STUDIES OF SPRAY DROPLET-LEAF INTERACTIONS, INCLUDING EFFECTS OF SURFACTANTS

R.D. Fox, J.A. Cooper, and R.D. Brazee[1]

ABSTRACT

This article reviews recent advances in instrument development and in measuring techniques for agricultural spray droplets impacting on leaf and artificial surfaces. In most cases, spray droplets that reflect from a plant leaf fall to the ground and are not useful in pest control. Two types of uniform droplet generators are described along with high-speed cinema and video techniques for observing droplet/leaf interactions. Studies of reflection of droplets from leaf surfaces have found variation in reflection from leaves of the same plant. Reflection from some plant leaves change with the age of the leaf, or the growing conditions of the plant (in a greenhouse or outdoors). Droplet reflection from some other leaves vary with position on the leaf, that is, droplets may be reflected in greater numbers from near the tip of the leaf, compared to reflection near the center of the leaf. For these reasons, random leaf sampling techniques and replication of trials are very important. The oscillating jet method for measuring dynamic surface tension (DST) at short surface ages is discussed and some measured results for typical surfactants are presented. The system described here is the best system known for measuring these fluid properties. We have found DST to be correlated to droplet reflection. Thus a careful measure of DST of the spray mixture will provide insight into the likelihood of spray reflection of loss from the leaf surface. A DST model based on thin-film diffusion of surfactant molecules to the liquid/air interface was developed. Measured DST values over a range of surface ages was used to compute model constants for several surfactants.

Key words: reflection, impaction, uniform droplet generators, leaf surfaces, dynamic surface tension, oscillating jet.

INTRODUCTION

Application of foliar sprays is a complex process that includes such events as spray atomization, transport to the plant, impaction on plant surfaces, retention, and for systemic compounds, uptake by the plant. These processes all influence spray effectiveness. Droplet retention on a plant surface is only one stage in the application process, but it is critical since only retained spray is useful for crop protection while reflected spray can result in economic loss and contribute to environmental contamination.

Whether a droplet is retained or reflected by a plant surface is a function of

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the properties of the spray solution (surface tension and viscosity), spray pattern (droplet size and velocity), and the surface morphology (degree of pubescence, venation, fine-structure) and chemistry of surface functional groups of the target surface.

We propose that a better understanding of the role of spray additives, delivery systems and plant surfaces on spray efficacy can be achieved by improved measurement of droplet/leaf interaction. Reichard et al. (1986) and Reichard (1988) used high-speed motion photography and an analytical projector to observe and analyze the impaction and reflection of uniform-sized droplets from a spray cloud. Fox et al. (1992) and Reichard et al. (1998) described the use of a video motion analysis system in conjunction with two different droplet generators to observe droplet impaction.

Both droplet reflection from plant leaves and droplet atomization have short reaction times. Unpublished data from our laboratory show water forming spray droplets less than 3 ms after liquid exits a hydraulic nozzle orifice. Research shows spray droplets rebounding from leaves are generally in contact with the leaves less than 1 ms. A key physical property of liquid spray materials affecting these processes is surface tension. Our research shows equilibrium surface tension is not a good indicator of spray droplet's potential to be reflected from a leaf surface (Reichard, et al., 1997). Some surfactant solutions at concentrations above critical micelle concentration (CMC) are readily reflected from leaves, while higher concentrations of the surfactant suppress reflection completely. Thus, we developed a method for measuring dynamic surface tension (DST) at young surface ages (Reichard et al., 1997).

These studies all focus on the observation and quantifying of droplet impaction on leaf surfaces and measuring factors that effect this interaction. This paper will highlight some of the results from these and other papers resulting from this series of studies.

The objective of these studies was to develop techniques for examining and quantifying droplet impaction and reflection from leaf and artificial surfaces and measuring properties of spray adjuvants that may affect these droplet interactions.

Many of the techniques used in studying the droplet/leaf interface used a monosized droplet generator to aid in the examination of one particular aspect of the impaction process. By means of a specific type of droplet generator with image capture and analysis, several types of useful results were obtained.

EXPERIMENTAL EQUIPMENT

Spray application

Drop-on-demand generator

A drop-on-demand (DOD) generator, similar to that developed by Young (1979) was constructed to produce single, monosized droplets (Reichard, 1990) from 100 to 800 μm in diameter. All droplets had negligible velocity close to the orifice, thus in order to obtain a range of incoming velocities, vertical distance from the orifice to the target was adjusted. The advantages of this system are the ability to produce single droplets that can be precisely placed on different parts of the target surface, in a range of sizes commonly used in pesticide application. The system can

also be used to follow the trajectory (and thus calculate velocity) of incoming and reflecting droplets, and to determine reflection height. A disadvantage of the system is the inability to produce high velocity droplets. It can only be used to describe what happens to droplets traveling at terminal velocity or slower, for example, at some distance from the sprayer or after the initial droplet impaction.

Berglund-Liu generator

A Berglund-Liu* (BL) vibrating mono-disperse aerosol generator was modified to produce a stream of monosized droplets in the size range of 50 - 1500 m. A brass ring positioned approximately 1 cm below the orifice, at the point where the ligament first broke up into droplets, was operated at a DC voltage to induce droplet charges sufficient only to disperse the droplet stream, providing a spray cone covering approximately 1 cm^2 at the impaction site. An advantage of the BL over the DOD generator is the production of a spray cloud, compared to a single droplet, which more closely simulates hydraulic nozzle applications. The velocity of droplets produced by the BL generator is less than those used in the field. For example, a 250 μm droplet would typically have a velocity of 7.0 m/s when produced using the BL generator, compared to 20 m/s measured directly beneath the orifice of a typical hydraulic nozzle operated at 276 kPa. A further advantage is the ability to determine the proportion of incoming droplets reflected from a given surface, along with reflection height.

Motion analysis systems

High-speed photography

A 16mm, Hycam, high-speed motion picture camera was used to photograph the impaction of droplets. The Hycam camera is a rotating-prism type, capable of taking from 20 to 11,000 full frames/s. The camera is equipped with an event synchronizer that can be adjusted to trigger an event after the desired amount of film passes through the camera. Neon lamps in the camera were used to put 1000 marks/s on the film. The camera is designed for "C" mount lenses. When the lens cap to subject distance is 20 cm, the image on the file is about 0.7 times the object size. With this arrangement, the area photographed is about 11mm high and 15 mm wide. The depth of field is about 3 mm. Eastman Ektachrome No. 7250 with a 400 ASA rating for color temperature of 3200 K was used. Color film was faster than black and white film and provided better visual analysis of the finished film.

A framing rate of 6000 frames/s was selected because it allowed observers to follow the path of individual drops, yet illumination could be provided with standard tungsten halogen, slide projector lamps.

Video Motion Analysis System

The video motion analysis system (VMAS) used a monochrome video camera with a newvicon tube and a high resolution imaging board controlled by a menu driven motion analysis software package. This system provided basic video operations along with a wide selection of image examination, processing, and measurement operations (Fox, et al., 1992).

Moveable rulers could be drawn on the screen, and used to measure image features such as droplet diameters, height of reflection from the surface, and distance

between successive images of the same droplet.

Droplet Illumination

To illuminate an incoming droplet spray from the BL droplet generator, two stroboscopes were placed 0.05 m behind, and to either side of, the target leaf at approximately 45° angles to the longitudinal axis of the camera. The strobe was used at a flash rate higher than the field rate of the camera, so that several images of the same droplet were visible in each frame. Trajectories of reflected droplets were defined by the tracks of sequential images of each droplet (Fig. 1).



Figure 1. Reflection of water droplets from a cabbage leaf.

Oscillating jet method

Details of the oscillating jet (OJ) system used to measure DST are given by Reichard et al. (1997). An elliptical orifice was made from a hypodermic needle with a major axis approximately 2.5 times the length of the minor axis. A liquid jet issuing from the elliptical orifice assumed a standing waveform, characteristic of its physical properties, as it emerged from the orifice. A mirror, inclined at a 45° angle to the strobe, was used to obtain simultaneous front and side views of the OJ waveform. The imaging system provided resolution at 1976 x 1234 pixels per frame in interlaced mode, corresponding to

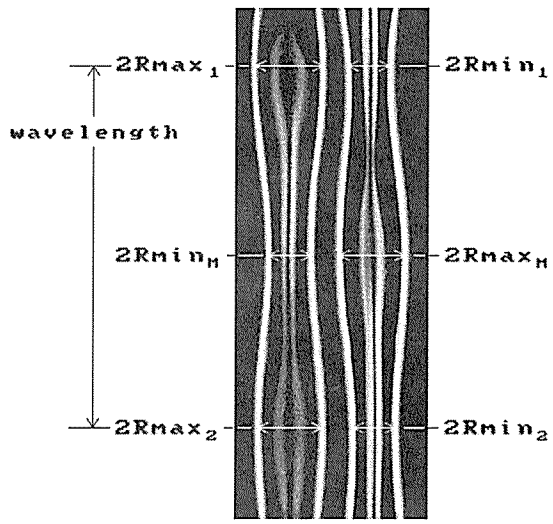


Figure 2. Digitized waveform of an oscillating jet, after edge enhancement, illustrating position of measured parameters.

horizontal and vertical scales of 2803 and 2393 pixels/cm respectively.

To calculate surface tension at a given surface age by two methods, seven measurements from the waveform were made (see Fig. 2). For examples shown here, surface tension was determined using four measurements on the left waveform in Fig. 2 and calculated by use of a modified Bohr equation (Thomas and Potter, 1975).

Solution surface tension at increasing surface ages was determined from waveform dimensions at increasing distances from the orifice until either the jet broke up due to capillary instability or oscillations were damped such that differences in amplitude were undetectable. To calculate surface age at which surface tension was measured, vertical distance from the orifice to $Rmin_M$ (the minimum between the two successive maxima used in calculation of surface tension) was divided by the jet axial velocity.

DST model

A DST model was developed by Brazee et al. (1994) using a thin-film diffusion theory. In the model, DST, $\sigma(t)$, at surface age t is

$$\sigma(t) = \sigma_m + m_0 C_0 \left[1 - \frac{2}{\pi} \sum_{n=0}^{\infty} \frac{(-1)^n e^{-\pi^2 D (n+\frac{1}{2})^2 \frac{1}{a^2}}}{n + \frac{1}{2}} \right] \quad (1)$$

where m_0 is a constant depending on solution equilibrium ST, surfactant concentration, C_0 and surface tension of water σ_m ; D is surfactant diffusivity; and a is apparent interfacial film thickness. Model development was concurrent with DST studies using maximum bubble pressure and oscillating jet methods.

RESULTS AND DISCUSSION

Droplet impaction and reflection

The most important factor in determining whether droplets reflect from leaf surfaces is the leaf surface itself. Leaves with a well-defined wax structure , such as cabbage, usually provide ideal surfaces for droplet rebound. We have tried to make an artificial surface for droplet reflection experiments, but have not been successful. We tested 21 weeds for reflection of water droplets. About 1/3 had no reflected droplets, 1/3 had a few reflected droplets and 1/3 reflected almost all impacting droplets. Several major agricultural crops, such as wheat and rice, are highly reflective.

Within a plant species, other subtle factors can affect droplet reflection. We have found that small plants (4 leaf stage) grown in ideal conditions within greenhouses during the winter do not develop a typical wax layer, and as a result, often will not reflect water droplets, even though similar plants grown outdoors, or to a greater size, will reflect droplets.

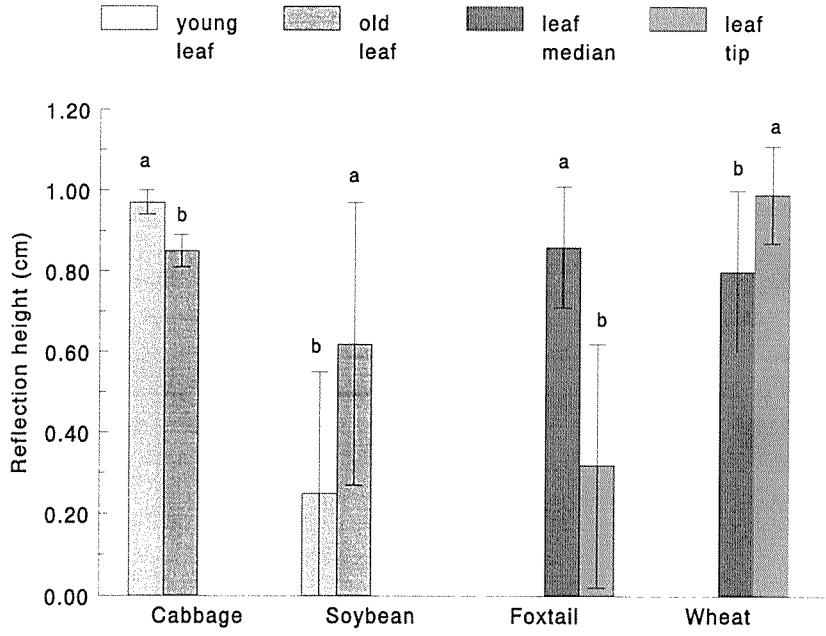


Figure 3. Reflection height of water droplets (230 μm, 0.6 m/s) from different areas of leaves (adaxial surface) of 4 plant species. Vertical bars refer to ± one standard deviation.

Variation with leaves from the same plant species is illustrated in Figure 3. Ten individual water droplets (230 μm, 0.6 m/s) were impacted on either two leaves of different ages from the same plant or, two different areas of the same leaf. When the reflection from young versus old leaves was compared, less reflection was observed from young soybean leaves compared to old ones: just the opposite was true for cabbage leaves. Similarly, the median part of the foxtail leaf showed twice the reflection from that of the leaf tip, while the leaf median gave lower reflection than the leaf tip for wheat leaves. Reflection also varied with the species tested. Cabbage, for example, had little variation among replicates compared to soya where the variability was large. These data illustrate the need for randomization and sufficient replication of plant material.

Reflection of droplets from leaves can be reduced or eliminated if sufficient adjuvants (surfactants) are added to the spray solution. However droplets with very low surface tension tend to roll on the leaf surface and may roll off the edge of the leaf. It is likely that other physical characteristics of the spray solution also effect reflection. Long chain polymers used to reduce drift have been shown to reduce droplet reflection. Good correlation was measured between concentration of the surfactant Kinetic and rebound height (Fig. 4). Rebound was not eliminated at the

concentrations tested but it was reduced significantly at the higher rates. Impaction is a dynamic process in which droplets remain on a leaf for less than 1 ms. The droplet undergoes extensive deformation during which new surface is formed in a short time and unless surfactant molecules are present at the new surface, or can diffuse to it during droplet deformation, surface tension will not be reduced and the surfactant will not reduce rebound. As the surfactant concentration is increased more surfactant molecules will reach the newly created surface during the impaction-process time. When this occurs, surface tension will be lowered and reflection will decrease.

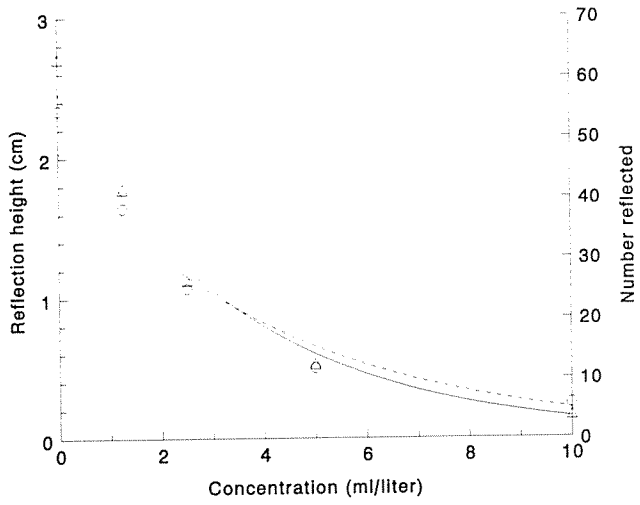


Figure 4. Effect of increasing surfactant (Kinetic) concentration on (O) height (y = 2.5 - 2.8 ln x, r^2 = 0.992) and (Δ) number (y = 47.6 - 2.3 ln x, r^2 = 0.992) of water droplets reflected from the adaxial surface of wheat leaves.

The oscillating jet system was tested by measuring surface tension of water and ethyl alcohol, two Newtonian fluids. Surface tension of Newtonian fluids should not change when the materials are sheared such as when droplets are formed or impact on leaf surfaces, i.e., equilibrium and dynamic surface tension should be equal. Results for equilibrium and DST for a range of alcohol-water concentrations are shown in Fig. 5.

Results of fitting the DST model to data for two concentrations of 2 surfactants (Igepal CO720 and Surfynol 465) are plotted in Fig. 6 over a range of surface ages from 0.5 to 8 ms. Surfactant composition appears to affect response to surface age. There were great differences among surfactants within one family and among families, as shown by these two examples. Most

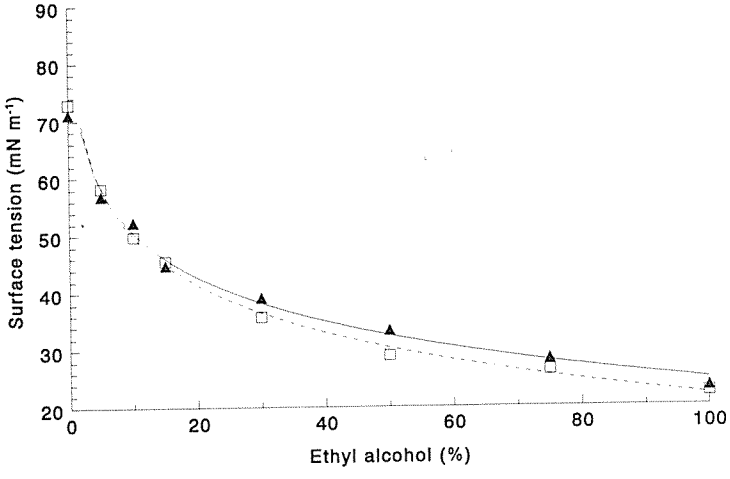


Figure 5. Surface tension of a range of ethanol concentrations obtained by static(□) and dynamic (▲) methods.

surfactants rapidly decreased in DST from values near water at short surface ages (< 2 ms) to equilibrium ST values at long surfaces ages (>70 ms). A few surfactants had low ST even at short surface ages. At 0.25% concentration, Surfynol had a much lower DST than Igepal; at 0.05% concentration, Surfynol DST decreased much more with increasing surface age than DST for Igepal. In general, increasing surfactant concentration improved a surfactant's ability to reduce DST even at short surface ages.

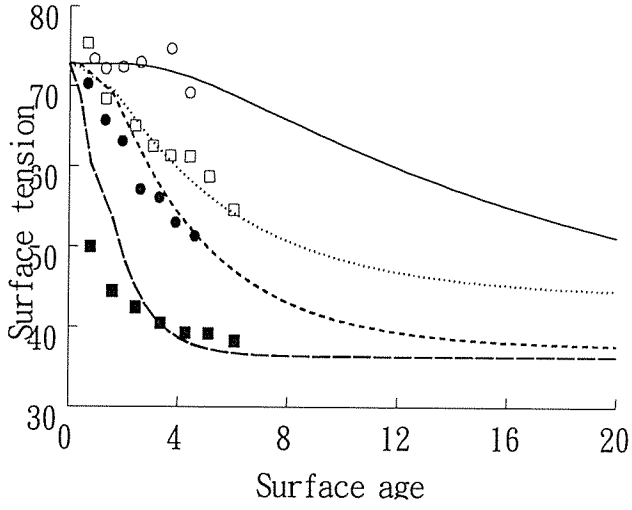


Figure 6. DST of two surfactants, measured (symbols) and computed with Eq. 1 (lines). (O) Igepal, 0.05%, (●) Igepal, 0.25%, (□) Surfynol, 0.05%, (■) Surfynol, 0.25%.

Spray retention

Retention experiments on growing corn, soybean, Johnsongrass, green foxtail, and velvetleaf were made with two adjuvants at two concentrations, with water as the control, sprayed at 100 L/ha. Retention of imazethapyr herbicide used as a tracer at two concentrations is shown as a function of DST at 20 ms in Fig. 7. The data show that the percentage of imazethapyr retained varies with the leaf surface, and that in all cases except for velvetleaf, retention is increased by a decrease in dynamic surface tension.

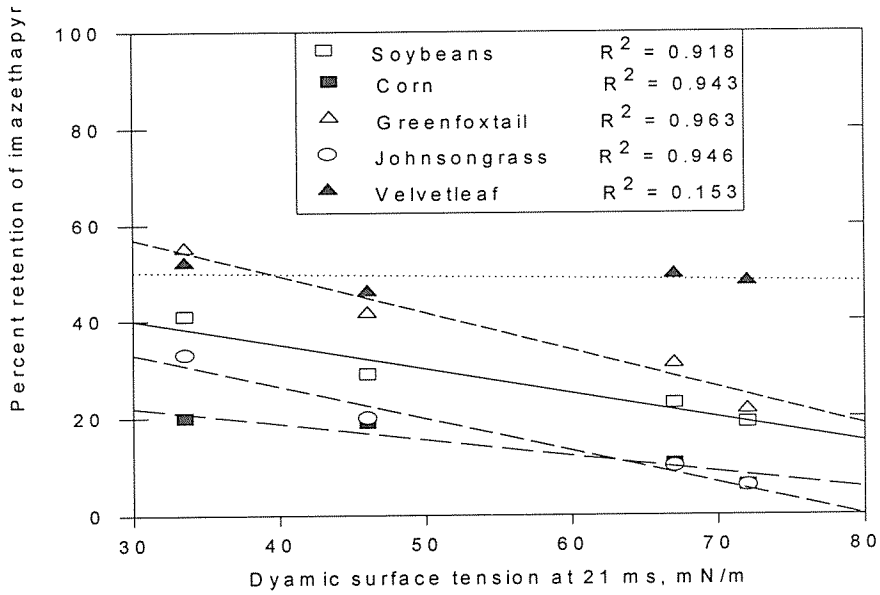


Figure 7. Retention of imazethapyr at a range of dynamic surface tensions.

DISCUSSION

We have accumulated several instruments that are useful in the study of droplet impaction/reflection on leaf surfaces. These studies have provided useful information about how droplets reflect, factors important in droplet reflection and how to reduce droplet reflection. We have also developed a technique to measure dynamic surface tension at short surface ages, DST can be used to predict droplet reflection of a spray mixture much better than static surface tension. We have also shown a positive relationship between DST and the retention of spray on several plant species. As surfactant activity at short surface ages is also important in atomization processes, DST may also be an important physical property in droplet size formation.

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*Names are necessary to report factually on available data; however, the U.S.

Department of Agriculture and Ohio State University neither guarantee nor warrant the standard of the product, and the use of the name of USDA or OSU implies no approval of the product to the exclusion of others that may also be suitable.

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