THE APPLICATION OF PESTICIDES TO GRAPE BUNCHES

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The application of pesticides to grape bunches is complicated by the different shapes and forms of the grape bunch during growth. Initially the grape bunch has a very porous structure, while in later stages the grapes are closely packed. We consider estimates of the flow velocity through the grape bunch, droplet density within the spray, probability of droplet impaction on a bunch or individual grape and the maximum size of drop that can adhere to a grape surface.

1. Introduction

Pesticides are usually applied to bunches of grapes by atomisation of a liquid into fine droplets which is carried to the grapes via the spray momentum and an air jet. It is important that the chemicals uniformly cover all parts of the grape surface, but this is difficult since the grape bunch may be obscured by foliage, and grapes at the back of the bunch may be obscured by those in front.

The Grape and Wine Research and Development Corporation posed the problem to the MISG of how to improve the application of the chemical to the grapes at all stages of growth; the problem of the air flow through the canopy was not to be considered at the workshop.

It is important to characterise the three stages of growth of the grapes as they have distinct properties:

1. In stage one, called capfall, the bunch is characterised by a massive surface of fine flowering parts. The typical scale of the flowers and buds is approximately 1 mm with the whole bunch approximately 10 cm long and formed in clusters of cross section about 1–2 cm.
2. In stage two, pre-bunch closure, the grapes have formed into distinct spheres uniformly distributed along the length of the grape bunch. The bunch is considered a sparse array of spheres with a high porosity, the approximate sphere radius is 0.4 cm and the spheres are arranged in a 10 cm cone.

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3. In stage three, called veraison, the grapes are fully grown and form a compact bunch. For the case of Chardonnay the grapes have closed to form an almost impenetrable surface, apart from a few minor gaps between the grapes. The dynamics of fluid filtration through this bunch is better modelled using a porous media/capillary model.

2. Droplet density

It is useful to estimate the number of droplets in a volume of air in the spray and the associated number of droplets impacting on a plane surface in the spray path.

If the pumping rate is α [m^3/s] (usually about 3 litres per minute), the radius of the jet at the bunch a [m] (about 0.5 m), the velocity of the jet at the bunch U [m/s] (about 10 m/s) then in a disc of air of width dl:

$$\begin{aligned}\text{volume of air in disc} &= dl\,\pi a^2\\ \text{volume of liquid in disc} &= \alpha\frac{dl}{U}\\ \text{ratio of liquid to air} &= \frac{\alpha}{U\pi a^2}.\end{aligned}$$

If a drop has diameter d then the average drop volume is $\pi d^3/6$ and the number of drops per unit volume is:

$$\text{drops per unit volume} = \frac{6\alpha}{\pi^2 U a^2 d^3}. \tag{1}$$

If the velocity of the tractor is v_t there are $2a/v_t$ seconds in which the surface is sprayed and the 'depth' of fluid is $U2a/v_t$. Hence the number of drops per unit surface area is:

$$\text{drops per unit surface area} = \frac{12\alpha}{\pi^2 a d^3 v_t}. \tag{2}$$

If each drop covers a surface area γd^2 depending on contact angle, then the fraction of area covered by droplets is:

$$\text{fraction of area covered by drops} = \frac{12\gamma\alpha}{\pi^2 a d v_t}. \tag{3}$$

This assumes an even distribution of droplets of all the same size. Simple modifications can be made for a distribution of droplet sizes.

3. Flow through a bunch

We consider here the fluid flow around the entire bunch of grapes treating it as a dense sphere as shown in Figure 1. By calculating the pressure drop across the sphere we can then calculate the flow through the bunch driven by this pressure drop. This is an ad hoc model that will underestimate the flow through the grapes particularly when the grapes are not packed.

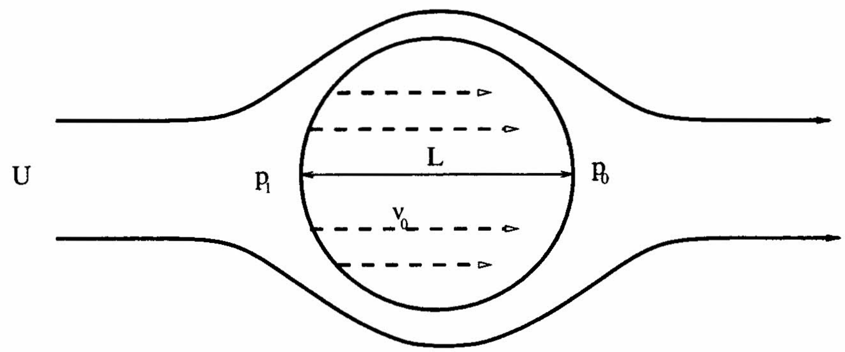

Figure 1: Flow past a sphere of diameter L causing a pressure drop $p_1 - p_0$.

The pressure drop $p_1 - p_0$ across a bunch of diameter L will be given by

$$\frac{p_1 - p_0}{L} = \frac{\rho U^2}{L}, \tag{4}$$

where U is the incoming velocity of the air and ρ is the density of the air.

The flow through the grapes may be modelled using the Ergun equation (a combination of the Burke-Plummer and Blake-Kozeny equations) for flow through a packed bed of spheres:

$$\frac{p_1 - p_0}{L} = \alpha v_0 + \beta v_0^2, \tag{5}$$

where v_0 is the superficial velocity through the spheres — the average velocity as if the spheres were not there (Bird *et al.* 1960, 6.4, p. 196). The constants α and β are:

$$\alpha = \frac{150\mu}{D^2}\frac{(1-\epsilon)^2}{\epsilon^3},$$
$$\beta = \frac{1.75\rho(1-\epsilon)}{D}\epsilon^3,$$

where ρ is the density of air (or in this case the density of the air fluid mixture), μ the viscosity, D is the diameter of the spheres (the grapes in this case), and ϵ is the void fraction — the ratio of voids to total volume.

If we take the density of the air to be

$$\begin{aligned} \rho &= 1.3\,\mathrm{kg/m^3}, \\ \mu &= 1.8 \times 10^{-5}\,\mathrm{kg/m.s}, \end{aligned}$$

we can make some elementary calculations to show that the first term in the Ergun equation is negligible and hence write the fluid velocity through the spheres as:

$$v_0 = UD\sqrt{\epsilon^3}1.75L(1-\epsilon), \tag{6}$$

which is easily calculated for any porosity ϵ, length of bunch L and grape diameter D.

4. Droplet impaction probabilities

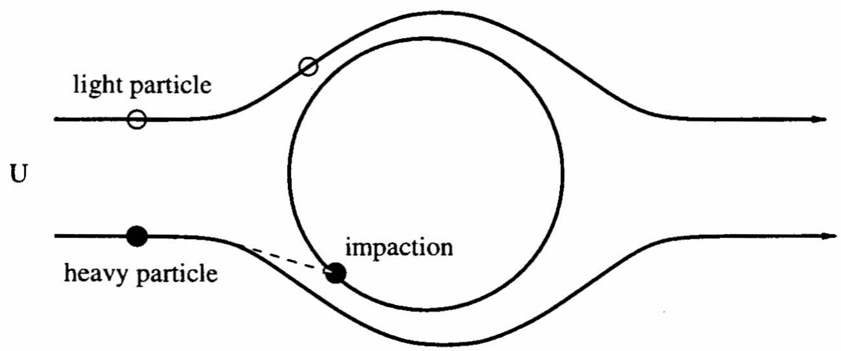

Figure 2: Impaction of a heavy droplet on a sphere while a lighter droplet is deflected by the flow field.

In Spillman (1984, Figure 4) the probability of a particle hitting an object was considered. The basic premise was that since fluid flows around an object, small particles will be swept with the flow while particles with more momentum (inertia) will continue against the flow for a certain distance and impact upon the surface (see Figure 2). Spillman defined a parameter P based on Stokes flow:

$$P = \frac{\rho d^2 v_0}{18\mu W}, \tag{7}$$

where W is the width of the obstacle (grape), v_0 is the drop velocity, d the drop diameter, ρ the density of the air and μ the air viscosity. The efficiency of the capture, E, is defined as the 'ratio of the number of particles caught to the number of particles that would have passed through the cross-sectional area of the object during the time of exposure, had the object not been there, expressed as percentage'. For a sphere the relationship was

$$E = 90(\log(P) - \log(0.1))/(\log(6) - \log(0.1)) \tag{8}$$

based on a linear approximation of Spillman's Figure 4 diagram.

Therefore, given an initial distribution of particle sizes one can calculate the distribution of particles that will hit the object (grape or grape bunch) and hence the distribution of particle sizes that progress around the object to impact on the next object.

This calculation can be used in two ways:

- By making the 'object' the grape bunch an estimate can be given of the particle size distribution that may actually impinge on the bunch. (See Figure 3).
- Given this distribution, one can then assume the small flow velocity discussed earlier (the actual flow velocity through the bunch) and estimate the number of particles that would actually impact on an individual grape — and hence the number and distribution able to impact on the grapes behind the first grape.

5. A concentration model

Another way of modelling the fluid deposition is as an advection diffusion model:

$$\frac{\partial C}{\partial t} + \mathbf{v} \cdot \nabla C = D\nabla^2 C - q(x,t)C, \tag{9}$$

where C is the concentration of fluid in the air (units of drops per unit volume or liquid volume per unit volume). This model includes advection (the velocity of the air $\mathbf{v}$), diffusion (mostly turbulent mixing type term), and a sink term qC, which models the adhesion of fluid to the grape surface.

As a first step we will consider steady, unidirectional flow past a single grape at the origin in the absence of diffusion:

$$U\frac{\partial C}{\partial x} = -\alpha\delta(x)f(y)C \tag{10}$$

where U is the velocity, $f(y) = 1$ on grape diameter and $f(y) = 0$ elsewhere, and we include a sink term — the Dirac delta functions $\delta(x)$. The term α is a

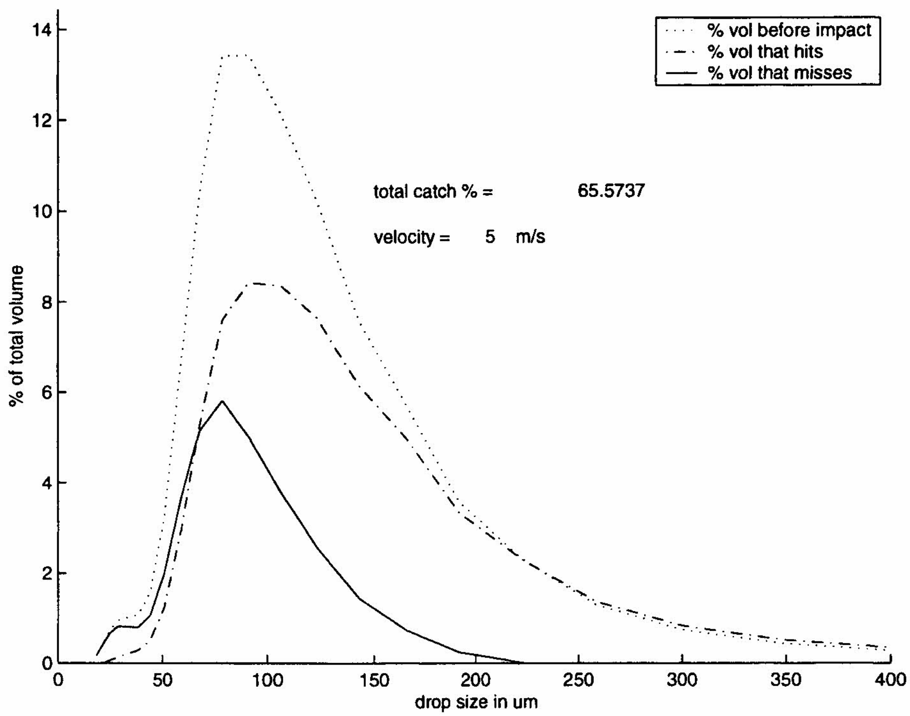

Figure 3: Droplet size distributions before hitting an object (grape bunch), the proportion that actually hit and the proportion that miss. This model can be repeated on a lower scale to see what hits an actual grape.

function of velocity, droplet mass and grape size in much the same way as the previous droplet interaction model was a function of velocity and mass of the incoming particle versus the size of the absorbing object.

Writing

$$\beta = \frac{\alpha f(y)}{U}, \tag{11}$$

the solution to equation (10) is

$$\frac{C}{C_0} = e^{-\beta H(x)} = 1 + H(x)(e^{-\beta} - 1), \tag{12}$$

where $H(x)$ is the Heaviside function. The concentration of particles is C_0 upstream of the grape. This equation illustrates the drop in concentration behind the object due to capture — that behind the object the concentration is $C_0 e^{-\beta}$.

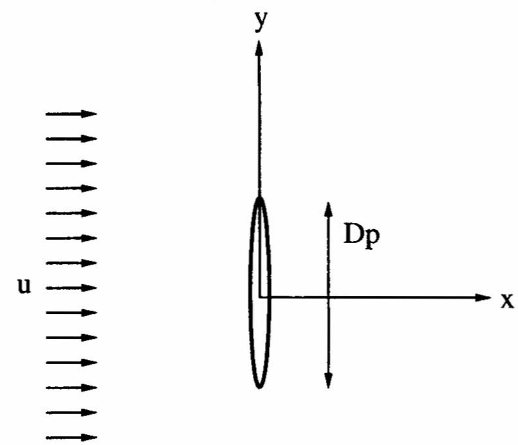

Figure 4: Uniform flow past a grape cross section.

Integrating this with respect to y gives the deposit amount

$$\int C(x=0^+,y)\,dy = C_0 D_p e^{-\alpha/U}, \tag{13}$$

so the fractional amount captured by the object, or deposited, C_d is

$$C_d = 1 - \frac{1}{C_0}\int C(x=0^+,y)\,dy = 1 - D_p e^{-\alpha/U}. \tag{14}$$

Equation 14 can be used to find α as a function of flow velocity and particle mass using the experimental and theoretical findings used in Section 4.

Considering only a theoretical point sink where $f(y) = \delta(y)$, this same process indicates that deposition on a sink would be

$$C_d = 1 - e^{-\alpha/U}, \tag{15}$$

with the appropriate α from the previous result.

This can be used in a more complete model with an array of point sinks at points (x_n, y_n), each representing a grape (see Figure 5)

$$U\frac{\partial C}{\partial x} = D\left(\frac{\partial^2 C}{\partial x^2} + \frac{\partial^2 C}{\partial y^2}\right) - \sum \alpha_n \delta(x-x_n)\delta(y-y_n)C + a\delta(x)\delta(y), \tag{16}$$

where the last term represents the source of the concentration.

A solution is then found by double Fourier transforms and appropriate inversion using integrals. The limitations of this crude model are that the flow velocity must be varied to allow for the reduced flow through the grape system, and this velocity must be calculated externally.

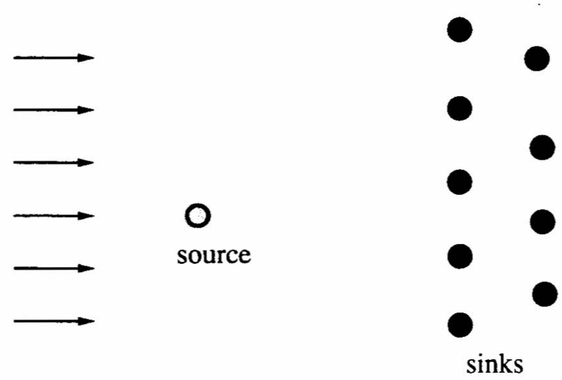

Figure 5: A point source of concentration flows past an array of point sinks who's strength varies with velocity, drop size etc.

6. Droplet adhesion

We consider here the maximum droplet size that can adhere to the grape surface. We take the contact angle of the fluid/solid interface to be γ. From Figure 6 the volume of the droplet is

$$V = \int_{z=R\cos\gamma}^{R} \pi r^2\, dz = \int_{z=R\cos\gamma}^{R} \pi R^2 - \pi z^2\, dz = \pi R^3 \left(\frac{2}{3} + \frac{\cos^3\gamma}{3} - \cos\gamma\right).$$

Hence the radius R of the adhered drop is

$$R = \left(\frac{V}{\pi(2/3 + (\cos^3\gamma)/3 - \cos\gamma)}\right)^{1/3}. \tag{17}$$

This drop will adhere due to a force proportional to the circumference. This proportionality constant, k, will need to be calculated experimentally. The force causing the drop to fall off is gravity (although air shear will also cause a droplet to fall off but this is a harder calculation that is yet to be done).

Thus a drop will fall off an inclined plane of angle θ to the horizontal if

$$\rho V g \sin\theta > k 2\pi R \sin\gamma \tag{18}$$

or upon rearrangement if the diameter of the original impacting droplet d is such that

$$d > k_1 \frac{\sqrt{\sin\gamma}}{(2/3 + (\cos^3\gamma)/3 - \cos\gamma)^{1/6}} \tag{19}$$

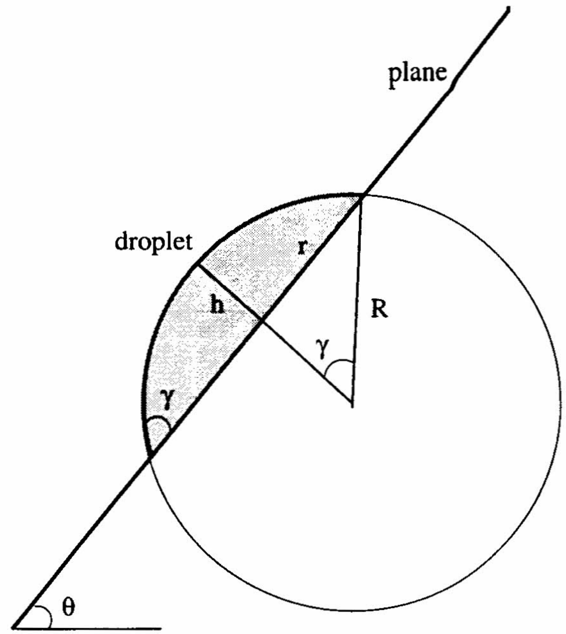

Figure 6: A droplet adhered to a angled plane with contact angle γ.

where

$$k_1 = \sqrt{\frac{72k}{\rho g \sin\theta}}. \tag{20}$$

A graph of this function for $k_1 = 1$ is shown in Figure 7.

7. Discussion of experimental results

We considered some results presented by Murphy *et al.* (2000) on the amount of spray volume retained on a bunch as a function of air velocity. Three separate cases were considered and discussed:

- **Open bunch**: Some some key results were:
  1. That retention on the front was approximately twice that of grapes in the rear.
  2. That inclusion of a surfactant reduced this 2/1 ratio to 1/1.
  3. That retention decreased with air velocity.

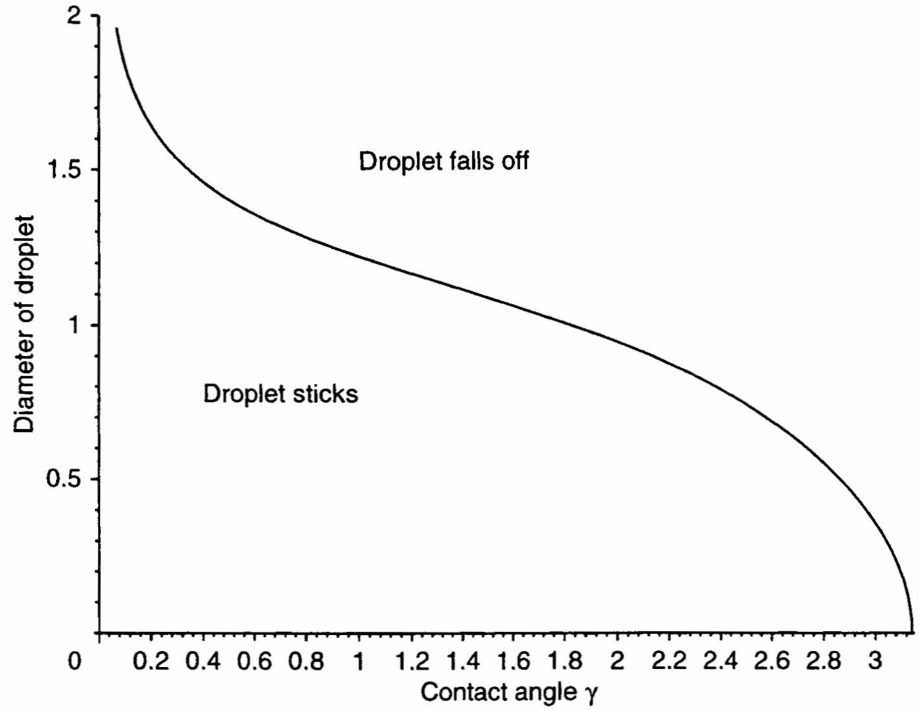

Figure 7: Minimum droplet diameter for adhesion against an angled face.

- **Medium bunch**: Some some key results were:
  1. The retention on the front decreased with air velocity while retention on the back increased slightly.
  2. The ratio of front/back retention went from roughly 4/1 to 1/1 with increased air velocity.
- **Closed bunch**: Some some key results were:
  1. The retention rate seemed unchanged with air velocity.
  2. The retention ratio front/back changed from 4/1 to 2/1 with surfactant.

Our opinion was that in the open bunch increased air velocity blew the droplets off the grapes, particularly on the front. In a medium packed bunch the extra air velocity blew drops off the front but helped filter liquid through the bunch to the grapes at the back. In the closed system blowing made no difference since filtration was negligible.

The effect of surface tension was most noticeable in the packed bunches since with no surfactant the liquid formed bridges between the grapes impeding further through flow. With surfactant added these bridges do not form and more filtration is able to occur (Figure 8).

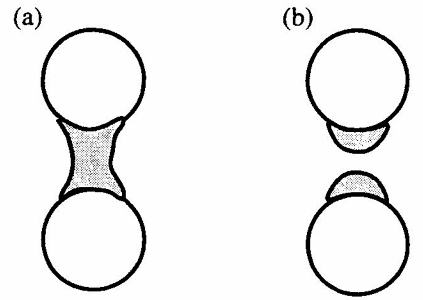

Figure 8: Formation of liquid bridges impedes flow (a) while surfactant acts to break the bridges allowing increased flow (b).

8. Laminar flow through a bunch of grapes modelled as a porous cylinder

In addition to modelling the flow using the Ergun equation, it was decided to examine the modern refinements to models for porous media flow; for example, as described by Nield (2000). There are some as yet unresolved modelling issues surrounding the correct set of terms to include in the equations for the flow, but we used a modification of the Navier-Stokes equations, where a Darcy-Forcheimer drag term is added to the momentum equations; linear and quadratic terms in the velocity being added to the momentum equation and suitable coefficients being chosen to model the effects of the porous medium on the flow in an averaged sense. The resulting equations were solved using *Fastflo*, which is a general purpose PDE solver developed at CSIRO Australia. *Fastflo* implements an Augmented Lagrangian method and in the present case 20 iterations seemed sufficient to reach a steady state. In Figure 9 the results shown are for airflow around a porous cylinder in a duct, with the Darcy-Forcheimer term being set to zero outside the cylinder.

The parameter values used are: Duct of dimensions 1 m by 0.5 m. Cylinder of diameter 0.1 m. Flow of air at speed 2 cm/sec, corresponding to a Reynolds number of 137. Permeability is 10^{-5} m^2 (the material does not impede the flow much). Unstructured triangular mesh, with 4715 total nodes and 2316 six-noded triangles.

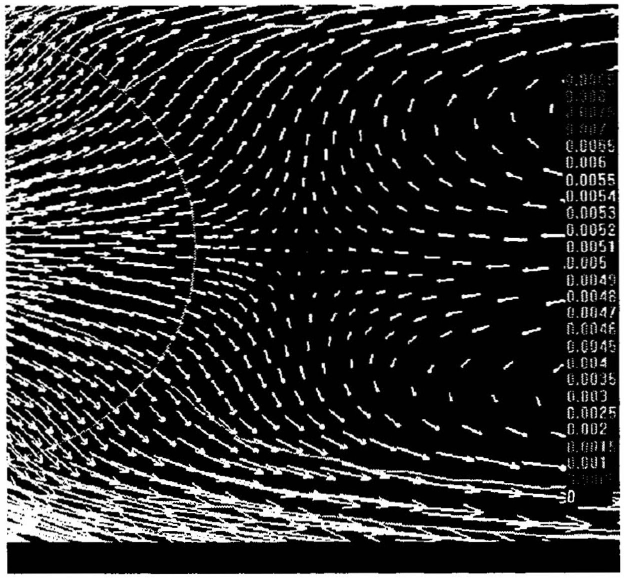

Figure 9: Stagnation point behind flow through a porous sphere.

The results from this calculation show a stagnation point in the flow behind the porous cylinder. Further work could investigate how sensitive this stagnation point is to the flow parameters and whether or not it could be positioned inside the cylinder to allow for improved deposition of pesticide on grapes.

9. Conclusions and recommendations

During the MISG, the group considered various options for calculating and estimating the quantity of pesticide which is actually applied to the grapes during the spraying process. Not surprisingly, it was realised that this is a difficult modelling problem and the majority of the work was concerned with inspired estimation. From this it was possible to determine the typical pressures and consequent flow rates inside a bunch of grapes at the three key stages of physical change of the bunch (capfall, pre-bunch closure and veraison). It was then possible to use this to estimate the range of droplet sizes for which impaction on grapes would be successful and for subsequent adhesion of droplets on grapes. Our key conclusions from this were that in the first stage of grape growth, increased air velocity is likely to result in reduced pesticide application, while in the second it could lead to better penetration. In the third stage it seems to have little effect. There was some speculation on application from above, to use the 'natural channels' of the stalks as the only promising route for pesticide application once grapes have reached veraison.

Other models were also considered, notably a sink model in which the grapes are delta function sinks for pesticide. This could provide a different method of determining the pattern of deposition, but would require further investigation. Finally, a computation of porous media flow suggested that careful examination of the flow field around bunches of grapes could help identify salient flow patterns, such as stagnation points, which could offer some opportunities for novel application strategies.

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