	12.3 a	12.7 a	2.1 b	2.6 b	1.2 c	8.0 a	1.2 b	1.0 b
	Fan pos. 20/0	4.3 a	12.1 a	12.2 a	2.0 b	2.7 b	2.7 a	5.8 b	1.0 b	1.0 b
	Std dev.	1.4	2.0	1.5	1.2	1.3	0.9	1.3	1.2	0.7
Integrated velocity (m/s · s)	Fan pos. 0/0	1.1 a	3.6 b	1.8 c	1.5 a	1.5 a	1.4 b	1.8 c	2.3 a	1.4 a
	Fan pos. 15/12	0.5 b	3.4 b	5.6 a	0.9 b	1.4 a	0.8 c	4.5 a	1.0 b	0.9 b
	Fan pos. 20/0	1.2 a	3.9 a	4.5 b	0.9 b	1.3 a	1.8 a	3.1 b	0.8 b	0.8 b
	Std dev.	0.4	0.6	1.0	0.6	0.8	0.4	0.8	0.6	0.5
Velocity cubed ($[m/s]^3$)	Fan pos. 0/0	210 a	2897 a	195 b	413 a	100 a	18.2 ab	42.4 c	128 a	13.7 a
	Fan pos. 15/12	17.5 b	2541 a	2935 a	20.3 b	29.1 b	6.9 b	684 a	4.6 b	1.6 b
	Fan pos. 20/0	311 a	2825 a	2616 a	19.4 b	26.4 b	26.7 a	277 b	2.0 b	2.5 b
	Std dev.	220	1278	1104	237	127	28.7	196	101	9.7
Integrated velocity cubed ($[m/s]^3 \cdot s$)	Fan pos. 0/0	27.4 a	417 a	35.6 c	48.2 a	20.8 a	3.0 b	7.5 c	20.4 a	2.9 a
	Fan pos. 15/12	4.5 b	321 b	761 a	6.2 b	14.2 a	0.9 c	151 a	1.3 b	0.6 b
	Fan pos. 20/0	33.9 a	451 a	472 b	6.7 b	6.9 a	4.6 a	50.3 b	0.5 b	0.4 b
	Std dev.	21.4	195	319	24.4	28.0	3.0	47.3	13.9	1.6

[a] Fan position–notations indicate fan unit inclination.

[b] Means (in columns, for each velocity parameter) followed by the same letter are not significantly different (Duncan's multiple range test, $P < 0.05$).

EFFECTS OF TREATMENTS ON THE IN–CANOPY SITUATION

Effects of Fan Positions

Measured air velocities as a function of fan position are presented in table 2. Changing the bottom fan unit from its vertical position had great influence on the air velocity at the lowest measurement position in the tree canopy.

Treatments 0/0 and 20/0 resulted in significantly higher air velocities. For the 1.2 m elevation, in the middle of the canopy, differences were small and not always significant. For the integrated result calculations, some differences were detected where the fan arrangement 15/12 showed a lower value than the 20/0 treatment.

In the upper tree center, at the 1.8 m elevation, the differences were significant in almost all cases. The converging air jets (15/12) showed the highest air velocities, followed by the 20/0 arrangement. The fan arrangement with both fan units vertical (0/0) showed low air velocities. At the first position over treetop level (3.0 m elevation), the arrangements with both fans vertical showed a significantly higher velocity.

There were no significant differences between the two fan arrangements with the top fan units tilted. At the highest measurement position, far over the treetop level (4.2 m elevation), only small differences were noted, and generally no significant differences were present. For tower 2, behind the tree, similar air velocity distributions were observed. However, the amplitudes and signals were reduced and diffused, especially at the two top positions.

Machine output (m^3/m of forward travel) was calculated for different fan conditions and is displayed in figure 2. Outlet flow and travel speed are combined in the same way as by Hale (1978). At the 1.2 and 1.8 m elevations, the integrated velocity showed a consistent and significant increase with increased machine output. The values from the converging fan alternatives were significantly higher and increased more at the 1.8 m elevation. Over treetop level, 3.0 m, the

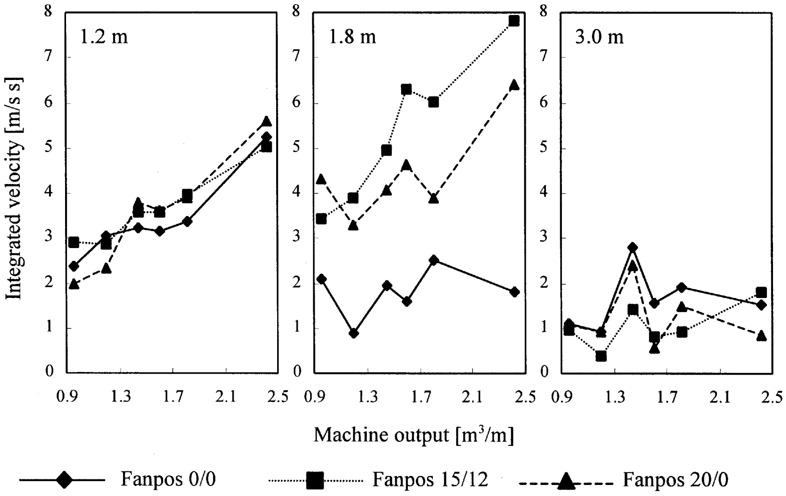

Figure 2. Integrated air velocity for different machine outputs measured at tower 1 (tree center) at heights of 1.2, 1.8, and 3.0 m. The figure shows the NST treatment (from north to south with trees). Fan position notations indicate fan unit inclination.

Table 3. Travel speed influence on measured air velocities at tower 1 (tree center) and tower 2 (behind trees).

Parameter Studied	Treatment Combinations[a]	Tower 1 Sensors (heights in m)[b]					Tower 2 Sensors (heights in m)[b]			
		0.6	1.2	1.8	3.0	4.2	0.6	1.8	3.0	4.2
Maximum air velocity (m/s)	Travel speed I	2.6 b	12.5 a	9.9 a	3.0 b	2.2 b	2.1 a	6.0 a	2.2 a	1.4 a
	Travel speed II	3.0 ab	12.1 a	9.8 a	2.9 b	3.2 a	2.2 a	5.4 a	2.2 a	1.3 a
	Travel speed III	3.5 a	12.2 a	9.5 a	3.8 a	3.3 a	1.8 a	5.3 a	1.9 a	1.4 a
	Std dev.	1.4	2.0	1.5	1.2	1.3	0.9	1.3	1.2	0.7
Integrated air velocity (m/s · s)	Travel speed I	1.0 a	4.6 a	4.9 a	1.1 a	1.1 b	1.4 a	3.6 a	1.3 a	1.0 a
	Travel speed II	1.0 a	3.3 b	3.5 b	1.0 a	1.5 ab	1.4 a	2.9 b	1.4 a	1.0 a
	Travel speed III	0.9 a	3.0 c	3.5 b	1.2 a	1.6 a	1.2 a	2.8 b	1.4 a	1.1 a
	Std dev.	0.4	0.6	1.0	0.6	0.8	0.4	0.8	0.6	0.5
Air velocity cubed ($[m/s]^3$)	Travel speed I	140 a	2923 a	2091 a	138 ab	15.0 b	17.4 ab	391 a	63.2 a	7.4 a
	Travel speed II	180 a	2637 a	1888 a	86.3 b	91.5 a	24.5 a	252 b	53.9 a	5.3 a
	Travel speed III	238 a	2715 a	1766 a	228 a	48.7 ab	9.9 b	328 ab	19.8 a	5.7 a
	Std dev.	220	1278	1104	237	127	28.7	196	101	9.7
Integrated air velocity cubed ($[m/s]^3 \cdot s$)	Travel speed I	17.9 a	567 a	599 a	19.4 a	5.3 a	3.2 ab	83.0 a	9.6 a	1.5 a
	Travel speed II	27.2 a	329 b	346 b	15.9 a	19.9 a	3.4 a	60.6 ab	8.8 a	1.2 a
	Travel speed III	22.2 a	292 b	323 b	25.7 a	15.9 a	1.8 b	58.6 b	3.7 a	1.3 a
	Std dev.	21.4	195	319	24.4	28.0	3.0	47.3	13.9	1.6

[a] Travel speed I = 4.8 km/h, travel speed II = 6.4 km/h, and travel speed III = 8.0 km/h.

[b] Means (in columns, for each velocity parameter) followed by the same letter are not significantly different (Duncan's multiple range test, $P < 0.05$).

consistent increase no longer existed, and here the differences between the fan conditions were indistinct.

Effects of Travel Speed

Travel speed effects expressed as maximum velocities showed very small differences, and few were significant. As shown in table 3, air velocities were much higher for the two positions inside the tree canopy, near the center of the fan outlets (1.2 and 1.8 m elevation), than for the other positions.

When integrated velocities were calculated, travel speed effects became clearly visible, especially at the 1.2 and 1.8 m elevations. At these elevations, integrated velocity values were significantly higher for the lowest travel speed. However, the second travel speed followed with smaller and not always significant differences in integrated velocities compared to those measured for the greatest travel speed.

At the lowest position inside the canopy and at the two positions above the tree, no significant differences among travel speeds were present. The relationships among values at these positions were not affected by using maximum or integrated values.

For tower 2, behind the tree, most differences caused by travel speeds were not significant or consistent.

Effects of Fan Speed

Table 4 displays the effect of fan speeds analyzed over all fan positions and travel speeds. Independent of the type of velocity parameter studied, higher fan speeds produced significantly greater air velocities inside the canopy at the 1.2 and 1.8 m elevations. For both high and low fan speeds, the results were similar for the 1.2 and 1.8 m elevations when using the integrated and integrated cubed values. However, the maximum and maximum cubed values decreased noticeably from the 1.2 to the 1.8 m elevation.

At the lowest position inside the canopy and at the two positions over the tree (3.0 and 4.2 m elevations), differences were small and seldom significant. Behind the tree, at tower 2, the values were clearly reduced.

Effects of Canopy Conditions

In the ANOVA above, the canopy conditions (NST, SNT) were treated as blocks. The differences between blocks were clear and significant, especially for positions inside canopies, as shown in table 5. For tower 2, significant differences were reduced, both in number and size.

The effect of tree canopy on air velocities at the anemometer sensors was evaluated through an ANOVA in

Table 4. Fan speed influence on measured air velocities at tower 1 (tree center) and tower 2 (behind trees).

Parameter Studied	Treatment Combinations	Tower 1 Sensors (heights in m)[a]					Tower 2 Sensors (heights in m)[a]			
		0.6	1.2	1.8	3.0	4.2	0.6	1.8	3.0	4.2
Maximum air velocity (m/s)	Fan speed 18 r/s	2.8 a	9.8 b	8.1 b	2.9 b	2.7 a	1.8 b	4.1 b	1.8 b	1.2 a
	Fan speed 24.5 r/s	3.3 a	14.6 a	11.3 a	3.5 a	3.2 a	2.3 a	7.0 a	2.5 a	1.5 a
	Std dev.	1.4	2.0	1.5	1.2	1.3	0.9	1.3	1.2	0.7
Integrated air velocity (m/s · s)	Fan speed 18 r/s	0.9 a	3.0 b	3.3 b	0.9 b	1.3 a	1.2 b	2.5 b	1.2 b	1.0 a
	Fan speed 24.5 r/s	1.0 a	4.2 a	4.6 a	1.3 a	1.5 a	1.4 a	3.7 a	1.6 a	1.1 a
	Std dev.	0.4	0.6	1.0	0.6	0.8	0.4	0.8	0.6	0.5
Air velocity cubed ([m/s]^3)	Fan speed 18 r/s	153 a	1342 b	1061 b	85.3 b	30.6 a	11.3 a	117 b	29.4 a	4.0 b
	Fan speed 24.5 r/s	221 a	4073 a	2770 a	216 a	79.1 a	22.9 a	519 a	62.4 a	8.2 a
	Std dev.	220	1278	1104	237	127	28.7	196	101	9.7
Integrated air velocity cubed ([m/s]^3 · s)	Fan speed 18 r/s	18.2 b	204 b	229 b	12.7 b	9.1 a	2.0 b	30.2 b	4.8 a	1.0 a
	Fan speed 24.5 r/s	26.6 a	578 a	616 a	28.0 a	20.3 a	3.5 a	103 a	10.0 a	1.6 a
	Std dev.	21.4	195	319	24.4	28	3.0	47.3	13.9	1.6

[a] Means (in columns, for each velocity parameter) followed by the same letter are not significantly different (Duncan's multiple range test, $P < 0.05$).

Table 5. Block differences (expressed as canopy condition influence on measured air velocities) at tower 1 (tree center) and tower 2 (behind trees). The ANOVA includes all fan positions, travel speeds, and fan speeds.

Parameter Studied	Block (travel direction)	Tower 1 Sensors (heights in m)[a]					Tower 2 Sensors (heights in m)[a]			
		0.6	1.2	1.8	3.0	4.2	0.6	1.8	3.0	4.2
Maximum air velocity (m/s)	North to south	2.0 b	10.0 b	7.7 b	2.8 b	2.6 b	2.1 a	6.0 a	2.3 a	1.2 b
	South to north	4.0 a	14.6 a	11.7 a	3.6 a	3.2 a	2.0 a	5.1 b	1.9 a	1.5 a
	Std dev.	1.4	2.0	1.5	1.2	1.3	0.9	1.3	1.2	0.7
Integrated air velocity (m/s · s)	North to south	0.6 b	2.8 b	3.1 b	1.0 a	1.3 a	1.2 b	3.2 a	1.5 a	1.0 a
	South to north	1.2 a	4.5 a	4.8 a	1.2 a	1.5 a	1.4 a	3.0 a	1.3 a	1.0 a
	Std dev.	0.4	0.6	1.0	0.6	0.8	0.4	0.8	0.6	0.5
Air velocity cubed ([m/s]^3)	North to south	64.8 b	1481 b	919 b	128 a	53.1 a	19.3 a	382 a	66.6 a	4.1 b
	South to north	303 a	4093 a	2912 a	173 a	50.4 a	15.1 a	265 b	24.3 b	8.4 a
	Std dev.	220	1278	1104	237	127	28.7	196	101	9.7
Integrated air velocity cubed ([m/s]^3 · s)	North to south	8.6 b	191 b	183 b	15.2 b	13.6 a	2.9 a	83.8 a	10.2 a	1.0 a
	South to north	35.9 a	613 a	662 a	25.5 a	14.8 a	2.6 a	50.6 b	4.7 b	1.6 a
	Std dev.	21.4	195	319	24.4	28	3.0	47.3	13.9	1.6

[a] Means (in columns, for each velocity parameter) followed by the same letter are not significantly different (Duncan's multiple range test, $P < 0.05$).

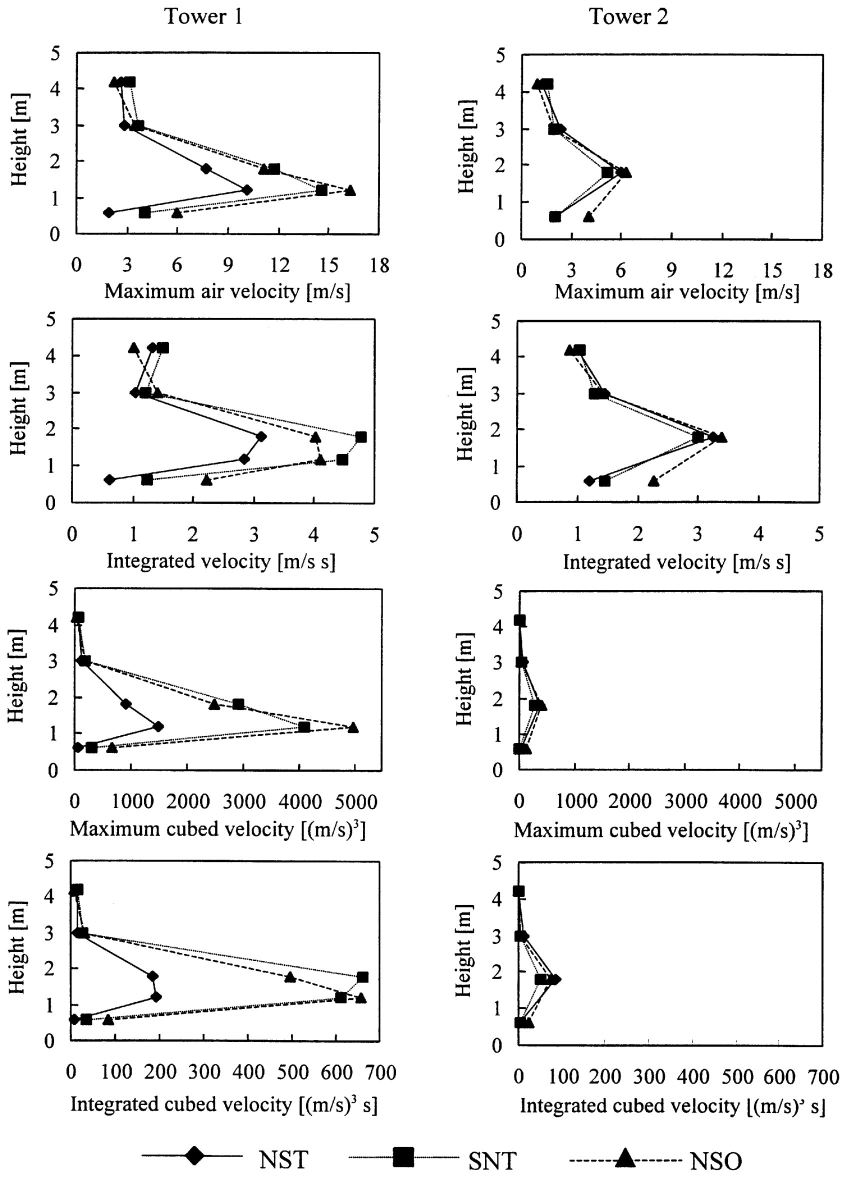

Figure 3. Measured air velocity results for two in–canopy (NST, SNT) treatments and one in–open (NSO) treatment. All fan speeds, travel speeds, and fan positions are included in results shown for tower 1 (tree center) and tower 2 (behind trees). From top: maximum velocity, velocity integrated over time, maximum cubed velocity, and maximum cubed velocity integrated over time.

which the north–south with–tree condition (NST) was compared to the north–south without–tree condition (NSO) in a model that included fan speed, travel speed, and fan positions (data not shown).

Significantly greater velocity values were observed in the open, compared to inside the canopy, except at the 4.2 m elevation at tower 1. The difference was also small at the 3.0 m level. Tower 2 values showed more smoothed out profiles, lower values, and much less significant differences.

In figure 3, the means from the three canopy conditions (SNT, NST, and NSO) are displayed, showing that results from SNT and NSO were rather close, and greater than the NST values. Tower 2 values showed less and inconsistent differences.

DISCUSSION

When discussing the results, it is important to distinguish between airflow around and airflow through the canopy. The first part, displayed at the measurement points above the canopy, is related to potential drift, while the second part, based on positions inside the canopy, is related to penetration. These factors should be regarded in combination, as it is important not only to penetrate the canopy but also to achieve penetration without causing wind drift. An air pulse above the tree indicates that part of the air jet missed the tree or was deflected upwards by the canopy, which acts to some extent as a solid body, especially late in the season.

The top position (4.2 m elevation) seldom displayed any distinct pulses and could in general be described as unaffected by the air jets. However, those air velocities detected were higher for the in–canopy treatments (NST and SNT) than for the in–open treatment (NSO), indicating that

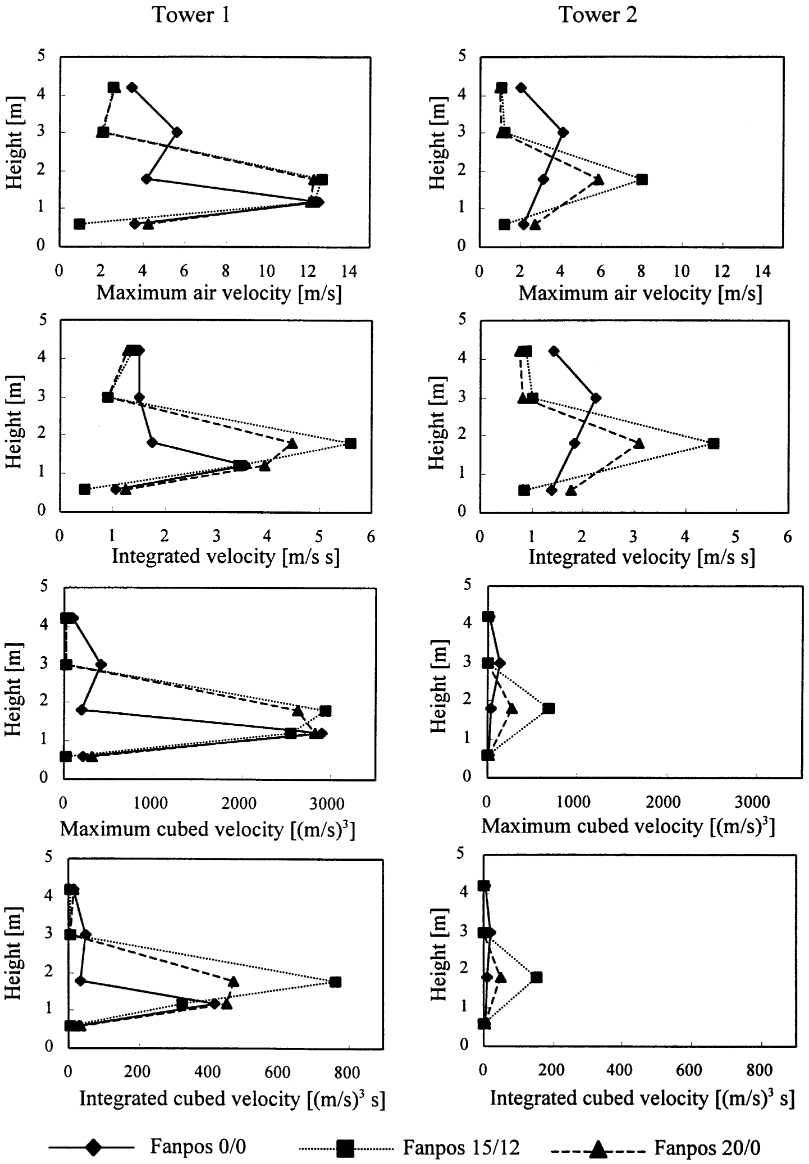

Figure 4. Fan position influence on measured air velocities at tower 1 (tree center) and tower 2 (behind trees). From top: maximum velocity, velocity integrated over time, maximum cubed velocity, and maximum cubed velocity integrated over time. Fan position notations indicate fan unit inclination.

even at this elevation there seems to be an upward spreading caused by the canopy.

Fan positions had greater influence than canopy conditions at the 3.0 m level (fig. 4). For vertical fans, all measured parameters showed a significantly higher value compared to the fan positions in which the top fan unit was tilted. The differences were greatest for the single maximum values. Svensson (1994), who measured spray deposits at similar levels, reported similar results. At this position, there were also some significant but small differences in integrated velocity caused by different fan speeds.

Penetration effects of the canopy were illustrated by measurements at the 0.6, 1.2, and 1.8 m elevations inside the canopy. The lowest position was just on the bottom edge of the vertical air jets, and only a few air pulses were observed for treatments in which the lower fan unit was tilted. Low velocities were measured for fan position 0/0 at the 1.8 m elevation. This position was close to the elevation of the gap between the upper and lower fan units.

The parameters calculated here to compare treatments provide different insights into the basic structure of the flow field. Maximum air velocity values can be used to illustrate differences, but they exhibit large, rapid variation during each pulse. They should be interpreted with care, as few replications were made.

The integrated values of velocity over the time period of the pulse were more stable. They are of great interest for deposition, as they represent a value corresponding to the airflow volume through the sample position, a factor representing one of the important prerequisites for deposition. In addition, the cubed maximum values, related to air jet power, show great variation over time. The velocity cubed values, integrated over time, are related to energy in the air pulse and thus to penetration ability.

Differences in canopy air velocity fields due to fan position (0/0, 20/0, and 15/12) were obvious in most combinations of measurement parameters, treatments, and analysis methods. The converged air jets showed higher

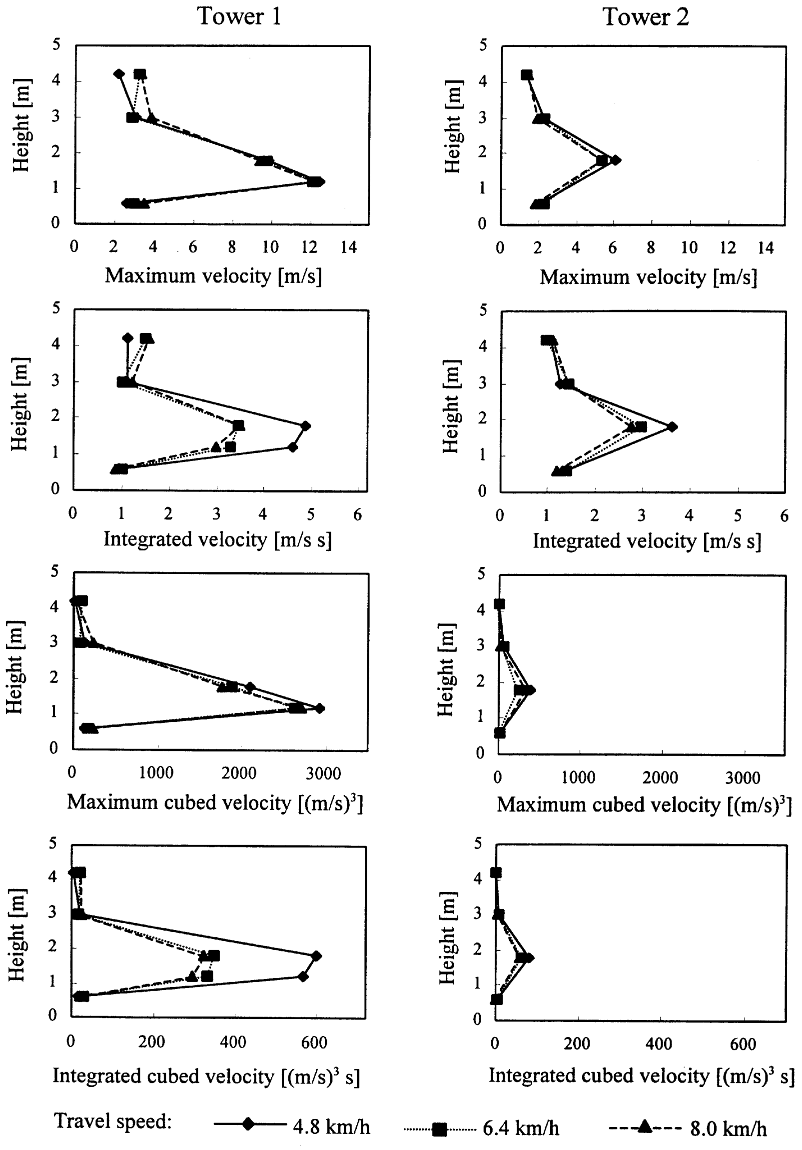

Figure 5. Travel speed influence on measured air velocities at tower 1 (tree center) and tower 2 (behind trees). From top: maximum velocity, velocity integrated over time, maximum cubed velocity, and maximum cubed velocity integrated over time. Travel speeds were 4.8, 6.4, and 8.0 km/h.

measured values, implying better conditions for deposition and penetration.

The influence of travel speed on spray deposition has been discussed in earlier research (Zhu et al., 1997; Planas et al. 1998; Salyani, 2000). No significant differences among travel speed were detected by comparing maximum velocities. This supports the results of Derksen and Gray (1995), who measured air velocities in a side canopy. They used two travel speeds but did not record significant differences between peak velocities. However, our results showed significant differences for integrated velocities, with lower travel speed producing higher values (fig. 5). As there were no differences among travel speeds for single maximum velocities, the differences in integrated values were likely due to a time effect (i.e., air velocity remained high for a longer time during the low travel speed treatments).

An example of this is shown in figure 6, where three velocity pulses are plotted in the same diagram, slightly displaced. The higher air velocities act on a leaf during about 1.0 s, giving the leaf more time to move about and increasing the opportunity for the spray cloud to deposit on all sides of the leaf. This effect was also reported by Locher and Moser (1981).

Hale's (1978) method for relating the sprayer's outlet airflow volume rate to travel distance (m^3/m of forward travel) was used to combine two of the treatment variables into one. This displayed a firmer relation for integral values than maximum velocities. Integrated velocities increased with increased flow per forward travel, indicating a greater volume of air passing a position, once again supporting the converging air jets and the theory of using the output power in airflow, rather than in air velocity (Randall, 1971).

Differences in fan speed were visible, great, and significant for most parameters considered (fig. 7). The output power, here expressed as air velocity and airflow at the outlet, showed a great influence on velocity factors inside the canopy.

Measurements in NST, SNT and NSO showed that canopy influence on air velocities was an important factor (fig. 3).

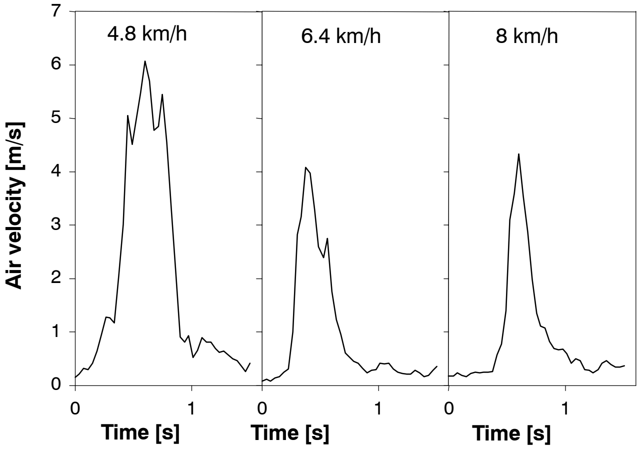

Figure 6. Air velocity pulses for different travel speeds; example shows fan condition 0/0, high fan speed, 1.2 m elevation, and inside canopy (tower 1).

We noted that in many cases canopy influence caused an increased variation among positions and treatment.

The SNT results in general were closer to the NSO results than to the NST results. These differences in velocities within the canopy was probably due to local effects, such as limbs, twigs, and leaves, by which the tree may have shielded the sensors from the air jet to a greater extent during the NS passes than for the SN passes. This could also be a "channeling effect" reported by Walklate et al. (1996). There were great differences in measured velocities within the canopy (tower 1) between SNT and NST passes. However, there were only small differences in velocities measured beyond the trees (tower 2) between SNT and NST passes. These results support the observation that the tree was less dense on the west side (between the sensors and the air jet in the SNT passes) than on the east side (between the sensors and the jet from the NST passes). There were only rather small differences between NST and NSO at tower 2 positions, indicating that at this distance from the outlet, no canopy influence was measured.

Our measurements illustrate the variation between positions inside canopies and between trees. Even though the measurement positions were not changed, totally different

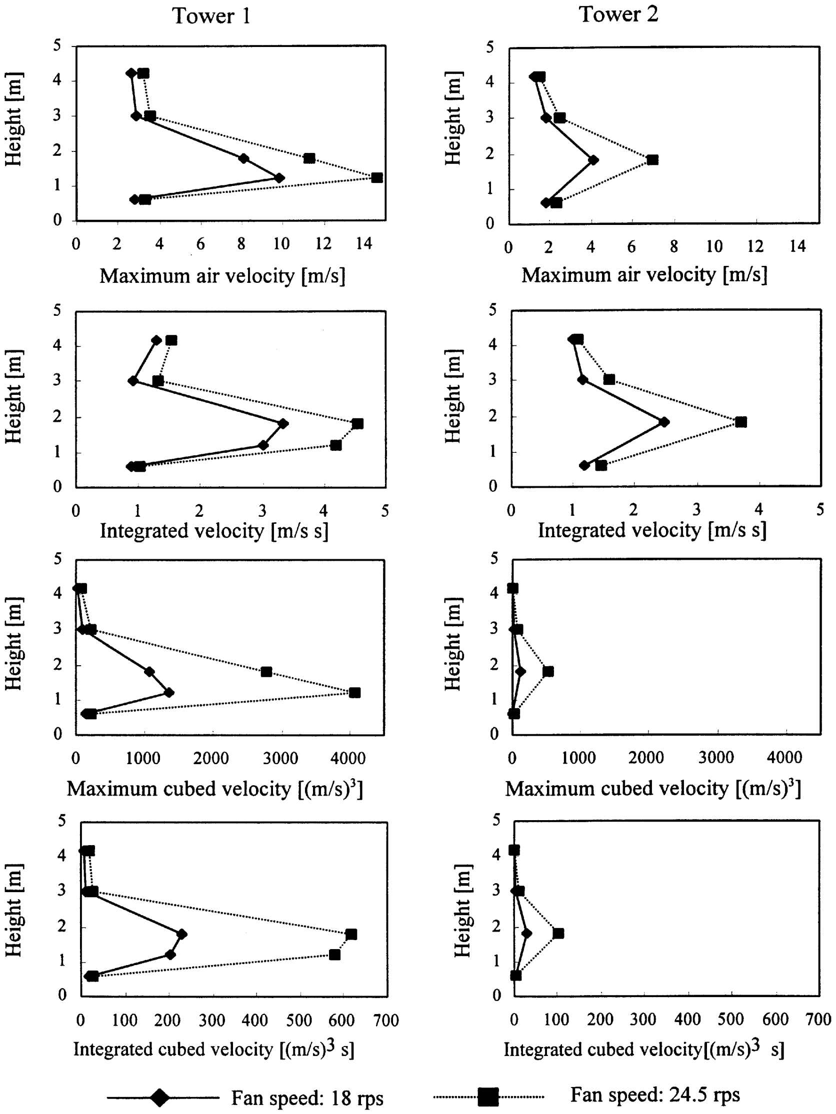

Figure 7. Fan speed influence on measured air velocities at tower 1 (tree center) and tower 2 (behind trees). From top: maximum velocity, velocity integrated over time, maximum cubed velocity, and maximum cubed velocity integrated over time. Fan speeds were 18 r/s (low) and 24.5 r/s (high).

velocity results were recorded when the air jet was directed from the other side of the tree. The rapid velocity variations over time were strong arguments to use sensors with high resolution and high–frequency sampling to be able to record an adequate picture of what was happening during the pass. All this, in combination with the variation between replicates, underlines the strong influence of sensor position and that it is important to make measurements in several trees, with several replicates.

CONCLUSION

It was possible to relate the integrated air velocity at a canopy position to the airflow volume through the canopy, and the integrated cubed velocity to air jet energy, indicating two parameters relevant for deposition and canopy penetration. Air velocity measurements above the trees were indications of losses and potential wind drift.

Bearing this in mind in a summation of the results, we conclude that:

- The airflow characteristics of the converging fan position alternatives promoted penetration and were better prerequisites for deposition than the original plane jets.
- Airflow from converging air jets reduced flow above the tree canopy.
- Low travel speed and high air output power improved air penetration in general.
- Traditional problems in air velocity measurements in canopy situations, also experienced in this experiment, such as great and rapid velocity variations and strong sensor position influence, call for alternative research methods.

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Air jet velocities in and beyond apple trees from a two cross-flow fan sprayer

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Abstract

The penetration of a sprayer air jet into an apple tree canopy was measured. An air-assisted sprayer with two vertical, cross-flow fan units, moving past the tree (without spraying liquid), provided the air jet. Treatments included 3 fan positions (fans vertical [0/0], top fan inclined 20° [20/0], and top fan inclined 15°, bottom fan inclined 12° [15/12]); 3 travel speeds (4.8, 6.4, and 8 km/h); two fan speeds (18 and 24.5 r/s); and 3 canopy conditions (south to north [SNT], north to south [NST], and north to south without a tree [NSO]). Vertical air velocities profiles were measured with hot-film anemometers in the center of the tree row and in the drive lane beyond the tree row. Maximum measured velocity, velocity integrated over the time of the air velocity pulse, air power (velocity cubed) and integrated power over the velocity pulse were measured or computed. The passing air jet produced distinct velocity pulses at elevations of 0.6 (except for [15/12]), 1.2 and 1.8 m within the tree and 0.6 and 1.8 m beyond the tree. Only fan position [0/0] produced distinct velocity pulses at the 3.0 m elevation, and no treatment produced visible pulses at the 4.2 m elevation. Fan positions had great and significant influence on air velocities inside tree canopies. At the 1.8 m elevation in the tree center, converging air jets [15/12] produced the highest velocities, followed by the [20/0] treatment. Fan position had little significant difference on air velocities at the 1.2 m elevation in the tree. Fan speed had great and significant influence on air velocities. Travel speed produced little difference among treatments when maximum velocities were considered, however there were greater differences when integrated velocities were considered. For the canopy conditions, greater velocities were measured for the treatments without canopy, however velocities for the treatment SNT were nearly as great. Velocities for NST treatments were significantly less. This illustrates the effect of velocity sensor position (local canopy differences) on measured velocities. In general, converging air jets, low travel speed and high fan output power improved penetration velocity and power into the tree canopy.

Keywords: orchard spraying, fan sprayer, air jets, air velocity measurements, application technology, cross-flow fan, converging air jet, plant protection.

Introduction

Orchard sprayers commonly use air jets to transport spray droplets into tree canopies. The air jet conditions as well as the liquid part of the spray cloud influence deposition (Hislop, 1991). Air velocities in the sprayer jets are critical to how effectively the droplets are transported into the canopy and deposited on the leaves. Typical sprayers use an axial fan to produce the air jet. Air velocities in these jets have been shown to decrease rapidly as distance from the jet increases (Randall, 1971, Brazee et al., 1981). Because of the distance from the sprayer outlet to the tops of trees and the attenuation of air jets by the diverging air jet and by tree canopy interaction, spray deposits in the top-center of trees are usually much less than deposits near the sprayer outlet (Hall et al., 1975, Vang-Petersen, 1982, Juste et al., 1990).

The measured air velocity, integrated over time of the sprayer pass, expresses the flow of air through a position, thus indicating how much of the available flow has penetrated the canopy. Because the air contains spray droplets, air flow volume during a pass is one of the factors influencing the deposition result. The power of an air jet is proportional to the velocity value cubed (Fox et al., 1982). Thus integrating the cubed velocity values over time-interval of a sprayer pass produces a result that is related to the available energy in this position of the tree.

Several studies have attempted to measure the air velocities required to effectively transport spray droplets into tree canopies. Several other parameters have also been used to describe characteristics of the air jet that may be related to the jet's effectiveness to penetrate into the canopy and to disperse droplets.

Randall (1971) measured air velocities in and between apple tree canopies as produced by three sizes of axial-fan sprayers. He calculated the air power values from the air velocity pulse, measured at each sample position, and used that as an expression for the air jet penetration ability. He found that sprayer jets with greater air volumes at lower air velocities penetrated trees better than jets with lower air volumes and greater air velocities, given that all sprayers produced the same air power.

Planas et al. (1998) observed contradictory results. By reducing the flow rate from 8.2 m^3/s to 4.5 m^3/s (or increasing travel speed), they gained deposition but got reduced uniformity within the canopy.

One of the sprayer operating properties is a combination of the fan output flow and forward travel speed. It is expressed as the available flow per m in travel direction or 'machine output', stated in m^3/m forward travel (Hale, 1978). He conducted a study of model sprayers in a wind tunnel to determine the optimum sprayer-outlet size to effectively penetrate model trees. He concluded that it would require an air output of 3.7 m^3/m in calm winds and 5.6 m^3/m in windy conditions to penetrate trees that were 5 m tall. For hedgerow plantings (about 2 m tall), 2.8 m^3/m would be sufficient to penetrate the trees at forward speeds up to 11 km/h.

Reichard et al. (1979) measured air velocities from two axial-fan sprayers that were driven past a vertical array of anemometers at several speeds and at several distances from the anemometer sensors. They found that measured air velocities decreased as distance between the sprayer fan and the anemometers increased and that air velocities decreased as travel speed of the sprayer increased.

Derksen & Gray (1995) found no significant difference among air velocities within apple trees when an axial fan sprayer drove past at 0.9 and 1.3 m/s or when the fan air-volume output was 652 or 822 m^3/min. There was also no significant difference between total deposits on trees sprayed with these sprayer treatments.

Several commercial sprayers have been introduced that use cross-flow fans (Van Ee et al., 1984, Bäcker, 1984, Svensson, 1994, Derksen et al., 1999). Air jets from cross-flow fans are 'plane jets' and produce velocity fields that decrease less with increasing distance from the outlet than velocity fields from axial fans (Fox, et al., 1992). Cross-flow fans are usually mounted in a vertical array for spraying trees. This reduces the distance from the fan outlet (spray atomizers) to the intended target in the tree.

Vertically inclining cross-flow fan units to create converging air jets in most cases gave improved chemical deposition or at least more uniform distribution, compared to axial fan sprayers (Van Ee et al., 1984, Furness & Pinczewski, 1985, Whitney & Salyani, 1991).

Svensson (1994) used a two-fan cross-flow sprayer, where the fan units were vertically inclined to produce a converging air jet. He found that in general this increased spray deposit and improved deposit uniformity through the tree canopy. He also made limited measurements of air velocities inside canopies of the same apple trees and found higher air velocities for the converging air jets.

Objectives

The objectives of this study were: 1. to determine if a converging air velocity pattern from two cross-flow fan jets penetrated a dwarf apple tree canopy better than a plane jet pattern. 2. to measure the effects of sprayer speed, fan outlet air velocity and fan jet characteristics on the air velocity of the sprayer jet in the center and beyond a typical small, dwarf (European-style) apple tree.

Materials and methods

Orchard site

These experiments were conducted at the Ohio State University/Ohio Agricultural Research and Development Center (OSU/OARDC) Horticulture Unit #2 orchards in Wooster, Ohio. Treatment trees were selected because they were similar in shape to trees being grown in North Europe. The trees were four year old 'Smoothee Golden Delicious' planted on Mark rootstock and trained as slender spindles. Tree spacing was 4 m between rows and 2 m between trees in each row. Tree height was about 2.4 m, and row width was about 2.4 m. Row direction was north-south. A tree with uniform density and characteristic shape was chosen for the study.

Anemometer system

Figure 1 displays the locations and type of sensor-probes used for measuring air velocities. All sensors were anemometers of 6-mil constant temperature hot-film type; the probes used were: two triple-sensor, two x- and five single-sensor probes (model 1294-60, 1240-60, and 1244-60, respectively, TSI, Inc., St. Paul MN). The triple-sensors were controlled by TSI model 1054b linearized servoamplifiers and the output signals were resolved by an analog resolver and combined with flow directional data (Fox et al., 1980) to produce three velocity components along the sensor axes at the sensing points. The resultant signals were recorded on FM analog tape recorders (model 3500, Sangamo Inc., Indianapolis IN and model 3900 Hewlett-Packard). The x-probes were controlled by servoamplifiers (model 700, Flow Corporation, Watertown MA) and the output signals were connected to sum and difference correlators (model 1015C, TSI, Inc.) for separating the signals into longitudinal and transverse components.

The sensors were mounted on two vertical towers; tower #1 was located north of and near the center of the tree, and tower #2 was in the drive path east of the sprayed tree. The x-probes and the triple sensor probes were mounted facing south for all experiments. The cross-flow fan sprayer was pulled northwards past the west side of the tree with the fans operating, but without spraying liquid (south to north with trees – SNT). For a second series of experiments, tower #2 was moved into the west drive path and the sprayer was moved along the east drive path (NST). A third experiment was conducted with the towers set up in an east-west drive path; air velocities were measured as the sprayer moved past the towers with no tree foliage to deflect or absorb air flow (NSO).

Sensor calibration

All anemometer units were calibrated each day with a portable calibration system (Fox et al., 1991) which had been calibrated using a standard hot-film sensor calibrated in a TSI model 1125 calibrator.

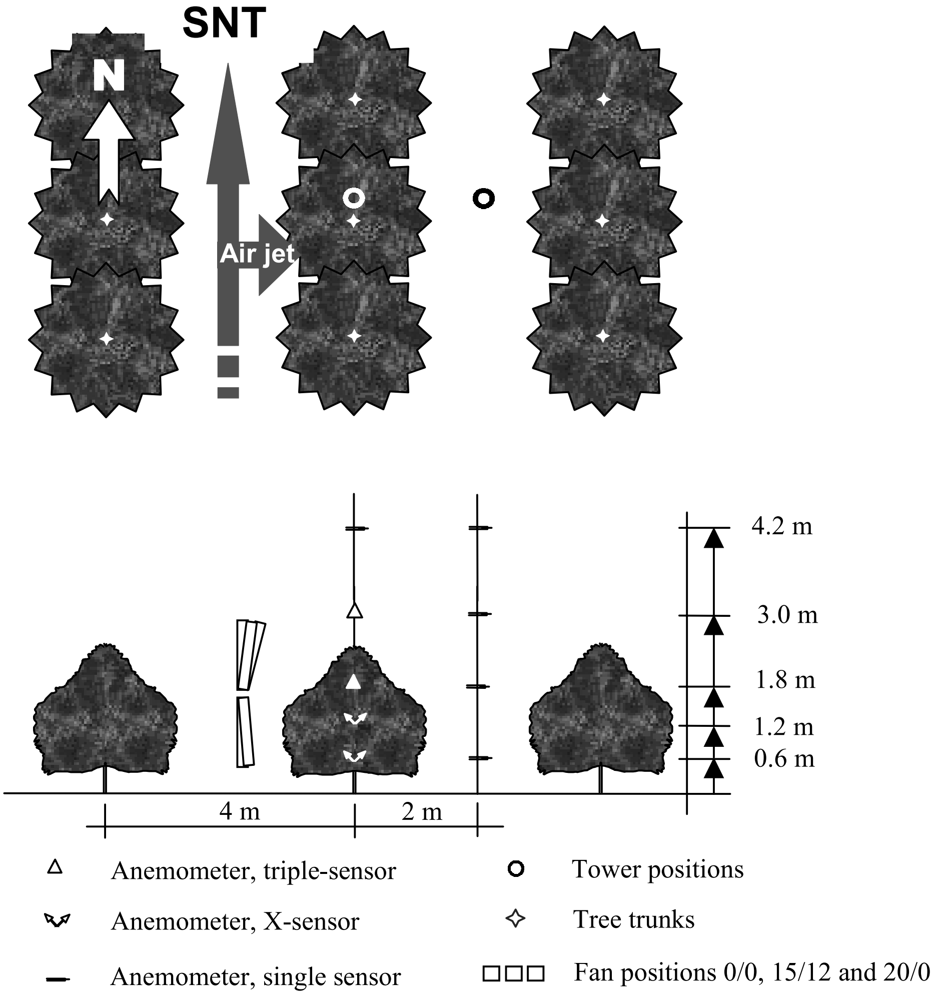

Figure 1. Plan and section, showing anemometer positions and types. The figure displays one of the treatment setups (from South to North in Trees - SNT)

Multi-sensor probes were mounted so that air flow from the air jets was near 90° to the probe axis. Response of the triple-sensor and x-probes to flow near 90° to the probe axis was measured in the portable calibrator. Output voltage from the x-probes was nearly constant for flow angles near 90°. The triple-sensor probes had reduced response when flow angle was near 90°; correction factors were determined and used to adjust measured voltages.

Two switch plates were used to mark the beginning and end of each sprayer pass. When the tractor tire crossed each plate, a 5-volt signal (positive - start, negative - stop) was recorded on channel one of each recorder. These signals and a voice track were used to identify the 160 sprayer passes.

Meteorological measurements

Background wind directions were measured with a three-propeller anemometer (Model Gill UVW Anemometer Model 27004, R.M. Young Co. Traverse City MI) mounted at 5.9 m elevation; temperatures were measured with a vertical array of thermocouples.

The experiments were conducted during times of low wind velocities; when one-minute averaged wind velocities were consistently greater than 1 m/s experiments were postponed until wind velocity decreased. On August 5, wind direction varied from NNW to NNE during the experiments, with a maximum velocity of 1.65 m/s for one series of three passes but during 42 of 54 passes, wind speed was less than 1 m/s. Air temperature was 21 to 24 °C and relative humidity was about 68%. The sprayer air jet was directed toward the east for the experiments on August 5.

On August 6, wind direction varied from NW to NE with a maximum speed of 1.6 m/s but with wind speeds less than 1.1 m/s during 39 of 54 passes. Air temperature was 20 to 24 °C and relative humidity was about 60%. The sprayer air jet was directed toward the west for experiments on August 6. On August 24, wind direction varied from SE to W during the experiments, with a maximum velocity of 1.09 m/s. During 53 of 54 sprayer passes, the wind speed was less than 1 m/s. Air temperature was 14 to 17 °C and relative humidity was about 75%. The sprayer air jets were directed toward the west during experiments on August 24.

Sprayer air jets

The air jet for the sprayer used in the experiments was produced by two cross-flow fans (Gebr. HOLDER GmdH. & Co., Metzinger, Germany) and were mounted on a three-point hitch chassis built in the laboratory. Each fan had an outlet of 1.1 by 0.086 m; they were powered by hydraulic motors and hinged at the common support between the fans so that the top and bottom could be inclined from the vertical. The fans were inclined to produce a converging jet. Air flow per fan unit was 7 700 m^3/h (at 18 rps[1]) and 11 600 m^3/h (at 24.5 rps). See Fox et al. (1992) and Svensson (1994) for more details on the fans.

Experimental treatments

The treatments were:

- Three travel speeds (4.8, 6.4, and 8.0 km/h)
- Three fan positions: both fans vertical (0/0), top fan inclined 20° from vertical (20/0), and top fan inclined 15° from the vertical and bottom fan inclined 12° from the nadir (15/12)
- Two fan speeds: 18 and 24.5 rps

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[1] rps: revolutions per second

Two in-canopy conditions were used and in the analysis regarded as blocks: from south to north with trees (SNT), from north to south with trees (NST). In one comparison, the canopy condition from north to south in the open (NSO), was used together with NST as treatments.

Measurements of each treatment were repeated three times.

Data Analysis

The velocity signals were played back from the tape recorder and sampled using a measurement and control system (model 500A, Keithley, Inc., Cleveland OH). An analysis program was written to sample the signals, to convert from voltages to velocities, to make necessary corrective computations and to store the results in computer files on diskettes.

For the triple sensor and x-probe signals, about 15 000 values were sampled for each sensor at each elevation. Samples were recorded during the time interval between the start and stop pulses, approximately 6.5 s. Concurrent values for the triple sensors were multiplied by a transformation matrix to change the velocity vectors from the recorded coordinate system (along the sensors) to the cardinal direction coordinate system. The resulting velocity component in the x-z-plane (perpendicular to the tree row direction) was also calculated. At this stage, with a sample rate of 2 300 Hz, each value was also cubed. The resolved samples were then averaged in groups of 75 to produce 200 velocity values in each direction for each sprayer pass, resulting in a final sampling frequency of 31 Hz. The x-z-plane components and the cubed values for the x-probe sensors were computed in the same way as were the triple-sensor values. The single sensors were sampled in a similar way, however with a lower original sampling frequency.

A second analysis program was written to read the files of 200 velocity points stored by the previous program, to correct for background wind, and to record the greatest single sample for v, v^3, and the sample number where these maximums occurred. The program also computed the start and end of the velocity pulse from the sprayer pass and plotted the result. The operator then could adjust the pulse start and stop sample number and the total area under the velocity curve was calculated. The integrated values of v and v^3, together with locations and maximum velocities, were stored in a file.

The program SPSS, vers. 10.0.5, (SPSS Inc, Chicago Ill) was used to compute the analysis of variance (ANOVA) of the various treatments and result parameters at each elevation, for south to north with trees and north to south with trees (SNT + NST). ANOVA were also computed for treatments including north to south with trees and north to south without trees (NST + NSO).

Results

Air velocity pulses

Sprayer passes produced obvious air velocity pulses at the 1.2 and 1.8 m elevations on tower #1. At the 0.6 m elevation, the fan arrangement with the bottom fan inclined 12° did not produce pulses for all passes. Both fan arrangements with the top fan inclined did not produce air pulses for all passes at the 3.0 m elevation. None of the three fan arrangements produced a noticeable pulse at the 4.2 m elevation; sprayer passage was noticeable for many passes at this elevation because the anemometer signal became more active. Velocity pulses on tower #2 were similar in that the only consistently visible pulses for all treatments occurred at the 0.6 m and 1.8 m elevations. Only passes with both fans vertical produced visible pulses at the top two elevations.

Air in the air jet was turbulent at the fan outlet, and turbulence increased upon contact with leaves and twigs. The entire air jet pulse passed the sensors during about one second (depending on travel speed). These facts, despite the high sampling frequency, explain the great variation shown by the velocity maximum values. Integrated velocities were more stable and also included the time factor related to travel speed.

Effects of treatments on the in-canopy situation

Effects of fan positions

The effects of fan position on vertical velocity profiles is shown in Figure 2. Velocity profiles were similar, independent of whether maximum or integrated velocities were used as a criterion. Changing the bottom fan unit from its vertical position had great influence on the air velocity at the lowest measurement position in the tree canopy. Here treatments 0/0 and 20/0 resulted in significantly higher air velocities. For the 1.2 m elevation, in the middle of the canopy, differences were small and not always significant. For the integrated result calculations, some differences were detected where the fan arrangement 15/12 showed a lower value than the 20/0 treatment.

In the upper tree center, at the 1.8 m elevation, the differences were significant in almost all cases. The converging air jets (15/12) showed the highest air velocities, followed by the 20/0 arrangement. The fan arrangement with both fan units vertical (0/0), showed low air velocities. At the first position over tree top level (3.0 m elevation) the arrangements with both fans vertical showed a significantly higher velocity. There were no significant differences between the two fan arrangements with the top fan units tilted. At the highest measurement position, far over the tree top level (4.2 m elevation), only small differences were noted and, generally, no significant differences were present. For the second measuring tower, behind the tree, similar air velocity distributions were observed. However, the amplitudes and signals were reduced and diffused, especially on the two top positions.

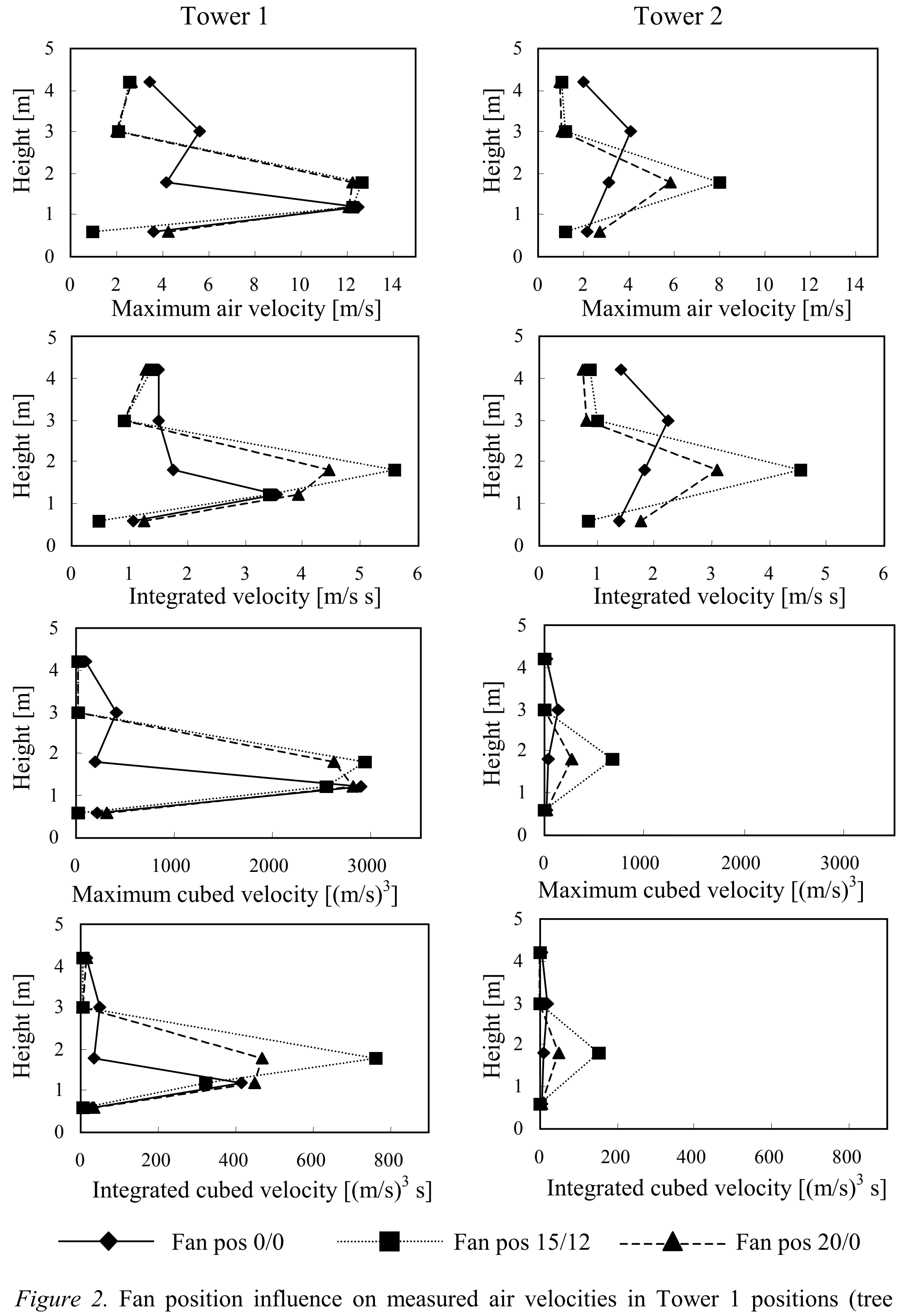

Figure 2. Fan position influence on measured air velocities in Tower 1 positions (tree center) and Tower 2 (behind trees). From top: maximum velocity, velocity integrated over time, maximum cubed velocity and maximum cubed velocity integrated over time. Fan positions notation indicate fan unit inclination.

Machine output (m^3/m of forward travel) was calculated for different fan conditions and are displayed in Figure 3. Outlet flow and travel speed are combined in the same way as by Hale (1978). At the 1.2 m and 1.8 m elevations, the integrated velocity showed a consistent and significant increase with increased machine output. The values from the converging fan alternatives were significantly higher and increased more at the 1.8 m elevation. Over tree top level, 3.0 m, the consistent increase no longer existed, and here the differences between the fan conditions once again were indistinct.

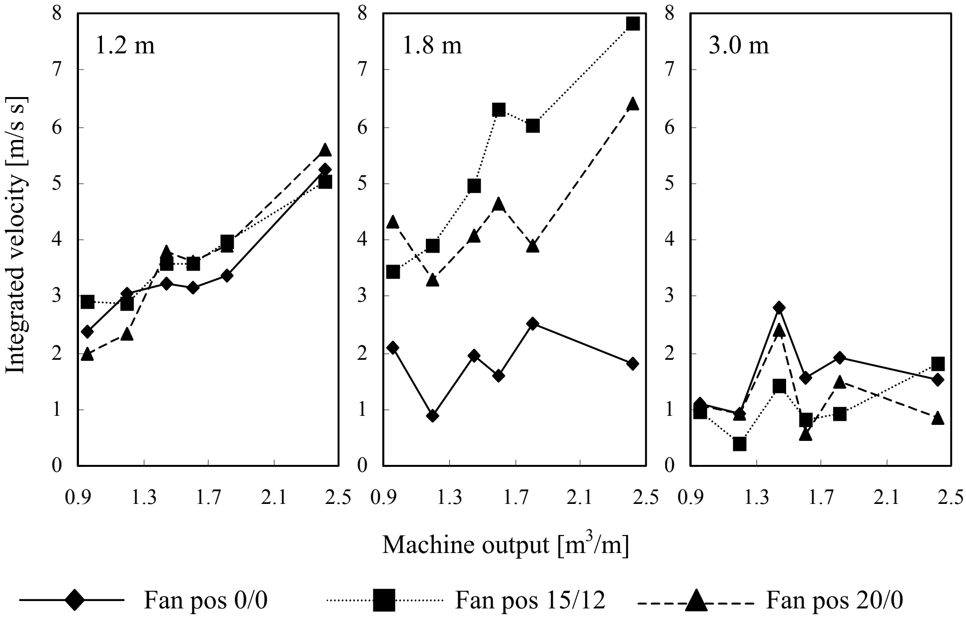

Figure 3. Integrated air velocity for different machine outputs measured at Tower 1 positions (tree center) at heights 1.2 m, 1.8 m and 3.0 m over ground. The figure shows the treatment NST (driving from North to South in Trees). Fan positions notation indicate fan unit inclination.

Effects of travel speed

Travel speed effects expressed as maximum velocities showed very small differences, where few were significant. As shown in figure 4, air velocities were much higher for the two positions inside the tree canopy, near the center of the fan outlets (1.2 and 1.8 m elevation) than for the other positions.

When integrated velocities were calculated, travel speed effects became clearly visible, especially at the 1.2 and 1.8 m elevation. Here integrated velocity values were significantly higher for the lowest travel speed (over all treatment combinations). The second travel speed followed, however with smaller and not always significant differences in integrated velocities compared to those measured for the greatest travel speed.

At the lowest position inside the canopy and at the two positions above the tree, no significant differences among travel speeds were present. The relations among values at these positions were not affected by using maximum or integrated values.

For tower #2, behind the tree, most differences caused by travel speeds were not significant.

Effects of fan speed

Figure 5 shows effects of fan speeds. Independent of analysis method, higher fan speeds produced significantly greater air velocities inside the canopy at the 1.2 and the 1.8 m elevations. For both high and low fan speeds, the results did not change much from the 1.2 to the 1.8 m elevation, when using the integrated and integrated cubed values. However, the maximum and maximum cubed values decreased noticeably from the 1.2 to the 1.8 m elevation.

At the lowest position inside the canopy and at the two positions over the tree, 3.0 and 4.2 m elevations, differences in general were small and seldom significant. Behind the tree, at positions in tower #2, the values were clearly reduced.

Effects of canopy conditions

In the ANOVA above, the canopy conditions (NST, SNT) were treated as blocks. The differences between blocks were clear and significant, especially for positions inside canopies. For tower #2, significant differences were reduced, both in number and size.

The effect of tree canopy on air velocities at the anemometer sensors was evaluated through an ANOVA where the north-south in-tree condition (NST) was compared to the north-south without-tree condition (NSO), in a model that included fan speed, travel speed, and fan positions.

Significantly greater velocity values were observed in the open, compared to inside the canopy, except at the 4.2 m elevation at tower #1. The difference was also small at the 3.0 m level. Tower #2 values showed more smoothed out profiles, lower values and much less significant differences.

In figure 6, the means from all three canopy conditions (SNT, NST and NSO) were displayed, showing that results from SNT and NSO were rather close, and also greater than the NST-values. Tower #2-values showed less and inconsistent differences.

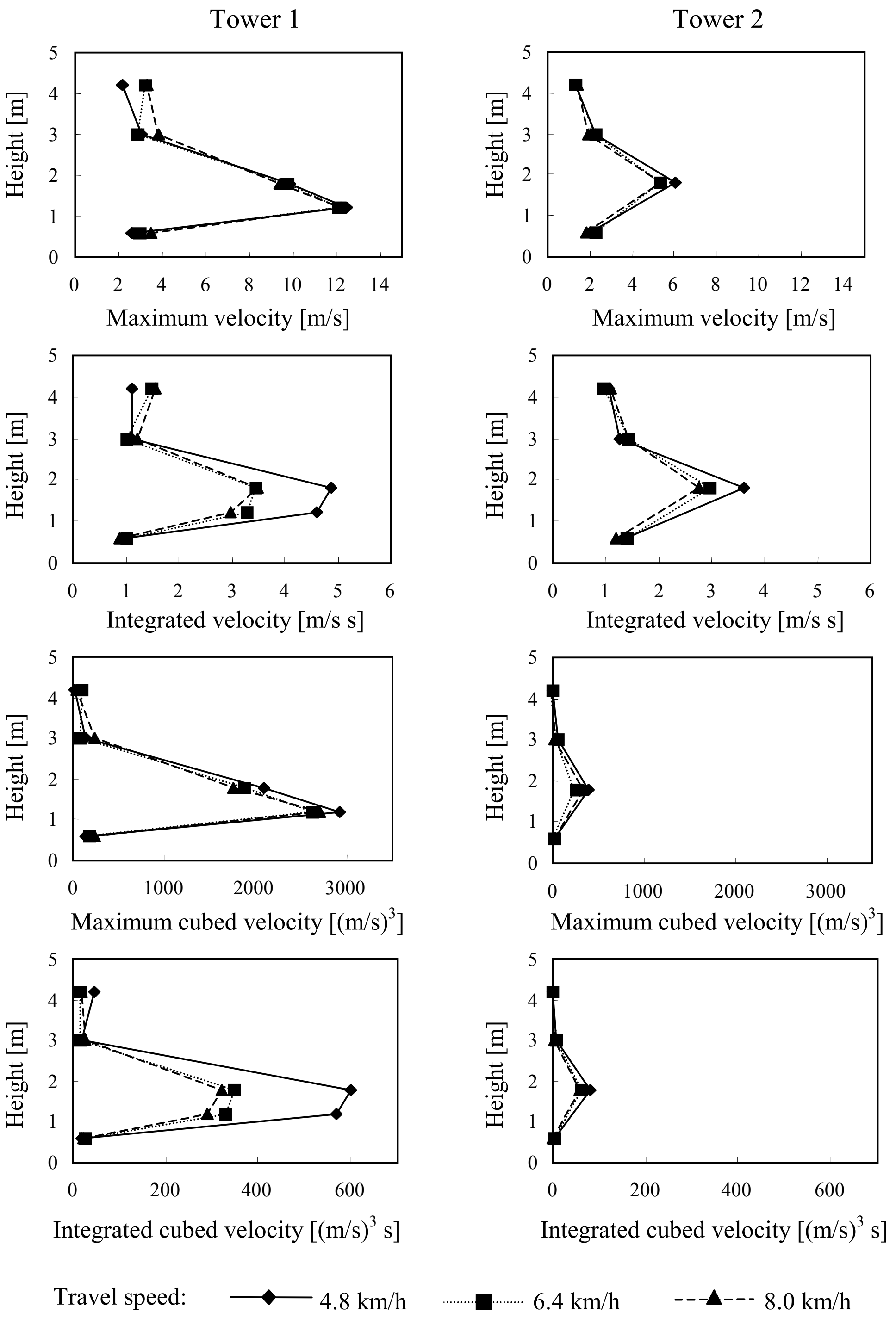

Figure 4. Travel speed influence on measured air velocities in Tower 1 positions (tree center) and Tower 2 (behind trees). From top: maximum velocity, velocity integrated over time, maximum cubed velocity and maximum cubed velocity integrated over time. Travel speeds were 4.8 km/h, 6.4 km/h and 8.0 km/h.

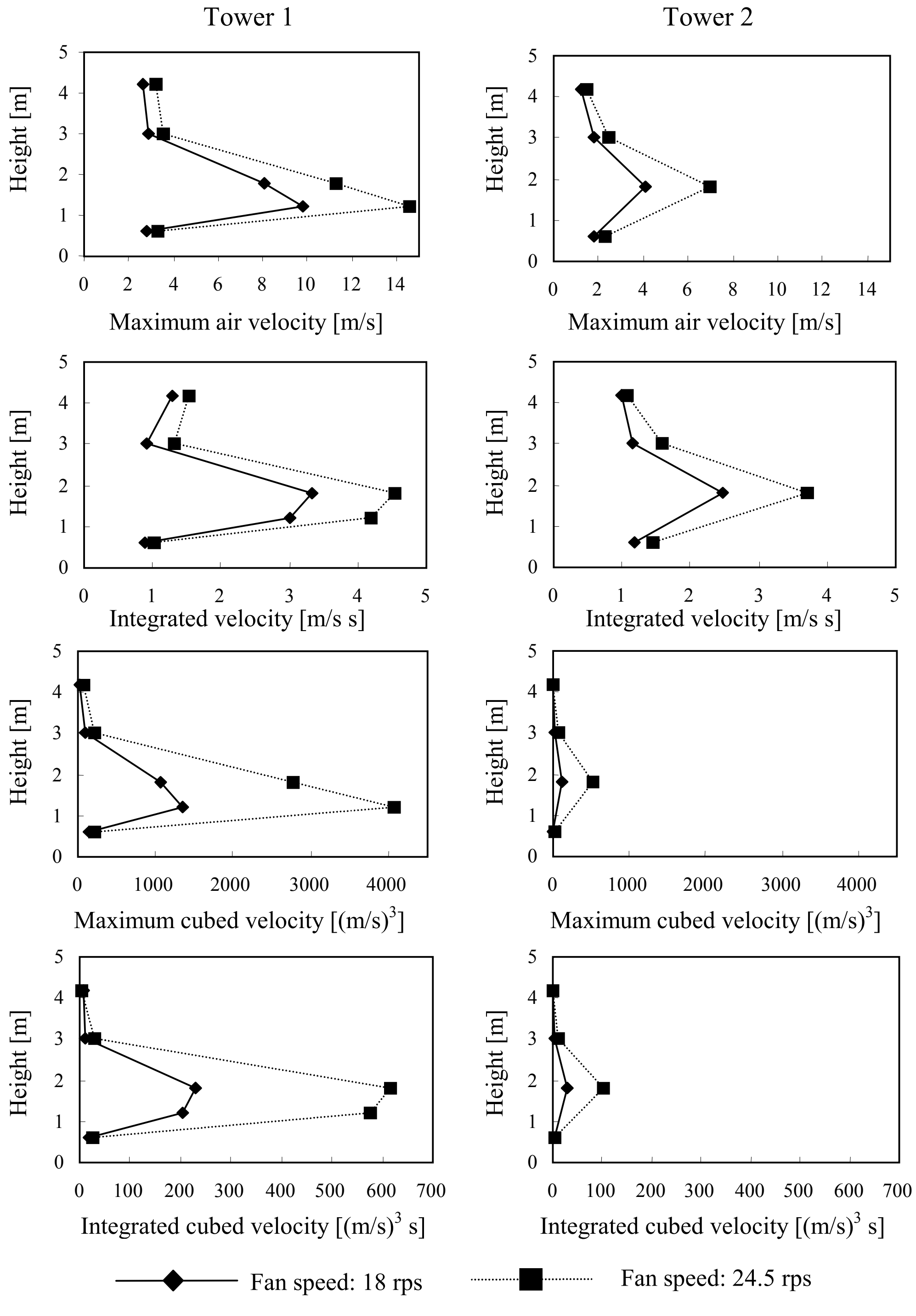

Figure 5. Fan speed influence on measured air velocities in Tower 1 positions (tree center) and Tower 2 (behind trees). From top: maximum velocity, velocity integrated over time, maximum cubed velocity and maximum cubed velocity integrated over time. Fan speeds were 18 rps (low) and 24.5 rps (high).

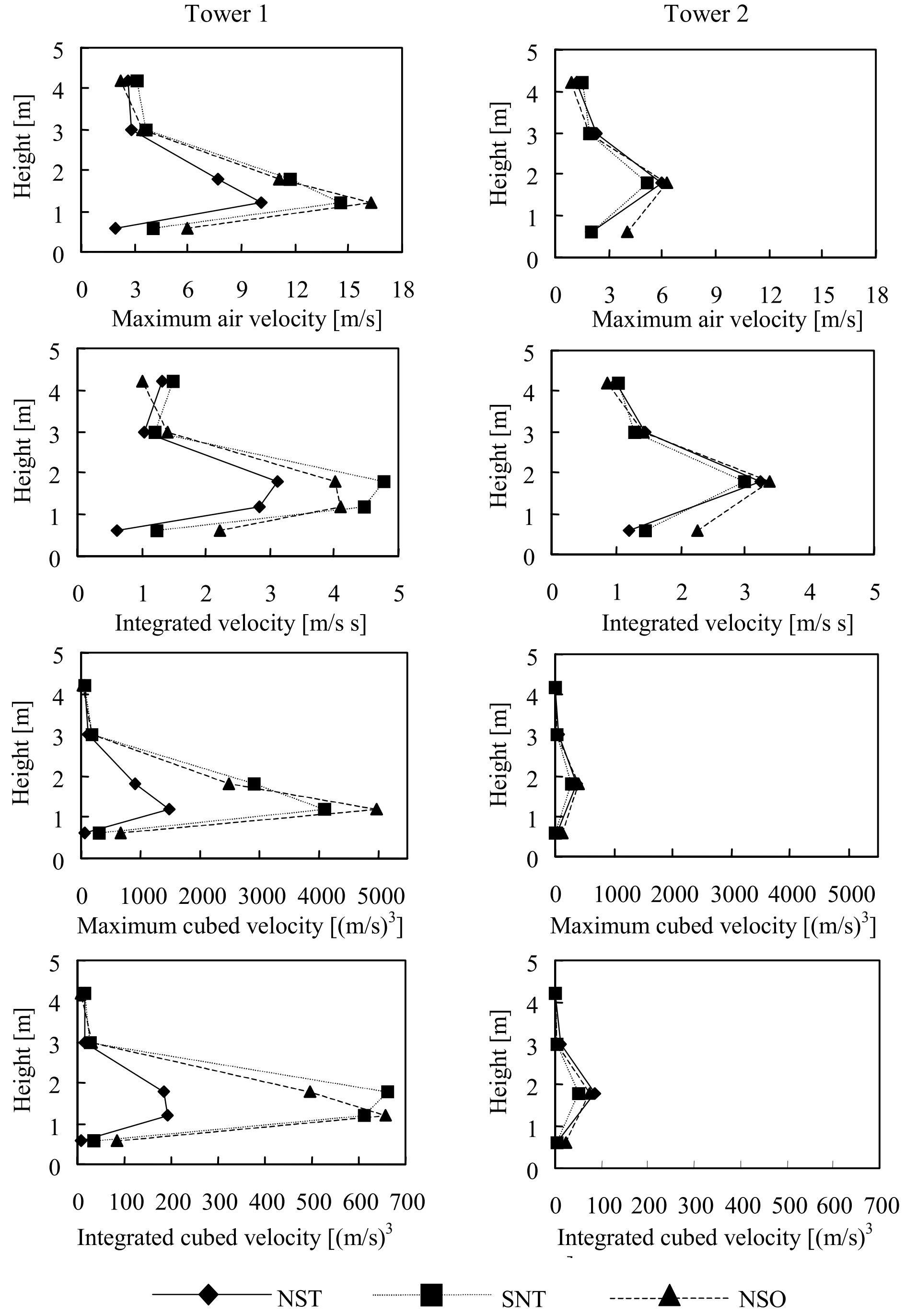

Figure 6. Measured air velocity results for all canopy conditions and positions in Tower 1 positions (tree center) and Tower 2 (behind trees). Canopy conditions: from North to South in Trees (NST), from South to North in Trees (SNT) and from North to South in the Open (NSO). From top: maximum velocity, velocity integrated over time, maximum cubed velocity and maximum cubed velocity integrated over time.

Discussion

When discussing the results, it is important to distinguish between airflow around and airflow through the canopy. The first part, displayed at the measurement points above the canopy, is related to potential drift, while the second part, based on positions inside the canopy, is related to penetration. These factors should be regarded in combination, as it is important not only to penetrate the canopy, but also to achieve penetration without causing wind drift. An air pulse above the tree indicates jets missing the tree or deflected upwards by the canopy that acts, to some extent as a solid body, especially late in the season.

The top position (4.2 m elevation) seldom displayed any distinct pulses and could in general be described as unaffected by the air jets. However, those air velocities detected were higher for the 'in-canopy' treatments (NST, SNT), than the 'in-open' (NSO), indicating that even at this elevation there seems to be a spreading upwards caused by the canopy.

Fan position had greater influence than canopy conditions at the 3.0 m level. For vertical fans, all measured parameters showed a significantly higher value compared to the fan positions where the top fan unit was tilted. The differences were greatest for the single maximum values. Svensson (1994), who measured spray deposits at similar levels, reported results that supports this. At this position, there were also some significant but small differences in integrated velocity caused by different fan speeds.

Penetration effects of the canopy were illustrated by measurements at the 0.6 m, 1.2 m and 1.8 m elevation positions inside the canopy. The lowest position was just on the bottom edge of the vertical air jets, and only a few air pulses were observed for treatments in which the lower fan unit was tilted. The 1.8 m elevation position was close to the elevation of the gap between the upper and lower fan units.

The parameters calculated here to compare treatments provide different insights into the basic structure of the flow field. Maximum air velocity values can be used to illustrate differences, however they exhibit large, rapid variation during each pulse. They should be interpreted with care as few replications were made.

The integrated values of velocity over the time period of the pulse were more stable. They are of great interest for deposition, as they represent a value corresponding to the air volume flow through the sample position, a factor representing one of the important prerequisites for deposition. Also the cubed maximum values, related to air jet power, show great variation over time. The velocity-cubed values, integrated over time are related to energy in the air pulse and thus to penetration ability.

Differences in canopy air velocity fields due to fan position (0/0, 15/12 and 20/0) were obvious in most combinations of measurement parameters, treatments and analysis methods. The converged air jets showed higher parameter values, implying better conditions for deposition and penetration.

The influence of travel speed on spray deposition has been discussed in earlier research (Zhu et al., 1997, Planas et al. 1998, Salyani, 2000). No significant differences among travel speed were detected by comparing maximum velocities. This supports the results of Derksen and Gray (1995), who measured air velocities inside canopy. They used two travel speeds, but did not record significant differences between peak velocities. However, our results showed significant differences for 'integrated velocities' with lower travel speed producing higher values. As there were no differences among travel speeds for 'single maximum velocities', differences in integrated values was likely due to a time effect, i.e. air velocity remained high for a longer time during the low travel speed treatments. An example of this is shown in figure 7, where three velocity pulses are plotted in the same diagram, slightly displaced. The higher air velocities act on a leaf during about 1.0 s, giving the leaf more time to move about and increasing the opportunity for the spray cloud to deposit on all sides of the leaf. This effect is supported by Locher & Moser (1981).

Hale's (1978) method for relating the sprayer's outlet air flow volume rate to travel distance (m^3/m of forward travel) was used to combine two of the treatment variables to one. This displayed a more firm relation for integral values than maximum velocities. Integrated velocities increased with increased flow per forward travel, indicating a greater volume of air passing a position, once again supporting the converging air jets and the theory of using the output power in air flow, rather than in air velocity (Randall, 1971).

Differences in fan speed were visible, great and significant for most parameters considered. The output power, here expressed as air velocity and air flow at the outlet, showed a great influence on velocity factors inside the canopy.

Measurements in NST, SNT and NSO showed that canopy influence on air velocities was an important factor. We noted that in many cases canopy influence caused an increased variation among positions and treatment.

The SNT-results in general were closer to the NSO-results than to NST-results. These differences in velocities within the canopy was probably due to local effects such as limbs, twigs, and leaves, where the tree may have shielded the sensors from the air jet to a greater extent during the NS passes than for the SN passes. This could also be an effect of what Walklate et al. (1996) define as 'channeling effects'. Great differences inside the tree from canopy differences, combined with small differences in tower #2 measurements support the observation that the tree was thinner on the west side (facing the air jet in the SN situations), but that after passing the whole canopy, differences could be disregarded. This, however, was in contradiction to the fact that rather small differences between NST and NSO at tower #2 positions were found, indicating that at this distance from the outlet, no canopy influence was measured.

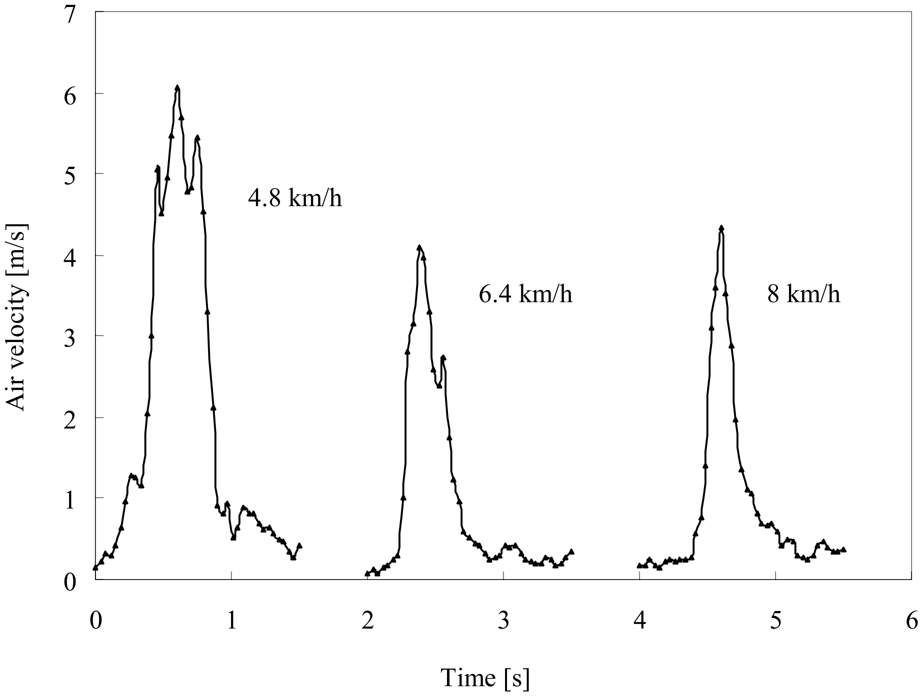

Figure 7. Air velocity pulses for different travel speeds (example shows: fan condition 0/0, high fan speed, 1.2 m elevation, inside canopy (Tower 1).

Our measurements illustrate the variation between positions inside canopies and between trees. Even though the measurement positions were not changed, totally different velocity results were recorded when the air jet was directed from the other side of the tree. The rapid velocity variations over time were strong arguments to use sensors with high resolution and high frequency sampling, to be able to record an adequate picture of what was happening during the pass. All this, in combination with the variation between replicates, underlines the strong influence from the sensor position and that it is important to make measurements in several trees, with several replicates, or to find other measuring methods, where position influence is reduced.

Conclusion

It was possible to relate the integrated air velocity in a canopy position to the air volume flow through canopy and the integrated cubed velocity to air jet energy, indicating two parameters, relevant for deposition and canopy penetration. Measurements above the trees were indications of losses and potential wind drift.

Bearing this in mind in a summation of the results, we conclude that:

- The airflow characteristics of the converging fan position alternatives promoted penetration and were better prerequisites for deposition than the original plane jets.
- Airflow from converging air jets reduced flow above the tree canopy.
- Low travel speed and high air output power improved penetration in general.
- Traditional problems in air velocity measurements in canopy situations, also experienced in this experiment, such as great and rapid velocity variations and strong sensor position influence, call for alternative research methods.

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Forces on apple trees sprayed with a cross-flow fan air-jet

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Abstract

To provide necessary plant protection in orchards, spray drops are transported to and into the canopy with an air jet from a fan sprayer. The interaction between the spray air jet and the tree canopy is central to effective droplet transport, spray coverage and pest control in orchard spraying. A new method was developed to study this interaction by measuring forces applied to the tree by the sprayer jet during spray passes. A dwarf apple tree, sawed off at the trunk, was attached to the top of a multi-component force transducer, that in turn had its base secured to the ground. Forces in three directions, as well as the moment about the axis parallel to the fruit tree row, were measured. A two-unit cross-flow fan orchard sprayer was moved past the sensor-equipped tree. A plane jet with both fan units vertical, and a converging air jet, with the top fan unit inclined 19° towards the sprayed tree were used. Two output power levels (fan rpm) were used with both fan conditions. Results presented are: maximum x-forces and moments, and the integral over time for forces and moments created by the moving air jet. There were significant differences between all treatments. Highest values were obtained with the converged air jets and high fan speed, followed by the plane jet and high fan output. Next was the converged jet-low fan output while the lowest force and moment values were measured for the plane jet-low fan output. Greater force and moment values resulted in more output power being transferred to the tree through jet air velocity acting on the canopy. Measured forces provide an integration of many individual actions between the air-jet and the separate elements of the tree canopy and thus balance out short time fluctuations. Repeatability in the measurements was very high, both for single values of force and moment and in the shape of pulses for each treatment replication.

Keywords: orchard spraying, fan sprayer, air jets, force measurements, canopies, application technology, cross-flow fan, converging air jet, apple, pest control, plant protection.

Introduction

Air-assisted sprayers use air-jets to transport spray droplets into the plant canopy and promote uniform deposition of the spray throughout the canopy. Achieving a uniform spray coverage on trees, without great loss, is more difficult than on field crops. Air jet velocity and volume, jet exit direction with respect to the sprayed tree, size and growth stage of the tree, volume, distribution and drop size of spray solution applied, as well as wind conditions all may affect the deposition pattern of the spray within the canopy. Air velocity at the target object has been shown to be of great influence for spray deposition from a general and theoretical viewpoint (May & Clifford, 1967), but the relationships in the practical situation are yet not quantified and verified in widely used models.

Determining the proper match between an air-jet/sprayer system and a tree canopy has been a subject for study for many years. Other research have compared deposits in tree canopies when using air-blast sprayers with several air jet characteristics.

Furness & Pinczewski (1985) measured spray deposits in citrus and vineyard canopies from spraying with several sprayers with unusual fan arrangements for a range of travel speeds and application rates. A prototype, multi-head sprayer was used with both converging and diverging jet configurations. They found that the converging jet arrangement gave significant improvement in the uniformity of spray coverage on plant foliage compared to coverage when using diverging air-jets.

Doruchowski et al. (1996), continued by Holownicki et al. (2000a, 2000b), measured spray deposit on dwarf and semi-dwarf apple trees, using sprayer types with different air flow characteristics. Some of the initial results varied from year to year, but the studies presented in 2000 showed that the sprayer design with 10 directed air-outlet sprayer aimed 20° upwards produced the greatest in-canopy and lowest off-target deposition in both orchard types. They also showed how the balance between deposition and losses for different tree conditions and sizes was affected by altering the air outlet direction, both in the vertical and horizontal planes. Walklate et al. (1996a) used an axial-fan orchard sprayer with two air volume outputs; the larger volume was twice the smaller. In general, they found that the sprayer with the high volume air-jet produced greater spray deposits in the top and bottom sections of trees.

Several air-assisted sprayer studies have measured air velocities produced by air-jets from stationary sprayers, from sprayers moving past towers or from sprayers moving past anemometers within tree canopies. Some of these measurements were combined with spray deposit measurements.

Many studies, beginning with Randall (1971), have found that making air velocity measurements of passing sprayer air jets in plant canopies is a difficult task. The jet passes very quickly, so a fast response sensor system is required. The jet, interacting with the canopy structure, produces considerable irregular flow and turbulence. This adds to the variability in velocity values among samples. Because sensors must be small to achieve the fast response required, measured values are greatly affected by the placement of the sensor, i.e., canopy features near the sensor. Thus air velocities measured in these conditions must be made at many positions, with many treatment replications, at a high sampling rate to expect to collect stable data on a jet/specific plant canopy interaction. This implies a large data processing load, with many numbers to analyze to estimate the actual flow field produced by the sprayer jet in the tree canopy. Thus, air velocity fields, while an important factor in droplet impaction on leaves are time consuming and expensive to obtain.

Randall (1971) measured air velocity profiles at several distances from the outlet of three sprayer air-jets and compared these profiles with velocity profiles predicted by fan plane jet theory. The sprayers produced equal output power, but showed three combinations of air volume/outlet-air velocity. He measured air velocities within a tree canopy with accelerometer-equipped permeable balls as air velocity sensors. For sprayers traveling at low travel speeds, he found that air velocities close to sprayer outlet were nearly equal for all three sprayers. At greater travel speeds and further from the sprayer, the sprayer with greater air volume produced greater velocities. He also used these sprayers in trials in an apple orchard and rated their operating efficiency based on the amount of spray deposit captured on targets in the trees. Using this criterion, he found that the greatest ratio of air volume/air velocity resulted in the highest and most uniform deposits.

Reichard et al. (1979) measured vertical profiles of air velocities produced by several sprayers traveling at a range of travel speeds and at a range of distances from the measurement tower. Air velocity profiles were also measured within a peach tree as the same sprayers were driven past. Sprayers producing high volume but lower velocity air-jets produced higher velocities at distances beyond 1.5 m from the jet outlet than did sprayers with low volume/high air velocities at the outlet. They found that increasing travel speed reduced measured air velocities. Air velocities measured within the tree canopy were more variable than velocities measured without trees. While most air velocities were less than those measured at the same distance from the sprayer without a tree, at a few positions, the velocities were greater than at the same location without a tree. This seemed to indicate a channeling of flow due to the canopy structure.

Brazee et al. (1981) extended the theory of air velocity fields produced by jets from the plane jet theory to a theory for a diverging ‘fan-shaped’ jet typical of axial-fan orchard sprayers. They also measured air velocity profiles produced by two stationary axial-fan orchard sprayers for 0 to 5.0 m from the sprayer jet outlet. They compared normalized measured velocity fields with the fan-jet theory and found good agreement.

Rosswag (1985) measured the air velocity distribution inside fruit tree canopies in stationary situations and found great influence from growth stage, canopy positions, and fruit varieties. The air velocity inside an apple tree was often reduced by 70 % from early spring to late summer and by 80 % from the densest parts to the most open parts in the lower canopy. Based on these measurements, he calculated drag coefficient-values for trees. He also measured air velocity distribution from the free air jet and how it was influenced by primary fan conditions, by travel speed and by distance from the outlet.

Svensson (1994) sprayed apple trees with a two-fan cross-flow fan sprayer where converging or parallel air jets was the only treatment parameter. He measured 50% greater spray deposition and more uniform spray distribution pattern in the tree with the converging air-jet sprayers. A limited study of maximum air velocities was also made. The converging jet system was found to produce larger air velocities than the parallel air-jet sprayer. He also reported great variations in air velocity measurements between trees, positions and replicates.

Fox et al. (1992) measured air velocity profiles from a stationary cross-flow fan sprayer and determined that the measured velocity field agreed well with velocities predicted by plane jet theory. Derksen & Gray (1995) found no significant difference among peak air velocities within apple canopies when an axial fan sprayer passed at 0.9 and 1.3 m/s or when the fan air-volume output was 652 or 822 m^3/min. There was also no significant difference between total deposit on trees sprayed with these sprayer treatments, and they did not find any correlation between air velocity and spray deposit.

Salyani & Hoffmann (1996) measured air velocities at four positions along four radial lines extending outward from an axial-fan sprayer. Velocities were measured for both a stationary sprayer and when the sprayer was traveling at 2.6 km/h. At 0.7 m from the fan outlet, when the sprayer was traveling, measured air velocities at all measurement points was less than half of the air velocities measured for the stationary sprayer. They also measured spray deposits on leaves and filter paper targets (liquid rates: 681, 2016 and 3855 l/ha). They measured a significant increase in deposit on the filter paper with increased air velocity, however deposit on leaves was not affected by sprayer jet air velocity.

Svensson et al. (2001) measured air velocities inside, above and beyond apple trees as affected by sprayer operation conditions. They found that converged air jets could concentrate the airflow to the dense part of the tree and reduce air flow above the tree. They also noted great variability among velocities measured, depending on tree structure, canopy position and even replications.

The interaction between the air-jet and tree canopy is very complex and changes with time, wind conditions and nearly random response of individual leaves to jet air velocities. Still, some studies have attempted to create models of this process.

Walklate et al. (1996b) developed a model of the interaction between sprayer air-jets and tree canopies with a range of leaf-blocking area/volume ratios. They built an artificial canopy with a range of area densities. They tested the model by fitting a theoretical equation for centerline velocity and turbulent kinetic energy decay with penetration distance with measured velocity values. Correlations were made between the derived empirical decay coefficients and area density and provided reasonable results after local flow channeling effects were included in the model.

Vieri et al. (1998) developed a model to assist operators to determine the optimum sprayer characteristics for orchards. They developed equations for resistance of the canopy to air-flow and developed a sensor to measure aerodynamic forces at several points within the canopy. These sensors could be used to determine proper coefficients for the resistance equations for a particular canopy. A combination of an air-jet model with the resistance model for a tree should aid sprayer operators in selecting the optimum air-jet velocity and volume for maximum spray deposition in the tree.

The referenced studies have shown that we expect air velocity to have an important effect on the deposit of spray droplets on tree leaves. However, measured air velocity almost always exhibits large variability due in part to the influence of plant canopy obstructions at a very local scale. In addition, there is also great variability in measured spray deposits. Thus it has been difficult to obtain consistent results that provide a cause and effect relationship between sprayer jet velocity within a tree canopy and the amount of spray deposit within the same canopy.

One way to decrease the variability of measurements would be to combine many of the small, individual interactions into a larger integrated system. This was attempted in this study by using a force sensor to measure the total force on a series of dwarf apple trees produced by several orchard sprayer air jets. This system should provide increased consistency and repeatability, but still allow for differentiation among sprayer configurations and individual canopy characteristics.

The objective of this study was to determine air-jet/tree canopy interaction by measuring forces applied to the tree by the sprayer jet during spray passes. Measured forces should provide an integration of many individual actions between the air-jet and the separate elements of the tree canopy. The size, shape, and density of the tree canopy, air-jet power, and the point of application of the air-jet to the tree should be important factors in the total force applied to the tree by the air-jet.

Methods and materials

Force sensing unit

The force-sensing unit consisted of a multicomponent dynamometer (Figure 1). It was furnished with 16 strain gages, combined in a control unit to provide force measurements in the X-, Y-, and Z-directions and measure of the moment about the Y-axis. The dynamometer unit is described by Gebresenbet (1989). It was bolted to a steel frame that included fixtures for attaching a small tree (trunk diameter less than 10 cm) and for attaching to a circular support unit. The circular support was leveled and secured to the ground with metal stakes.

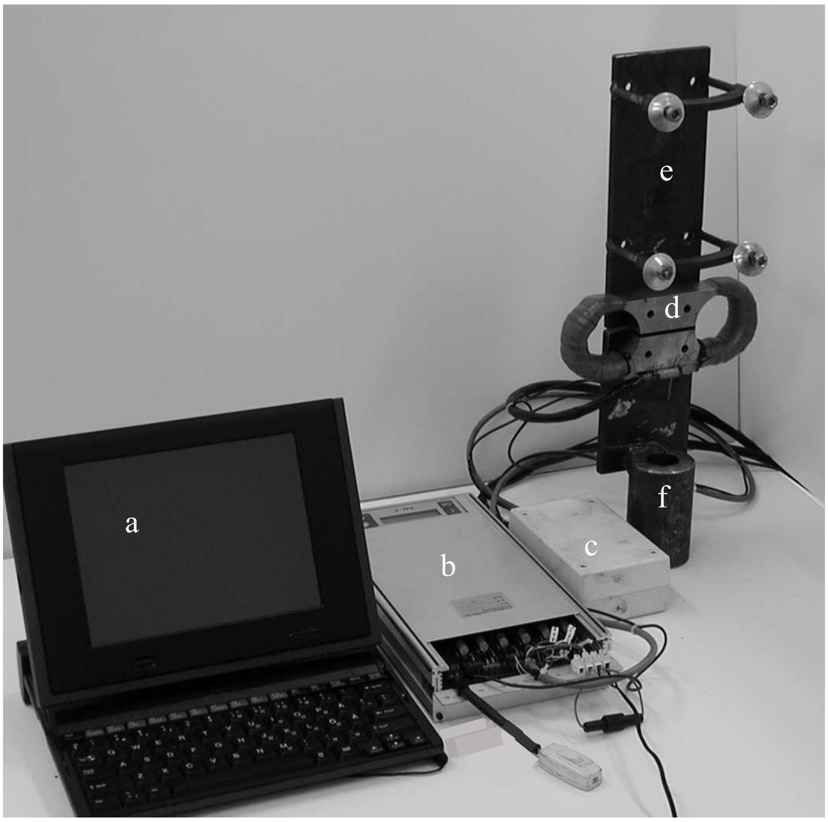

Figure 1. Measuring device. From left: a) Computer b) Logger c) Control unit with electronic bridges and adjustments d) Multicomponent dynamometer, with e) tree fixture (top) and f) ground support (below).

Figure 2 shows how the measuring unit was positioned so that the X-direction was in the nominal direction of the sprayer air-jet, Y-direction was in the travel direction, and the Z-direction was vertical. Bridge resistors in the control unit determined the gain of each force. The zero force (or moment) value could be adjusted with a multi-turn potentiometer. In practice the X-direction output was adjusted for a zero-force value of about + 60 mV, the moment output was set at – 50 mV, Y- and Z-direction outputs were set near 0 mV. The zero force values were reset after each tree was mounted on the sensing unit. By using zero-force offsets, the maximum dynamic range of the sensors in each direction could be used.

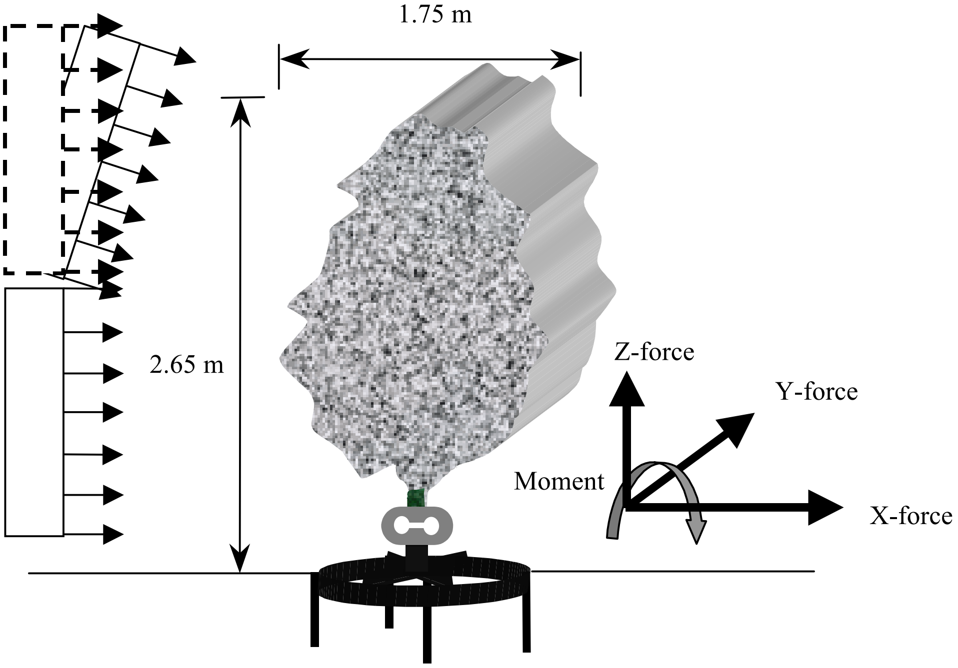

Figure 2. Cross-section of the sprayer travel path and “tree row”, showing the setup of the force measurements

Calibration

The sensing element was calibrated by mounting the unit on the circular support frame fastened firmly to a laboratory bench. The tree was replaced by a 4-cm diameter, 1.3 m long, thin-walled steel pipe. A spring dynamometer was attached to the pipe at a point 1 m above the center of the sensing element, wherein the force was applied in a horizontal plane. A series of forces from zero to 60 N were applied and the sensor system output in mV recorded. The applied force was sufficient to include the same range of values as measured in field experiments. A linear regression was used to calculate the slope of the calibration curve for each gain condition used. Trials made by varying the zero-force voltage output produced similar values for the calibration curve slope.

Experimental site

Experiments were conducted in an experiment field at Swedish University of Agricultural Sciences (SUAS), Alnarp, Sweden. Two sites were used. It appeared that the first location was exposed to south and southwest winds and it became difficult to find extended time periods with low wind speeds desired for the experiments. The second site selected was sheltered on the east by a 5 m high shelter belt and on the west by plantings of birch trees about 4 m tall. This location reduced maximum wind speeds to less than 3 m/s at elevations up to about 4 m.

Three apple trees were cut in a neighboring orchard and transported to the experimental site. The test tree was bolted to the sensing fixture, with a small container of water covering the cut area on the bottom. With this treatment the tree would retain its fresh appearance for over 24 hours. The other two trees were placed in support frames and used as edge trees for the test. The trees were placed 1.75 m apart in the row, and centerline of the sprayer path was 2 m from the trees, i.e., row spacing was 4 m. At the second site, the first row of birch trees was about 4 m behind the row of apple trees. The sprayer drive path was parallel to the hedgerow and in the north to south direction. The sprayer air-jets were directed to the right, or west toward the test tree row.

For each pass, the sprayer fans were started and proper speed set, whereafter the tractor was driven past the test trees at 4.7 km/h. The data logger was initiated as the tractor began moving and samples of the X-, Y-, Z-forces, and the moment about the y-axis were recorded at a sample rate of 250 samples/s. About 15 s of data were recorded for each pass.

Sprayer

The sprayer was an experimental orchard sprayer with two cross flow fan units (Gebr. HOLDER GmdH. & Co., Metzinger, Germany) as described by Fox et al. (1992) and Svensson et al. (2001). Top fan unit could be inclined 19° towards the tree row, (Svensson, 1994), by that creating a converging air jet. Fan outlet size was each 0.085 x 1.065 m. The fans were hydraulically powered. Fan rotary speed was displayed and controlled from the tractor cabin. The experiment setup with tree sizes, fan unit arrangements, distances, etc is displayed in Figure 2.

Standard sprayer equipment (Hardi Sweden, Eksjö, Sweden), mounted on the trailer with a 100 l tank, provided spray liquid. There were four nozzles (Albuz ATR yellow) in each fan outlet. With a liquid pressure of 0.5 MPa, travel speed 4.7 km/h and a calculated row distance 4 m, the application rate was 360 l/ha.

Trees

Trees were selected from 4 rows of Mutzu variety dwarf apple trees that were to be removed by the grower. The trees were rated for their suitability for these experiments. Criteria were: size of trunk, height and uniformity of the canopy, and symmetry of the limbs. After 20 passes planned for each tree, the specimen tree was rotated about 180° and a new series of experiments conducted. Each side of the test trees was considered a different tree.

By weighing all leaves of the trees and measuring the area of a 100 g sample, the leaf area index (LAI) was calculated to about 1.3 (based on the tree planting density in the orchard).

Meteorology

A cup anemometer with a wind vane was mounted at about 3.5 m elevation, and wind velocities and direction were recorded on a data logger every 15 seconds during experiments.

Design of experiment

Four treatments were used in this experiment. Fan speed was 1080 and 1470 rpm[1] ("low" and "high"). The cross-flow fan position was both fans vertical or the top fan inclined 19° toward the sprayed tree. Each treatment was applied 5 times to each tree, for a total of 20 spray passes per tree. Six trees were used in the study.

Force measurements

Forces in the X-direction were large, distinctive pulses. Because the strain gage system was less sensitive to X-forces than to other forces measured, the gain within the control unit was much greater. This lead to some problems in signal analysis, because the passing of the tractor and sprayer engines induced a response on the X-direction signal when the engines passed the sensing unit. Background signals of the tractor/sprayer passing without the air-jet operating were recorded for most trees. On this sprayer unit the tractor was about 5 m from the cross-flow fans, so background noise was reduced by the time air-jet forces were measured.

Because electronic noise preceded the force pulse, the background value used for determining the strength of the pulse was computed from the X-force signals after the pulse was completed. The X-force signal trace exhibited a damped sinusoidal signal about the background value after the force pulse. The background value was computed by averaging 800 samples beginning 500 samples after the maximum signal value. For each individual trial, the background value could be changed during the analysis to improve consistency. This background value was used for calculating magnitude of the forces and for determining beginning and end of the integration interval when area under the force pulses was computed.

Electronic noise from the tractor engine was small for the moment signals. However, because moment signals also exhibited a damped sinusoidal signal

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[1] rpm: revolutions per minute

after the main force pulse, the signal preceding the force pulse was selected as more representative of the background value and was used in signal calculations.

Forces in the Z- and Y-direction were not analyzed. Z-forces did not respond to the air-jet. Y-direction signals appeared to be pseudo-sinusoidal waves with a frequency of about 1.5 Hz. The pulses slowly damped off after the air-jet passed the tree. Y-direction force signals were similar to signals produced by applying and quickly releasing a torsion force to a tree.

Results and discussion

Typical moment pulses measured in these experiments are shown in Figure 3. The same treatment (vertical fans, high fan speed) and replication is shown for trees 3 and 4, which are the same tree, with opposite sides facing the sprayer air-jet. From Figure 3, it can be seen that the pulses have a similar, but reversed shape. This was noticed quite often in reviewing the data. If a tree produced a distinctively shaped pulse, say, with a shoulder on leading side, most passes displayed this shape. Then when the tree was turned 180° to be used as the next treatment tree, the pulse often had a shoulder on the trailing side. This supports the premise that tree shape is related to the force produced on the tree by the air-jet. In addition, it demonstrates that force measurement can detect the interaction between jet velocity and tree shape.

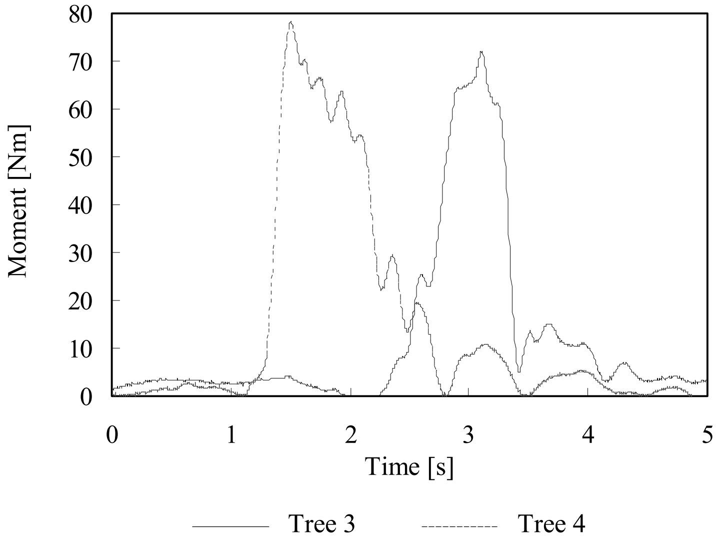

Figure 3. Examples of symmetric moment pulses from tree number 3 and 4 (same tree, turned 180 °). Both pulses represent Vertical fans and High fan speed.

Mean values and standard deviation of maximum X-forces for the four sprayer treatments are shown in Figure 4. From the program SPSS, vers. 10.0.5 (SPSS Inc, Chicago, Ill) Duncan's Multiple Range Test (DMRT) was used for a statistical analysis of these data. They were all significantly different at the 95% level, showing that the highest maximum force was obtained with the combination of inclined top fan and high fan velocity, followed by the combination vertical top fan and high fan velocity. Next in order was the combination inclined-low and the combination resulting in the lowest maximum force value was vertical-low.

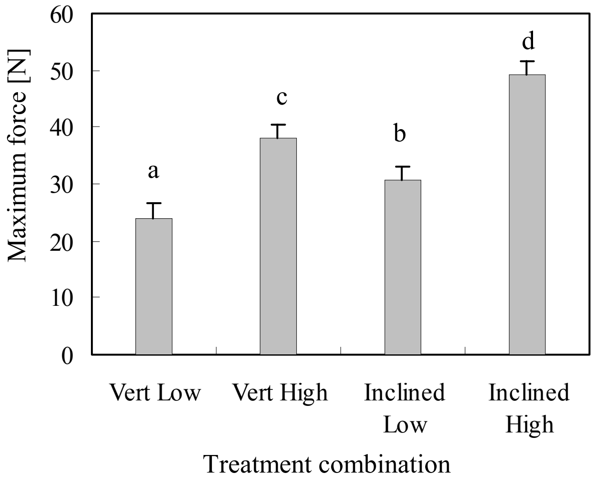

Figure 4. Maximum X-forces. Error bars show 1 standard deviation. Letters above bars show significant differences at the 95% level.

The force values integrated over time were calculated. Combining the maximum force values and the area under the force curve we gain information, not only on the instantaneous force magnitude, but also on the combined effect of the force and impact time, which is related to the sprayer jet – tree interaction, as well as the spray cloud affecting the canopy.

The area under the X-force signal is presented in Figure 5, and it can be seen that, even though the standard deviation was somewhat larger, all treatments had the same order as for the maximum force results, and were all significantly different at the 95% level using DMRT.

Mean values of moment pulses are shown in Figure 6, and the integrated area under the moment pulses in Figure 7. Again all sprayer treatments were significantly different at the 95% level for both measurement methods. The order of the sprayer treatments (from greatest to smallest moments) was the same as for the maximum force and integrated force measurements.

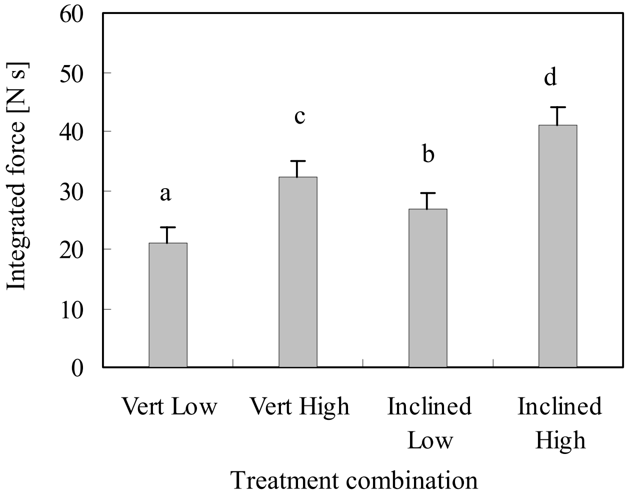

Figure 5. X-force integrated under pulse. Error bars show 1 standard deviation. Letters above bars show significant differences at the 95% level.

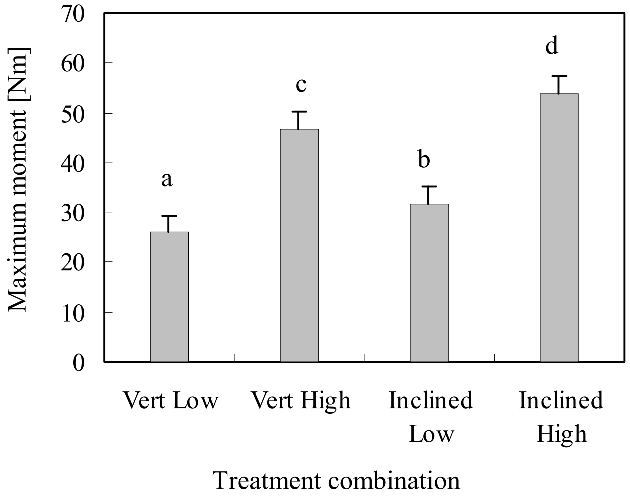

Figure 6. Maximum moments. Error bars show 1 standard deviation. Letters above bars show significant differences at the 95% level.

Repeatability in the measurements were very high, both for single values of forces and moments and in the shape of curves for each treatment replication. This was also demonstrated by the overall results, where small differences were statistically significant.

Statistical comparisons were also made among the 6 trees used. There were significant differences between some trees for some measurement methods, but results were not consistent (Figure 8). In general, there was little difference among trees when the maximum values of X-force or moment were used. However for integrated values, tree 3 and 4 were smallest and trees 1 and 2 were the largest. While trees 1 and 2 were the same tree rotated 180°, there was significant difference between these trees for both moment methods and for the maximum X-force.

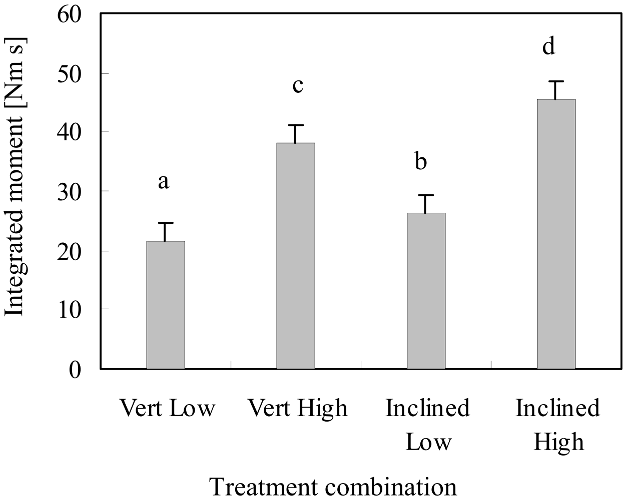

Figure 7. Moment integrated under pulse. Error bars show 1 standard deviation. Letters above bars show significant differences at the 95% level.

The elevation in the canopy where an apparent resulting force was to be applied to produce measured moments was calculated by dividing the moment value by the x-force value. During the main interacting period, the computed averaged signals were rather stable and showed high repeatability within trees. It was found that the vertical fan arrangements resulted in a slightly greater "lever-arm", than the converging fans, but the difference was not statistically significant. The relations between the tree shapes and the fan arrangements supported this result, as the densest and dominate part of the trees were mainly in the focus of both air jets. Part of the air jet from the top vertical fan missed the tree or was intercepted only by sparse foliage which resulted in a limited contribution to the moment. However, calculations of the apparent force applied by the air jet does open the possibility for studies of the interaction between different sprayer jets and tree structure on a detailed vertical basis. Such a study would provide additional information about the relationship between tree shape and air jet design.

The time during which the forces/moments were acting on the trees was significantly longer for the converging air jets than for the plane jets. Even though the difference was just 0.2 s, it represented about 10 % of the action time and would have influence on the exposure of moving leaves in the air jet.

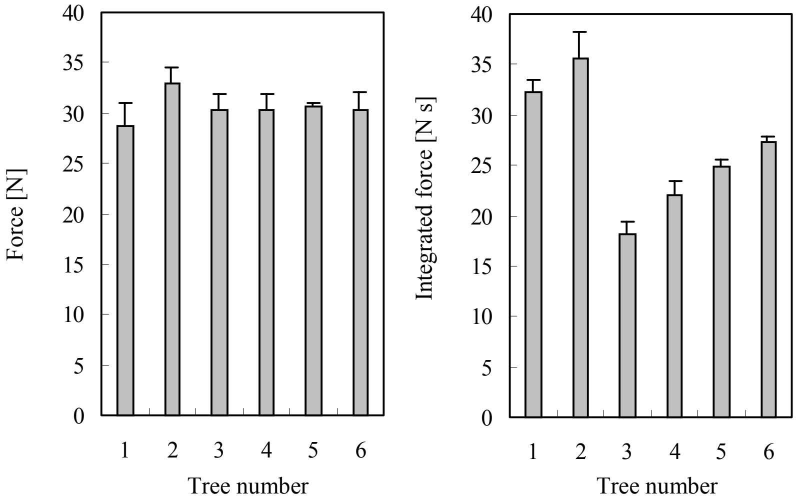

Figure 8. Differences between trees for maximum force and the force, integrated over pulse time. Both diagrams show Inclined fans and Low fan speed. Error bars show 1 standard deviation.

Svensson et al. (2001) found that both higher fan speeds and converging jets resulted in higher velocities in the densest part of the canopy. This was confirmed in this study, wherein we found that both higher fan speeds and converging jets produced greater forces on trees.

The converging air-jets, combined with liquid spray as shown by Furness & Pinczewski (1985), van Ee & Ledebuhr (1988) and Svensson (1994), transported more of the liquid with more power into the canopy, which resulted in higher deposition and less losses. The force measurements reported here show that converging jets are a beneficial way to concentrate the air power in denser parts of the canopy.

Measured forces are expressions for the power transferred to the tree canopy, based on the interaction between the air-jet and the tree properties. Such forces reflect air jet actions integrated over individual leaves and limbs. These forces are consequently related to the air velocity part of the deposition mechanism, as they result from contact between leaf and air-jet.

The vertical liquid distribution, as well as drop size spectra, also has an important influence on deposition values. Therefore, force measurements (without liquid distribution information) should be used with care. However, force measurements would still contribute to better understanding of the application problem, by their capability of measuring, with high repeatability, instantaneous forces delivered to trees by sprayer air jets.

Measurement of the total forces on a tree due to sprayer air-jets provides a method to identify significant differences among air-jet treatments. This measurement method eliminates some of the disadvantages in air velocity measurements related earlier. As force measurements are expressions for the tree taken as a whole, the measurement method could be used to study the influence of tree factors as shape, density, etc on the interaction. In traditional air velocity measurements inside canopies, it is often difficult to determine if detected differences are due to actual differences between flow in the trees or the result of sensor position factors.

The high repeatability observed with this measurement method encourages further development. Results show very small differences between replications and also small influence from random factors such as climate, settings of machines, etc. Differences detected are between treatments and between trees.

Ambient wind, normally a difficult background factor to handle in all spray application measurements, seems to have a limited influence on repeatability. By zeroing the force signals onsite, with the tree mounted, it was possible to compensate for asymmetric tree weight and ambient wind load. As long as the wind variability was moderate, its influence was limited.

Conclusion

In this paper we have presented studies of air flow factors, where we detected differences between fan arrangements, fan speeds and tree shape. These differences can be expressed in terms of air velocities, friction, drag forces, power transfer from air to leaf, shape and movement of canopy, etc. These factors are related to the deposition mechanism.

Cross-flow fan sprayers configured to produce converging air-jets produced significantly greater forces on dwarf apple trees than parallel air-jets with the same air velocities and volumes, i.e. the same mechanical output. This was a result of more of the jet output power being transferred to the tree through jet air velocity acting on the canopy.

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