Penetration of spray in apple trees as a function of airspeed, airflow, and power for tower sprayers

B. Panneton[1]*, B. Lacasse[1] and R. Thériault[2]

[1]*Horticultural Research & Development Center, Agriculture and Agri-Food Canada, 430, boul. Gouin, Saint-Jean-sur-Richelieu, Québec J3B 3E6, Canada; and* [2]*Faculty of Agriculture and Food Sciences, Université Laval, Saint-Foy, Québec G1K 7P4, Canada. *Email: pannetonb@agr.gc.ca*

Panneton, B., Lacasse, B. and Thériault, R. 2005. **Penetration of spray in apple trees as a function of airspeed, airflow, and power for tower sprayers**. Canadian Biosystems Engineering/Le génie des biosystèmes au Canada **47**: 2.13-2.20. In orchards, tower sprayers are machines where the droplet-laden air is released horizontally as a two-dimensional air jet extending the full height of the trees. Such sprayers offer good potential for drift reduction because very little, if any, spray material is projected above the top of the orchard canopy. To be successful, such sprayers must provide adequate spray penetration within the canopy. In this study, the effect of air speed and air flow rate on the penetration of spray in the canopy was measured. Spray was collected by impacting of droplets on rigid cylindrical targets. From the data, models of spray coverage at different horizontal distances from the source of air were obtained. These models were then used to relate power requirements to coverage. The effect of the sampling process on the coverage data is discussed. It was shown that, at constant power, priority should be given to air flow rate over air speed and that adequate coverage can be obtained at low power. Furthermore, doubling the fan power from 4 to 8 kW increased target coverage by no more than 7%, a small difference. **Keywords**: sprayer, pesticide, orchard, air speed, air flow rate.

En verger, les pulvérisateurs tours génèrent un flot d'air horizontal dont les caractéristiques sont essentiellement bidimensionnelles. Ce flot se déploie sur toute la hauteur des arbres pour y faire pénétrer les gouttes. Ces pulvérisateurs ont un bon potentiel pour le contrôle de la dérive parce qu'il y a peu ou pas de gouttes qui sont entraînées au-dessus de la cime des arbres. Comme tout pulvérisateur à verger, les pulvérisateurs tours doivent permettre une pénétration adéquate du feuillage. Cette étude a été élaborée pour quantifier l'effet de la vitesse d'air et du débit d'air sur la pénétration du couvert végétal pour le flot d'air chargé de gouttes. Des échantillons de gouttes ont été recueillis par impact sur des cylindres rigides. A partir des mesures, des modèles de régression ont été calculés pour prédire la couverture à différentes profondeurs dans le couvert végétal. Ces modèles ont été utilisés pour établir une relation entre la demande en puissance au ventilateur et la couverture. L'effet de la méthode d'échantillonnage sur les résultats de couverture est discuté. Il a été démontré qu'à puissance constante, il vaut mieux favoriser un plus grand débit d'air qu'une plus grande vitesse pour obtenir une bonne couverture. De plus, lorsque la puissance requise au ventilateur passe de 4 à 8 kW, la couverture augmente au plus de 7% ce qui représente un faible gain. **Mots clefs:** pulvérisateur, pesticide, verger, vitesse d'air, débit d'air.

INTRODUCTION

Sustainable agriculture requires a parsimonious use of synthetic pesticides and fuel energy. In the context of pesticide application technology for orchards, this implies distributing pest control products to the target sites in appropriate amounts for proper pest control and in such a way that the total quantity required is as low as feasible. This needs to be done with as little power as possible for sprayer operation.

While debatable, it is generally accepted that a sprayer should uniformly deposit material on the plants (Furness and Pinczewski 1985; Pergher et al. 1997; Stafford et al. 1970). Appropriate use of air assistance is required to improve the distribution of deposits and collection efficiency of plant parts (Matthews 2000). At the leaf scale, a better balance between coverage of the upper and lower surfaces requires some form of air-assistance (Viret et al. 2003). At a larger scale, spray penetration within the canopy is affected by air flow rate (Pergher and Gubiani 1995) and air speed (Randall 1971) as well as the orientation of the airflow and the number of air outlets used to direct the air and the spray to the canopy (Furness and Pinczewski 1985; Gohlich 1985; Pergher et al. 1997; Pezzi and Rondelli 2000, Svensson et al. 2003).

With a radial orchard sprayer, a higher air flow rate at a lower air speed penetrated trees better and produced better leaf coverage than lower volumes of higher velocity air. This held true provided that the air speed was high enough to form openings in the canopy for the air stream to penetrate (Randall 1971). Total deposit was better using a lower air flow rate while, for a higher air flow rate, the amount of spray blown through the canopy was increased (Holownicki et al. 2002). These results were reproduced when wind speed was low but, in higher wind speeds, mean deposits were lower at the lowest air flow rate (Cross et al. 2003).

The effect of two-dimensional air jet characteristics and crop canopy parameters on the penetration of the air inside the canopy have been studied by Walklate et al. (1996). An analytical model was developed and validated on an artificial canopy having well defined characteristics. The model described the variation of airspeed with distance into the canopy as an exponential decay process with a relaxation length comprising three components. The relaxation length is the length required for the air speed to decay to 36.7% of its initial value. The first component was the relaxation length for a stationary jet expanding in the absence of a canopy and it increased with an increase in the initial jet width. The second component determines the influence of crop density. Proper modeling of this component required defining crop density as

Fig. 1. RÉCUPAIR sprayer for orchard – spray recovery sprayer (SRS).

the weighted sum of the inverse of the two orthogonal mean flow gaps (i.e. mean distance between two adjacent leaves) in the horizontal plane. Modeling crop density in this manner accounted for both momentum loss to the canopy by form drag and loss produced by local flow channeling within dense canopies. The relaxation length increased as the crop density decreased. Finally, the third term described the apparent increase in crop density produced by sprayer movement. As the sprayer speed increased, the relaxation length decreased. It was stressed that using an airstream with a high flow rate to speed ratio improved air and spray penetration into low density canopies. In denser canopies, when the leaves respond to the force exerted by the air flow causing a reduction of leaf spacing along the jet axis, a high flow rate to speed ratio may reduce penetration due to the momentum loss associated with the flow channeling effect. Under these circumstances, Walklate et al. (1996) recommended that the air stream should assist in creating openings in the outer leaves.

A new type (Panneton et al. 2001a) of spray-recovery sprayer (SRS) combines most of the advantages of tunnel and tower sprayers while removing some of the limitations associated with tunnels (Panneton et al. 2001b). It uses vertical air sleeves to distribute a droplet-laden airflow along the full height of the canopy. It also uses a porous air-droplet separator

(a) (b)

Fig. 2. Basic sprayer configuration: (a) - air exit slot, (b) - air/droplet separator.

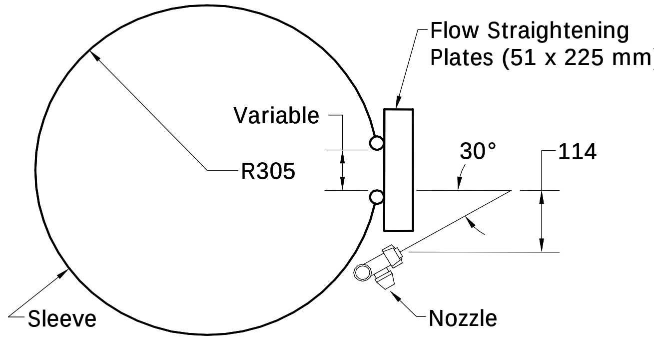


Fig. 3. Geometry of the flow straightening plates, the air exit slot, and nozzles position with respect to the sleeve. Cross-section taken at the top of the sleeve. All linear dimensions in millimeters.

on the opposite side of the trees to catch the droplets not retained by the foliage. Similar to tower sprayers, the air flow generated by the SRS, combined with the use of smaller spray droplets, can improve pesticide efficiency while reducing spray drift (Van Ee 1998). The success of the SRS depends on the quality of leaf coverage by pesticides in relation to the power requirements that depend on air speed and air flow rate.

The objective of the present study was to measure spray penetration in apple trees as a function of both air speed and air flow rate for a sprayer generating a nearly two-dimensional horizontal air jet and to relate these results to required fan power. For apple orchards, such data is available for radial sprayers (Randall 1971) but there is no such data available for equipment such as tower sprayers.

MATERIAL and METHODS

Basic sprayer configuration

An air-assisted spray-recovery sprayer was used (Panneton et al. 2001b). The tractor-drawn SRS used an over-the-row structure to support the air sleeve and spray nozzles, directing the air-assisted spray against the far side of the tree row and back toward the main sprayer body (Fig.1). Air exited from the sleeve through a longitudinal slot 2.38 m long with a width adjustable from 25 to 150 mm (Fig. 2a). The sleeve geometry was such that the exit air speed at the slot was constant from top to bottom (Panneton et al. 2001a). Flat plate deflectors spaced at 50 mm intervals in front of the slot produced a horizontal flow (Fig. 3). The direction of the air flow at the exit slot was visualized using ribbons attached to the deflecting plates and it confirmed that the air velocity vector was parallel to the ground. The axis of the two-dimensional horizontal air jet emerging from the slot was perpendicular to the row of trees. A droplet catching structure mounted on the sprayer body intercepted spray passing through the canopy (Fig. 2b).

Sprayer setup

The sprayer was fitted with eight nozzle bodies along the vertical. Water was sprayed using D1.5-23 TeeJet nozzles (Spraying Systems Co., Wheaton, IL) at 300 mm spacing operated at a pressure of 345 kPA. Nozzle placement with respect to the air exit slot is illustrated in Fig. 3. The traveling speed varied between 2.04 and 2.47 km/h with a coefficient of variation of 7% (Table 1). Travel speed varied as a result of the

Table 1. Experimental conditions.

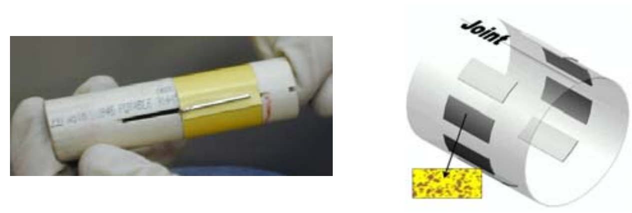
Air speed (m/s)	Air flow rate (m^3/s)	Air exit slot openings (mm)	Specific air flow rate (%)	Travel speed (km/h)
20	2.36	51	38	2.47
	3.54	76	57	2.40
	4.72	102	76	2.33
	5.90	125	94	2.12
30	2.36	36	38	2.24
	3.54	49	57	2.04
	4.72	70	76	2.10
	5.90	90	94	2.36
40	2.36	25	38	2.16
	3.54	38	57	2.47
	4.72	53	76	2.08

different combinations of tractor engine rpm and gear selection that were necessary to suit the air flow rate and air speed combinations required by the experimental design. An average speed of 2.25 km/h was used for calculations. The application volume was 258 L/ha.

Evaluation of spray penetration

Spray penetration within the canopy was evaluated using water sensitive paper wrapped around a tubular support. Tubes were used because sampling is not sensitive to local air flow direction projected in the plane perpendicular to the tube axis. Measurements on the cylindrical targets are far from measurements on the foliage. The deposition process on leaves is more complex and more variable because leaves are essentially 2D flexible objects of different sizes and at varying orientation with respect to the local airflow. But here the focus was on sprayer optimization and the sampling strategy adopted clearly helped in identifying the effect of air flow rate and air speed on spray flux within the canopy. The tube axis was set vertical. Strips of water-sensitive paper, 25 mm wide, (Spraying Systems Co., Wheaton, IL) were wrapped around PVC tubes (22 mm in diameter) and held in place with a metal clip near the joint (Fig. 4). The joint in the sampling tubes was always oriented toward the sprayer as it passed away. Three tubes comprising a sampling station were installed inside the canopy in a single line perpendicular to the row. One tube was located on the row centerline with the other two 600 mm to either side. The vertical position of the sampling stations (1170 mm) corresponded to the height of the widest part of the tree canopy. The locations of the samplers inside the tree are referred to as the sleeve side (near the air/droplet source), the center, and the tractor side (near the air/droplet separator, away from the air source). The distances from the air-droplet source to the sampling tube on the sleeve side, at the center, and on the tractor side were 900, 1500, and 2100 mm, respectively. There were six sampling stations at random locations along a row of trees. When installing the sampling tubes, leaves touching a tube were removed.

Great care was taken to maintain the tubes in as dry an environment as feasible. As a result, the contrast between stained and unstained areas of the water-sensitive paper was



(a) (b)

Fig. 4. (a) Strip of water-sensitive paper wrapped around a tube with the metal clip inserted. (b) Location of the image around a single sampling tube (to scale) and a sample image.

always excellent. Image analysis of sampling tubes was performed to extract the surface of the stained area using a procedure developed previously (Panneton 2002). A single image taken by the camera covered 42 mm^2 on the sample card with a resolution of 320 x 160 pixels, the longest dimension of the image taken along the axis of the tube. Given the size of the image with respect to the diameter of the tube, deformation of the image associated with the curvature of the target surface was negligible. By rotating the sample in front of a camera, a series of eight images were grabbed for analysis (Fig. 4). No image was acquired at the location of the joint in the wrapped paper and at 180° from this location to maintain sampling symmetry around the tube. Image numbers identified a unique angular location. For each image, the area stained by water was measured. The ratio of this area over the total surface of the image is referred to as the coverage. Two variables were considered for analysis, the mean coverage and the coefficient of variation (CV). The mean coverage was the average of the coverage values from a single tube and the CV was the ratio of the standard deviation (SD) to the mean taken on a single tube (8 images).

Meteorological conditions were not recorded during the tests. In all cases, experiments were conducted under low-wind conditions estimated to be less than 2 m/s. Wind direction was generally perpendicular to the rows.

Experimental design

The experiment took place on an experimental farm of Agriculture and Agri-Food Canada (Frelishburg, Québec) in September over a one week period when foliage was fully developed and before fruit picking. Experiments were performed over a short period of time to avoid the effect on the canopy area index on deposition as discussed in Walklate et al. (2000). The section of the orchard used for the experiment was planted with McIntosh on Ottawa 3 rootstock. The distance between rows was 5 m and the tree row was about 3.35 m wide and 3 m high (Fig. 1). As assessed visually, the canopy density corresponded to a crop adjustment factor (defined in Walklate and Cross 2005) in the range from 0.75 to 1.0.

Spray coverage was measured for different combinations of two factors, the specific air flow rate and the air speed (V) measured at the exit of the air exit slot. To obtain the specific air flow rate, calculations were made using:

$$Q_s = \frac{Q_v}{10 v_t} \times 100 \qquad (1)$$

where:

Q_s = specific air flow rate (%),
Q_v = total air flow rate through the fan (m^3/s), and
v_t = traveling speed (m/s).

In Eq.1, the constant in the denominator is the volume of the space comprised between the sleeve and the air-droplet separator per meter of row and had a value of 10 m^3/m.

The experiment followed an incomplete factorial design with three replications. The specific air flow rate levels were 38, 57, 76, and 94%, and the air speed levels were 20, 30, and 40 m/s. All combinations of these two variables were realized except for the 94% - 40 m/s treatment that was not achievable because of mechanical limitations. A total of 11 treatments resulted.

The adjustments of the air delivery system required to meet the experimental design (values of specific airflow rate and air speed) were determined based on the fan performance curves and the system curve for the sprayer. The fan performance curves were computed using the software provided by the fan manufacturer (Multi-Wing Performance Optimiser version 1.16, Multi-Wing International, Vedbaek, Denmark). The system curve at various widths of the exit slot was obtained from measurements of the static pressure just downstream from the fan at different fan speeds. These two sets of curves were combined in a single graph (Fig. 5). Usually, such graphs show static pressure as a function of the air flow rate. Conversion of the vertical axis from static pressure to the horizontal air speed at the exit slot was performed using Bernouilli's law. In performing the transformation, it was assumed that the velocity coefficient (Streeter and Wylie 1979) was equal to 1, which should be accurate to within 2 - 3% for a slot. During the experiments, the sprayer was set up and a Pitot tube was used to measure the air speed at the exit slot to verify that the required experimental conditions were actually implemented.

Table 1 summarizes the different experimental conditions. Coverage data used for analysis were the mean coverage and the coefficient of variation (CV). The analyses were performed with R (Fox 2002) using stepwise linear regression for fitting quadratic models to the data.

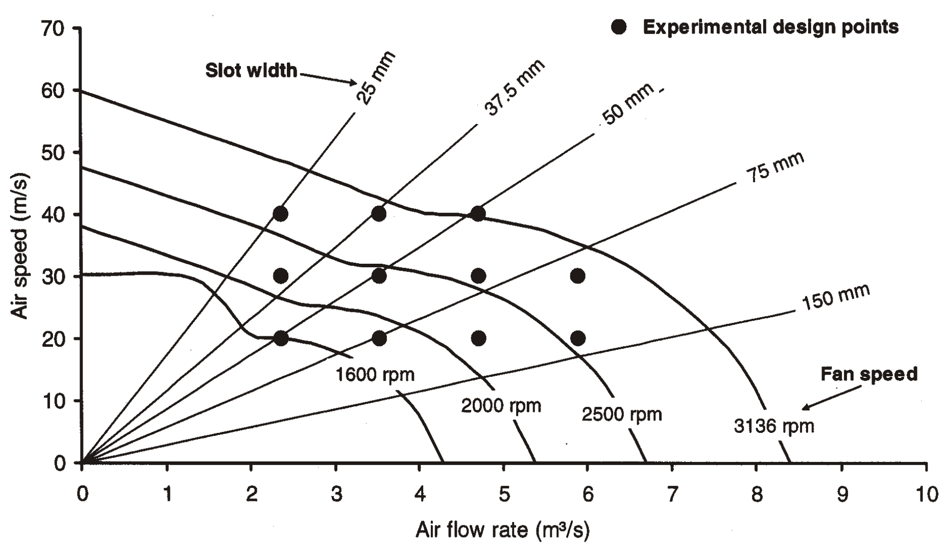


Fig. 5. Experimental conditions obtained by calculation. Curves indicate the different fan speeds.

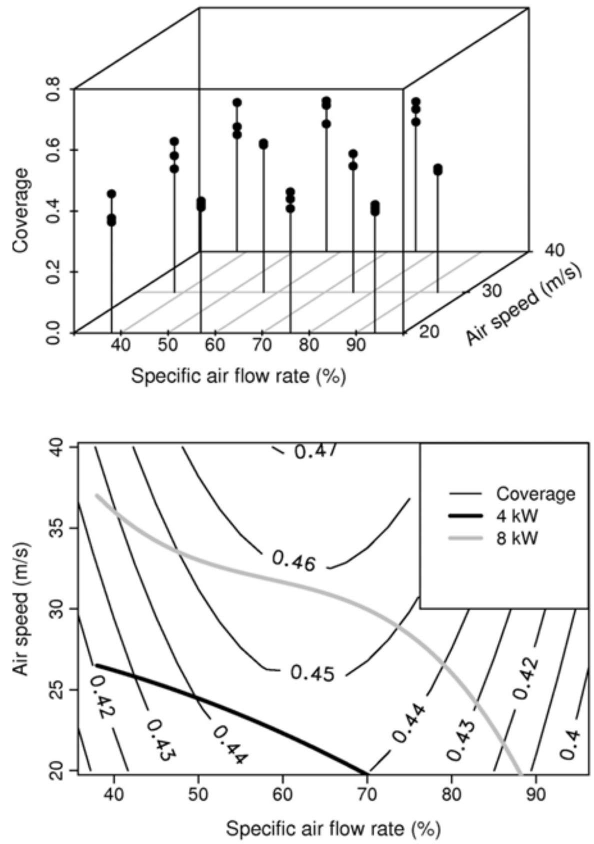


Fig. 6. Mean coverage value on the sleeve side. The top diagram shows the data and the bottom one shows the results obtained based on the mathematical model.

RESULTS

For a given combination of the independent variables (Q_s and V), the scatter in the data was low at all three lateral positions within the canopy (Figs. 6, 7, and 8). For spray deposition experiments, this is not always the case. Here, the use of artificial cylindrical targets at fixed location from test to test has limited the scatter in the data. By sampling on the foliage, it is expected that the identification of the effects reported here would have required a much greater number of samples and repetitions.

On the sleeve side, the stepwise regression procedure retained Q_s and Q_s^2, both significant at the 5% level, and V significant at the 10% level (Table 2). The regression was significant and the adjusted R^2 (Fox 2002) was low at 0.26 (Table 3). This low value reflects the fact that the range of the variation explained by the regression was smaller than the scatter in the data. The model

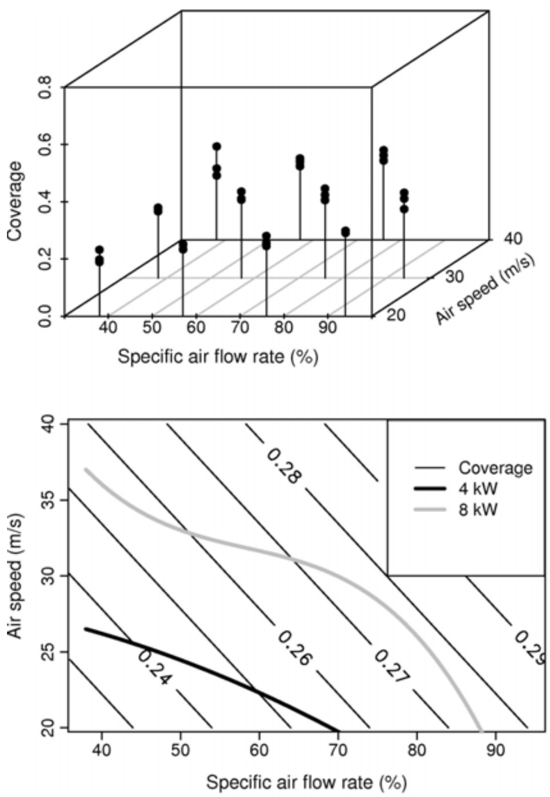


Fig. 7. Mean coverage value on the center of the row. The top diagram shows the data and the bottom one shows the results obtained based on the mathematical model.

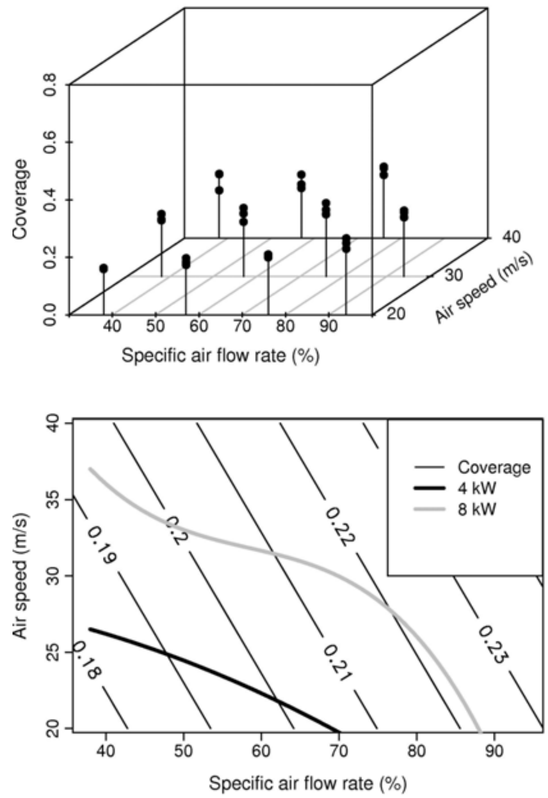


Fig. 8. Mean coverage value on the tractor side. The top diagram shows the data and the bottom one shows the results obtained based on the mathematical model.

suggests that coverage can be optimized with Q_s = 63% (Fig. 6). Curves of constant fan power are shown in Fig. 6 for 4 and 8 kW. Clearly, almost equally good coverage was obtained at low power. For example, a coverage of 0.460 was obtained with 8 kW of fan power for Q_s = 60% and V = 32.5 m/s. At Q_s = 60% and V = 22.5 m/s, 4 kW of fan power were required but the coverage was only reduced by 3% to 0.445. At specific air flow rates less than 63% and constant power, increasing flow rate was preferable to increasing air speed to improve coverage. Orchard sprayers usually operate at Q_s less than 63% with typical values in the range of 30 to 40% (Barrufet 2005). Given the low R^2 value, conclusions drawn from the model should be used with caution. However, the conclusion that lowering fan power had little effect on measured coverage on the sleeve side is well supported by the data.

Table 3. Values of the adjusted R^2 and their probabilities for the three regression models.

	Sleeve side	Center of the row	Tractor side
Adjusted R^2	0.26	0.45	0.43
p-value	0.008	<0.001	<0.001

In the center, the variables Q_s and V entered the model and their coefficients were significant at the 5% level. Quadratic and interaction terms were rejected (Table 2). The regression was significant and the adjusted R^2 was 0.45 (Table 2). In the center, increasing air speed or air flow rate resulted in an increase in

Table 2. Coefficients of the stepwise linear regression models for the mean coverage values.

Regression model term	Regression coefficient units	Location		
		Sleeve side	Center	Tractor side
Intercept		0.22**#	0.15**	0.12**
Air speed, V	$(m/s)^{-1}$	0.00143*	0.00178**	0.0011**
Specific air flow rate, Q_s	$(\%)^{-1}$	0.00602**	0.00100**	0.000935**
Air flow rate - quadratic, Q_s^2	$(\%)^{-2}$	-4.757e-05**		

* Coefficient statistically significant at P < 0.10
** Coefficient statistically significant at P < 0.05

Table 4. Coefficients for pairwise correlation between mean coverage data sets at the three foliage locations at fixed air speed and at fixed specific air flow rate.

Fixed air speed - pooled over specific air flow rate			
Air speed (m/s)	Sleeve - Center	Sleeve - Tractor	Center - Tractor
20	0.46	0.10	0.88*
30	0.18	-0.33	0.32
40	0.86*#	0.57	0.72*
Fixed specific air flow rate - pooled over air speed			
Specific air flow rate (%)	Sleeve - Center	Sleeve - Tractor	Center - Tractor
38	0.74*	0.47	0.74*
57	0.86*	0.70*	0.47
76	0.79*	0.24	0.55
94	0.27	0.36	0.69

#* Correlation coefficient statistically significant at P < 0.05

coverage and no optimum was identified (Fig. 7). As in the case of the sleeve location, there is scope to maintain good coverage even at limited fan power. Comparing the coverage at V = 32.5 m/s, Q_s = 60%, and 8 kW to coverage at V = 22.5 m/s, Q_s = 60%, and 4 kW showed a decrease from 0.268 to 0.250, a loss of 7%. In the center of the row, the best use of power at a fixed level was to move a larger volume of air at a lower air speed except at higher air flow rates where the fan efficiency dropped sharply (see 8 kW curve on Fig. 7).

On the tractor side, the results were similar to the one for the center of the row. However, the range of variation in coverage was smaller (Fig. 8). The significant factors affecting coverage were V and Q_s with regression coefficients significant at the 5% level (Table 2). The regression was significant and the adjusted R^2 was 0.46. At constant fan power, the coverage was better with a lower air speed and a greater air flow rate. Comparing the coverage at V = 32.5 m/s, Q_s = 60%, and 8 kW to coverage at V = 22.5 m/s, Q_s = 60%, and 4 kW showed a decrease from 0.209 to 0.198, a loss of 5%.

As the droplet carrying air stream penetrated the canopy, droplets were gradually filtered out by the foliage. As a result, it was expected that a high coverage on the sleeve side of the tree would imply less coverage in the center and on the tractor side. A correlation analysis was performed to verify this hypothesis (Table 4) and it revealed that it was not the case. All correlation coefficients that were significant (P < 0.05) were positive indicating that at a fixed air speed or a fixed air flow rate increasing coverage at one location resulted in an increase in coverage at a downstream location. According to the regression models (Figs. 6 to 8) this was true for Q_s less than 63%. At greater air flow rates, coverage on the sleeve side decreased while it increased in the center and on the tractor side.

The impact of Q_s and V on the gradient in coverage across the tree was evaluated by fitting a exponential decay curve to the data:

$$C = C_0 \exp\left(-\frac{x}{L}\right) \qquad (2)$$

where:

C = coverage,
C_0 = coverage at x=0,
x = distance from nozzle taken perpendicular to row (m), and
L = relaxation distance (m).

A large value of L indicates a smaller gradient in coverage across the row. When fitting Eq. 2 at each V-Q_s setting, R^2 values ranged from 0.89 to 0.96. Values of L (Fig. 9) were in the range of 1.0 to 2.5 m. A linear regression analysis of L as a function of Q_s and V revealed that the effect of the air speed was not significant while the effect of the specific air flow rate was (P>0.05). Increasing the air flow rate increased the relaxation length. Over the range of the experimental data, L was increased by a factor of 2. Pooling the data over air speed, the ratio of coverage at the sleeve to the coverage on the tractor side was 0.42/0.19 for Q_s = 38% and 0.41/0.23 for Q_s = 94%. Therefore the increase in L was mostly due to an increase in coverage on the tractor side.

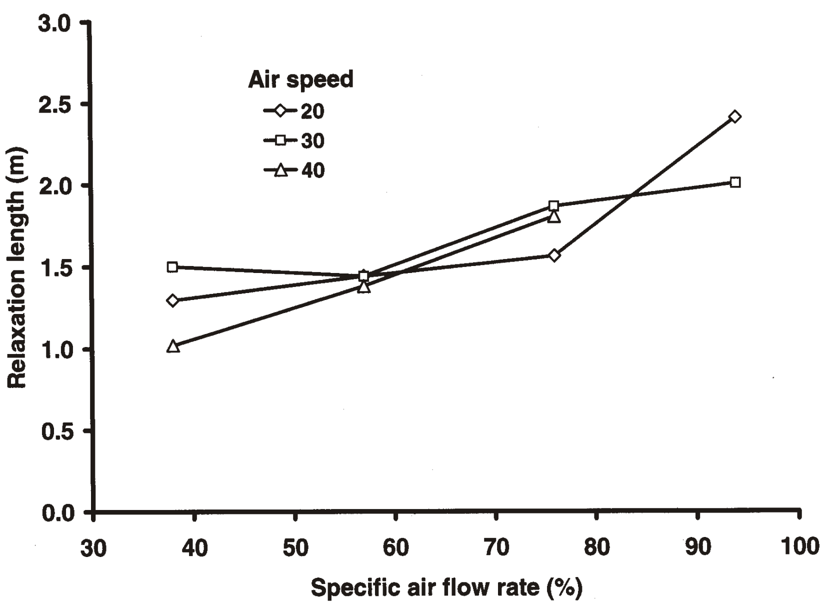


Fig. 9. Relaxation length for coverage decay across the row.

Coefficient of variation

None of the regression analysis based on the CV was significant. The local distribution of the spray on the sampling tubes was not varying significantly with a change in air speed or air flow rate. On the sleeve side, the coefficient of variation for the coverage around the tube varied between 81 and 83% and increased to 90 - 93% in the center and 92 - 96% on the tractor side. In the simple case where coverage on the upwind half of a cylinder was constant and the coverage on the downwind side of a cylinder was null, the CV was 100%. In our experiments, the values of CV were high for all three positions in the foliage which implies that the spray droplets impacted almost exclusively on the upwind half of the sampling cylinders. This indicated that the droplets were following more or less straight paths within the foliage with no or minimal wrap around effect from turbulent motion.

DISCUSSION and CONCLUSION

The sampling process confounded the effect of local droplet density and air speed at the sampler. Increasing air speed at the sampler should result in an increase in the catch efficiency of the target (Bache and Johnstone 1992). At a given sampling location, an increase in coverage associated with an increase in air flow rate or air speed at the source has partly resulted from an increase in air speed at the location of the sampler. In the same way, the decrease in coverage with distance at a fixed air speed and air flow rate at the source has partly resulted from speed decay as the air moved through the canopy. The same should apply to foliage except that leaves are not rigid and adapted their shape to the local airflow in response to air pressure (i.e. V^2). Therefore, coverage measured on cylindrical targets should correlate better to leaf coverage at low air speed where leaf deformation is less pronounced. For Cox apple, Randall (1971) found that an air speed higher than approximately 12.2 m/s was necessary to displace leaves and create openings facilitating air penetration into the canopy. Assuming this result applies approximately to the apple trees used in our experiment, it can be hypothesized that when the air speed is less than about 12 m/s, leaf motion is marginal and sampling on an artificial rigid target should correlate positively to sampling on the foliage. The classical theoretical model describing air velocity decay on the axis of a stationary two-dimensional jet (Abramovich 1963) can be used to calculate an air speed at various locations in the canopy. For a real sprayer, the decay rate is higher for a greater sprayer speed and a dense canopy (Walklate et al. 1996). Ignoring these two factors, the decay rate will be underestimated and local air speeds overestimated. Therefore, use of the classical model provides an upper bound for the expected air speed at a downwind location. The classical model can be written as:

$$u(x) = \frac{\sqrt{3\sigma}}{2}\sqrt{\frac{U_0^{\,2} d}{x}} \tag{3}$$

where:

- $u(x)$ = air velocity component along jet axis at distance x from the source,
- σ = constant (best fit to data obtained with σ = 7.67 (Bird et al. 1960),
- U_0 = air speed at the jet exit, and
- d = width of the jet at the source.

In terms of air flow rate and air speed, Eq. 2 becomes:

$$u(x) = 2.4\sqrt{\frac{Q_v U_0}{hx}} \tag{4}$$

where: h = height of the air sleeve (2.38 m).

Using Eq. 3, curves of constant $u(x)$ can be computed in the U_0-Q_0 plane. Curves for $u(x)$ = 12 m/s are shown in Fig. 10.

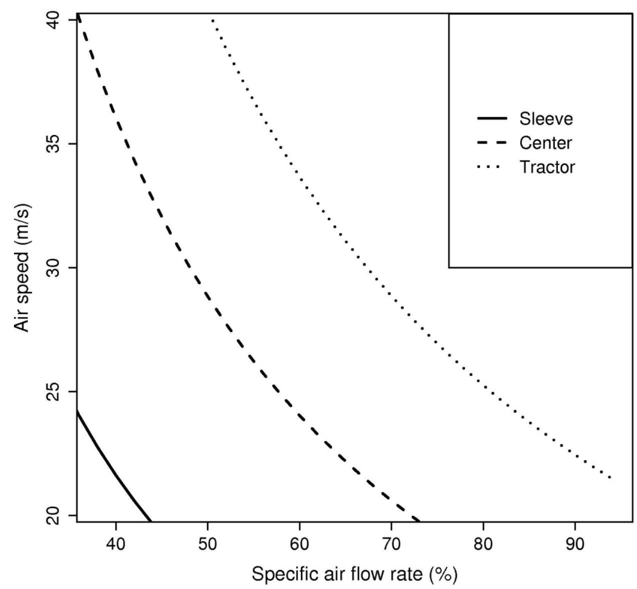


Fig. 10. Boundaries corresponding to an estimated local air speed of 12 m/s at the three locations in the canopy.

From these curves, it can be concluded that on the sleeve side, most of the experimental design space was in a region where it could be expected that significant leaf motion should occur and that the correlation between coverage measured here and leaf coverage should be low. On the tractor side, most of the experimental design space was in a region where leaf motion was probably negligible, in agreement with visual observations that showed only gentle motion of the leaves on the tractor side. At this location, the correlation between leaf coverage and coverage measured on cylindrical targets should be positive and the trends in coverage with air speed and air flow rate observed in our experiments should reproduce on foliage but with different amplitudes.

In general, the power requirements of the system can be reduced while maintaining acceptable coverage values by keeping the air flow rate to a greaterr value associated with a lower air speed. With a radial sprayer, it was shown that the best use of fan power was to increase flow rate up to the point where there is sufficient air speed to open up the canopy by displacing leaves under air pressure (Randall 1971). Our results showed that the same concept should apply for a two-dimensional horizontal air jet.

While spray penetration can be manipulated to a certain extent by a proper adjustment of the air flow rate and air speed, fairly large coverage gradients from one side of the tree to the other remained. In our experiments, over 1.2 m centered on the tree trunk, coverage decreased by a factor of approximately 2. It has also been demonstrated that doubling the fan power from 4 to 8 kW increased target coverage by no more than 7%, a small difference. To the designer of the sprayer, this suggests a design with two low power sources of air, one on each side of the row. Assuming that the two opposing air jets are not interacting, the coverage gradient associated with each source would cancel out. This last process is likely to improve coverage of both faces of the leaves instead of segregating a single face when attacking the row from a single side. In the context of a spray recovery sprayer, this would require two spray recovery panels, one on each side of the row. Another solution was investigated for vineyard spraying where the two air jets were interacting in such a way that a significant amount of the air from the two jets merged into a single stream directed towards a single recovery panel on the tractor side (Panneton et al. 2005). This proved to be feasible at the expense of reduced spray recovery. For apple orchards, the cost associated with the deployment of a second spray recovery panel on the other side of the row with respect to the tractor would be significant. In this context the approach involving two interacting jets offers a definite advantage.

ACKNOWLEDGMENTS

The authors thank M. Gilles St-Laurent for his technical support during this experiment and Ms. Marlène Piché for her help in preparing the manuscript.

REFERENCES

Abramovich, G.N. 1963. General properties of turbulent jets. In *The Theory of Turbulent Jets*, ed. L.H. Schindel, 3-49. Cambridge, MA: The Massachusetts Institute of Technology.

Bache, D.H. and D.R. Johnstone. 1992. *Microclimate and Spray Dispersion.* Chichester, UK: Ellis Horwood.

Barrufet, J.M. 2005. Hardi International Application Technology Course *Mistblower Technology*. www.hardi-international.com/Agronomy/Educational_Material/pdf/12a.pdf. (2005/07/14)

Bird RB, W.E. Stewart and E.N. Lightfoot. 1960. *Transport Phenomena*. New York, NY: John Wiley and Sons.

Cross, J.V., P.J. Walklate, R.A. Murray and G.M. Richardson. 2003. Spray deposits and losses in different sized apple trees from an axial fan orchard sprayer: 3. Effects of air volumetric flow rate. *Crop Protection* 22: 381-394.

Fox, J. 2002. *An R and S-Plus Companion to Applied Regression*. Thousand Oaks, CA: Sage Publications, Inc.

Furness, G.O. and W.V. Pinczewski. 1985. A comparison of the spray distribution obtained from sprayers with converging and diverging airjets with low volume air assisted spraying on citrus and grapevines. *Journal of Agricultural Engineering Research* 32: 291-310.

Gohlich, H. 1985. Deposition and penetration of sprays. In *Symposium on Application and Biology*, BCPC Monogram No. 28, 173-182. Alton, Hampshire, UK: BCPC.

Holownicki, R., G. Doruchowski, A. Godyn and W. Swiechowski. 2002. The effect of air jet velocity on spray deposit in an apple orchard. *Aspects of Applied Biology* 66: 277-283.

Matthews, G.A. 2000. A review of the use of air in atomisation of sprays, dispersion of droplets down wind and collection on crop foliage. *Aspects of Applied Biology* 57: 21-27.

Panneton, B. 2002. Image analysis of water-sensitive cards for spray coverage experiments. *Applied Engineering in Agriculture* 18: 179-182.

Panneton, B., R. Thériault and B. Lacasse. 2001a. Efficacy evaluation of a new spray-recovery sprayer for orchards. *Transactions of the ASAE* 44: 473-479.

Panneton, B., R. Thériault and B. Lacasse. 2001b. Method and apparatus for spraying trees, plants, etc. US Patent No. US6302332, United States Patent Office, Washington, DC.

Panneton B., B. Lacasse and M. Piché. 2005. Effect of air-jet configuration on spray coverage in vineyards. *Biosystems Engineering* 90(2):173 184.

Pergher, G. and R. Gubiani. 1995. The effect of spray application rate and airflow rate on foliar deposition in a hedgerow vineyard. *Journal of Agricultural Engineering Research* 61: 205-216.

Pergher, G., R. Gubiani and G. Tonetto. 1997. Foliar deposition and pesticide losses from three air-assisted sprayers in a hedgerow vineyard. *Crop Protection* 16: 25-33.

Pezzi, F. and V. Rondelli. 2000. The performance of an air-assisted sprayer operating in vines. *Journal of Agricultural Engineering Research* 76: 331-340.

Randall, J.M. 1971. The relationships between air volume and pressure on spray distribution in fruit trees. *Journal of Agricultural Engineering Research* 16: 1-31.

Stafford, E.M., J.B. Byass and N.B. Akesson. 1970. A fluorescent pigment to measure spray coverage. *Journal of Economic Entomology* 63: 769-776.

Streeter, V.L. and E.B. Wylie. 1979. *Fluid Mechanics*, 7th edition. New York, NY: McGraw-Hill.

Svensson, S.A., R.D. Brazee, R.D. Fox and K.A. Williams. 2003. Air jet velocities in and beyond apple trees from a two-fan cross-flow sprayer. *Transactions of the ASAE*: 46(3):611-621.

Van Ee, G.R. 1998. Reducing drift from air-carrier sprayer using:Timing, Targeting and Towers. In *Proceedings North American Conference on Pesticide Spray Drift Management*, 221-223. University of Maine Cooperative Extension, Orono, ME.

Viret, O., W. Siegfried, E. Holliger and U. Raisigl. 2003. Comparison of spray deposits and efficacy against powdery mildew of aerial and ground-based spraying equipment in viticulture. *Crop Protection* 22: 1023-1032.

Walklate, P.J. and J.V. Cross. 2005. Pesticide dose adjustment to the crop environment (PACE) for UK apple orchards. www.sri.bbsrc.ac.uk/images/posters/pace.pdf. (2005/07/10)

Walklate, P.J., K.L. Weiner and C.S. Parkin. 1996. Analysis of and experimental measurements made on a moving air-assisted sprayer with two-dimensional air-jets penetrating a uniform crop canopy. *Journal of Agricultural Engineering Research* 63: 365 378.

Walklate, P.J., G.M. Richardson, J.V. Cross and R.A. Murray. 2000. Relationship between orchard tree crop structure and performance characteristic of an axial fan sprayer. *Aspects of Applied Biology* 57:285-292.