Modeling and Experimental Validation of the Atomization Efficiency of a Rotary Atomizer for Aerial Spraying

Gen Li, Liping Chen, Longlong Li, Tongchuan Yi, Chenchen Ding, Juan Wang, Chunjiang Zhao, and Ruirui Zhang

1. Introduction

In agriculture, the aerial application of products has the advantages of high spraying speed, high spraying efficiency, relatively low energy consumption, and wide terrain adaptability. Moreover, it can cope with sudden large-scale natural disasters, which is important for pest control. However, there is a large distance between the aircraft and the target, and it is difficult to control the deposition of the droplets during the application process. Atomization technology that can control the particle size is an effective method of achieving controlled deposition [1,2].

Rotary atomizers are widely used with fixed-wing manned aircraft, and the particle size is controllable. However, they generate resistance during flight, and the extra resistance increases fuel consumption and cost of the spraying operation. In addition, the atomization efficiency directly affects the cost of aerial application. Therefore, it is necessary to be able to determine the atomization efficiency of an atomizer [3–6].

Atomizers are a core part of the equipment used in agricultural aerial application. The spraying atomization device is divided into a hydraulic atomizing nozzle and a rotary atomizer.
atomizing nozzle. The latter consists of a rotary cage centrifugal nozzle and a rotary disc centrifugal nozzle [4,7–10]. The rotary cage centrifugal nozzle is power-actuated or wind-driven based on the driving mode. Commonly available hydraulic nozzles include flat fan and hollow cone nozzles [11]. Large-flow rotary atomizers are most suitable for high-speed fixed-wing aircraft and manned helicopters [12–14]. In the case of the high flow rate of a liquid, rotary atomizers are used most frequently. If there is a high demand for atomization in operation, and fine atomization is needed; for this, atomizers with low flow rate and high energy consumption need to be used. Zhang et al. [15] studied the spray characteristics of pressure–swirl nozzles, which are widely used in agriculture, combustion, aerospace, and other fields. In particular, they focused on the effects of the nozzle hole size and injection pressure on the spray morphology, velocity distribution, and spray angle. They used particle image velocimetry (PIV) to measure the velocity distribution of the spray nozzle. The empirical correlation between the injection angle and Reynolds number (Re) was obtained using the Buckingham π theorem.

Dorr et al. [16] measured the initial spray characteristics (initial droplet size and velocity, fan angle, and spray liquid density) of a hydraulic nozzle with different spray mixtures, and the spray sheet velocity was measured using PIV. Their results showed that the initial spray characteristics varied depending on nozzle design, operating parameters, and spray formulation. There was a significant correlation between the initial droplet velocity and the droplet size and spray pressure.

Craig et al. [17] concluded that the efficiency of pesticides applied via aircraft can be improved if sharp issuing points or pins are added to the rotating gauze surface of a rotary atomizer. This means that existing rotary atomizers, which have been successfully used in ultra-low-volume (ULV) insecticide application, can also be used for large droplet placement (LDP) herbicide application.

Guler et al. [18] evaluated the spray coverage density of seven nozzles with different flow rates using water-sensitive paper as the target under controlled environmental conditions. Each nozzle—including conventional flat nozzles, air-induction flat nozzles, and hollow cone nozzles—had advantages in different environments.

Ryan et al. [7] calculated the plume generated by two rotary atomizers, AU4000 and AU6539, using the Reynolds-averaged Navier–Stokes (RANS) model. Then, they compared the calculated results with experimental parameters, such as the droplet size that was measured using a phase-Doppler interferometer.

In recent years, new nozzles, such as electrostatic nozzles, have been widely used. In electrostatic nozzles, electrostatic charges are generated between the droplets and targets using the principle of electrostatic induction. Thus, the droplets are attracted to and deposited on the targets, effectively decreasing the degree of drift [19].

Martin and Latheef [20] mixed daylight visible fluorescent dye (10% v/v) with water and sprayed cotton using electrostatic and rotary atomizer nozzles, with spraying rates of 9.4 and 28 L/ha, respectively. They employed ImageJ software to digitally analyze the spray droplets in images of the cotton leaves. The charged spray cloud increased the deposition on the top canopy by a factor of 2–3, compared with the uncharged spray. The spray application method did not affect the penetration of the spray through the canopy to the lower layer of foliage.

Recently, the research on agricultural atomization has increased. Darwish et al. [21,22] explained the size distribution of the droplets. They stated that the droplet size became more uniform by enlarging the lateral distance. Oswald et al. [23] demonstrated that the elongational resistance flow influences the disintegration process in the bell atomizer. Shen et al. [24] studied the droplet disintegration process and the non-Newtonian fluid behavior that is injected into the orifice and bell surface. Pendar and Páscoa [25,26] investigated the fundamental flow behavior around the sprayer.

There has been little research on the atomization performance index of manned aerial vehicles for plant protection. In this study, a measurement-based model of the atomization efficiency for manned aerial agricultural application is established. Specifically, a model
considering the effects of multiple variables on atomization efficiency is developed based on several experiments.

2. Measurement, Analysis, and Modeling of Atomization Efficiency

2.1. Analysis of Droplet Break-Up

The process of droplet break-up is the same regardless of the type of atomization, and there are three types of break-up: jet break-up, liquid sheet break-up, and droplet break-up. A single atomization process involves all three break-up types simultaneously [27]. For atomizers typical in agricultural sprays, liquid media is forced through a slit orifice to produce a radially expanding thin film, or liquid sheet. The atomization of a simple liquid film occurs in a series of instabilities, wherein the sheet first breaks up into ligaments, then the ligaments break up into droplets [28].

Break-up is a process by which the droplet size is reduced. An external force is applied to the droplet to overcome the cohesion between internal particles, that is, work is performed on the droplet to enable transformation into deformation energy. Break-up occurs only when the deformation reaches its limit. In mechanics, droplet break-up is an energy transformation process. When liquid is atomized using an atomizer, the energy consumption for the overall droplet break-up is high.

According to the volume theory of droplet break-up, the energy consumption during droplet break-up is directly proportional to the change in volume, as given by the equation [28]:

\[ W = k\Delta v \log \frac{d}{D_{0.5}} \]  

(1)

Here, \( W \) is the energy consumed by breaking up the liquid into droplets; \( k \) is the comprehensive proportional coefficient, and it is different for each broken object and should be verified; \( \Delta v \) is the change in volume; and \( \log \) is the logarithm of the break-up ratio. In the volume calculation, the droplets can be approximated as spheres.

Therefore, \( \Delta v \) is given by:

\[ \Delta v = \frac{4}{3}\pi \left( \frac{d}{2} \right)^3 - \frac{4}{3}\pi \left( \frac{D_{0.5}}{2} \right)^3 \]  

(2)

and:

\[ W = \frac{k\log \frac{d}{D_{0.5}}}{6} \pi \left( d^3 - D_{0.5}^3 \right) \]  

(3)

Here, \( d \) is the diameter of a single liquid drop before the liquid is atomized, and \( D_{0.5} \) is the volume median diameter (VMD). The VMD is the median diameter of the droplets after atomization, which corresponds to the median volume, and it is considered to be the standard size of a droplet after break-up.

The liquid used in this experiment was water, and the liquid spray in a single operation was stable during normal atomization. Therefore, the specific constant in the above equation can be summarized as a coefficient \( f_1 \), that is:

\[ f_1 = \frac{k\log \frac{d}{D_{0.5}}}{6} \]  

(4)

Furthermore, the equation for the work model equation of energy consumption during droplet break-up is as follows:

\[ W = f_1 \left( d^3 - D_{0.5}^3 \right) \]  

(5)

2.2. Theory of the Atomization Efficiency Model

During application, a plurality of atomizers is installed on the spray boom. The fan blades of the atomizers are driven by the high-speed airflow, which rotates the atomizer and exerts a force on the spray boom; the high-speed airflow generates resistance to the spray boom. According to the balance relationship, the aircraft reacts with traction to the spray
boom. Consequently, the aircraft exhibits excessive power consumption. The relationship between applied work and energy utilization is a measure of energy conversion, and the work performed by the force is equal to the energy conversion, which is a physical relation. In this experiment, the relationship between the applied work and energy was similar to that between the kinetic energy and energy conversion of the atomized droplets broken up by an atomizer. This can be expressed as follows:

$$\eta = \frac{W_{\text{available work}}}{W_{\text{total work}}}$$

(6)

The equation shows that the efficiency between applied work and energy is an important indicator reflecting the advantages and disadvantages of atomization performance. The total work is equal to the sum of the available work and extra work, and the available work only accounts for part of the total work. When the available work is proportionally large, the utilization rate for the wind tunnel work will be higher, thereby enhancing the atomization efficiency. The available work is the energy generated by atomization via the atomizer, and the total work is the work applied by traction from the aircraft to the atomizer. This is described by Equation (7) as:

$$\eta = \frac{W_{\text{available work}}}{W_{\text{total work}}} = \frac{E_{(D_{v,5})}}{FVt} = \frac{f}{f_0} \int_0^t FV dt$$

(7)

where $\eta$ is the atomization efficiency and $E_{(D_{v,5})}$ is the energy consumed by the atomizer to form the droplets from the liquid. The droplet size after atomization is given by $D_{v,5}$; the droplet break-up energy is $E_{(D_{v,5})} = W_{\text{break}}$; $F$ is the traction force on spray boom; and $V$ is the wind speed.

The model equation for the atomization efficiency measurement can be derived from Equation (5) as:

$$\eta = \frac{W_{\text{available work}}}{W_{\text{total work}}} = \frac{E_{(D_{v,5})}}{FVt} = \frac{f_1 (d^3 - D_{v,5}^3)}{f_0} \int_0^t FV dt$$

(8)

We used tap water as the liquid throughout the experiment. Therefore, $f_1$ and $d$ can be derived from Equation (5) as constants. Hence, if $D_{v,5}$, $F$, and $V$ are measured, the atomization efficiency can be evaluated. This study discusses the relationship between the partial consumption of energy in the process of manned aircraft operation and the energy of liquid finally broken-up into tiny droplets. The corresponding relationship can be obtained only by discussing the above two processes, and thus the energy conversion in the middle is not included in this study.

3. Materials and Methods

3.1. Composition of Atomization Experimental Platform

The atomization test bench was set up based on the IEA-I wind tunnel, which comprised a wind tunnel, traction measurement instrument, atomizer, liquid system, and laser diffraction particle size analyzer (LD), as shown in Figure 1.

The linear distance between the fixed platform of the atomizer and the LD was 0.95 m, and the linear distance between the outlet of the wind tunnel and the fixed platform of the atomizer was 0.25 m. The IEA-I wind tunnel could accurately adjust the wind speed in the range 6.7–98 m/s via the gearbox, and the degree of turbulence was less than 1.0%. The traction measurement instrument is shown in Figure 1, and the traction of the atomizer during atomization was measured using the traction measurement instrument.
The box containing the liquid, flowmeter, and water pump formed the liquid system, and the liquid spraying unit comprised the atomizer and liquid system. A rotary atomizer was used in this study because of the large flow rate of the experimental liquid. A Micronair AU5000 rotary atomizer was used in this study, which consisted of a diaphragm check valve, atomizer gauze, adjustable fan blades, and variable restrictor unit. It was driven by three fan blades, and the angle was adjustable in the range 25°–85°. The flow bearing range was 0–23 L/min. Its operating airspeed is 40.27–66.67 m/s. The mean size of the
spray droplets produced by an atomizer is determined by the rotational speed of the gauze. The gauze is turned by the fan blades in the airstream, the speed of rotation is controlled by both airspeed and blade angle. The airspeed is determined by the type of aircraft and spraying operation; hence, the droplet size is controlled by the setting of the fan blades. By adjusting the angles of the three fan blades, the speed range is controlled, and the speed is 2000–10,000 rpm (maximum). This study did not analyze the atomizer speed.

The instrument used for the atomization particle size measurement was the Malvern Spraytec LD, which is based on the principle of laser diffraction. Laser-emitting and receiving lenses were installed on both sides of the wind tunnel outlet, as shown in Figure 1. During the spraying process, the LD moved up and down via an elevator. As it moved, the LD scanned all the droplets in the cross section, obtained the diffraction intensity distribution, and converted it to the droplet spectrum parameters. Table 1 lists the specifications of the equipment.

| Equipment                          | Specification                  | Parameter          |
|------------------------------------|--------------------------------|--------------------|
| Traction measurement instrument   | Indicating error               | ±0.5%              |
| Wind tunnel                        | Wind speed                     | 6.70–98.0 m/s      |
|                                    | Dynamic pressure stability coefficient | <2%               |
|                                    | Turbulence scale               | <1.0%              |
|                                    | Mean airflow bias              | <0.5%              |
| Rotary atomizer                   | Fan blade adjustable angle     | 25–85°             |
|                                    | Flow bearing range             | 0–23 L/min         |
| Laser diffraction particle size analyzer | Particle size range          | 0.1–3500.0 µm      |

3.2. Experimental Methods

In this experiment, 2 flow rates, 32 wind speeds, and 4 specific fan blade angles were used, and the droplet spectrum parameters and traction were measured under different conditions. The flow rate control range of the atomizer is 0–23 L/min. According to the agricultural spray quantity and the load of laboratory water pump, the flow is selected as 5 L/min and 10.8 L/min. The operating airspeed of the rotary atomizer is 40.27–66.67 m/s, and the range of wind speed in the wind tunnel test can be set to 50.11–61.41 m/s according to the common speed of manned aircraft during agricultural spraying. The adjustable angle range of the fan blade of the atomizer is 25°–85°, and the angle range of the atomizer working normally is usually an integer, and is mostly within 35°–65°. In this study, the angle was selected at 10 intervals. The main steps of the operation are described below.

The experiment was conducted at a stable room temperature (approximately 20 °C) and humidity. Clearwater was supplied as the liquid. The traction measurement instrument and LD were turned on, and then the wind tunnel and water pump were turned on.

In the first group of tests, the flow rate was 5.0 L/min and the atomizer fan blade angle was 35°. The initial wind speed was 50.11 m/s, and it was increased in increments of 0.35 m/s up to 61.41 m/s for a total of 32 data points. The droplet spectrum parameters and traction values were recorded for each wind speed. The measurements were repeated three times, and the average was taken. With the flow rate unchanged, the fan blade angle was changed to 45°, 55°, and 65°, and the process was repeated.

In the second group of tests, the flow rate was set to 10.8 L/min, and the measurement procedure used for the first group was adopted. After the experiments, the droplet spectrum parameters and traction measurement were recorded.
4. Results and Analysis

The results, including the droplet size $D_{v,5}$, traction $F$, and wind speed $V$, are presented in Supplementary Materials Tables S1–S4. Preliminary discussions and analysis of the test results are presented based on the relationship between these three parameters.

The atomization capability of the atomizer with different fan blade angles was investigated. Two different flow values were used. As shown in Supplementary Materials Table S1, when the flow rate was 5.0 L/min and the fan blade angle was 35°, the VMD gradually decreased from 119.2 to 95.1 µm as the wind speed increased from 50.11 to 61.41 m/s, without large fluctuation or cliff-type decline. As shown in Supplementary Materials Table S2, when the flow rate was 5.0 L/min and the fan blade angle was increased to 45°, the overall trend was the same, but the VMD was larger than that at 35° and decreased from 144.9 to 103.39 µm as the wind speed increased. As shown in Supplementary Materials Table S3, when the flow rate was 5.0 L/min and the fan blade angle was increased to 55°, a similar trend was observed again; the VMD was larger and then decreased from 181.9 to 129.6 µm as the wind speed increased. Finally, as shown in Supplementary Materials Table S4, when the flow rate was 5.0 L/min and the fan blade angle was increased to 65°, the overall trend was similar, and the VMD was larger than that at 55° and decreased from 204.8 to 147.8 µm as the wind speed increased.

The following results were obtained from the analysis:

1. When the wind speed remained constant and the angle of the atomizer fan blade increased, the size of the droplets increased;
2. As the wind speed increased by the same value, the decrease in the droplet size depended on the fan blade angle. The smaller the fan blade angle, the smaller the droplet size; the larger the change in wind speed, the larger the change in droplet size;
3. The traction force was directly proportional to the wind speed. The higher the wind speed, the larger the traction force;
4. The traction force was dependent on the fan blade angle. At a wind speed of 50.11 m/s, the traction forces were 31.6, 30.4, 29.6, and 29.6 N at fan blade angles of 35°, 45°, 55°, and 65°, respectively. Thus, the smaller the fan blade angle, the higher the traction force of the atomizer. Hence, there was a clear correlation between the fan blade angle and traction force. However, as the fan blade angle increased, the rate of change in traction force decreased;
5. The traction power increased as the wind speed increased, and it was proportional to the wind speed.

When spraying the same liquid, as the fan blade angle increased, the VMD of the droplets increased and traction decreased gradually, as shown in Supplementary Materials Tables S1–S4. Considering the same change in wind speed, the smaller the fan blade angle, the higher the atomization efficiency ($\eta$), as shown in Supplementary Materials Tables S1–S4 and Equation (8). This indicates an inversely proportional relationship, and the following figure was plotted using the data given in Supplementary Materials Tables S1–S4.

As shown in Figure 2, at a flow rate of 5.0 L/min and atomizer fan blade angles of 35°, 45°, 55°, and 65°, the atomized droplet VMD changed smoothly, and with the decrease in droplet VMD, the power value increased continuously. The trend line for droplet size against power is an inverse proportional function curve, and the numerical value of the determining coefficient $R^2$ is 0.9891 (the trend lines of droplet size and power at flow rates of 5.0 L/min and 10.8 L/min are given in Supplementary Materials Figures S1 and S2). The VMD has a correlation with power, and the numerical trend of droplet volume median diameter changes significantly.
Figure 2. Relationship between power and droplet VMD for different atomizer fan blade angles at a flow rate of 5.0 L/min.

Considering a power of 2000 W as an example, the droplet VMD was quite different at the four different fan blade angles tested, and as the angle increased, the VMD increased. From Equation (8), it can be seen that when the fan blade angle was smaller, the atomization efficiency $\eta$ was larger. Because the law for each power condition was the same, the $D_{0.5}$ values for all powers were evaluated. The integration in Equation (8) shows that increasing the fan blade angle decreases the atomization efficiency. When the fan blade angle was 35°, the atomization efficiency was highest, and when the fan blade angle was 65°, the atomization efficiency was lowest.

At a flow rate of 10.8 L/min, the data regularity of the atomizer was the same as that at 5.0 L/min, as shown in Supplementary Materials Tables S1–S4 and Figure 3. That is, the higher the flow rate, the larger the droplet size. This is a general law that does not affect the laws for the atomizer.

Figure 3. Relationship between power and droplet VMD for different atomizer fan blade angles at a flow rate of 10.8 L/min.

5. Conclusions

In this study, the model equation of the atomization efficiency measurement of manned aerial agricultural application was established. The model equation of the atomization efficiency measurement was derived and used for the experimental evaluation of an atomizer. The following conclusions can be drawn based on the results:
(1) The atomization efficiency decreased as the fan blade angle of the atomizer increased. When the fan blade angle was 35°, the atomization efficiency was optimal, regardless of the wind speed. In contrast, when the fan blade angle was 65°, the efficiency degraded, regardless of the wind speed;

(2) Variations in the flow rate did not affect the trends in the atomization efficiency of the atomizer. At flow rates of 5.0 and 10.8 L/min, the model equation was valid, and the visualization curves for the data measured experimentally showed the same regularity;

(3) In this study, an AU5000 atomizer was used to simulate a rotary atomizer in use by a manned aerial vehicle. The variable quantity regularity also applied when the flow rate extended beyond the range of this experiment;

(4) At present, studies have only been performed in the wind tunnel of the laboratory platform. Due to financial and technical reasons, there is no field experiment in farmland. Therefore, this study does not include the comparison of spray atomization performance when the outcomes are tested with a field experiment. This study has not solved this work, and is currently moving towards this goal.

**Supplementary Materials:** The following are available online at https://www.mdpi.com/article/10.3390/agronomy12020419/s1, Table S1: Test data for an atomizer with a fan blade angle of 35°; Table S2: Test data for an atomizer with a fan blade angle of 45°; Table S3: Test data for an atomizer with a fan blade angle of 55°; Table S4: Test data for an atomizer with a fan blade angle of 65°; Figure S1: Trend line of droplet size and power at flow rate of 5.0 L/min; Figure S2: Trend line of droplet size and power at flow rate of 10.8 L/min.

**Author Contributions:** Conceptualization, G.L. and R.Z.; methodology, R.Z.; software, G.L. and T.Y.; validation, G.L., R.Z. and L.L.; formal analysis, G.L.; investigation, G.L. and L.L.; resources, C.D., J.W. and C.Z.; data curation, G.L.; writing—original draft preparation, G.L.; writing—review and editing, R.Z., L.C. and L.L. All authors have read and agreed to the published version of the manuscript.

**Funding:** This work was funded by the National Key R & D Program of China (grant number 2019YFD1101-102-3), the National Natural Science Foundation of China (grant number 32071907), the Outstanding Scientist Cultivation Project of Beijing Academy of Agriculture and Forestry Sciences (grant number JKZX201903), and the Key R & D projects in Hainan Province (grant number ZDYF2020195).

**Institutional Review Board Statement:** Not applicable.

**Informed Consent Statement:** Not applicable.

**Data Availability Statement:** The data presented in this study are available in Supplementary Materials here.

**Conflicts of Interest:** The authors declare no conflict of interest.

**References**

1. Zhang, R.; Li, L.; Wen, Y.; Chen, L.; Tang, Q.; Yi, T.; Song, J. Fluorescent tracer analysis of the deposition characteristics of spray droplets in the plant protection UAV. *Agric. Eng. J.* 2020, 36, 47–55.

2. Martin, D.; Singh, V.; Latheef, M.A.; Bagavathiannan, M. Spray deposition on weeds (palmer amaranth and morning glory) from a remotely piloted aerial application system and backpack sprayer. *Drones* 2020, 4, 59. [CrossRef]

3. Faiçal, B.S.; Freitas, H.; Gomes, P.H.; Mano, L.Y.; Pessin, G.; de Carvalho, A.C.; Krishnamachari, B.; Ueyama, J. An adaptive approach for UAV-based pesticide spraying in dynamic environments. *Comput. Electron. Agric.* 2017, 138, 210–223. [CrossRef]

4. Hooper, G.H.S.; Spurgin, P.A. Droplet size spectra produced by the atomization of a ULV formulation of fenitrothion with a Micronair AU5000 rotary atomizer. *Crop Prot.* 1995, 14, 27–30. [CrossRef]

5. Tsai, M.Y.; Elgethun, K.; Ramaprasad, J.; Yost, M.G.; Felsot, A.S.; Hebert, V.R.; Fenske, R.A. The Washington aerial spray drift study: Modeling pesticide spray drift deposition from an aerial application. *Atmos. Environ.* 2005, 39, 6194–6203. [CrossRef]

6. Teske, M.E.; Thistle, H.W. Aerial application model extension into the far field. *Biosyst. Eng.* 2004, 89, 29–36. [CrossRef]

7. Ryan, S.D.; Gerber, A.G.; Holloway, A.G.L. A computational study of sprays produced by rotary cage atomizers. *Trans. ASABE* 2012, 55, 1133–1148. [CrossRef]

8. Lebeau, F.; El Bahir, L.; Destain, M.F.; Kinnaert, M.; Hanus, R. Improvement of spray deposit homogeneity using a PWM spray controller to compensate horizontal boom speed variations. *Comput. Electron. Agric.* 2004, 43, 149–161. [CrossRef]
9. Berenstein, R.; Edan, Y. Automatic Adjustable Spraying Device for Site-Specific Agricultural Application. *IEEE Trans. Autom. Sci. Eng.* 2018, 15, 4–15. [CrossRef]

10. Van Deventer, H.; Houben, R.; Koldewej, R. New atomization nozzle for spray drying. *Dry. Technol.* 2013, 31, 891–897. [CrossRef]

11. Fabiano, G.; Ricardo, A.; Cicero, A.; Eduardo, S.; Nelson, H.; Marcelo, C. How much do adjuvant and nozzles models reduce the spraying drift? Drift in agricultural spraying. *Am. J. Plant Sci.* 2017, 8, 15–23.

12. Weicai, Q.; Baijing, Q.; Xinyu, X. Droplet deposition and control effect of insecticides sprayed with an unmanned aerial vehicle against plant hoppers. *Crop Prot.* 2016, 85, 79–88.

13. Zhang, B.; Tang, Q.; Chen, L.P.; Zhang, R.R.; Xu, M. Numerical simulation of spray drift and deposition from a crop spraying aircraft using a CFD approach. *Biosyst. Eng.* 2018, 166, 84–199. [CrossRef]

14. Wen, Y.; Zhang, R.; Chen, L.; Huang, Y.; Yi, T.; Xu, G.; Li, L.; Hewitt, A.J. A new spray deposition pattern measurement system based on spectral analysis of a fluorescent tracer. *Comput. Electron. Agric.* 2019, 160, 14–22. [CrossRef]

15. Zhang, T.; Dong, B.; Chen, X.; Qiu, Z.; Jiang, R.; Li, W. Spray characteristics of pressure-swirl nozzles at different nozzle diameters. *Appl. Therm. Eng.* 2017, 121, 984–991. [CrossRef]

16. Dorr, G.J.; Hewitt, A.J.; Adkins, S.W.; Hanan, J.; Zhang, H.; Noller, B. A comparison of initial spray characteristics produced by agricultural nozzles. *Crop Prot.* 2013, 53, 109–117. [CrossRef]

17. Craig, I.P.; Hewitt, A.; Terry, H. Rotary atomiser design requirements for optimum pesticide application efficiency. *Crop Prot.* 2014, 66, 34–39. [CrossRef]

18. Guler, H.; Zhu, H.; Ozkan, H.E.; Ling, P. Characterization of hydraulic nozzles for droplet size and spray coverage. *Atom. Sprays* 2012, 22, 627–645. [CrossRef]

19. Martin, D.E.; Carlton, J.B. Airspeed and orifice size affect spray droplet spectra from an aerial electrostatic nozzle for rotary-wing applications. *Atom. Sprays* 2012, 22, 997–1010. [CrossRef]

20. Martin, D.E.; Latheef, M.A. Aerial electrostatic spray deposition and canopy penetration in cotton. *J. Electrost.* 2017, 90, 38–44. [CrossRef]

21. Darwish, A.; Abubaker, A.; Salaimeh, A.; Akafuah, N. Schlieren visualization of shaping air during operation of an electrostatic rotary bell sprayer: Impact of shaping air on droplet atomization and transport. *J. Coat.* 2018, 8, 279. [CrossRef]

22. Darwish, A.; Singh, B.; Doerre, M.; Abubaker, A.; Arabghahestani, M.; Salaimeh, A.; Akafuah, N. Spatial Positioning and Operating Parameters of a Rotary Bell Sprayer: 3D Mapping of Droplet Size Distributions. *J. Fluids* 2019, 33, 317. [CrossRef]

23. Oswald, W.; Gödeke, L.; Ehrhard, P.; Willenbacher, N. Influence of the elongational flow resistance and pigmentation of coating fluids on high-speed rotary bell atomization. *J. At. Sprays* 2019, 29, 913–935. [CrossRef]

24. Shen, B.; Ye, Q.; Guettler, N.; Tiedje, O.; Domnick, J. Primary breakup of a non-Newtonian liquid using a high-speed rotary bell atomizer for spray-painting processes. *J. Coat. Technol. Res.* 2019, 16, 1581–1596. [CrossRef]

25. Pendar, M.; Pascoa, J. Atomization and spray characteristics around an ERBS using various operational models and conditions: Numerical investigation. *Int. J. Heat Mass Transf.* 2020, 161, 122–123. [CrossRef]

26. Pendar, M.; Pascoa, J. Numerical analysis of charged droplets size distribution in the electrostatic coating process: Effect of different operational conditions. *J. Phys. Fluids* 2021, 33, 317. [CrossRef]

27. Kumar, A.; Sahu, S. Liquid jet breakup unsteadiness in a coaxial air-blast atomizer. *Int. J. Spray Combust. Dyn.* 2018, 10, 211–230. [CrossRef]

28. Makhnenko, I.; Alonzi, E.; Fredericks, S. A review of liquid sheet breakup: Perspectives from agricultural sprays. *J. Aerosol Sci.* 2021, 157, 105. [CrossRef]