Real-Time Control of Spray Drop Application

S. Post[1], N. Kabaliuk[2], M. Jermy[2], P. Gaynor[2]

[1]Lincoln Agritech Ltd., PO Box 69 133, Lincoln, Canterbury 7640, New Zealand
[2]University of Canterbury, Private Bag 4800, Christchurch 8041, New Zealand

A paper from the Proceedings of the
14th International Conference on Precision Agriculture
June 24 – June 27, 2018
Montreal, Quebec, Canada

Abstract. *Electrostatic application of spray drops provides unique opportunities to precisely control the application of pesticides due to the additional electrostatic force on the spray drops, in addition to the normally seen forces of aerodynamic drag, gravity, and inertia. In this work, we develop a computational model to predict the spray drop trajectories. The model is validated through experiments with high speed photography of spray drop trajectories, and quantification of which trajectories lead to the "wrap-around effect", which results in drop deposition on the back side of the target leaf or fruit surface.*

Keywords. *Pesticide spraying, electrostatic spraying, computational fluid dynamics (CFD), precision spraying*

Introduction

Electrostatic spraying has shown the potential to greatly reduce the amount of chemical volumes applied in pesticide applications (refs). While field studies of electrostatic sprayers consistently show they achieve comparable levels of spray coverage and pest control as conventional sprayers while using much lower application rates, there still exists a gap between empirical and theoretical knowledge. Previous reviews of electrostatic spraying equipment for agriculture (Matthews, 1989) (Law, 2001) (Patel, 2016) have focused on the hardware options and performance in the field. Electrostatic spraying still has not achieved wide market acceptance, and its performance could be improved even further with a better understanding of the physical processes of drop charging and transport in an electric field from the nozzle to the target.

To ensure both bottom and top surfaces of leaves and fruit are coated with spray "wrap around", the electrostatic forces must be greater than the weight of the applied drop, also strong enough to overcome aerodynamic forces. There are four components of the electric field force, as shown in Fig. 1. The image charge force is only effective when drops are less than 1 mm from the target. Therefore some combination of applied electric field, space charge, and aerodynamic forces must bring the drop close enough to the leaf for the image charge force to capture it.

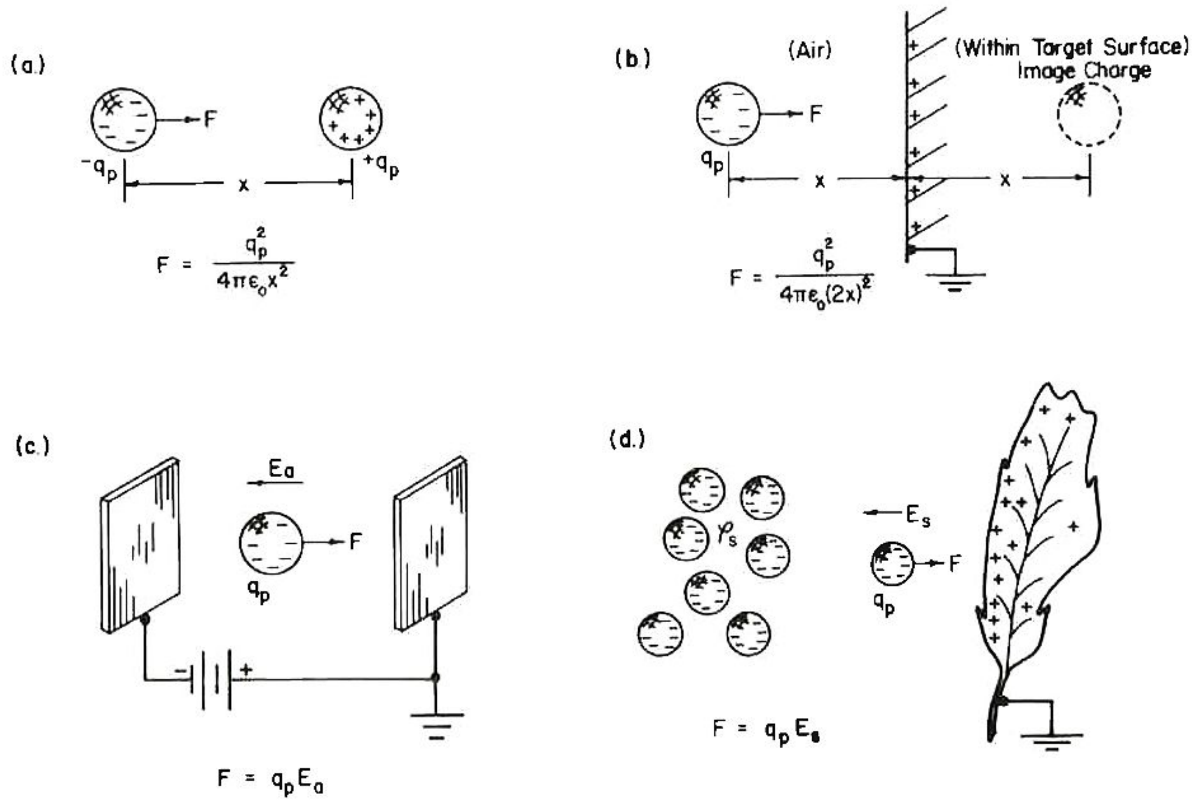

Fig 1. Illustration of the four electrostatic forces present on a charged drop in flight: (a) drop-drop pairwise force (b) image charge force (c) applied electric field force, and (d) space charge force. (Law, 1987)

All of the forces shown in Fig. 1 depend upon the charge on the individual spray drops, q. The Rayleigh limit is the maximum amount of charge a spray drop can carry for a droplet size, d:

$$q_{max} = \sqrt{2} \times 2\pi\sqrt{\varepsilon_o \sigma}\, d^{3/2} \tag{1}$$

Where σ is the surface tension (N/m), d is the diameter of the drop (m), and ε_o is the permittivity of free space, $\varepsilon_o = 8.854 \times 10^{-12}\ C^2\ N^{-1}\ m^{-2}$. Here d represents an individual spray drop and not an average diameter for an entire spray cloud. The Rayleigh limit represents the balance between the repulsive electrostatic force trying to pull the drop apart and the cohesive surface tension force that holds it together. The Rayleigh limit is the relevant limit to drop charging under conditions seen by agricultural sprayers. The maximum charge per unit mass of spray drop can be calculated as:

$$\frac{q_{max}}{m} = \frac{\sqrt{2}\times 2\pi\sqrt{\varepsilon_o\sigma}\, d^{3/2}}{\rho\frac{\pi}{6}d^3} = \frac{\sqrt{2}\times 12\sqrt{\varepsilon_o\sigma}}{\rho\, d^{3/2}} \qquad (2)$$

Where ρ is the density of the spray liquid (kg/m^3). A drop charge per mass of q/m > 1 mC/kg is needed for effective electrostatic spraying to achieve enhanced deposition over uncharged sprays (Law, 2014).

Due to the complex, non-linear nature of the forces diagrammed in Fig. 1, the spray drop trajectories cannot be calculated analytically, and must be solved numerically. Previous efforts at using computational fluid dynamics (CFD) simulations of electrostatic spray drop trajectories include (Al-Mamury et al., 2014; Jahannama et al., 1999; Jahannama et al., 2005a, 2005b; Jaworek et al., 2001; Zhao et al., 2007; Zhao et al., 2008). CFD simulations are necessary for sprays since the aerodynamic forces are of comparable magnitude to the electric forces.

Materials and methods

COMSOL Multiphysics software was used to analyse the four electrostatic forces to understand the relative importance of each and then analyze for what range of initial conditions wrap-around deposition was observed on a simulated target leaf. The design space of electrostatic parameters (electrode voltage, holes size, distance from nozzle, and geometry) is analyzed to determine combinations of design variables that lead to a viable system.

The drop trajectory simulations are done within a Lagrangian approach. We incorporate the image method approach for the induced charge on a simulated plant. The droplets were treated as negatively charged spherical particles with initial inlet velocity and uniform size subject to drag, gravitational and Coulomb forces. Particle-particle interactions were ignored. A leaf surface was represented by a plane surface with the induced charge as that for the case of a point charge and an infinite conducting plane. Droplets movement in with the stationary solution for the turbulent atomising fluid flow was tracked using the Fluid Flow and Particle Tracking modules. This was coupled with the transient solution for the electric field and potential around the leaf surface in the presence of movement of charged spray droplets obtained within the AC/DC module. Conditions under which the wrap-around effect occurs and the parameters contributing to the optimum pesticide deposition were investigated. The initial conditions for COMSOL simulations were varied:

- Drop sizes 5-200 microns
- Drop charged to 5-100% of Rayleigh limit
- Initial drop velocities 1-50 m/s
- Charging electrode at 1-10 kV

For input into the model, a Phase Doppler Interferometer (PDI) was used to measure drop sizes and velocities from an electrostatic charge spray system (Electrostatic Spraying Systems MaxCharge™ nozzles, ESS Watkinsville, Georgia, USA) with induction charging electrode at 1.5 kV. The PDI used the Demeter Probe, which is also suitable for outdoor field measurements; this PDI was previously described in Roten et al. (2016). The Demeter probe uses a 532 nm wavelength with a 300 mm focal length and a 30° collection angle. The static range for drop size measurement is 3.3-547.0 μm, which is suitable for the fine sprays from electrostatic nozzles (typically ASABE classifications Fine, Very Fine, or Extremely Fine). The exact lower limit of drop size detectability depends on the photo-multiplier tube (PMT) voltage used. For this study, a PMT gain of 500 V was used. For the results shown in Figure 1, a 75% data validation rate was obtained. Measurements were made 5 cm from the nozzle outlet.

For validation of the computational trajectories, a Photron SA5 high speed camera (up to 50,000 frames per second) was used to assess extent of drop motion and deposition.

Results

Figure 1 shows the measured drop size distribution from the PDI. It can be seen that the drop sizes from the electrostatic spray nozzle are very fine, with an arithmetic mean diameter D_{10} = 18 μm, and a volume median diameter D_{v50} = 53 μm.

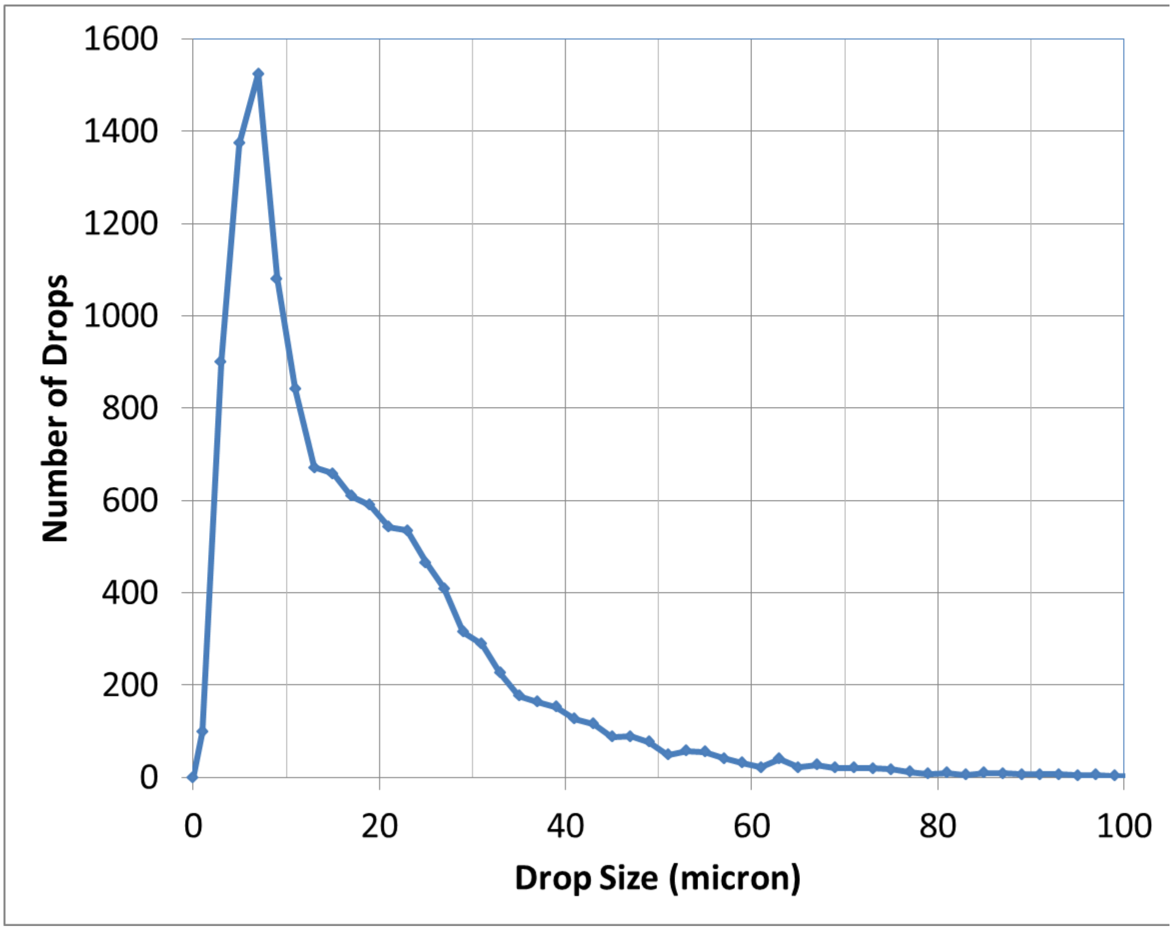

Fig 1. Drop size distribution from an ESS electrostatic spray nozzle measured using Phase-Doppler Interferometry.

Figure 2 shows a snapshot of the electric potential field, with the high-voltage electrode on the top surface, and the grounded leaf in the middle. Figures 3-5 show different computed droplet trajectory tracks for different computational conditions. Figure 6 shows two still frames from the high speed video tests with the same ESS nozzle as in the computations.

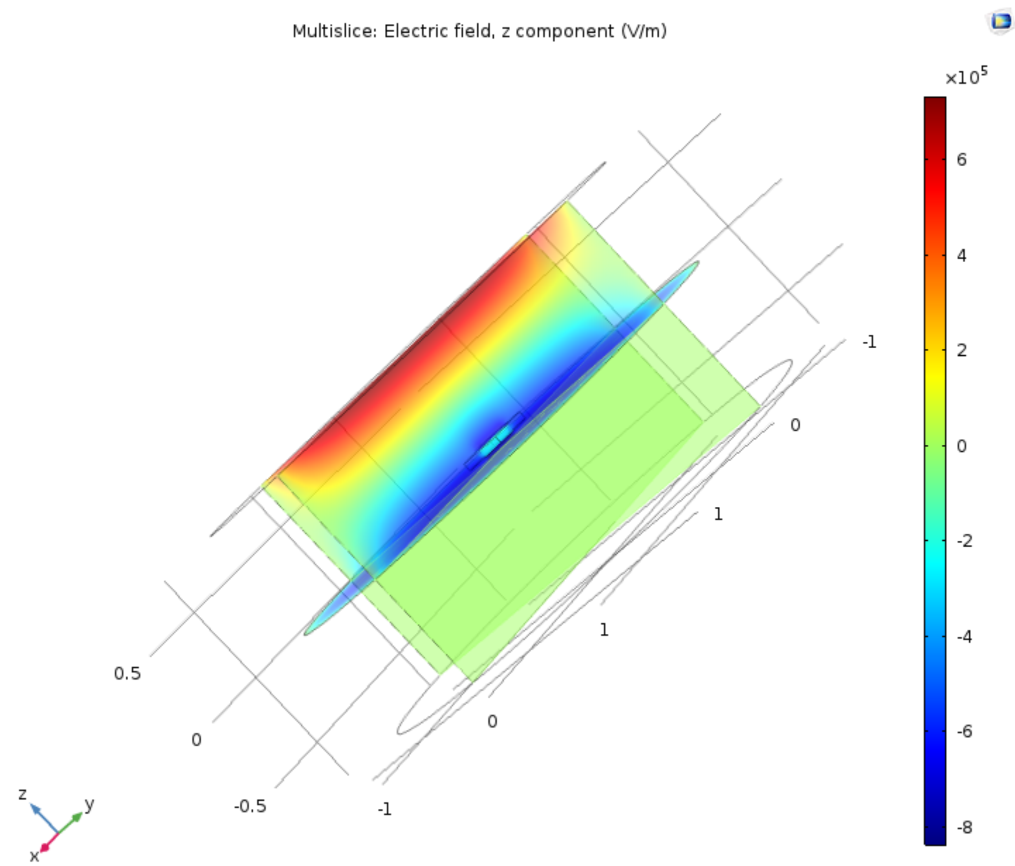

Fig 2. Computed electric potential field from charged spray nozzle.

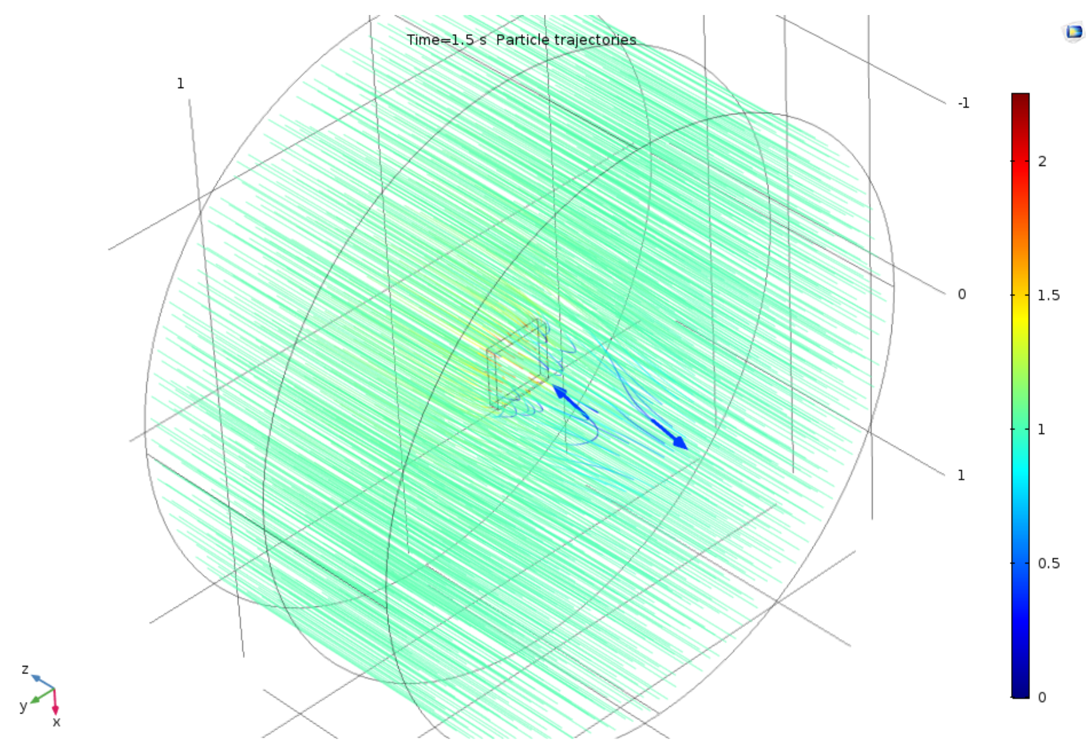

Fig 3. Computed particle trajectories, with blue arrows marking an example of a particle that achieves wrap-around deposition, and another that is not captured by the leaf.

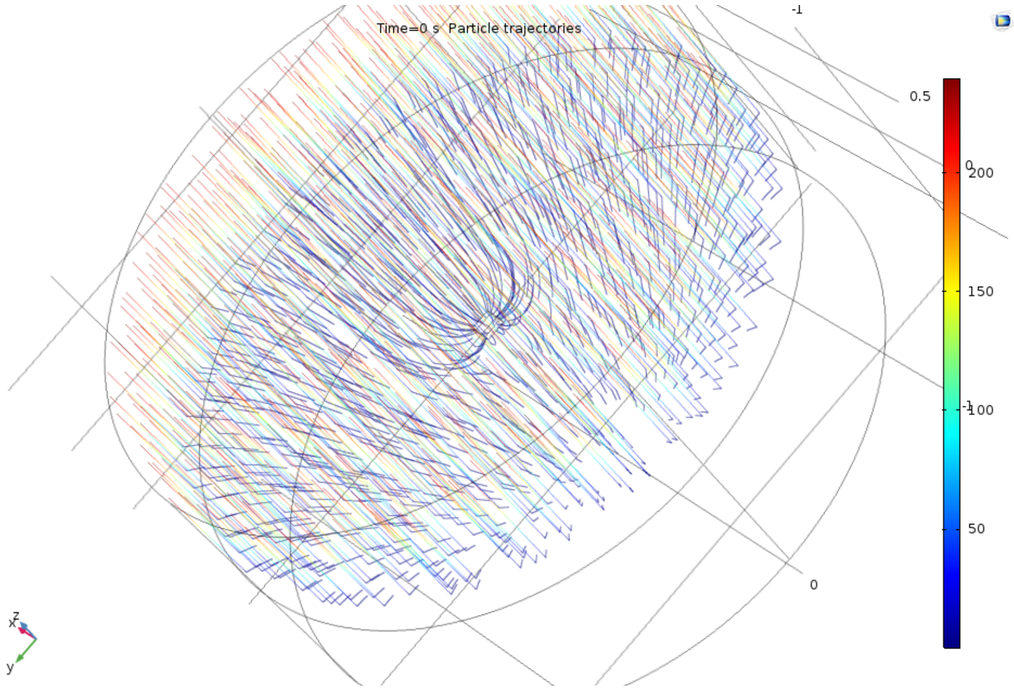

Fig 4. Computed particle velocity tracks. Those particles with initial trajectories near the grounded leaf are drawn towards it.

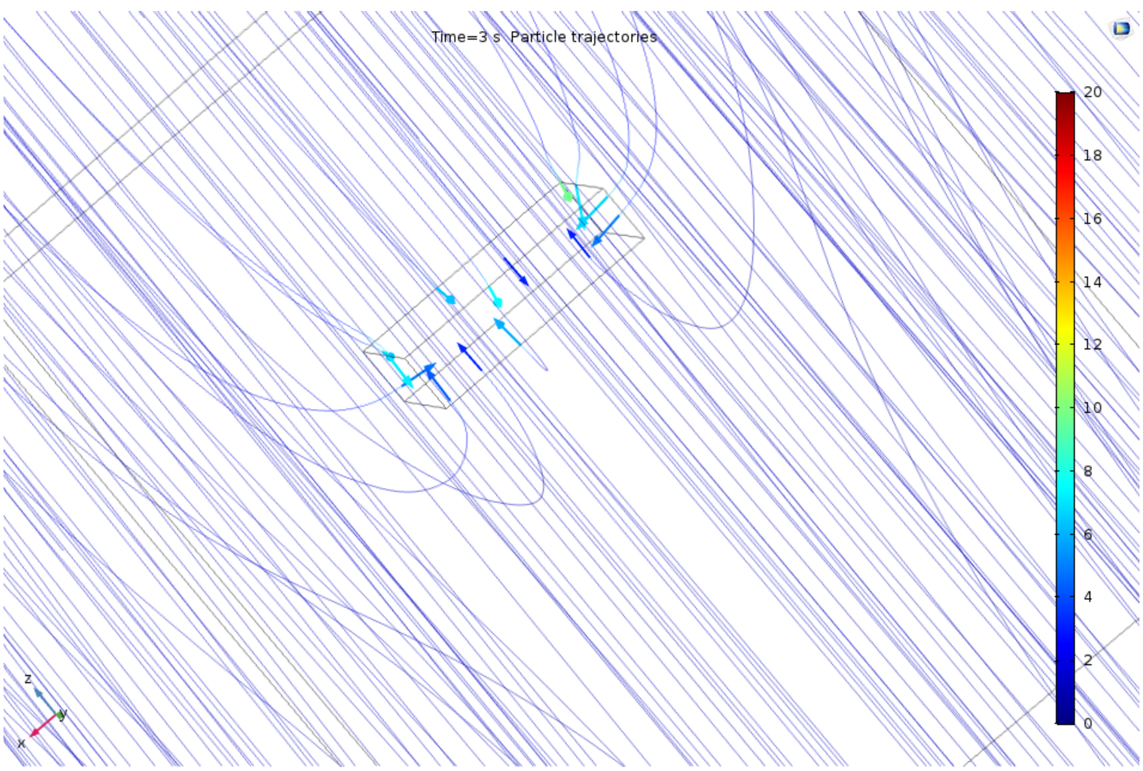

Fig 5. Closeup of some particle trajectory tracks, showing some that lead to wrap-around deposition on the bottom of the leaf.

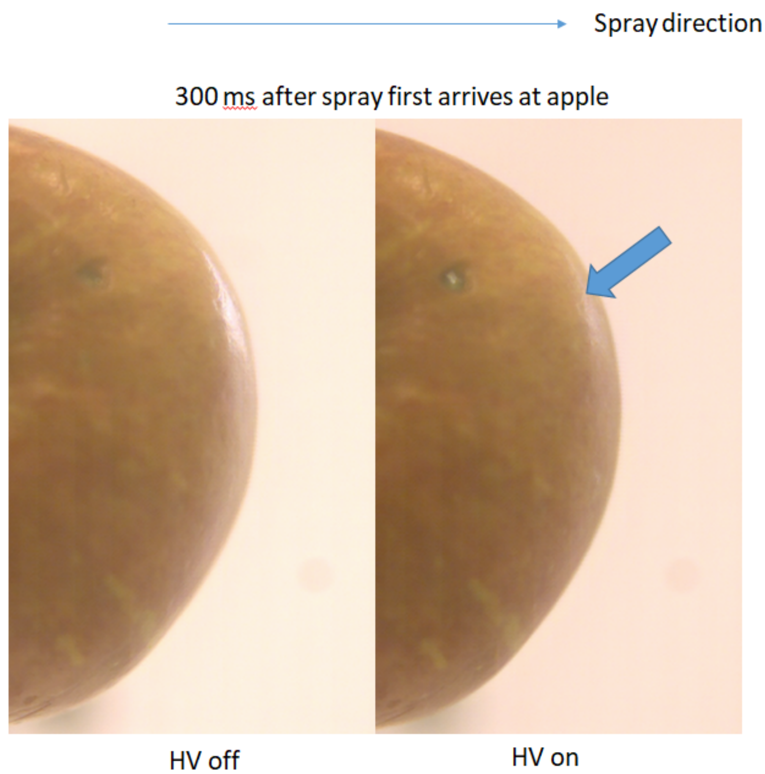

Fig 6. Still photographs showing the difference in back-side deposition on a target apple due to the effects of electrostatic charge. With the high-voltage (HV) on, there is less reflection from the light on the apple due to spray deposition.

Discussion

From the COMSOL studies (and theoretical computations) the wrap-around would occur where el forces overcome both gravity and inertial forces. It is challenging to achieve the effect within the defined (representative) range of droplet and leaf charges as the inertial flow (i.e. flow separation) effects prevail downstream the leaf edge. Based on the comparison of the droplet trajectories for different computational conditions, it was observed that high voltage, high droplet charge, and/or very small drops were required to achieve wrap-around deposition on the under-side of the computed target leaf. Simulations with 1 kV boundary potential did not show wrap-around even at low air velocities.

When modelling the image charge force as the only electric force, wrap-around was achieved only for drops whose initial trajectories bring them very close (less than 1 mm) to the leaf. These small drops will have a very short aerodynamic response time, and will follow the streamlines very closely. If a large-scale wake vortex and/or turbulence creates streamlines in the air that come close to the bottom leaf surface, the drag force could bring the drops close enough for the image charge force to capture them. Thus it seems likely that that the image charge force captures the drops when they are close enough to the leaf, but some other force must alter the initial straight line trajectories to bring them close enough. In addition to the aerodynamic force, the applied electric field force also serves to propel the drops towards the grounded target surface. For 30 micron drops in an average gradient of 1 kV/m is this force would be about 40% of the drop weight, but at points where the field lines converge this gradient could be higher.

It is found that only very small drops (around 20 microns) achieve wrap-around in the simulations. This implies for real electrostatic pesticide sprays, where there is a range of drop sizes, as shown in the measured distribution in Fig. 1, that the larger drops may be relatively unaffected by the electrostatic charge, and it is the smaller drops that achieve the beneficial enhanced deposition that is observed in field trials. Changing the drop charge from 5 to 10% of Rayleigh limit increases drop deposition on spray target by 74%

Conclusions

The computed simulation results highlight the need to achieve higher charge-to-mass ratios in electrostatic pesticide sprays than what is currently achieved with equipment on the market. It is known that drop charge per mass can be increased by increasing voltage, decreasing drop size, or reducing flow rate per nozzle, but for practical reasons it is undesirable to further reduce drop size due to risks of spray drop or the possibility the drops evaporate before reaching the target. Reducing the flowrate reduces the maximum amount of chemical that can be applied, (or more nozzles have to be added to compensate), which is also undesirable. Thus is more effective charging systems could be developed, larger drop sizes could be used with electrostatics, which would have beneficial effects for field applications.

Acknowledgements

This research was funded under a seed grant from New Zealand's National Science Challenge #10: Science for Technological Innovation.

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