Overview of spray nozzles for plant protection from manned aircrafts: Present research and prospective

Haibo Chen[1,2], Bradley K Fritz[3*], Yubin Lan[2,4*], Zhiyan Zhou[2,5], Jingfu Zheng[5]

(1. *Engineering Fundamental Teaching and Training Center, South China Agricultural University, Guangzhou 510642, China*;
2. *National Center for International Collaboration Research on Precision Agricultural Aviation Pesticides Spraying Technology, Guangzhou 510642, China*;
3. *USDA-ARS Aerial Application Technology Research Unit, College Station, TX 77845, USA*;
4. *College of Electronic Engineering, South China Agricultural University, Guangzhou 510642, China*;
5. *College of Engineering, South China Agricultural University, Guangzhou 510642, China*)

Abstract: Aerial application is a critical component of modern agriculture, and it is crucial for aerial application of pesticides to be environmentally protective and efficacious. The spray nozzles involved in the application process are a vital component in the precise and safe delivery of applied products. This paper reviews and summarizes the state-of-the-art in aviation nozzle technology and the physical processes of nozzle atomization on manned platforms. Highlights are two main aerial nozzle types along with their working principle, the factors that influence atomization performance and new technologies for reducing drift and enhancing application efficiency. Moving forward, the research mainly focused on the development and evaluation of drift-reducing and variable-rate technologies, enhanced atomization models, the impacts of aerial tank mix adjuvants, and non-conventional application technologies (such as electrostatic or pulse-width modulation systems) are likely to have the most significant impact on the aerial application industry. This review provides a summary of the history and advancements in nozzle technologies and encourages further development.

Keywords: aerial application, nozzle, droplet size, atomization performance, drift-reducing
DOI: 10.33440/j.ijpaa.20200302.76

Citation: Chen H B, Fritz K B, Lan Y B, Zhou Z Y, Zheng J F. An overview of spray nozzles for plant protection from manned aircrafts: Present research and prospective. Int J Precis Agric Aviat, 2020; 3(2): 1–12.

1 Introduction

The increase in intensive agriculture stimulated by the need to feed a growing global population has relied on the use of chemical pesticides as the first line of defense in crop protection programs[1-4]. The use of pesticides is an integral part of modern agriculture and contributes to the productivity and quality of the cultivated crop[5]. It is estimated that the use of agrochemicals will prevent a loss of up to 45% of the world's food supply[6]. The application of pesticides by air, or aerial application, is often the most economical method for timely pesticide application. It permits large and often remote areas to be treated rapidly, far faster than any other form of application. Additionally, it is not destructive to the crop or soil physical structure, which can be damaged because of wheels or tracks. However, the potential for uneven spray distribution and drift to adjacent areas continues to be one of the most important issues with respect to aerial spray delivery[7-10]. Optimizing aerial spray applications requires the proper setup of the spray system, with proper nozzle selection and operation being the most critical components. Nozzle performance, especially the atomization characteristics, can significantly improve the uniformity of droplet deposition, reduce drift and, improve product efficacy[11-16].

With any spray application system, there is a range of droplet sizes created during the atomization process. This range is referred to as the spray droplet spectra and can be described in various ways. The volume median diameter (VMD) or Dv0.5 (droplet diameter at which 50% of the total spray volume is contained in droplets of lesser diameter) is commonly used. Droplet size and spray droplet spectra are the dominant factors for determining spray drift [17-20]. Smaller droplets in the spray cloud have a greater tendency to move off the application site than larger ones. Droplets below 150 mm in diameter are considered to be the most prone to spray drift[21], but applicators must also consider droplet size for optimum efficacy of the applied material. Spray nozzle selection is the first factor to be considered for aerial applicators in determining spray droplet size or spectrum[22-25]. Secondary considerations are those operational factors that influence atomization, such as nozzle angle or deflection relative to the airstream, aircraft speed, and spray pressure[26-29]. Secondary factors often considered for drift reduction by aerial applicators, once nozzle selection and operation are determined, is spray mix additives or adjuvants. Materials added to aerial spray tank mixes that alter the physical properties of the spray mixture also affect the droplet size spectrum produced[30,31].

Received date: 2020-04-13 **Accepted date:** 2020-06-15

Biographies: Haibo Chen, PhD, Associate Professor, research interests: Agricultural mechanization, automation and information, Email: huanongchb@scau.edu.cn; **Zhiyan Zhou**, PhD, Professor, research interests: Agricultural mechanization, automation and information, Email: ZYzhou@scau.edu.cn; **Jingfu Zheng**, undergraduate, research interests: Agricultural mechanization, automation, Email: 1599158198@qq.com.

***Corresponding author: Bradley K Fritz,** PhD, Professor, research interests: Agricultural aerial application technology. Mailing Address: USDA-ARS Aerial Application Technology Research Unit. Email: brad.fritz@ars.usda.gov. **Yubin Lan**, PhD, Distinguished Professor, Director, research interests: precision agricultural aviation application. Mailing Address: College of Electronic Engineering, South China Agricultural University. Email: ylan@scau.edu.cn.

With the growing concern regarding environmental protection, controlling the drift of pesticides will certainly drive the research and development of new spray technologies[32]. Since the first use of aircrafts for pesticide spray application in 1921, aerial spraying technologies, in particular nozzle technologies, have made considerable progress with the continuous development of agricultural aircrafts. The research status and progress of agricultural aerial spray nozzles are reviewed and summarized, with the two main types of spray nozzles and their working principles discussed. Additionally, the factors influencing nozzle atomization performance and a number of new technologies for reducing drift and enhancing application efficiency are considered. Based on the reviewed literature, research focused on the development and evaluation of drift-reducing and variable-rate technologies, enhanced atomization models, the impacts of aerial tank-mix adjuvants, and non-conventional application technologies (such as electrostatic or pulse-width modulation systems) are likely to have the most significant impact on the aerial application industry.

2 Development history of agricultural manned aircraft-based spraying

Agricultural aerial spraying has been widely used and promoted in agricultural production. The United States of America was the first country to use aircrafts for pesticide spray application. As early as 1921, a modified Curtiss JN-6 “Super Jenny” was used for spraying chemical pesticides to eliminate grass pests in Ohio, paving the way for the further use and development of manned aircraft spraying technologies[33]. In 1922, Curtiss biplanes were used to dust cotton fields near Tallulah, LA, to control boll weevils. In 1923, Huff-Daland Dusters, Inc., the forerunner of Delta Airlines, performed the first commercial dusting of crops with its own specially built aircraft[34]. In the early days, aerial applicators were known as “crop dusters” because they worked with dry chemicals, mostly insecticides. Currently, aerial applicators primarily deliver liquid based products to control pests and diseases and to provide nutrients for agriculture. By the 1950s, the aerial application industry began to develop planes made especially for aerial application, and some other countries began the use of aircrafts for pesticide spray application[35,36]. In the 1960s, electrostatic spray technologies began to be applied for agricultural aerial application[37].

a. Air Tractor AT-502B is powered by a turbine engine and has a 1893-L capacity hopper. Typical application speed is between 58 and 65 m/s

b. A Bell/Texas Helicopter M74A Wasp helicopter with spray system that has two 208-L tanks.
Typical application speed is 26.8 m/s (Sidahmed et al., 2005)

Figure 1 Modern manned spray system

Aerial applications can be performed with both fixed-wing aircrafts (Figure 1a) and helicopters (Figure 1b), and the volume of the tank ranges from 340 L to 3030 L. Aircraft airspeeds were generally less than 45 m/s in the early days. Today, they are capable of up to 80 m/s[38]. Along with the continuous development of agricultural aircrafts and the advancement of several types of precision agriculture technologies including global positioning system (GPS), geographic information system (GIS), aerial remote sensing technologies, variable-rate controllers, and variable-rate nozzles, aerial spraying technology has made considerable progress[2].

3 Development status of agricultural aerial spray nozzles

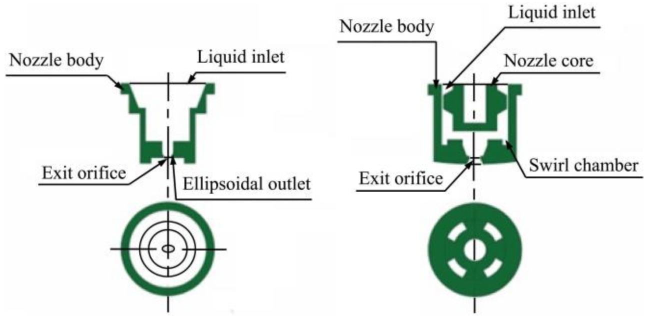
Nozzles provide the primary means of controlling three factors that affect any application and possible off-target movement of the pesticide: the application volume, droplet size, and spray pattern. Nozzle size and design selection are the most critical parameters in aerial spraying because they determine the spray droplet size and characteristics of the droplet velocity delivered to the target species[39,40].

Many types of nozzles exist for aerial applications which can be divided into two primary atomization methods—hydraulic and centrifugal nozzles. Regardless of nozzle type, droplet breakup from secondary air sheer is a unique characteristic associated with aerial applications. While aerial application consists of both fixed and rotary wing platforms, the droplet size associated with a given application is associated with the nozzle type and operational parameters and the airspeed of the application. Reduction in spray droplet size from secondary breakup associated with air sheer typically occurs at airspeeds above 20-35 m/s, after which droplet size continually decreases with increasing airspeed[41]. Consequently, the following discussions of nozzle types and operational responses are platform (manned fixed-wing versus manned rotary-wing) independent, with the assumption that applications are being made at airspeeds where secondary breakup occurs, which is a valid assumption for most manned aerial applications. In conditions where secondary breakup does not occur, the resulting droplet size is associated with nozzle type, size, spray pressure, and formulation.

3.1 Hydraulic atomizing nozzle

Hydraulic atomizers are a class of devices in which pressurized liquid is the primary source of energy utilized to produce a spray[42,43]. Hydraulic nozzles include the most commonly used types in agricultural spraying, with four of the most common types being flat fans, hollow-cones, straight streams, and anvil deflection nozzles.

We take two basic types of nozzles (standard flat-fan nozzles and cone spray nozzles) as examples. The structure of the standard flat-fan nozzle is relatively simple (Figure 2a), and the liquid inlet is large and wide. The liquid forms an unstable liquid film through the ellipsoid at the bottom and then splits into droplets of different sizes. In a hollow cone spray nozzle, the liquid is swirled, typically by means of tangential inlets, slotted distributors, vanes, or cores. As showed in Figure 2b, the spray core is supported by four gear-like parts against the inner edge of the nozzle body after the liquid enters the swirl chamber through the liquid inlet under high pressure. A hollow conical atomizing sheet is ejected from the orifice at a certain angle by centrifugal force. The angle of the sheet is controlled by the swirl generating device, chamber design, and the discharge orifice[42].



a. Standard fan nozzle b. Hollow cone nozzle

Figure 2 Structure diagram of hydraulic atomizing nozzles

3.1.1 Flat-Fan nozzle

Standard flat-fan nozzles (Figure 3) produce a uniform and stable fan-shaped spray with tapered edges and form a long and narrow spray pattern while sprayed vertically on the ground[44]. Nozzle tips are designed to produce fan-shaped patterns at angles of 25°, 40°, 65°, 80°, or 110°. The narrower the fan angle, the larger the droplet spectra created. This is true for both ground and aerial applications. Therefore, fan nozzle tips designed to emit no more than an 80° spray pattern are better suited for aerial spray applications. Typically, 40° flat fans are recommended for the higher speeds associated with fixed winged aircrafts and 80° flat fans are recommended for slower speeds associated with rotary wing aircrafts.

Figure 3 Standard flat-fan nozzle

3.1.2 Cone spray nozzle

Cone sprays come in two basic variations—hollow cone and full cone (Figure 4). Hollow cone nozzles form a ring-shaped pattern and a finely atomized spray, which is not easy to block. They typically produce smaller droplet spectra compared to flat-fan nozzles and are more common in helicopters than in fixed-wing aircrafts[38]. The full cone spray nozzle creates a full, circular spray pattern. Full cones typically produce coarser droplets and are offered in larger capacities than hollow cone nozzles.

a. Hollow cone nozzle b. Full cone nozzle

Figure 4 Common-used cone nozzles

3.1.3 Straight stream nozzle

Straight stream nozzles (Figure 5) create a stream of spray at the nozzle outlet as opposed to the fan-shaped pattern of a flat-fan nozzle. Straight stream nozzles may be referred to as 00-degree fan angle nozzles because they are typically oriented straight back with the spray stream parallel to the surrounding airstream to produce large droplets with lower drift potential compared to other nozzle types. These nozzles provide a way to produce large droplets at higher airspeeds when the flow volume of the stream from the nozzle matches the airspeed.

3.1.4 Anvil deflection nozzles

Anvil deflection nozzles (Figure 6) also create a fan-shaped pattern. They are different from flat-fan nozzles in that the fan pattern is created by deflecting a straight stream downward and outward by a deflector[42]. The deflector is a smooth curved surface at the end of the nozzle. With this type of nozzle, primary atomization can be achieved more effectively by impacting or deflecting the liquid stream on a surface. Greater secondary atomization is also achieved with a deflection because the liquid is injected into the flow field at a greater angle of incidence (the relative velocity of the flow field is increased)[45]. Atomization with this type of nozzle results in the generation of a wide spectrum of droplet sizes. Anvil deflection nozzles used for aerial applications have adjustable orifice sizes and deflection angles. The ability to change the orifice size on a single nozzle allows the aerial applicator to quickly change between spray application rates. Changing the deflection angle changes droplet spectra.

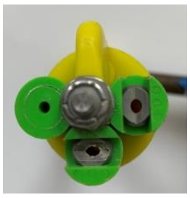


Figure 5 A nozzle body with three individual tips mounted on it. The tip on the left is a straight stream nozzle. The other two tips are flat-fan nozzles.

Figure 6 Anvil deflection nozzle with 3-Way deflector with 30°, 55°, and 90° deflections

3.2 Centrifugal atomizers (rotary atomizers)

The hydraulic atomizing nozzle works on the nozzle liquid film colliding with the air to form finer droplets. A centrifugal atomizer utilizes the kinetic energy of a rotating mechanism as the primary source of energy to produce a spray spectra[42]. Therefore, the required pressure is much smaller, which results in a narrower droplet spectrum[46,47]. The advantage of this type of atomizer offers is that it does not clog.

The rotating surface may take the form of a disk, cup, or hollow cylindrical cage. Thus, a centrifugal atomizer is divided into three categories: rotary disk atomizer (Figure 7a), rotary cup atomizer (Figure 7b), and rotary cage atomizer (Figure 7c). We take the rotary cup atomizer as an example (Figure 8). Liquid is fed to the interior surface of a spinning cup, from which it is dispensed by centrifugal force to form a spray. In some designs, the edge of the cup is serrated to encourage more uniform drop size distribution in the spray. A flow of air around the periphery is sometimes used to shape the spray and to assist in transporting the droplets away from the atomizer [48]. Rotary nozzles are the most effective when being used on low to medium viscosity liquids. When dealing with high viscosity liquids, atomization becomes very coarse, which is not good for most applications.

The droplet spectrum size of rotary atomizers is determined by the speed of the rotating mechanism. The faster the mechanism spins, the smaller the droplet spectrum is[49,50]. Rotary atomizers have a smaller droplet spectrum compared to flat-fan, straight stream, and deflector style nozzles. They are commonly used for low volume and ultra-low volume applications of insecticides and fungicides and are used in vector control applications for adult mosquitoes. While unmanned platforms use rotary disk atomizers and rotating cup atomizers, manned platforms primarily use rotary cage atomizers that comprise a rotating, hollow cylindrical cage in the interior of which liquid is introduced that flows through passages to the cage openings, where it is broken up into drops, rotary cage atomizers cannot produce narrow distribution as rotary disc or cup. Aircraft speed and the pitch setting of the atomizer blades determine the cage rotational speed of wind driven units.


a. Rotary disk atomizer b. Rotary cup atomizer

c. Rotary cage atomizer

Figure 7 Rotary atomizers

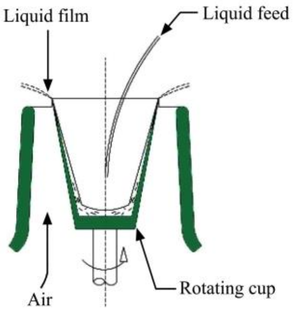


Figure 8 Structure diagram of rotary cup atomizer

3.3 Aerial electrostatic nozzles

Electrostatic application to agricultural pesticide spraying has made advances and developments via off-target pest control to increase bio-efficacy and deposition efficiency[51-53].

The electrostatic spray of pesticides forms an electric field between the electrostatic spray nozzle and the crop target through a high-voltage static electricity generating device. The spray droplets are charged under the action of the electric field of the electrode to form a charged mist droplet group. Pesticide droplets are rapidly deposited on the surface of the plant by electrostatic force, airflow drag, and gravity. The droplets that are off the target are also affected by the canopy attraction force, forming a “static surround” effect, which reduces the drift of the pesticide droplets and increases the amount of droplets deposited on the back of the blade. In the 1960s, Law and Bowen[54] used inductive charging for electrostatic spray of pesticides and proposed that electrostatic spray combined with air spray can help droplet deposition and penetration. The best electrostatic spray droplet size was recommended. Carlton[55], and Carlton et al.[56] conducted a study on electrostatic aerial spraying technology and developed an electric rotary nozzle designed to reduce spray drift. The results showed that electrostatic spray technologies can decrease the droplet drift to a certain degree by accelerating the deposition process of charged droplets and increasing the penetration of droplets in a crop canopy. Spectrum electrostatic sprayers (SES), Inc. purchased the patent of Carlton and brought the aerial electrostatic spray system to the market. With the new injection nozzle body developed by SES, the aerial electrostatic spray system was more developed, as shown in Figure 9, and has been used on various small and medium aircrafts[57].

Figure 9 Spectrum electrostatic spray system

Other scholars have also performed a lot of scientific research on electrostatic spray technologies. Zhou et al.[58] designed and studied aerial electrostatic single-nozzle applied in the light plane. Results showed the improved nozzle increased the droplet deposition by 18/cm^2, shortened the operation time, reduced the pesticide quantity by 5.22 L/hectare, and improved the effective pest control rate by 33.8%. Lan et al.[59] studied the atomization characteristics and spray deposition of electronic nozzles. The results showed that the optimal electrode voltage was 8 kv, and the optimal electrode material was copper. Of all droplets, electrostatic force had the most effect on the droplets between 50 μm and 120 μm, doubling the deposition amount. Furthermore, the spray droplet density was decreased as the droplet size was increased over 120 μm. The size of most droplets deposited on target was under 180 μm.

3.4 Characteristics and application of commonly used nozzles for plant protection of manned aircrafts

The type of nozzle determines the internal structure of the nozzle, which in turn determines the characteristics of spray and its application. Various parameters to quantify the performance of nozzles include anti-clogging, volumetric flow rate, discharge angle, droplet spectrum values of Dv0.1 (droplet diameter at which 10% of the total spray volume is contained in droplets of lesser diameter), Dv0.5 (similar to Dv0.1 but 50% of total spray volume), and Dv0.9 (similar to Dv0.1 but 90% of total spray volume), and uniformity of deposition distribution[60]. Table 1 summarizes the performance parameters, characteristics, and applicable occasions of the commonly used nozzles for plant protection of manned aircrafts. Generally, larger angle flat-fan nozzles (>80°, hollow cone nozzles) and larger anvil angle (>5°) nozzles are used at lower airspeeds (rotary and smaller fixed-wing platforms) as a result of the smaller droplet sizes generated, particularly as secondary breakup increases (i.e. higher airspeeds). Modern, faster aircrafts tend to use smaller angle flat fans (<40°), straight stream nozzles, and in some unique cases, rotary atomizers. With increased public and regulatory concerns related to spray drift and off-target impacts, most agrochemical applications (across all platforms, ground or air) tend toward more conservative, larger droplet-sized sprays with the primary goal of reducing drift potential. This can lead to poor coverage or efficacy unless metrics such as spray pattern uniformity and coverage are considered along with droplet size.

Table 1 Nozzle parameters, characteristics, and applications of commonly used nozzles for plant protection using manned aircrafts

Nozzle type	Spray angle	Advantage	Disadvantage	Application
Flat-fan nozzles	40°,80°	produce a uniform and stable fan-shaped spray, a very common nozzle type for aerial applications	easy to clog	application of many different types of pesticides, including fungicides, insecticides, and herbicides
Hollow cone nozzles	80°	finely atomized spray, not easy to clog, operated pressures range from 276 kPa to 690 kPa	the spray angle is generally only 80°, and smaller droplet spectra than that of fan nozzle	directed spraying and other specialty applications, and more common on helicopters than on fixed-wing aircrafts
Straight stream nozzles	0°	larger droplet spectrums size than the flat-fan nozzles	Only 0-degree deflection	herbicide applications
Deflector nozzles	adjustable	have adjustable orifice sizes and deflection angles, and produce a wide spectrum of droplet sizes	more fine droplets than flat-fan nozzles	wide variety of applications
Rotary atomizers	not changed	high flow rate; low pressure; small droplet spectra, uniform and controllable; not clog	complex system; air pumping effect; generate large lateral spray cloud dispersion	commonly used for low volume and ultra-low volume applications of insecticides and fungicides and are used in vector control applications for adult mosquitoes

4 Research status of spray nozzle technology

Agricultural aviation research has long focused on atomization characteristics of the spray nozzles used in agricultural aircrafts. Droplet size and spray droplet spectra are the dominant factors determining spray drift, with small droplets more prone to drift from the application zone than large droplets. According to a study conducted at the Ohio State University, drift is far less likely to be a problem when spraying with droplets of 200 µm and larger in size[61]. Droplet size associated with aerial application nozzles, within specific nozzle types and spray solutions, is dependent upon four primary factors: orifice size, spray pressure, orientation angle, and airspeed[62].

4.1 Factors affecting nozzle performance

4.1.1 Nozzle parameters (orifice size and orientation angle)

The effect that the orifice size has on the droplet spectrums size which is dependent on the type of nozzle has been highlighted in several studies. As for flat-fan, hollow cone, and deflector nozzles, the larger the orifice size, the larger the droplet size. However, the variation in droplet spectrum size among the different orifice sizes of deflector nozzles tends not to be as great as with the flat-fan or hollow cone nozzles. Orifice size of straight stream nozzles affects droplet spectra as well, but the trend is the opposite of the other nozzle types at similar pressures. Increasing the orifice size decreases droplet size at fixed wing speeds[63-67].

The orientation angle of nozzles is also one primary factor that affects droplet size because different angles produce various degrees of shearing. For a specific nozzle type and operating parameters, increasing the angle decreases droplet size and increases the percentage of spray volume in small droplets. The largest droplet spectra will be created when a nozzle is oriented so that the liquid enters the airstream parallel to high-speed air[20,26,62,68,69]. Nozzle types include flat-fan nozzles, straight stream nozzles, and hollow cone nozzles whose orientation angle can be adjusted by orienting the entire nozzle body. For a deflector nozzle, the nozzle itself remains mounted parallel to the airstream; the deflection is changed by switching the deflector plate at the end of the nozzle[42].

4.1.2 Spray operational variables (aircraft speed and operating pressure)

Compared with unmanned aerial application, aircraft speed plays a key role in the atomization process, as the corresponding air shear results in secondary breakup of the spray with higher airspeeds resulting in smaller droplets[20,26,70]. Shear stress is exerted on droplets as they exit the nozzle, with the velocity differential between the fluid velocity and the surrounding airstream causing secondary breakup. In a high-speed airstream, there exists some critical droplet diameter, for a given differential velocity between the droplet and the surrounding airstream, below which shatter does not occur[71,72].

Secondary breakup from air shear for typical agricultural nozzles typically occurs at airspeeds above 20-35 m/s[41]. Manned aircrafts normally operate at airspeeds that result in secondary atomization. Fritz et al.[73] evaluated the potential of using elevated spray pressures to mitigate air shear effects by increasing nozzle fluid exit velocities under aerial application airspeeds using a formulated active product and adjuvant-based spray solutions. Results showed that for typical high-end application airspeeds, increasing spray pressure from the lowest to highest values tested generally resulted in spray classifications increasing at least one size coarser. Although higher spray pressures do not offer a complete solution to obtaining larger droplets at higher airspeeds, higher pressures will generate a medium to coarse spray for a formulated herbicide product at the industry’s typical maximum application airspeed of 71.5 m/s; and further, they have the potential to create a medium spray at even higher airspeeds.

As for operating pressure, a general rule for aerial applications for many nozzle types operating at a higher pressure is the increase in droplet spectrum size[74], which is the opposite of what occurs for ground applications. This occurs because the higher pressure generates a higher exit velocity, which reduces the shear effect and secondary break up from the high air flow. As the airflow velocity increased, the significance of spray pressure on the spraying spectra of nozzles was gradually weakened[75].

4.1.3 Additives or adjuvants

There are active ingredients and other constituents called additives or adjuvants in pesticide formulation. The active ingredient ensures biological activity, and additives or adjuvants are compounds that are not biologically active and that are combined with the active ingredient as part of the formulation to help improve the performance of the active ingredient or modify the physical properties of the spray[76]. These effects cause changes in the spray formation mechanism and break-up is altered; subsequently, droplet formation and size distribution may be significantly modified[77]. These adjuvants or additives can be very diverse with classifications such as water conditioning agents, surfactants, oil concentrates, humectants (evaporation retardants), ammonium fertilizer solutions, compatibility agents, defoamers (antifoamers), stickers, and drift suppressing agents (deposition and detention aids). A classification based on the chemical class of the compounds is shown in Table 2. There are essentially three relevant physical properties of spray liquids that influence the mechanism of spray formation[78]. These properties are 1) shear, 2) extensional viscosity, 3) surface tension, and 4) the presence of inhomogeneities in the spray liquid such as emulsion droplets or solid particles[5]. As the velocity of the flow field is increased relative to the droplet, the disruptive aerodynamic forces exerted on the droplet overcome its forces of surface tension and viscosity, which act to stabilize it[46]. Thus, the greater the surface tension and the greater the viscosity of the spray liquid, the greater will be its ability to resist shear stress and retain its aerodynamically stable spherical shape in the atomization process. It is often held that modification of the surface tension and viscosity of the spray liquid by inclusion of adjuvant will result in the generation of a coarser spray[79].

Table 2 Classification of adjuvants by chemical class

Classes	Subclasses
Oils	Mineral or petroleum oil Vegetable (seed or crop oil) Derivatives [(EO/PO) transesterified plant triglycerides]
Surfactants (emulsifier, wetter, spreader, penetrator, trisiloxane)	Anionic Cationic Nonionic Amphoteric
Fatty acids (vegetable origin)	Esterified fatty acids Alkoxylated (EO/PO) esterified fatty acids
Wax polymers	Natural polymers Synthetic polymers
Solvents	Cosolvents, coupling agents
Terpenes	
Alcohols	Mono-, di-, or polyalcohols
Diluents	
Buffer aids	Inorganic or organic Acids or bases
Phospholipids	
Inorganic salts	
Urea	
Proteins	
Inorganic fillers	

The general mode of action of polymeric materials is based on the increase of the liquid viscosity which induces the formation of coarse sprays by shifting the droplet size distribution to a larger size. Water soluble synthetic polymers were the dominant components of most of the adjuvants that were first designed and marketed for spray drift control[80]. Gratkowski and Stewart[81] discussed several spray adjuvants designed to reduce herbicide drift by increasing droplet size because of either increased viscosity of the spray solution or the production of larger particles or globules containing the herbicide. These adjuvants were classified as invert emulsions, spray thickeners, particular agents, and foaming agents. Research has shown that polymers can be an effective tool for increasing droplet size and reducing spray drift. Bouse et al.[18] tested six different polymer materials to determine their effectiveness for modifying the size of spray droplets produced in an airstream. The effect of polymer concentration on droplet size was found to be dependent on polymer type. Polyvinyl and polyacrylamide polymers were found to be more effective than linear alkyl epoxide or polyamide copolymers in increasing VMD and reducing the percentage of spray volume comprising small droplets subject to spray drift. Shearing the polymer spray mixtures by multiple passes through a gear pump reduced both the liquid viscosity and the size of spray droplets produced by disc-core nozzles in a 190 km/h airstream. Guler et al.[82] performed a laboratory study and found both nonionic colloidal and polyvinyl polymer drift retardants reduced the drift potential compared to the spray carrier containing water only.

The effect of surface tension and inhomogeneities on the spray droplet size differs as the nozzle type changes[77,83]. A decrease in the dynamic surface tension generally leads to the formation of finer sprays for flat fan and hollow cone nozzles[84,85]. Nozzles that use air in the spray formation process such as the air induction design are more sensitive to changes in the physical characteristics of the spray liquid than conventional hydraulic pressure nozzles, and the changes do not follow the same trends as with conventional nozzles[30,86]. Polymers have little effect on the surface tension of spray solutions, so surface tension is mostly controlled by surfactants. Additives such as spreader and wetting agents contain surfactants that promote the wetting and coverage of the target surface by reducing surface tension[87]. Other works demonstrated that spray liquids that contain emulsified oils increased spray droplet size and at the same time decreased the fine spray fraction compared to water sprays when atomized through a flat fan, a hollow cone, or a twin fluid nozzle[88-90]. Emulsions decreased the sheet length at breakup and thus produced coarser sprays than water. However, when sprayed through an air induction nozzle, emulsions can reduce the mean droplet size compared to water[91,92]. Hoffmann et al.[93] evaluated the effects of six commonly used classes of spray adjuvants with rotary atomizers and found if an applicator's only concern was minimizing spray drift, the applicator could choose a polymer or high surfactant oil concentrate for helicopter speeds and a polymer for fixed-wing applications. For applicators working under hot, dry conditions where evaporation is a concern, choosing an oil-based adjuvant to help get better coverage by increasing non-volatile fraction. Fritz et al.[73] demonstrated by testing that crop oil-containing adjuvants resulted in the largest droplet-sized sprays and the silicones and polymers resulted in the smallest. Increasing spray pressure increased droplet size across all combinations of nozzle, airspeed, and spray solutions. Fritz et al.[94] also found that the addition of several adjuvants and foliar fertilizers was found to increase the numbers of fine droplets seen in the applied spray clouds. Efforts were made to correlate physical properties such as surface tension and viscosity to spray droplet size, but these efforts were unsuccessful.

The use of anti-drift and anti-evaporation tank-mix spray adjuvants has been studied to improve the efficiency of spraying performance both in wind tunnel and field aerial spray studies[95-101]. The results indicated that a few of the products exhibited the potential to reduce the amount of drift. Droplet sizes for Dv0.1, Dv0.5, and Dv0.9 increased with the addition of drift control/deposition aid products into the tank mix. The increases were variable across products and aircrafts. However, drift reduction adjuvants (DRA) into an aerial pesticide application were ultimately dependent upon the operating conditions. Overall, airspeed had the greatest treatment effect. At airspeeds below the air shear effect, the droplet size distributions (DSD) were most affected by nozzle type. At higher airspeeds, the DSD could be influenced toward lower drift potential by inclusion of a DRA, particularly when using a narrower angle, higher flow rate nozzle and at a lower airspeed for fixed-wing aircrafts[22,31].

4.2 Spray nozzle classification by droplet spectra

Accountability of spray drift, nozzle selection, and spray application droplet spectra has increased the interest in standardizing spray nozzles. Nozzle classification standards provide for relative classification of spray produced from nozzles by comparison with the droplet spectra produced by specified reference nozzles.

In 1985, the British Crop Protection Council (BCPC) proposed a system for classifying sprays, and the nozzles producing them, into categories of spray quality[102]. The resulting droplet size spectra were compared to a set of standardized sprays produced by specific combinations of reference nozzles and pressures. The BCPC method was subsequently modified to define droplet spectra thresholds or boundaries between categories by considering the drift potential of sprays[103]. This allows a more accurate and comprehensive way to characterize the spray produced by nozzles and other atomizers and a more flexible way to indicate the desirable or mandatory spray characteristics to the end-user. It specifies the flat spray reference nozzle discharge angles, flow capacities, and operating pressures. Following the BCPC classification scheme, the American Society of Agricultural and Biological Engineers (ASABE, former ASAE) developed a similar scheme in August 1999. It was reaffirmed in February 2004, after revision in March 2009, and ASAE Standard S572.1 “spray nozzle classification by droplet spectra” was approved as a American national standard in 1999 and used by US EPA[104]. There was a recent revision to fix a couple of types and is currently called S572.2 since July 2018. The ASAE standard used the general term “droplet spectra classification,” or DSC, to define a modified range of droplet size categories, and it defines DSC categories ranging from very fine (VF) through fine (F), medium (M), coarse (C), very coarse (VC), to extremely course (XC) (Table 3). These categories and thresholds between categories were further defined by a set of reference spray nozzles operating at specified conditions and measured by a laser-based droplet-sizing instrument. Numeric thresholds between adjacent categories were not specified in the standard because exact droplet spectra data depended on the laser instrument being used, measurement methods, sampling technique, etc.[105]. The standard specifies that the same laser instrument and operating protocol must be used for classifying both the reference nozzles and nozzles being classified. The purpose of classification was to provide the nozzle user with droplet size information primarily to indicate off-site spray drift potential and secondarily for application efficacy. This standard defined droplet spectrum categories for the classification of ground application nozzles, relative to the specified reference fan nozzles discharging spray into static air or so that no stream of air enhances atomization. It provided a method by which different labs can compare droplet sizes from nozzles and spray solutions of interest. The use of a relative classification scheme based on a set of reference sprays was used. The reference nozzles also allowed for relative comparisons of nozzles operating at different conditions for changes in DSC[29].

Table 3 Droplet classification system (ASAE standard S572 classes)

Nozzle category	Symbol	Color code	VMD
Very fine	VF	Red	<150
Fine	F	Orange	150-250
Medium	M	Yellow	250-350
Coarse	C	Blue	350-450
Very coarse	VC	Green	450-550
Extremely coarse	XC	White	>550

Kirk was the first to apply the droplet size classification (DSC) standard to aerial nozzles in 2003. He assessed spray droplet size for a given nozzle based on the effects of the four significant parameters—orifice size, spray pressure, orientation angle, and airspeed—using a response surface method (RSM), specifically the experimental design proposed by Box and Behnken[106]. Kirk developed a series of models such as “atomization models for helicopter spray nozzle” and “atomization models for fixed-wing aircraft spray nozzles” that allowed prediction of droplet size characteristics at any combination of the four parameters [20, 107].These models have been well received by now and provide a significant benefit to the agricultural aviation industry. However, with today’s modern, larger aircrafts with cruising speeds of up to 85 m/s and while typical application working speeds do not exceed 71.5 m/s, as agricultural production and crop production needs an increase, future application speeds might well exceed these airspeeds. For the former fixed-wing nozzle models, airspeeds are limited to 71.5 m/s because of the maximum velocity that could be generated by the fan that is used. Additionally, the models limit spray pressure to 414 kPa, but with the potential for higher spray pressures to increase droplet size, there is a need to increase the range of existing models to higher pressures. Increasing the pressure limits with the new models will allow applicators an additional means of controlling droplet size. Finally, the models limit the nozzle orientation angle on the CP11TT and disc orifice straight stream tips to 20°. For these reasons, with the update of the droplet-sizing facilities used in the testing and evaluation of nozzles and other spray technologies, Fritz and Hoffmann [14] updated these models to reflect the current state-of-the-art measurement methods to extend the operational limits of spray pressure and airspeed and to include new nozzles that were not in the previously developed models in 2015. Fritz and Hoffmann[15] also developed a set of computational models for 14 commonly used aerial application spray nozzles used on rotary and lower airspeed aircrafts and released them for use by applicators. These models (the USDA ARS spray nozzle atomization models for rotary wing aircraft) allow applicators to determine the droplet size characteristics associated with their specific nozzle and operational setup, determining the proper combination of orifice, pressure, orientation, and airspeeds from 22 to 54 m/s. Teske et al.[108] updated AGDISP (AGricultural DISPersal) models, including the implementation of a quadratic droplet evaporation model and its behavior as Reynolds number approaches zero, a more accurate time step algorithm tied to droplet settling velocity, an optical canopy model, a Gaussian model for far-field extension (downwind to 20 km), an Eulerian model for tracking volatile active spray material.

Hewitt[109] determined a set of nozzles and pressures that could be operated at typical aerial application airspeeds and return similar droplet size data and DSCs to those from ASAE S572.1. Several national and international regulatory agencies highlighted the need for a recognized standard defining DSCs associated with these aerial nozzle models. ASABE Standard S641 “DSC of aerial application nozzles” was developed based on the nozzles and pressure established by Hewitt in 2008. The new standard dedicated nozzle/spray pressure pairs designed to generate similar classification boundaries to current standards while operating in high airspeed conditions. To support the application of this standard, multiple sets of dedicated droplet size matched nozzles were developed[110].

4.3 Variable-rate spray technology

Variable-rate spray technology is the core of precision aerial spraying. In the context of aerial application, variable-rate control can simply mean terminating spray over field areas that do not require inputs, terminating spray near pre-defined buffer areas determined by Global Positioning, or applying multiple rates to meet the variable needs of the crop[2]. The technology for variable flow rate includes: pressure control, variable flow rate nozzles, and pulse-width modulation (PWM) control technology.

The earliest applied technology for variable flow rate involves increasing or decreasing the system pressure. Discharge rate across a fixed nozzle orifice is proportional to the square root of pressure, and it is a typical nonlinear relationship. Slightly increasing or decreasing the spray pressure allows minor adjustments to the nozzle flow volume, and changing pressure also changes atomization dynamics, but this adversely affects spray deposit and spray drift; therefore, the pressure variation range of pressure regulation cannot be large when using the linear control method.

Using the traditional fixed orifice nozzle for variable-rate spray has some limitations. Therefore, the need for a variable-rate nozzle with uniform pressure has emerged. Based on the theory of the orifice area varying with pressure, the nozzle orifice size is flexible and enlarges or reduces as the system pressure increases or decreases. Walker and Bansel[111] developed a variable-orifice nozzle. They used two thin flat rectangular plates joined along the long sides and at one end. Liquid was forced between the plates such that the hydraulic pressure deformed the plates to open the end that was not joined. Spray was discharged through the opened end. Flow rate depended on the width of the nozzle, plate thickness, water pressure, metal strength properties, and shape of the tip. The discharged flow rate linearly increased as hydraulic pressure increased. They noted that a characteristic small spray fan angle was a limitation. Womac and Bui[112] discovered that a split-end meter plunger in a tapered sleeve can serve as a variable orifice that varied flow rate and droplet size and created a fan spray by impinging streams of liquid together. They developed a new-concept variable-flow fan nozzle (VFFN) that was capable of controlling flow rate and maintaining a proper spray pattern and droplet size over an expected range of flow rates. The design of the VFFN nozzle was a combination of variable-area pre-orifice and variable-area spray orifice. The design has been adopted by the US Spray Target company to form the VariTarget series, VeriJet series, and VeriFlow series products.

Another development direction of the variable nozzle is the integration of the electronic control into the nozzle to realize mechatronic nozzles. Daggupati[113] designed a nozzle integration scheme that drove the spool action by controlling the on/off of the solenoid valve to achieve variable spray. Funseth et al.[114] developed an agricultural spray nozzle. A circular flow control disk was located in the fluid chamber on the planar surface so as to be between the inlet and outlet, and it was controlled by an electric stepper motor. Needham et al.[115] proposed a method of coupling a proportional solenoid valve to nozzles to control the fluid pressure to individual agricultural spray nozzles to regulate the resulting spray droplet size spectrum.

In recent years, PWM has been used to control nozzle flow rates while maintaining constant pressure. This general approach is typically used in industrial control systems using electrical, hydraulic, or pneumatic actuators. The electronic execution unit is controlled mainly by a fast on and off (pulse mode) conversion device, and the speed at which the conversion device is pulse driven is the frequency. The relative proportion of time during which the valve is open is called the duty cycle and is an important parameter in the PWM technology. PWM ground sprayers have successfully improved the application accuracy through flow control, turn compensation, and high-resolution overlap control by pulsing an electronically actuated solenoid valve that controls the relative proportion of the time each solenoid valve is open. Giles et al.[116] experimentally studied the effects of variable frequency and pulse-width intermittent spraying on the velocity and kinetic energy of spray droplets, and gave a flow adjustment range of 4:1 for the flat-mouth fan nozzle. Giles et al.[117] further studied the relationship between system pressure and flow under PWM control by installing a solenoid valve at the inlet of the nozzle, determined the flow control range, and predicted the feasibility of a commercial variable sprayer. Gopalapillai et al.[118] used PWM control to vary the nozzle flow rate in the ratio of up to 9.5 to 1 without a significant change in the spray pattern. Shahemabadi and Moayed[119] proposed an algorithm to improve the PWM algorithm. By controlling the rising or falling state of the valve opening corresponding to the high and low pulse levels, an adjustment range of the flow rate from 0% to 100% can be realized according to the adjustment precision of 2.5%. This should be a significant improvement over conventional PWM which limits the range of possible flow rates from 25% to 75%. Gu et al.[120] evaluated the effect of modulation rate, spray solution, air velocity, and liquid pressure on DSD produced from an air-assisted, five-port nozzle coupled with PWM solenoid valves. Liu et al.[121] developed a multi-channel PWM integrated controller for the needs of wide-beam spray nozzles, which can implement independent

PWM control for each head of a multi-head system. Qiu et al.[122] reported that a linear relationship between duty cycle and flow could be achieved. Butts et al.[123] researched the droplet size distribution and nozzle tip pressure when influenced by PWM duty cycle. Results showed that AI nozzles were not recommended for PWM systems as they may lead to inconsistent applications, specifically with regards to droplet size generation and nozzle tip pressures. Spray pressures of 276 kpa or greater and PWM duty cycles of 40% or greater are recommended to ensure proper PWM operation.

5 Future development of aerial nozzle

With the growing concern regarding environmental protection and the continuous development of agricultural aircrafts, the aerial spraying technology with nozzles has made considerable progress. As the demand for food and ecological security continues to rise, more research is needed to enhance the current technologies and create new ones to improve the delivery accuracy and efficiency.

5.1 Drift-reducing and variable technology

The design of aerial nozzles is similar to that of the ground application equipment, but there are some differences. First, the flow rate of aerial spray nozzles is very large as the speed of the aircraft is relatively fast. Second, the nozzles are affected by air shear as a result of high-speed air flow. Third, the installation angle of the aerial nozzle is different from that of the ground nozzle, and the high-speed air flow directly affects the droplet spectrum. Today's modern, larger aircrafts have cruising speeds up to 85 m/s, and high airspeed can result in further breakup of the spray liquid into smaller drops because of air shear. The higher the airspeed is, the more secondary breakup happens. Design of nozzles that produce optimal droplet size spectra for mitigation of off-target drift and to provide maximum application efficacy is the first step for the development of intelligent sprayers. These desired size ranges with consistent DSD require the nozzles to operate within proper boundaries of their design pressure.

5.2 Spray nozzle atomization model

Spray nozzle atomization models are needed to provide aerial applicators with droplet size information for an increased range of nozzles and operational settings, allowing for better nozzle selection and operational guidance. A series of models have been developed for nozzles being used on rotary wing aircrafts and fixed-wing aircrafts. With the droplet-sizing facilities used in the testing and evaluation of nozzles and other spray technologies being updated, more research is needed to enhance these technologies and create new technologies for accuracy. Additional atomization data and models should integrate the growing number of new, formulated active ingredient products as well as the growing number of spray adjuvants and complex tank mixtures used in the real-world.

5.3 Aerial adjuvants or additives

Spray atomization is influenced by the physical properties of spray liquids, and numerous studies have shown the effect of formulated products on spray drift, but drift reduction with an appropriate nozzle is greater than that achieved by a formulated product, and it appears that formulated products can be used in addition to accepted drift-reducing application technologies or when these technologies are not available for use. The formation of a spray is the result of interaction between the nozzle and the spray liquid and air shear. The way in which an individual adjuvant acts is nozzle dependent, so it is difficult to generalize the effect of adjuvants on the formation of sprays. Some studies on the combined effect of nozzle type and physical properties of spray liquids have been presented in this study, and more research is required to focus on the atomization mechanism and develop a classification scheme based on drift-reducing properties of formulation types.

5.4 Electrostatic spray technology

An analysis of the literature presented in this study has highlighted the potential applications for the use of electrostatic spray technology in aerial application of pesticides. Electrostatic spray has the advantage of high efficiency of droplet deposition, but the application effect is still not ideal and has not been widely promoted currently because the influencing factors of the electrostatic spray effect are numerous and complicated, and the influence mechanism of many parameters such as environmental parameters, operating parameters, and target parameters on the deposition efficiency of charged droplets is unclear. The technical suitable range and best operating conditions for different crop pests have not been established. More critically, while electrostatic systems have been available for some time, their use rate is low because of the lack of labeled pesticide products that allow their use. Additional field data documenting the impact of electrostatic systems on the ultimate transport and fate of applied sprays is required to aid the regulatory decision-making process.

6 Summary

Aerial application of pesticides is a critical component of modern agriculture, offering an economic and time-sensitive means of delivering crop production and protection products effectively while maintaining environmental stewardship and providing efficacious results. The nozzle is the core component of the spray system, and its performance, especially the atomization performance, can significantly improve the uniformity of droplet deposition, reduce drift, and improve product efficacy. New technologies in fields such as agricultural aviation aircraft, information, physics, and chemistry are developing quickly, resulting in faster, larger aircrafts, improved formulation chemistries, and smaller and lighter test devices, with higher sensitivity and ability to work. New nozzle technologies are required to provide increased control of drop size and eliminate driftable fine particles to provide the maximum application efficacy while mitigating off-target impacts.

Acknowledgments

The authors gratefully acknowledge the support provided by:

(1) National Key R&D Program, China (No. 2016YFD0200606; No. 2018YFD0200700). (2) Science and Technology Planning Project of Guangzhou, China (No. 201807010111)

[References]

[1] Wilson C, Tisdell C. Why farmers continue to use pesticides despite environmental, health and sustainability costs. Ecological economics, 2001; 39(3): 449–462. doi: 10.1016/S0921-8009(01)00238-5.

[2] Lan Y B, Thomson S J, Huang Y B, Hoffmann W C, Zhang H H. Current status and future directions of precision aerial application for site-specific crop management in the USA. Computers and electronics in agriculture, 2010; 74(1): 34–38. doi: 10.1016/j.compag.2010.07.001.

[3] Richard Glass C, Walters K F A, Gaskell P H, Lee Y C, Thompson H M, Emerson D R, et al. Recent advances in computational fluid dynamics relevant to the modelling of pesticide flow on leaf surfaces. Pest Management Science: formerly Pesticide Science, 2010; 66(1): 2–9. doi: 10.1002/ps.1824.

[4] Lebeau F, Verstraete A, Stainier C, Destain M F. RTDrift: A real time model for estimating spray drift from ground applications. Computers and Electronics in Agriculture, 2011; 77(2): 161–174. doi: 10.1016/j.compag.2011.04.009.

[5] Hilz E, Vermeer A W P. Spray drift review: The extent to which a formulation can contribute to spray drift reduction. Crop Protection, 2013; 44: 75–83. doi: 10.1016/j.cropro.2012.10.020.

[6] Oerke E C. Crop losses to pests. The Journal of Agricultural Science, 2006; 144(1): 31–43. https:// doi.org/10.1017/S0021859605005708.

[7] Viret O, Siegfried W, Holliger E, Raisigl U. Comparison of spray deposits and efficacy against powdery mildew of aerial and ground-based spraying equipment in viticulture. Crop Protection, 2003; 22(8): 1023–1032. doi: 10.1016/S0261-2194 (03) 00119-4.

[8] Guler H, Zhu H, Ozkan H E, Derksen R C, Yu Y, Krause C R. Spray characteristics and drift reduction potential with air induction and conventional flat-fan nozzles. Transactions of the ASABE, 2007; 50(3): 745–754. doi: 10.13031/2013.23129.

[9] Huang Y B, Ding W, Thomson S J, Reddy K N, Zablotowicz R M. Assessing crop injury caused by aerially applied glyphosate drift using spray sampling. Transactions of the ASABE, 2012; 55(3): 725–731. doi: 10.13031/2013.41504.

[10] Antuniassi U R, Motta A A B, Chechetto R G, Carvalho F K, Velini E D, Carbonari C A. Spray drift from aerial application. International Advances in Pesticide Application, Aspects of Applied Biology, 2014; 122: 279–284.

[11] Hewitt A J. Droplet size and agricultural spraying, Part 1: Atomization, spray transport, deposition, drift and droplet size measurement techniques. Atomization and Sprays, 1997; 7(3): 235–244. doi: 10.1615/AtomizSpr.v7.i3.10.

[12] Matthews G A. Pesticide Application Methods, 3. London: Backwell Science, 2000. doi:10.1002/9780470760130.

[13] Dorr G J, Hewitt A J, Adkins S W, Hanan J, Zhang H C, Noller B. A comparison of initial spray characteristics produced by agricultural nozzles. Crop Protection, 2013; 53: 109–117. doi: 10.1016/j.cropro.2013.06.017.

[14] Fritz B K, Hoffmann W C. Update to the USDA-ARS fixed-wing spray nozzle models. Transactions of the ASABE, 2015; 58(2): 281-295. doi: 10.13031/trans.58.10896.

[15] Fritz B K, Hoffmann W C. Developing the USDA ARS spray nozzle models for rotary wing applications. Applied Engineering in Agriculture, 2017; 33(5): 631–640. doi: 10.13031/aea.12364.

[16] Kluza P A, Kuna-Broniowska I, Parafiniuk S. Modeling and Prediction of the Uniformity of Spray Liquid Coverage from Flat Fan Spray Nozzles. Sustainability, 2019; 11(23): 6716. doi: 10.3390/su11236716.

[17] Yates W E, Akesson N B, Bayer D. Effects of spray adjuvants on drift hazards. Transactions of the ASAE, 1976; 19(1): 41–0046. doi: 10.13031/2013.35963.

[18] Bouse L F, Carlton J B, Jank P C. Effect of water soluble polymers on spray droplet size. Transactions of the ASAE, 1988; 31(6): 1633–1639. doi: 10.13031/2013.30911.

[19] Bird S L, Esterly D M, Perry S G. Off-target deposition of pesticides from agricultural aerial spray applications. Journal of Environmental Quality, 1996; 25(5): 1095–1104. doi: 10.2134/jeq1996.00472425002500050024x.

[20] Kirk I W. Measurement and prediction of atomization parameters from fixed-wing aircraft spray nozzles. Transactions of the ASABE, 2007; 50(3): 693–703. doi: 10.13031/2013.23123.

[21] Yates W E, Cowden R E, Akesson N B. Drop size spectra from nozzles in high-speed airstreams. Transactions of the ASAE, 1985; 28(2): 405–0410. doi: 10.13031/2013.32268.

[22] Lan Y B, Hoffmann W C, Fritz B K, Martin D E, Lopez J D. Spray drift mitigation with spray mix adjuvants. Applied Engineering in Agriculture, 2008; 24(1): 5–10. doi: 10.13031/2013. 24157.

[23] Celen I H. The effect of spray mix adjuvants on spray drift. Bulgarian Journal of Agricultural Science, 2010; 16(1): 105–110.

[24] Guler H, Zhu H, Ozkan H E, Ling P. Characterization of hydraulic nozzles for droplet size and spray coverage. Atomization and Sprays, 2012; 22(8): 627–645. doi: 10.1615/AtomizSpr.2012006181.

[25] Xiao L P, Zhu H, Wallhead M, Horst L, Ling P, Krause C R. Characterization of Biological Pesticide Deliveries through Hydraulic Nozzles. Transactions of the ASABE, 2018; 61(3): 897–908. doi: 10.13031/trans.12698.

[26] Bouse L F. Effect of nozzle type and operation on spray droplet size. Transactions of the ASAE, 1994; 37(5): 1389–1400. doi: 10.13031/2013.28219.

[27] Huang Y B, Zhan W, Fritz B K, Thomson S J, Fang A. Analysis of impact of various factors on downwind deposition using a simulation method. ASTM International, 2010; 7(6): 1–10. doi: 10.1520/STP152720120015.

[28] Huang Y B, Thomson S J. Characterization of in-swath spray deposition for CP-11TT flat-fan nozzles used in low-volume aerial application of crop production and protection materials. Transactions of the ASABE, 2011; 54(6): 1973–1979. doi: 10.13031/2013.40645.

[29] Czaczyk Z. Influence of air flow dynamics on droplet size in conditions of air-assisted sprayers. Atomization and Sprays, 2012; 22(4): 275–282. doi: 10.1615/AtomizSpr.2012003788.

[30] Miller P C H, Ellis M C B. Effects of formulation on spray nozzle performance for applications from ground-based boom sprayers. Crop Protection, 2000; 19(8-10): 609–615. https://doi.org/10.1016/S0261-2194(00)00080-6.

[31] Henry R S, Fritz B K, Hoffmann W C, Kruger G R. An evaluation of three drift reduction adjuvants for aerial application of pesticides. GSTF Journal on Agricultural Engineering (JAE), 2015; 2(1): 39–47. doi:10.7603/s40 872-015-0006-3.

[32] Dodge T. New spray technology driven by drift. American Farm Industry News, 1998; Mar 1. http://www.farmindustrynews.com/new-spray-technology-driven-drift.

[33] Lan Y B, Chen S D, Fritz B K. Current status and future trends of precision agricultural aviation technologies. International Journal of Agricultural and Biological Engineering, 2017; 10(3): 1–17. doi: 10.3965/j.ijabe.20171003.3088.

[34] Mayo A J, Nohria N, Rennella M. C. E. Woolman and Delta Air Lines. In Entrepreneurs, Managers, and Leaders, New York: Palgrave Macmillan, 2009. pp. 61–80.

[35] Zhou Z Y, Ming R, Zang Y, He X G, Luo X W, Lan, Y B. Development status and countermeasures of agricultural aviation in China. Transactions of the CSAE, 2017; 33(20): 1–13. doi: 10.11975/ j.issn.1002-6819.2017.20.001. (in Chinese)

[36] Yin X C, Lan Y B, Wen S, Deng J Z, Zhang J L, Zhang J T. The development of Japan agricultural aviation technology and its enlightenment for China. Journal of South China Agricultural University, 2018; 39: 1–8. doi: 10.7671/j.issn.1001-411X.2018.02.001. (in Chinese)

[37] Carlton J B, Isler D A. Development of a device to charge aerial sprays electrostatically. Agricultural Aviation, 1966; 8(2): 44–51.

[38] Bretthauer S. Aerial applications in the USA. Outlooks on Pest Management, 2015; 26(5): 192–198. doi: 10.1564/v26_oct_02.

[39] Sidahmed M M, Taher M D, Brown R B. A virtual nozzle for simulation of spray generation and droplet transport. Biosystems engineering, 2005; 92(3): 295–307. doi: 10. 1016/j.biosystemseng.2005.07.012.

[40] Fox R D, Derksen R C, Zhu H, Brazee R D, Svensson S A. A history of air-blast sprayer development and future prospects. Transactions of the ASABE, 2008; 51(2): 405–410. doi: 10.13031/2013.24375.

[41] Fritz B K, Hoffmann W C, Bagley W E, Kruger G R, Czaczyk Z, Henry R S. Influence of air shear and adjuvants on spray atomization. Pesticide Formulation and Delivery Systems 1569, 2014; 33:151–173. doi: 10.1520/STP156920120129.

[42] ANSI/ASAE Standards S327.4. Terminology and Definitions for Application of Crop, Animal, or Forestry Production and Protection Agents. St. Joseph, Mich.: ASABE, 2012.

[43] He Y, Xiao S P, Fang H, Dong T, Tang Y, Nie P C, et al. Development situation and spraying decision of spray nozzle for plant protection UAV. Transactions of the CSAE, 2018; 34(13): 113 –124. doi: 10.11975/ j.issn.1002–6819. 2018.13.014. (in Chinese)

[44] Gil E, Balsari P, Gallart M, Llorens J, Marucco P, Andersen P G, et al. Determination of drift potential of different flat fan nozzles on a boom sprayer using a test bench. Crop Protection, 2014; 56: 58–68. doi: 10.1016/j.cropro.2013.10.018.

[45] Kirk I W. Droplet spectra classification for fixed-wing aircraft spray nozzles. ASAE Paper No. 011082. ASAE, St. Joseph, MI, 2001. doi: 10.13031/2013.3433.

[46] Pilch M, Erdman C A. Use of breakup time data and velocity history data to predict the maximum size of stable fragments for acceleration-induced breakup of a liquid drop. International Journal of Multiphase Flow, 1987; 13(6): 741–757. doi: 10.1016/0301-9322 (87)90063-2.

[47] Hayashi H, Takeda S. Spray Drying Characteristics by a Centrifugal Pressure Nozzle with Large Orifice Diameter. Drying Technology, 1986; 4(3): 331–342. doi: 10.1080/07373938608916333.

[48] Masters K. Spray Drying, 2. New York: John Wiley & Sons. 1976.

[49] Hewitt A J. Droplet size spectra produced by air-assisted atomizers. Journal of aerosol science, 1993; 24(2): 155–162. doi: 10.1016/ 0021-8502(93)90055-E.

[50] Teske M E, Hewitt A J, Mickle R E. The measurement of droplet size distributions from rotary atomizers. In Pesticide Formulations and Application Systems: A New Century for Agricultural Formulations, 2001; 21: 197–209. doi: 10.1520/STP10729S.

[51] Hoffmann W C, Walker T W, Smith V L, Martinand D E, Fritz B K. Droplet size characterization of hand held atomization equipment typically used in vector control. Journal of the American mosquito control association, 2007; 23(3), 315–320. doi: 10.2987/8756-971X(2007)23 [315:DCOHAE]2.0.CO;2.

[52] Martin D E, Latheef M A, López Jr J D. Electrostatically charged aerial application improved spinosad deposition on early season cotton. Journal of Electrostatics, 2019; 97: 121–125. doi: 10.1016/j.elstat.2018.12.005.

[53] Martin D E, Latheef M A. Aerial application methods control spider mites on corn in Kansas, USA. Experimental and Applied Acarology, 2019; 77(4): 571–582. doi: 10.1007/s10493-019-00367-3.

[54] Law S E, Bowen H D. Charging liquid spray by electrostatic induction. TRANSACTIONS of the ASAE, 1966; 9(4): 501–0506. doi: 10.13031/ 2013.40016.

[55] Carlton J B. Electrical capacitance determination and some implications for an electrostatic spray-charging aircraft. Transactions of the ASAE, 1975; 18(4): 641–0644. doi: 10.13031/2013.36651.

[56] Carlton J B, Bouse L F, Kirk I W. Electrostatic charging of aerial spray

over cotton. Transactions of the ASAE, 1995; 38(6): 1641–1645. doi: 10.13031/2013.27989.

[57] Zhang Y L, Lan Y B, Bradley K, Xue X Y. Development of aerial electrostatic spraying systems in the United States and applications in China. Transactions of the CSAE, 2016; 32(10): 1–7. doi: 10.11975/j.issn.1002-6819.2016.10.001. (in Chinese)

[58] Zhou H P, Ru Y, Shu C R, Jia Z C. Improvement and experiment of aerial electrostatic spray device. Transactions of the CSAE, 2012; 28(12): 7–12. doi:10.3969/j.issn.1002-6819.2012.12.002. (in Chinese)

[59] Lan Y B, Zhang H Y, Wen S. Analysis and experiment on atomization characteristics and spray deposition of electrostatic nozzle. Transactions of the CSAM, 2018; 49: 130–139. doi: 10.6041/j.issn.1000-1298.2018.04.015. (in Chinese)

[60] Lafferty C L, Tian L F. The impacts of pre-orifice and air-inlet design features on nozzle performance. ASAE Paper No. 011079. ASAE, St. Joseph, MI, 2001. doi: 10.13031/2013.7343.

[61] Zhu H, Reichard D L, Fox R D, Brazee R D, Ozkan H E. Simulation of drift of discrete sizes of water droplets from field sprayers. Transactions of the ASAE, 1994; 37(5): 1401–1407. doi: 10.13031/2013.28220.

[62] Bouse L F, Carlton J B, Mitchel R D, Jank P C. Atomization of vegetable oils in an airstream. Transactions of the ASAE, 1990; 32(6): 1829–1836. doi: 10.13031/2013.31230.

[63] Nuyttens D, Baetens K, De Schampheleire M, Sonck B. Effect of nozzle type, size and pressure on spray droplet characteristics. Biosystems Engineering, 2007; 97(3): 333–345. doi: 10.1016/j.biosystemseng.2007.03.001.

[64] Nuyttens D, De Schampheleire M, Baetens K, Sonck B. The influence of operator-controlled variables on spray drift from field crop sprayers. Transactions of the ASABE, 2007; 50(4): 1129–1140. doi: 10.13031/2013.23622.

[65] Nuyttens D, Taylor W A, De Schampheleire M, Verboven P, Dekeyser D. Influence of nozzle type and size on drift potential by means of different wind tunnel evaluation methods. Biosystems Engineering, 2009; 103(3): 271–280. doi: 10.1016/j.biosystemseng.2009.04.001.

[66] Miller P C H, Tuck C R, Murphy S, Da Costa Ferreira M. Measurements of the droplet velocities in sprays produced by different designs of agricultural spray nozzle. Paper ID ILASS08–8-5, 22nd ILASS-Europe, 2008; 8-10.

[67] AI Heidary M, Douzals J P, Sinfort C, Vallet A. Influence of spray characteristics on potential spray drift of field crop sprayers: A literature review. Crop Protection, 2014; 63: 120–130. doi: 10.1016/j.cropro.2014.05.006.

[68] Yates W E, Cowden R E, Akesson N B. Nozzle orientation, air speed and spray formulation affects on drop size spectrums. Transactions of the ASAE, 1983; 26(6): 1638–1643. doi: 10.13031/2013.33816.

[69] Wolf R E, Bretthauer D S, Gardisser R. Determining the affect of flat-fan nozzle angle on aerial spray droplet spectra. ASAE Paper No. AA05e003. ASAE , St. Joseph, MI, 2005.

[70] Bouse L F, Carlton J B. Factors affecting size distribution of vegetable oil spray droplets. Transactions of the ASAE, 1985; 28(4): 1068–1073. doi: 10.13031/2013.32389.

[71] Lane W R. Shatter of drops in streams of air. Industrial & Engineering Chemistry, 1951; 43(6): 1312–1317.

[72] Fraser R P, Eisenklam P. Liquid atomization and the drop size of sprays. Institution of Chemical Engineers, 1956; 34(4): 294–313.

[73] Fritz B, Hoffmann W, Henry R. The effect of adjuvants at high spray pressures for aerial applications. In Pesticide Formulation and Delivery System, 2016; 36: 133–148. doi: 10.1520/STP159520150086.

[74] Kirk I W. Aerial applicators spray nozzle handbook. USDA Agricultural Research Service, Washington, D.C., USA, 2004.

[75] Yao W X, Lan Y B, Hoffmann W C, Guo S, Chen S D, Wen Z, et al. Atomization characteristics of multi-type aerial nozzles in wind tunnel and low airflow velocity condition in manned agricultural helicopter. International Journal of Precision Agricultural Aviation, 2019; 2(1): 9–17. doi: 10.33440/j.ijpaa.20190201.0031.

[76] Spanoghe P, Schampheleire M D, Meeren P V d, Steurbaut W. Influence of agricultural adjuvants on droplet spectra. Pest Management Science: formerly Pesticide Science, 2007; 63(1): 4–16. doi: 10.1002/ps.1321.

[77] Spanoghe P, Eeckhout H V, Steurbaut W, Meeren P V d. The effect of static and dynamic surface tension on atomization with agricultural nozzles. Meded Rijksuniv Gent Fak Landbouwkd Toegep Biol Wet, 2002; 67(2): 37–45.

[78] Hewitt A J. Spray optimization through application and liquid physical property variables-I. The Environmentalist, 2008; 28(1): 25–30. doi: 10.1007/s10669-007-9044-5.

[79] Kirk I W. Spray mix adjuvants for spray drift mitigation-progress report. ASAE Paper No. 031060. ASAE, St. Joseph, MI, 2003. doi: 10.13031/2013.13721.

[80] Akesson N B, Steinke W E, Yates W E. Spray atomization characteristics as a function of pesticide formulations and atomizer design. Journal of Environmental Science & Health Part B, 1994; 29(4): 785–814. doi: 10.1080/03601239409372904.

[81] Gratkowski H, Stewart R. Aerial spray adjuvants for herbicidal drift control. General Technical Report PNW-3. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station, 1973. 24p.

[82] Guler H, Zhu H, Ozkan E, Derksen R, Krause C. Wind tunnel evaluation of drift reduction potential and spray characteristics with drift retardants at high operating pressure. Journal of ASTM International, 2006; 3(5): 1–9. doi: 10.1520/JAI13527.

[83] Ellis M C B, Tuck C R, Miller P C H. How surface tension of surfactant solutions influences the characteristics of sprays produced by hydraulic nozzles used for pesticide application. Colloids and Surfaces A: Physicochemical and Engineering Aspects, 2001; 180(3): 267–276. doi: 10.1016/S0927-7757(00) 00776-7.

[84] Dombrowski N, Fraser R P. A photographic investigation into the disintegration of liquid sheets. Philosophical Transaction of the Royal Society of London. Series A, Mathematical and Physical Sciences, 1954; 247(924): 101–130. doi: 10.1098/rsta.1954.0014.

[85] Hewitt A J. The effects of tank mix and adjuvants on spray drift. In Proceedings of 5th International Symposium on Adjuvants for Agrochemicals (ISAA 1998), 1998; 451–462.

[86] Ellis M C B, Tuck C R. The variation in characteristics of air-included sprays with adjuvants. Aspects of Applied Biology, 2000; 57:155–162.

[87] Hazen J L. Adjuvants-terminology, classification, and chemistry. Weed Technology, 2000; 14(4): 773–784. doi: 10.1614/0890-037X(2000)014[0773:ATCAC]2.0.CO;2.

[88] Ellis M B, Tuck C R. The effect of liquid properties on spray formation by flat fan nozzles. Aspect of Applied Biology (United Kingdom), 1997; 48: 105–112.

[89] Western N M, Hislop E C, Bieswal M, Holloway P J, Coupland D. Drift reduction and droplet-size in sprays containing adjuvant oil emulsions. Pest Management Science, 1999; 55(6): 640–642. doi: 10.1002/(SICI)1096-9063(199906)55:6%3C640::AID-PS985%3E3.0.CO;2-U.

[90] Dexter R W. The effect of fluid properties on the spray quality from a flat fan nozzle. In Pesticide Formulations and Application Systems. ASTM STP 1400, 2001; 20: 27–43.

[91] Combellack J H, Westen N M, Richardson R G. A comparison of the drift potential of a novel twin fluid nozzle with conventional low volume flat fan nozzles when using a range of adjuvants. Crop Protection, 1996; 15(2): 147–152. doi: 10.1016/0261-2194(95)00089-5.

[92] Stainier C, Destain M F, Schiffers B, Lebeau F. Droplet size spectra and drift effect of two phenmedipham formulations and four adjuvants mixtures. Crop Protection, 2006; 25(12): 1238–1243. doi: 10.1016/j.cropro.2006.03.006.

[93] Hoffmann W C, Fritz B K, Yang C. Effects of spray adjuvants on spray droplet size from a rotary atomizer, In Pesticide Formulation and Delivery Systems, 2016; 35: 52–60. doi: 10. 1520/STP158720140099.

[94] Fritz B K, Hoffmann W C, Gizotti-De-Moraes J, Guerrerio M, Golus J, Kruger G. The impact of spray adjuvants on solution physical properties and spray droplet size. In Pesticide Formulation and Delivery Systems, 2018; 37: 22–32. doi: 10.1520/STP160220160134.

[95] Wolf R E, Gardisser D R. Field comparisons for drift-reducing/depositionaid tank mixes. ASAE Paper No. AA03-002. ASAE, St. Joseph, MI, 2003.

[96] Wolf R E, Gardisser D R, Minihan C. Comparing drift reducing tank mixes for aerial applications. Agricultural Aviation, 2003; 30(2): 14–21.

[97] Wolf R E, Gardisser D R, Loughin T M. Comparison of drift reducing/deposition aid tank mixes for fixed wing aerial applications. Journal of ASTM International, 2005; 2(8): 1–14. doi: 10.1520/JAI12921.

[98] Fritz B K, Hoffmann W C, Bagley W E. Effects of spray mixtures on droplet size under aerial application conditions and implications on drift.

Applied Engineering in Agriculture, 2010; 26(1): 21–29. doi: 10.13031/2013.29467.

[99] Fritz B K, Hoffmann W C, Bretthauer S, Wolf R E, Bagley W E. Wind tunnel and field evaluation of drift from aerial spray applications with multiple spray formulations. In Pesticide Formulations and Delivery Systems, 2013; 32: 96–113. doi: 10.1520/STP104403.

[100] Wang X N, He X K, Song J L, Herbst A. Effect of adjuvant types and concentration on spray drift potential of different nozzles. Transactions of the CSAE, 2015; 31(22): 49–55. doi: 10.11975/j.issn.1002-6819.2015.22.007.

[101] Chen X, Gong Y, Liu D J, Wang G, Zhang X. Effect of additives on atomization of pesticides and nozzles. ASAE Paper No. 1901399. ASAE, St. Joseph, MI, 2019. doi: doi: 10.13031/aim.201901399.

[102] Doble S J, Matthews G A, Rutherford I, Southcombe E S E. A system for classifying hydraulic and other atomizers into categories of spray quality. In Proceedings of British Crop Protection Conference – Weeds, 1985; 3: 1125–1133.

[103] Southcombe E S E, Miller P C H, Ganzelmeier H, van de Zande J C, Miralles A, Hewitt A J. The international (BCPC) spray classification system including a drift potential factor. In Proceeding of the Brighton Crop Protection Conference – Weeds, 1997; 371–380.

[104] ANSI/ASAE Standards, S572.1, Spray nozzle classification by droplet spectra. St. Joseph, Mich.: ASABE, 2009.

[105] ASAE Standards, S358.2, Standards engineering practices data, St. Joseph, Mich.: ASABE, 2000.

[106] Box G E, Behnken D W. Some new three-level designs for the study of quantitative variables. Technometrics, 1960; 2(4): 455–475. doi: 10.2307/1266454.

[107] Kirk I W. Measurement and prediction of helicopter spray nozzle atomization. Transaction of the ASAE, 2002; 45(1): 27–37. doi: 10.13031/2013.7866.

[108] Teske M E, Thistle H W, Fritz B K. Modeling aerially applied sprays: An update to AGDISP model development. Transactions of the ASABE, 2019; 62(2): 343–354. doi: 10.13031/trans.13129.

[109] Hewitt A J. Droplet size spectra classification categories in aerial application scenarios. Crop Protection, 2008; 27(9): 1284–1288.

[110] Fritz B K, Hoffmann W C. Establishing reference nozzles for classification of aerial application spray technologies. International Journal of Precision Agricultural Aviation, 2018; 1(1): 10–14. doi: 10.33440/j.ijpaa.20180101.0003.

[111] Walker J T, Bansal R K. Development and characterization of variable orifice nozzles for spraying agro-chemicals. ASAE Paper No. 991008. ASAE, St. Joseph, MI, 1999.

[112] Womac A R, Bui Q D. Variable-flow control device for precision application. U.S. Patent No. 5,908,161. Washington, DC: U.S. Patent and Trademark Office, 1999.

[113] Daggupati N P. Assessment of the varitarget nozzle for variable rate application of liquid crop protection products. Doctoral dissertation, Kansas State University, India, 2007.

[114] Funsenth T G, Mercer D S, Humpal R A. Sprayer pulsing nozzle flow control using rotational step positions, U.S. Patent Application No.13/333,541, Washington, DC: U.S. Patent and Trademark Office, 2013.

[115] Needham D L, Holtz A J, Giles D K. Actuator system for individual nozzle control of flow rate and spray droplet size. Transactions of the ASABE, 2012; 55(2): 379–386. doi: 10.13031/2013.41376.

[116] Giles D K, Ben-Salem E. Spray droplet velocity and energy in intermittent flow from hydraulic nozzles. Journal of Agricultural Engineering Research, 1992; 51: 101–112. doi: 10. 1016/0021-8634(92)80029-R.

[117] Giles D K, Henderson G W, Funk K. Digital control of flow rate and spray droplet size from agricultural nozzles for precision chemical application. Precision Agriculture, precisionagricu3, 1996; 3: 729–738.

[118] Gopalapillai S, Tian L, Zheng J. Evaluation of a flow control system for site-specific herbicide applications. Transactions of the ASAE, 1999; 42(4): 863–870. doi: 10.13031/2013.13265.

[119] Shahemabadi A R, Moayed M J. An algorithm for pulsed activation of solenoid valves for variable rate application of agricultural chemical. IEEE International Symposium on Information Technology, 2008; 4: 1–3. doi: 10.1109/ITSIM.2008.4631863.

[120] Gu J, Zhu H, Ding W, Jeon H Y. Droplet size distributions of adjuvant-amended sprays from an air-assisted five-port PWM nozzle. Atomization and sprays, 2011; 21(3): 263–274. doi: 10.1615/AtomizSpr.2011003258.

[121] Liu H, Zhu H, Shen Y, Chen Y, Ozkan H E. Development of digital flow control system for copy multi-channel variable-rate sprayers. Transactions of the ASABE, 2014; 57(1): 273–281. doi: 10.13031/trans.57.10216.

[122] Qiu B J, Yan R, Ma J, Guan X P, Ou M X. Research progress analysis of variable rate sprayer technology. Transactions of the CSAM, 2015; 46(3): 59–72. doi: 10.6041/j.issn.1000-1298. 2015.03.009. (in Chinese)

[123] Butts T R, Butts L E, Luck J D, Fritz B K, Hoffmann W C, Kruger G R. Droplet size and nozzle tip pressure from a pulse-width modulation sprayer. Biosystems Engineering, 2019; 178: 52–69. doi: 10.1016/j.biosystemseng.2018.11.004.