The most widely used form of spray technology is the household aerosol in a pressurized can, which is a simple system and well-developed technology. The number of cans of household aerosols sold in Japan annually is shown in Fig. 1 [1]. This graph shows that total household aerosol production is decreasing as manufacturers switch to hand sprays, which use pump technology. Nevertheless, total annual insecticide production is increasing.

There are three main problems with pressurized aerosol sprays: the production of volatile organic compounds (VOCs) [2-5], the use of oil-based energy, and the danger of explosion after disposal because of flammability. Most of the oil and propellant fail to reach the target, and fall to the ground. The propellant is used to break droplets into smaller droplets and to carry them to the target. Most of the propellant’s energy is used for carrying these droplets, although the remaining droplets are very small compared to those produced at the nozzle. We investigated the droplet characteristics over the entire distance from the nozzle to the target. Here, we tested different nozzle dimensions and compared single- and double-hole nozzles. We measured the spray characteristics near the nozzle to evaluate the droplet-forming process by examining droplet separation, agglomeration, collision, and size to elucidate the spray behavior and determine the dominant factors involved in designing and developing a nozzle for spraying insecticides most effectively. The key factor for developing the optimum nozzle for spraying insecticides is not the number of holes or nozzle diameter, but the agglomeration process and the amount at the target distance. The key to developing a system that decreases VOC dramatically is how the droplets are generated at the nozzle. Droplet diameter and velocity when exiting the nozzle need to be understood quantitatively and controlled; the most important considerations are to maximize spray agglomeration, in order to deliver droplets with an effective diameter to the target, and to reduce the number of oversized droplets failing to reach the target.

Keywords: Spray Characteristics, Agglomeration, Collision, Single- and Double-Hole Nozzles

1. INTRODUCTION

The most widely used form of spray technology is the household aerosol in a pressurized can, which is a simple system and well-developed technology. The number of cans of household aerosols sold in Japan annually is shown in Fig. 1 [1]. This graph shows that total household aerosol production is decreasing as manufacturers switch to hand sprays, which use pump technology. Nevertheless, total annual insecticide production is increasing.

There are three main problems with pressurized aerosol sprays: the production of volatile organic compounds (VOCs) [2-5], the use of oil-based energy, and the danger of explosion after disposal because of flammability. In the near future, restrictions will be placed on the VOC and greenhouse gas contents of pressurized aerosol spray cans. The European Union (EU) has agreed to reduce emissions of greenhouse gases by 8% by 2010 [6]. Therefore, it is necessary to develop more efficient aerosol spray cans, with lower VOC and dimethyl ether (DME) contents.

The initial goal in developing household aerosol sprays was to produce an inexpensive aerosol spray in a compact system, at low cost. In the development of aerosol nozzles that deliver insecticides optimally, they are conventionally evaluated by determining the knock-down time and the content remaining. Much less research has examined the spray characteristics from the nozzle, carrying process, attachment process, and effectiveness at killing insects. Therefore, this study examined droplet characteristics using optical diagnostics to determine how to reduce VOC content. To develop insecticide sprays for household purposes, we have spent many years evaluating the effects of spray nozzle dimensions and the chemical contents. We determined that the effective spray characteristics are determined by the initial conditions, such as the pressure, nozzle dimensions, and chemical contents. However, the effective spray distance, the effectiveness with which the spray attaches to the insect, and control over the direction of the spray are not direct functions of these properties. We need to develop an optimal insecticide spray nozzle in terms of chemical delivery.
Currently, the parameters used in insecticide development are bioassay methods and the estimated knockdown of 50% of the insects (KD₅₀) [7-19]. The bioassay method measures the amount of insecticide on a target insect after spraying it with an insecticide. The KD₅₀ is the time required to knock down 50% of the test insects. Figure 2 and Table 1 show typical results obtained using the bioassay method and KD₅₀ values.

We have investigated various aspects of aerosol sprays in terms of their effectiveness at reaching and attaching to insect targets and the physical properties of the spray device to reduce the release of VOC, which is an environmental hazard along with the liquefied propellant, and to develop a more effective insecticide spray device in terms of atomization and transportation energy, which are the main energies involved in aerosol sprays. Many factors must be considered in the practical development of insecticide sprays, including the effective droplet size and density, the surfactant, the amount of chemicals, the evaporation process, the propellant, flammability, and cost.

### Table 1. Attachment rate with single- and double-hole nozzle

<table>
<thead>
<tr>
<th>Nozzle</th>
<th>Pesticide/gas</th>
<th>Nozzle</th>
<th>Pesticide/gas</th>
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<tbody>
<tr>
<td>Single-hole</td>
<td>Case 1</td>
<td>Double-hole</td>
<td>Case 2</td>
</tr>
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<td>Case 3</td>
<td>A11</td>
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<tr>
<td>Double-hole</td>
<td>Case 1</td>
<td>Gas rich</td>
<td>Case 5</td>
</tr>
</tbody>
</table>

Figure 2 Sample data on the KD50 and the amount of attachment

Much effort has been put into minimizing the time required for fly knockdown by manipulating the spray characteristics, the amount of chemicals, and spray distance, while maintaining an economic perspective.

Studies have found that the effective amount of killing insecticide is less than 60 ppm of that actually used, with most of the spray falling to the ground or evaporating. As Fig. 3 shows, the main phenomena involved in an aerosol spray system are injection, momentum loss, separation, evaporation, agglomeration, and attachment to test insects. Since the target insect is usually flying, its wing movements and surface characteristics can lead to the collision of spray droplets, drag, and second stage agglomeration.

In studying the configuration of the spray nozzle, the spray characteristics near the nozzle can be evaluated using optical diagnostics. In developing aerosol sprays, it is necessary to consider the spray characteristics, mixture formation, and how droplets fall to the ground and are transported to the target insect.

We found that the attachment rate is higher with a single-hole nozzle than with a double-hole nozzle. However, we need to know where the droplets attach to test insects, the characteristics of the droplets that attach to test insects, how to generate droplets that readily attach to test insects and the associated spray nozzle characteristics, and the characteristics of the droplets that fall to the ground.

To develop an optimally effective aerosol spray nozzle specifically for spraying insecticides, it is necessary to measure the spray characteristics near the spray nozzle and the target insect and to consider the total energy balance, droplet quality, and efficiency.

We observed enlarged images of the area near the target insect to measure droplet attachment to test insects obtained using a high-speed camera with a long-distance microscope. We measured the spray characteristics near the nozzle to evaluate the break-up of spray and the droplet-formation process by examining droplet separation, agglomeration, collision, and size to elucidate the spray behavior and determine the dominant factors involved in designing and developing an aerosol spray nozzle for spraying insecticides most effectively. We tested many different nozzle dimensions and compared single- and double-hole nozzles. The purpose of this research was to identify the droplet characteristics that would allow a reduction in VOC content using optical diagnostics. In this paper, we report the differences between single- and double-hole nozzles as the first step in the development of an optimal aerosol spray nozzle.

Figure 3 Main phenomena that take place in an aerosol spray system
2. OBTAINING HIGH-SPEED IMAGES

2.1 Experimental Apparatus

A schematic of the high-speed camera system and the specifications of the high-speed camera and long-distance microscope are shown in Fig. 4. The light source was an argon-ion laser (Spectra Physics, Stabilite 2017-Ar-ion Laser, wavelength: 514.5 nm). A series of lenses formed the laser light into a 1.0-mm-thick sheet that illuminated a vertical plane for the high-speed camera (Shimadzu, Hyper vision HEX-108, Maximum camera speed: 1 Mfps), which obtained high-speed images through a long-distance microscope (working distance 280 mm). The charge coupled device (CCD) array consisted of 316×260 pixels and the area visualized was 6.0×4.9 mm. An injection control unit controlled the start of spray injection and the high-speed camera system. To elucidate the characteristics of the insecticide aerosol spray, we measured enlarged images near the test insect using this apparatus. We optimized the optics and high-speed camera to measure droplet movement and the up- and downstrokes of the test insect.

A standard phase Doppler anemometer (PDA) system was used to measure droplet diameter and velocity over the range from near the nozzle to a target 1,000 mm from the nozzle. The measurements were made in a glass tube 300 mm in diameter to avoid the effects of motion of the surrounding air, and the chemical components were quantified.

Air was drawn from the end of the pipe to produce a velocity of 20 cm/m at the end of the pipe, which is the standard condition used in the knockdown test. The camera, PDA, fan, and traversing system were synchronized using a personal computer and 10,000 samples were recorded. In each condition, at least ten insect samples were examined. The target insect was held in place with a pin.

2.2 High-Speed Images

We observed enlarged high-speed images of the area near the target insect to measure droplet attachment to the test insect using a high-speed camera with a long-distance microscope to elucidate how and where droplets attached to the test insect and the characteristics of the droplets that attached to the test insect.

Figure 5 shows enlarged high-speed images of (a) dead and (b) live test insects. Some droplets attached to the test insects, while others did not. Why did this happen? Is it a result of differences in droplet diameter, differences in the solvent, or the presence of a surfactant? In addition, we observed that wing movement changes the flow with live test insects. To answer these questions, we measured the spray characteristics in four areas between the spray nozzle and test insect using a dual PDA system.

2.3 Measurement Apparatus

It is impossible to characterize the optimal attachment of droplets to a test insect using the bioassay method or KD50. Therefore, we measured the spray characteristics in four areas using a dual PDA system

Figure 4 Schematic of the experimental apparatus consisting of a high-speed camera system and specifications of the high-speed camera with long-distance microscope

Figure 5 High-speed enlarged images near test insect area

Figure 6 Schematic of the experimental Phase Doppler Anemometer system and the specifications of the PDA system.
Figure 6 shows a schematic of the PDA system (Dantec, Dual PDA System) used to obtain the spray characteristics of the insecticide aerosol spray in this study. An argon-ion laser (Spectra Physics, Stabilite 2017-Ar-ion laser, wavelength: 514.5, 488 nm) was used as the light source for the PDA system and the laser power was set to 1.0 W. The injection control unit controlled not only the start of spray injection but also the high-speed camera and PDA systems. For each point, 20,000 data values were collected. The experiment was conducted under atmospheric conditions. The PDA system was optimized to obtain a high sampling rate.

Figure 7 shows the areas where the PDA system measured the diameter and velocity of the insecticide aerosol spray: area 1 (near the spray nozzle (Z = 10–110 mm)), area 2 (Z = 630 mm), area 3 (Z = 1,060 mm), and area 4 (near test insect (Z = 1,510 mm)). We tested two different nozzles: single-hole and double-hole. For the single-hole nozzle, measurements were made with and without a surfactant. The spray duration was 200 ms, and was controlled by the injection control unit. To elucidate the spray nozzle characteristics, 33 points were measured in area 1 for the single-hole nozzle and 36 points were measured for the double-hole nozzle, while 13 points were measured in areas 2 to 4.

3. SPRAY CHARACTERISTICS

Table 1 summarizes the results for aerosol sprays produced using single- and double-hole nozzles, using the bioassay method to determine the attachment rate. The single-hole nozzle was the most effective for killing insects.

Although the bioassay method is very useful for developing insecticide systems, it cannot evaluate the droplet characteristics over time, which is needed to evaluate the movement, collision, and agglomeration of droplets.

First, we measured the spray characteristics of single- and double-hole nozzles at the target point near the test insect (Y = 0 mm, Z = 1,510 mm) and the results are shown in Fig. 8. The droplet diameter at the target using a single-hole nozzle was the most effective for killing insects. The droplet diameter increased with distance.

The diameter for a double-hole nozzle without surfactant was 21.10 µm. There was no significant difference between a single-hole nozzle with and without surfactant in terms of droplet diameter and the probability density function (PDF). We found the most effective diameter and distribution of diameters at the target, which should increase the efficiency of aerosol sprays while reducing their environmental impact.

Next, we evaluated the spray characteristics near the nozzle, which is the most important parameter when developing aerosol sprays. We tested single- and double-hole nozzles. Figure 9 shows the measurements for droplets D32 and D10 using a single-hole nozzle without surfactant; the mean velocity and droplet diameter distribution at several distances are given, together with the nozzle specifications. The droplet velocity 30 mm from the nozzle was 25 m/s and decreased with distance to 10 m/s 110 mm from the nozzle, indicating that the droplets lost momentum. Most of the droplets were carried by the surrounding cloud of pressurized gas. Moreover, droplet diameter increased with distance.
The diameter of the droplets ($D_{10}$) that formed at the nozzle exit was about 50 µm. The droplet diameter decreased with distance in the first 30 mm from the nozzle exit, and the velocity increased over the same distance.

The initial droplet size was about 35 µm and this increased to 60 µm 110 mm from the nozzle. As with the single-hole nozzle, the droplet diameter decreased with distance over the first 30 mm from the nozzle exit, and then increased. The peaks for the distribution of velocity and droplet size were also lower than for the single-hole nozzle.

Figure 11 compares droplet momentum for single- and double-hole nozzles. The aerosol spray had a large initial velocity, but lost momentum with distance with both nozzles. For both nozzles, the velocity increased over the initial 30 mm as the diameter decreased because of atomization. After $Z = 30$ mm, the diameter increased with distance in both cases, while droplet velocity decreased, resulting in a loss of momentum. The droplets agglomerated at 90 to 100 mm from the nozzle exit. We concluded that aerosol spray formation did not depend on the size or number of holes in the nozzle, but was determined by the agglomeration process.

To elucidate spray characteristics from the nozzle exit to the target area, we made measurements in four areas using the dual PDA system.

Figure 12 Comparison of the spray characteristics of single and double-hole nozzles (Y = 0 mm)

We evaluated processes of atomization, agglomeration, falling, and attachment to the test insect.

Figure 12 shows the PDA measurement results at $Z = 90$, 630, 1,060, and 1,510 mm ($Y = 0$ mm) for single- and double-hole nozzles. For the single-hole nozzle, agglomeration occurred at a distance of 1,060 mm, at which time the droplet diameter increased to 80 µm. By contrast, for the double-hole nozzle, agglomeration occurred at a distance of 630 mm. This resulted in a difference in the spray characteristics at the target. After the agglomeration point, the droplet diameter again decreased with distance and was about 40 µm at the target with the single-hole nozzle and about 20 µm with the double-hole nozzle. The distribution of droplet diameters at $Z = 90$ mm was very different for the single- and double-hole nozzles. With the double nozzle, the atomization process occurred earlier and the diameter distribution was narrow.

Figure 13 compares the sampling rate ratio of the single-hole nozzle with and without surfactant and the double-hole nozzle. For the single-hole nozzle, the sampling rate ratio decreased with distance and there was almost no difference between with and without surfactant. Although the sampling rate ratio was very low after $Z = 1,060$ mm, the peak of the diameter distribution increased slowly because of agglomeration. For the double-hole nozzle, the sampling rate ratio increased initially up to $Z = 630$ mm, and then decreased dramatically.
In addition, most of the insecticide droplets fell to the ground or evaporated, and less than 60 ppm of the insecticide spray reached the target insect. Although we used a surfactant to improve spray formation, the surfactant had no effect on droplet diameter. Therefore, the surfactant facilitated agglomeration while carrying the spray, but had little or no effect on the droplet diameter at the target.

In the future, we plan to study the droplet density. The spray characteristics of agglomeration, collision, the fall of over-sized droplets before reaching the target, chemical transport, the effectiveness of droplet attachment to the insect, the effect of surfactants, and knockdown time will be examined further using PDA data and insect knockdown results.

4. CONCLUSION

We measured droplet characteristics to optimize the design of insecticide aerosols. The spray characteristics showed that the most important factor determining the formation of effective droplets is the agglomeration process during droplet transport.

We demonstrated high-speed visualization of insect movement and measured aerosol spray characteristics with single- and double-hole nozzles to elucidate how and where droplets attach to test insects and the characteristics of the attached droplets. Some droplets attached to the test insects, while others did not. We measured the spray characteristics in four areas using a dual PDA system. The results indicate that the key factor for developing the optimum nozzle for spraying insecticides is not the number of holes or nozzle diameter, but the agglomeration process. The droplet diameter and velocity on exiting the nozzle need to be understood quantitatively and controlled. The most important considerations are maximizing spray agglomeration in order to deliver an effective droplet diameter to the target and reducing the number of over-sized droplets that fail to reach the target. Further experiments are planned to decrease the VOC content in aerosol sprays.

5. NOMENCLATURE

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Unit</th>
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<tbody>
<tr>
<td>$D_{s2}$</td>
<td>Sauter mean diameter</td>
<td>[mm]</td>
</tr>
<tr>
<td>$K_{D_{50}}$</td>
<td>Knockdown of 50% of test insect</td>
<td>[%/sec]</td>
</tr>
<tr>
<td>PDF</td>
<td>Probability density function</td>
<td>[%]</td>
</tr>
<tr>
<td>$D_{10}$</td>
<td>Arithmetic mean</td>
<td>[mm]</td>
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</table>

6. REFERENCES


