Spray Performance of the High Pressure Air Inclusion Nozzle Used in Japan

—— In the aspects of the relative spray drift and the influence ——

of key design parameters on spray performance

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Contents

List of tables

List of figures

Chapter 1 General introduction

Agricultural industry in the modern world highly depends on pesticide application. However, the application not only brings us benefit but also suffering. A lot of health and environmental issues occur due to pesticide application. Therefore, the spray performance including spray drift control has been paid much attention. In this chapter, the basic information of pesticide, pesticide usage, pesticide spray and also spray drift were introduced. Therefore, a big picture of pesticide application could be drawn to get better understanding to the study carried out in the thesis. The study objectives of the thesis were also brought forward at the end of the chapter.

1.1. From pesticide to pesticide application

To understand the situation of pesticide application in the world, some basic information from the definition of pesticide to the consumption of pesticide was introduced in this section.

1.1.1. Definition of pesticide

Though different countries and regions may have their own definitions of pesticide, the contents are similar. According to the Food and Agriculture Organization of the United Nations (FAO, 2005), pesticide means any substance or mixture of substances intended for preventing, destroying or controlling any pest, including vectors of human or animal disease, unwanted species of plants or animals causing harm during or otherwise interfering with the production, processing, storage, transport or marketing of food, agricultural commodities, wood and wood products or animal feedstuffs, or substances which may be administered to animals for the control of insects, arachnids or other pests in or on their bodies. The term includes substances intended for use as a plant growth regulator, defoliant, desiccant or agent for thinning fruit or preventing the premature fall of fruit, and substances applied to crops either before or after harvest to protect the commodity from deterioration during storage and transport.

1.1.2. Development of pesticide

Human beings are fighting with crop disease since ancient period for avoiding hunger (Cremlyn, 1991). Theophrastus (300BC) described many plant diseases known today such as scorch, rot scab, and rust. Until today, locusts cause vast food losses in the Near East and Africa.

Human being uses their own methods to prevent the occurrence of the insects, fungi and weeds, which are the main pests harmful to the agricultural products. Some record could be found in ancient history of human being and only a few examples were given as follows. Sulphur was used as one kind of fumigant before 1000BC by Homer. Arsenic was used as an insecticide by Pliny (AD79) and also by the Chinese, who were applying the moderate amount of arsenic compounds as insecticides. Careful observation and large amounts of trial and error applications with patient may attribute to the development of these early pesticide.

The application of the systematic scientific methods of controlling agricultural pests has been carried out since the middle of the nineteenth century. The development of the systematic research of pesticide has always been related to the development of modern chemistry industry to a certain degree. The details of the development could be found in the reference (Cremlyn, 1991). Nowadays, a pesticide industry with a complicated system has been established.

In Japan, people are also confronting agriculture pest management since ancient time (Science of pesticide, 2004). Based on the record, Japanese used whale oil and rape-seed oil to create an oil film on the surface of the paddy field to kill the unwanted insects by suffocation in 1670. The shifting of the development of pesticide science was in the periods of Meiji (1868-1912) and Taisho (1912-1926) eras. During these periods, the new science and technology from Western Europe was introduced into Japan. In 1921, with the successful development of the chloropicrin by the domestic manufacturer, the systematic research of pesticide and the pesticide industry in Japan was initiated. Until 1955, the introduced pesticide from overseas were the main pesticide being used in Japan. After that, different kinds of new pesticide developed by research institutes were registered and entered the domestic market. After the popularization of these pesticide in the domestic market, the international market share of the pesticide manufactured in Japan also increased.

1.1.3. Advantages and disadvantages of pesticide application

From the definition, it could be generally understood that the application of the pesticide in agriculture sector can increase the yielding and quality of the agricultural products without heavy work, comparing with the pest management works without pesticide. To better illustrate this benefit, the investigation result of the crop yielding between using and without using pesticide was shown in Table 1 (Knutson, 1999). The result shows that the yielding of the agricultural products experienced a sharp decrease when no pesticide was applied. Besides, the broader the group of pesticide eliminated, the greater the yield impacts. In addition, comparing with fruits and vegetables, the field crops are relatively more independent on pesticide. And differences of yielding reduction were found among different agricultural products. In the region where had high humidity without hard frost, the yielding of the agricultural products are more depend on pesticide. With the application of the herbicides in paddy field from 1949 to 1997, a rapid decrease of the labor time for weeding was observed (Japan Association for Advancement of Phyto-Regulators).

Despite of the obvious benefit of pesticide application, it should be mentioned that lots of health and environmental issues caused by pesticide application were also found. One part of the pesticide deposits on the wanted target may lead to the issue of pesticide residues. The untargeted pesticide enters the environment include soil, water, atmosphere, which may lead to pollution or contamination at different places (Kanazawa, 1992). Therefore, the combination of the development of low-toxic or biopesticide and the new application technology which causes less untargeted pesticide residues could possibly contribute to solve the serious problem.

1.1.4. Category of pesticide

Generally, the pesticide could be divided into several categories based on the type of pest they control, the chemical structure, the physical state and also the toxicity. Usually, the classification method based on the type of pest they control is used. Table 2 shows the name and the corresponding functions of different categories of pesticide based on the type of pest they control (Science of pesticide, 2004; Agricultural pharmacology, 2003).

Table 1 Percent reduction in yield of different agricultural products under different application plan of pesticide

Crop	**1990**			**1993**		**1999**
	No pesticide	**No herbicides**	**No insecticides and no fungicides**	**No pesticide**	**50% reduction**	**No organophosphates and no carbamates**
Corn	32	30	5			4
Cotton	39	17	26			14
Peanuts	78	29	66			9
Rice	57	53	16			8
Soybeans	37	35	3			5
Wheat	24	23	4			1
Apples				100	43	38
Carrots						7
Grapes				89	57	9
Lettuce				67	47	
Onions				64	48	
Oranges				55	28	3
Peaches				81	59	2
Potatoes				57	27	3
Tomatoes				77	38	15

Table 2 Name and the corresponding functions of different categories of pesticide based on the type of pest they control

Macro classification	**Category name**	**Function**
Insects control agent (I)	Insecticides	Kill insects and other arthropods
Vermin control agent (V)	Miticides	Kill mites that feed on plants and animals
	Nematicides	Kill nematodes (microscopic, worm-like organisms that feed on plant roots)
	Rodenticides	Control mice and other rodents
Disease control agent (D)	Disinfectants	Kill or inactivate disease-producing microorganisms on inanimate objects
Weed control agent (W)	Herbicides	Kill weeds and other plants that grow where they are not wanted
(I)+(D) [a]	Insect-fungicide	Mixture of disinfectants and insecticides
Plant growth regulators (P)	Plant growth regulators	Substances (excluding fertilizers or other plant nutrients) that alter the expected growth, flowering, or reproduction rate of plants
(I)+(V)	Repellents	Repel pests, including insects (such as mosquitoes) and birds
(I)+(V)	Attractants	Attract pests (for example, to lure an insect or rodent to a trap). (However, food is not considered a pesticide when used as an attractant.)
No corresponding category	Spreader or adjuvant [b]	Improve the attachment result of pesticide on the body of unwanted insect and the surface of the plant when less volume of pesticide is applied

[a] (I)+(D) means the insect-fungicide could work as either insects control and disease control agents.

[b] In some references, spreader or adjuvant are not considered as one category of pesticide because they are not themselves active in kill pests.

1.1.5. Word market of pesticide

As shown in Table 1, the modern agricultural industry all over the world became highly dependent on pesticide application because of its advantages of increasing yielding and also of saving working hours. In current market economy, the application of pesticide often means the increase of the income, which is vital to farmers. Therefore, a huge market of pesticide has been formed since pesticide was invented. Table 3 shows the global pesticide expenditures and the amount of pesticide active ingredient used (United States Environmental Protection Agency (EPA), 2011).

Table 3 Global pesticide expenditures and the amount of pesticide active ingredient used, 2006 and 2007 estimates (EPA, 2011)

Year and pesticide type	**Millions of dollar**	**%**	**Millions of metric ton**	**%**
2006				
Herbicides	12247	40	0.916	39
Insecticides	10259	29	0.434	18
Fungicides	7987	22	0.236	10
Other	3320	9	0.774	33
Total	35814	100	2.359	100
2007				
Herbicides	15512	39	0.952	40
Insecticides	11158	28	0.405	17
Fungicides	9216	23	0.235	10
Other	3557	9	0.774	33
Total	39443	100	2.366	100

1.2. Pesticide spray

1.2.1. Development of agricultural sprayers

Nowadays, agricultural sprayers are the most widely used equipment to carry out pesticide application. Several kinds of sprayers have been developed from hand-operated, hydraulic sprayer to boom/speed sprayer or aircraft sprayer with the development of the agricultural engineering. Normally, the spray efficiency, which usually be estimated by cost-income of agricultural industry, increases from hand-operated sprayer with low application rate, small coverage area in a certain time interval and low travel speed to large-scale sprayers which could apply pesticide with much higher application rate, bigger coverage area in a certain time interval and also higher travel speed.

Based on the internet information, horse-drawn traction sprayer was firstly invented in 1887. Since then, many industry productions were applied on the sprayers and were improved for specific goals of pesticide application later, such as gasoline engines (1900), pressure regulator and air chamber for smooth and continuous spray (1911), attachments for water injection and low pressure, low volume sprayers (1944), etc. Similarly, other kinds of agricultural sprayers has been highly mechanized and automated to a certain degree by introducing the new products of industry community into the agricultural sprayer manufacture.

To carry out efficient spray works, many kinds of sprayers have been developed by domestic manufactures in Japan (Miyahara, 2013). Table 4 shows the main sprayer types which are currently used in Japan. Because of the limited area of the agriculture field, no large-scale aircraft sprayer is used in Japan based on literature. Therefore, the boom sprayer and the speed sprayer might be the most efficient sprayer for large-scale field crop and vertical target, respectively. In these years, the sales of the two kinds of sprayers were about 2500/year.

Table 4 Main equipment for pesticide application in Japan

Formulation	**Working style /Situation**	**Application equipment**
Ground Application		
Liquid	Walking	Manual sprayer (knapsack type, etc.) Power sprayer (knapsack type, portable, self-propelled)
	Riding	Boom sprayer (tractor mounted, self-propelled), Air blast sprayer
	in Orchard	Sprinkler
	in Green house	Power sprayer (portable, self-propelled/motor driven), Cold fogger
	by RC helicopter	Low volume sprayer unit
Granule	Walking	Manual applicator (hanging type, knapsack type) Power applicator (knapsack type, self-propelled)
	Riding	Power applicator (self-propelled/boom type blow head) Rice transplanter attachment type applicator unit
	by RC helicopter	Granule applicator unit
Dust	Walking	Manual duster (hanging type, knapsack type) Power duster (knapsack type, tractor mounted)
Smoke	in Green house	Smoking machine
Aerial Application		
Liquid	by Manned helicopter	Low/Ultra-low volume sprayer unit
Granule	by Manned helicopter	Granule applicator unit

1.2.2. Spray nozzles

Several kinds of nozzles have been developed for application of different kinds of pesticide on different sprayers. There are two main nozzle types including flat fan type and cone type. The flat fan nozzles are widely used on boom sprayers while cone nozzles are usually used on hand-operated sprayers and orchard sprayers.

For flat fan nozzles, a very uniform distribution of spray could be achieved by the overlap of the individual application patterns along the boom. This is one main reason to use flat fan nozzles on the boom sprayers. There are several subdivisions among the flat fan nozzles which includes conventional flat fan nozzle, pre-orifice flat fan nozzle and air inclusion nozzle.

The biggest difference among the three kinds of flat fan nozzles is the droplet size. Generally, the biggest droplet size is produced by the air inclusion nozzle, followed by pre-orifice flat fan nozzle and the conventional flat fan nozzle. In addition, the manufactures acclaim that the air inclusion nozzle could produce included air within droplet which results in a better deposition result than pure water droplet.

1.3. Initial spray characteristics

Initial spray characteristics include droplet size characteristics, spray angle, amount of include air and also the liquid flow rate. These characteristics influence the spray performance which is vital for pesticide spray.

1.3.1. Droplet size characteristics

The droplet size is a very important parameter related to the spray drift and the spray coverage rate. Keeping the total application volume unchanged, smaller droplets which have more number of droplets have higher coverage rate than that of larger droplets with small number of droplets (Fig. 1 and 2). However, the smaller droplets have longer drift distance than bigger droplets due to the ballistic theory of droplet movement. Therefore, more spray drift might be produced when small droplets are sprayed.

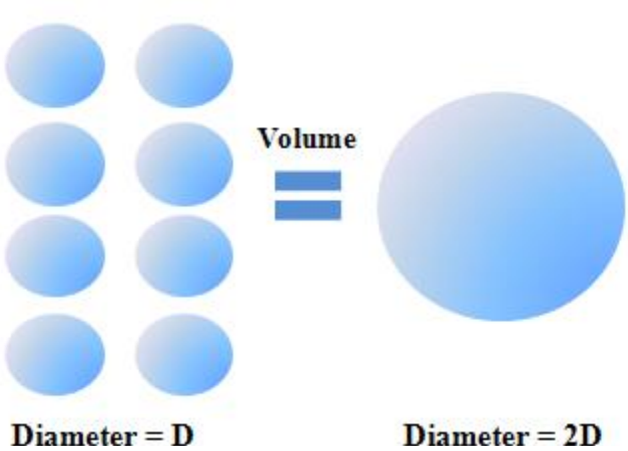

Figure 1 Comparison of coverage area between two groups of droplets with equivalent volume

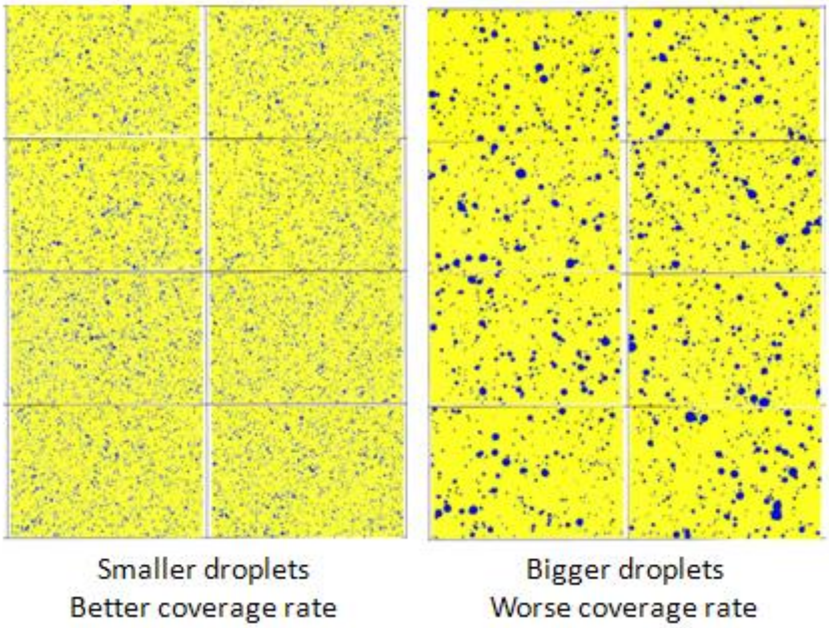

Figure 2 Illustration of the difference of coverage rates produced by small and big droplets

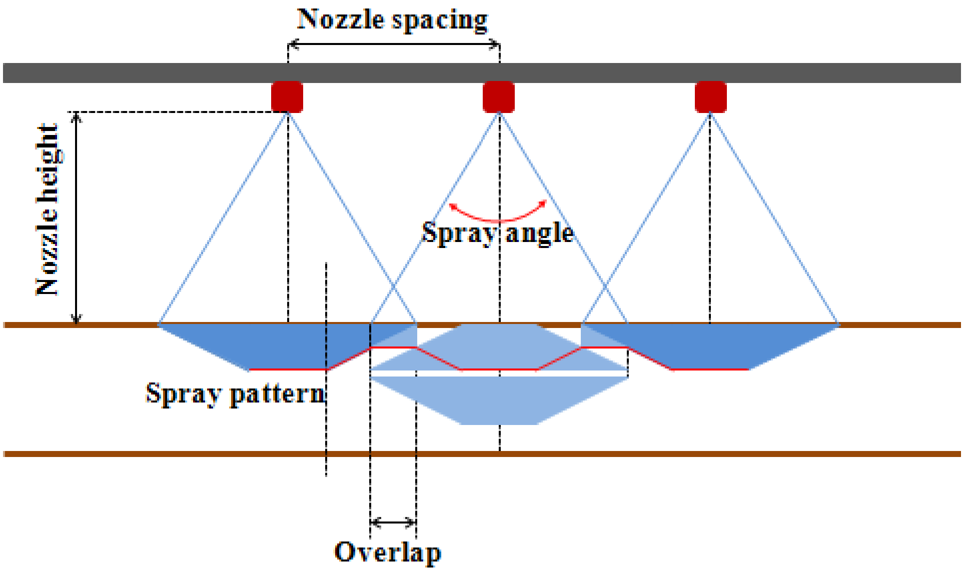

Figure 3 Potential spray pattern of nozzles when the spray angle is too narrow at low nozzle height

1.3.2. Spray angle

The spray angle means the angle between the two edges of the spray sheet along the major axis of the spray pattern. For the boom sprayer, the combined spray pattern of the nozzles might be uneven when the spray angle is too narrow at low nozzle height (Fig. 3).

1.3.3. Amount of included air

Almost all the manufactures claim that the air inclusion nozzle could produce droplets with included air within it which improve the deposit efficiency of the droplets (Fig. 4). However, no solid data was provided to investigate the independent influence of the included air within droplets on important spray performance indicators, such as coverage rate.

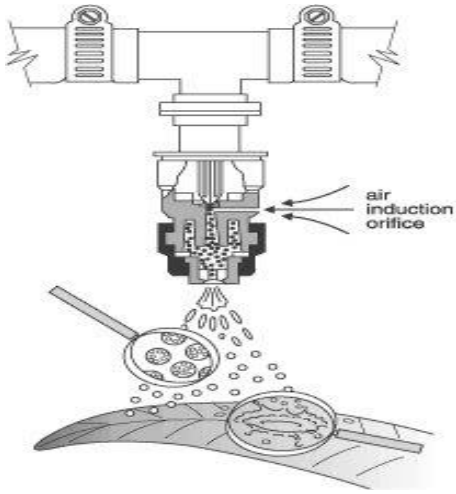

Figure 4 Illustration of the good deposit performance of the droplet with included air produced by air inclusion nozzle (Internet picture)

1.3.4. Liquid flow rate

Liquid flow rate of the individual nozzle has strong effect on the forward speed of the boom sprayer. Therefore, it might decide the working time of pesticide application when spray drift level is acceptable at higher forward speed. A shorter working time means lower labor cost and energy consumption.

1.4. Key design parameters of flat fan nozzle

For the conventional flat fan nozzle, the only orifice at the end of the liquid passage controls all the initial spray characteristics. For the pre-orifice type, a pre-orifice was inserted right before the conventional orifice to decreases the nozzle pressure and control the liquid flow rate (Fig. 5). Therefore, coarser droplet size could be produced due to the reduced nozzle pressure.

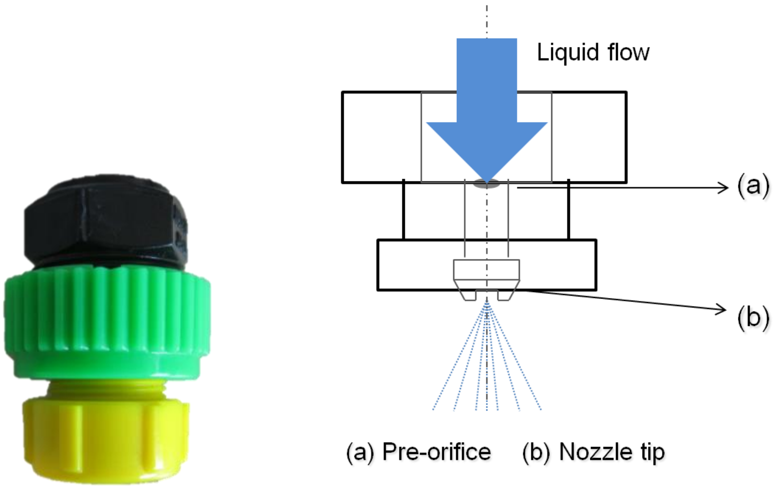

Figure 5 Photo and the corresponding structure view of the pre-orifice nozzle (SAVING series, YAMAHO Company) used on boom sprayers in Japan

Comparing with the conventional and pre-orifice flat fan nozzles, air inclusion nozzle is the most complicated nozzle (Fig. 6). A pre-orifice is set to control the liquid flow rate. In addition, an air inlet is set right below the pre-orifice to induce the air into the liquid passage. A nozzle tip was assembled at the end of the liquid passage. Therefore, the key parameters for the air inclusion nozzle include the pre-orifice, the air inlet and the nozzle tip. The influence of the parameters on the initial spray characteristics will be discussed in details in Chapter 3 and 4.

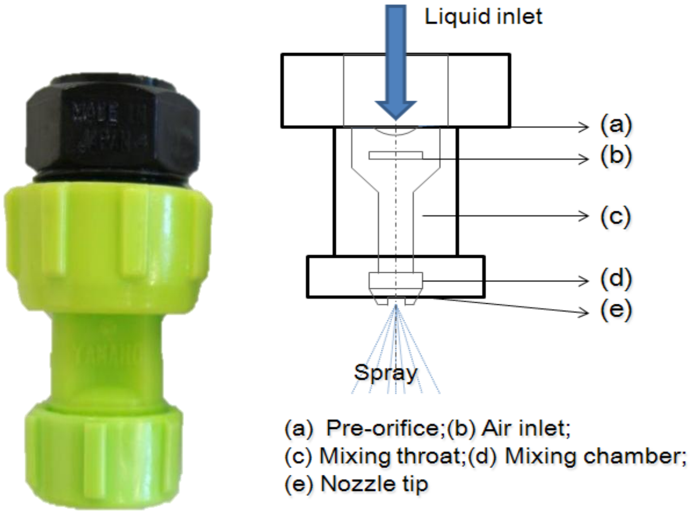

Figure 6 Photo and the corresponding structure view of the air inclusion nozzle (KIRINASHI ES series, YAMAHO Company) used on boom sprayers in Japan

1.5. The spray drift

Nowadays, spray drift produced by the pesticide spray has caused much attention since 1970s in many developed countries or regions. To understand the reason why spray drift should be controlled, the definition, mechanism and the potential hazard of the spray drift should be understood. In addition, the influence factors of spray drift are also necessary to understood for carry out spray drift control. The information was already concluded by public institutes. Therefore, the relative materials were used as a brief introduction.

1.5.1. Definition of spray drift

Spray drift of pesticide is defined as the physical movement of a pesticide through air at the time of application or soon thereafter, to any site other than that intended for application (often referred to as off-target). The movement of pesticide to off-target site caused by erosion, migration, volatility, or contaminated soil particles that are windblown after application are not included, unless specifically addressed on a pesticide product label with respect to drift control requirements (EPA).

1.5.2. The mechanism of spray drift

Different sizes of pesticide droplets are produced by sprayers. Compared with big droplets, the small droplets are earlier to move with the wind. When the droplets are sprayed out from sprayers, bigger droplets tend to deposit at the location close to the sprayer while the smaller ones tend to deposit at the location relatively far from the sprayer. A part of the small droplets evaporated before they deposit (Japan Plant Protection Association, 2010).

1.5.3. The potential hazard of spray drift

The spray drift could lead to the uncomfortable feelings or even health problems of nearby residents, contamination of nearby crops and mixture with nearby public water resources. And some examples were introduced as fellow (Japan Plant Protection Association, 2010):

For the influence on the nearby residents, the nasty smell and the deposit of pesticide on washed clothes on utensils are always complained. In recent years, the requests to considerate the anaphylaxis of chemical substance has been brought forward by nearby residents. It is also necessary to consider the spray drift which has potential to deposit on the people and vehicles passing by. The guidance announcement of pesticide application near residential block must be followed.

For the risk of the contamination of nearby crops, more and more people have realized the problem caused by spray drift after the positive list system for pesticide residues was introduced. The system for pesticide residues, as part of a revision of the Food Sanitation Law, was enacted in May 2006, in which the uniform criterion of 0.01 mg/kg as the maximum residue limit for pesticide residues was set for the first time (Mizukami et al., 2012).

If large amount of spray drift enters into the nearby public water resources, it will not only lead to the water contamination but also has bad influence on the fish and shellfish. It should be noticed that the pesticide residues limitation has also been set for the fish and shellfish, especially when high-toxic pesticide is sprayed near the water resources. Regardless of the pesticide category, the spray should be paid attention when spraying near drinking water sources. It is also important to pay attention when spraying pesticide near mulberry fields and the region of beekeeping.

1.5.4. The factors influence the spray drift

The property of the pesticide, the type of the spray system, operation parameters and the environmental conditions are the main factors which could potentially cause the problem by spray drift (Japan Plant Protection Association, 2010). According to the examples of problem mentioned in the last section, the corresponding suggestions were provided to users.

Although there are lots of specific situations need to be paid attention to avoid the problems caused by spray drift, one of the most direct and fundamental method is to decrease the quantity of the spray drift itself. The main factors that influence the risk of drift from boom sprayers are the droplet size characteristics, nozzle height, wind speed, the forward speed and the variables relating to the mounting of the nozzles on the boom (Miller et al., 2011).

1.5.5. Drift control methods

From the last section, it could be known that the drift control can be achieved by controlling the main factors which influence the spray drift for boom sprayers. For common pesticide application, spraying under low wind speed, using appropriate nozzle and working pressure, spraying appropriate volume are encouraged (Japan Plant Protection Association, 2010).

1.5.6. Spray drift estimation

Droplet size measurement, measurement of the relative spray drift in the wind tunnel and real spray drift measurement in the field have been used to estimate the drift reduction ability of the nozzle or the whole boom sprayer. Many relative researches were carried out and a comprehensive review was done by Nuyttens (2007). The main advantages and disadvantages of the methods were concluded as follows:

The reason why the droplet size measurement could be used to estimate the spray drift is because that the strong relationship was found between the volume proportion with the small droplets accounts and the drift reduction ability. Comparing with other two methods, the advantages of the method includes its maturity, high speed and also low labor cost. However, the influence of the nozzle height, which was mentioned as one of the most important factors influence the spray drift reduction ability, could not be investigated by droplet size measurement.

Comparing with the droplet size measurement, the measurement of the relative spray drift in the wind tunnel could investigate the influence of the nozzle height on the spray drift reduction ability. In addition, the method could be considered as a cost-saving method when compared with the field measurement of real spray drift. It should be also mentioned that the method could only obtain the relative result of spray drift reduction ability.

On one hand, the real spray drift measurement requires high cost and the repeatability of the measurement decreases due to the variation of the environment parameter during the experiment. On another hand, this method could estimate the spray drift reduction ability of the whole boom sprayer.

In Japan, the experiment of spray drift on boom sprayer was carried out as a part of a 3-year project which developed new spray technologies with low spray drift, such as the development of the new nozzles which could produces large droplets (Japan Plant Protection Association, 2004-2006). Since 2004, adequate field experiments of spray drift measurement were carried out. For boom sprayer, spray drift produced by the conventional and new nozzles was investigated.

In 2004, one kind of pre-orifice flat fan nozzle (SAVING series, YAMAHO Company) was proved to have better drift reduction ability while keeping similar result of pest control (Japan Plant Protection Association, 2004). In addition, one kind of new boom sprayer under development was also investigated (Japan Plant Protection Association, 2004). The result shows that the new boom sprayer had potential to reduce a large amount of spray drift.

In 2005, the performance of the nozzle which produce large droplet was investigated. The main performance investigated included deposit characteristics, pest control ability and drift reduction ability. For boom sprayer, the performance of the two new developed nozzles was investigated in cabbage field. The result showed that the new nozzles had much better drift reduction ability while had similar pest control result, comparing with the conventional nozzles (Japan Plant Protection Association, 2005).

The experiment carried out in Japan focused on the field test and also the droplet size measurement. The field test could estimate the situation of real spray drift and obtain the real performance of the pest control ability, which means that the result is relatively convincing. However, there are also some disadvantages for the field measurement. The cost of the field test is extremely high in Japan and the results could vary due to the unstable environment parameters during the test. If the categories of the nozzle series increase in the future, it might be difficult to test the performance of every new nozzle by the field test. In addition, it is also very difficult to test the performance of new nozzles on different types/brands of boom sprayers under different environment parameters.

1.5.7. The nozzle classification based on the spray drift

Wind tunnel test was introduced to compare the drift reduction ability among different nozzle systems without the influence of other parameters of the boom sprayer on the drift reduction ability. The advantages of this method also include the relatively high repeatability, time-saving and the possibility of investigating the nozzle height effect, comparing with the above field test and the droplet size measurement. Therefore, useful information could be obtained by the wind tunnel method, such as the classification of nozzles based on the spray drift and the influence of nozzle parameters on the spray drift (Donkersley and Nuyttens, 2011; Herbst, 2001; Nuyttens et al., 2011; Qi et al., 2008; Southcombe et al., 1997; Taylor et al., 2004).

1.6. Study objectives

To obtain a better understanding of the performance of the drift reduction nozzle used in Japan, the study objective of this thesis are: to (1) fill in the gap of the relative spray drift measurement of drift reduction nozzles used in Japan by wind tunnel method; and (2) investigate the influence of key design parameters of drift reduction nozzles used in Japan on initial spray characteristics.

Chapter 2 Characteristics and classification of Japanese nozzles based on relative spray drift potential

Abstract

European spray nozzle drift classifications have enabled the objective evaluation of the drift reduction performance of different nozzles with various operating parameters available in certain areas. The drift potential index reduction percentage (DIXRP) for one series of drift reduction nozzles used in Japan was investigated by wind tunnel tests. Based on the reference spray (Hypro ISO F110 03), most of the YAMAHO KIRINASHI ES nozzles had DIXRP values above 50% at nozzle heights from 0.3 m to 0.5 m, which means these nozzles can be considered as drift reduction nozzles. The best nozzle height range was found to be between 0.3 m and 0.4 m above the crop canopy. In addition, the DIXRP values were above 80% for a nozzle height of 0.3 m, except for one nozzle (the ES 05). Its smallest droplet size and low liquid flow rate could contribute to the large decrease in the DIXRP values for this nozzle size when nozzle pressure increased. Large droplet diameter, high droplet velocity and low recommended nozzle height are considered to be important factors that can provide good drift reduction performance although droplet velocity was not measured in this study. The DIXRP value was inversely proportional to nozzle height. In addition, the influence of nozzle size on the DIXRP values was found to be statistically significant (**$P < 0.01$), although the influence was not as obvious as that of nozzle height. Finally, a nozzle classification system for use in Japan based on the relative drift potential has been established.

2.1. Introduction

Spray drift from agricultural sprayers has attracted a great deal of attention in Japan because of its influence on neighboring residents, pollution of nearby crops, and contamination of adjacent water bodies (Japan Plant Protection Association, 2010). Boom sprayers are often used in field agriculture, and spray drift produced by boom sprayers is a potential pollution source (Miller and Butler Ellis, 2000; Kennedy et al., 2012). The construction and working parameters of spray nozzles are the main factors that influence spray drift from boom sprayers. Droplet size characteristics can be considered as an important factor related to spray drift (Taylor et al., 2004), and the effects of nozzle type, size and pressure on spray droplet size characteristics have been investigated (Nuyttens et al., 2007). In addition, the influence of nozzle type and size on relative spray drift potential was also found to be statistically significant (Nuyttens et al., 2009). Besides, droplet size distribution and nozzle height were investigated as two of the most important factors that influenced the spray drift from boom sprayers (Carlsen et al., 2006; Baetens et al., 2009; Miller et al., 2011). Therefore, air-inclusion nozzles that produce relatively larger droplet sizes have been developed to control spray drift in Japan, and these nozzles are commercially available (Japan Plant Protection Association, 2009). Drift reduction performance of the nozzles developed was evaluated qualitatively (Kubota et al., 2010). This type of nozzle now accounts for a substantial percentage of new agricultural nozzle sales in the UK (Miller et al., 2011). Recently, the demand for air inclusion nozzles in Japan has been increasing in the market (Miyahara, 2012).

The measurement of relative drift potential of drift reduction nozzles through wind tunnel tests was introduced in order to evaluate the drift reduction performance of the nozzles investigated (Herbst, 2001; Southcombe et al., 1997). The wind tunnel method has been proven to be a valuable alternative to field measurement of drift potential for evaluating the drift reduction performance of the spray nozzles (Nuyttens et al., 2011). Compared to field drift experiments, which can evaluate the drift reduction performance of the entire spray system, wind tunnel tests provide a repeatable and economical way to measure relative drift reduction potential of different nozzle types, sizes, pressures, heights and air speeds. This means that this method can consider not only the droplet size distribution but also important working parameters of nozzles (Taylor et al., 2004; Donkersley and Nuyttens, 2011). Wind tunnel tests have also been applied to drift classifications of nozzles (Southcombe et al., 1997; Herbst, 2001; Qi et al., 2008; Nuyttens et al., 2011) and an international standard for the wind tunnel measurement of the spray drift potential has been established (ISO 22856, 2008).

Due to the higher nozzle pressures (above 1.0 MPa) used in Japan, droplet size distribution, droplet velocity and nozzle height were assumed to differ from those of European nozzles, which are operated at lower pressures (usually below 0.5 MPa). Therefore, the drift reduction performance might also be different from that produced by lower pressure nozzles.

The objectives of the present study were (1) the measurement of relative spray potential for one series of Japanese drift reduction nozzles under different working parameters by the wind tunnel method and estimation of the drift reduction performance by comparison with the internationally accepted reference spray, (2) to investigate the influence of nozzle size, pressure and height on the drift reduction performance of this series of nozzles, and (3) to establish a nozzle classification system for drift reduction nozzles used in Japan.

2.2. Materials and methods

2.2.1. Wind tunnel parameters

The present study was carried out in the Bio-oriented Technology Research Advancement Institution (BRAIN), Saitama City, Japan. A sketch of the wind tunnel used in the present study is presented (Fig. 7). In this study, we did not adopt the horizontal deposit but focused on the vertical deposit at 2 m downwind of the wind tunnel because the length of the wind tunnel was not great enough for the horizontal deposit measurement according to the ISO standard (ISO 22856, 2008). The working section of the tunnel of the present study was from 0.3 m to 1.2 m above the tunnel floor at a location of 0–2 m downwind from the nozzle. The height of the lowest sampling line was set to be 0.3 m above tunnel floor for preventing droplet splash from the floor because there was no artificial turf on the floor and this gave an acceptable wind speed distribution for drift test. Owing to the various nozzle heights used in the field, the upper limitation of the nozzle height was set to be 1.2m.

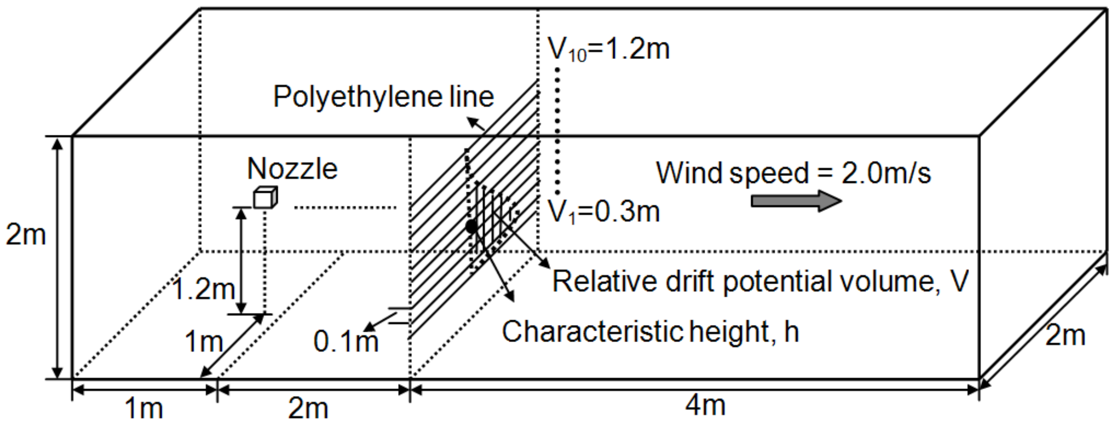

Figure 7 Sketch of the wind tunnel and the layout of the nozzle and polyethylene lines for the measurement of the relative drift potential

The wind tunnel produced a uniform flow with an average airspeed in the range from 0 to 5 m/s. In the present study, a wind speed of 2 m/s was applied in order to simulate the forward moving speed of a boom sprayer with a speed of 8 km/h (Nuyttens et al., 2009). In addition, other measurement results were found to be the most similar for the wind tunnel test when air speed was between 2.0 and 2.5 m/s (Parkin and Wheeler, 1996). According to the ISO standard (ISO 22856, 2008), the measurement of airflow parameters was performed using a three-cup anemometer, and the degree of turbulence and the local variability of air velocity were below 5% and 8% at 2 m downwind from the nozzle for nozzle heights of 0.3 and 1.2 m, respectively. An electronic pressure monitor and an electronic switch were installed directly above the investigated nozzle. In addition, one hygrothermograph was installed approximately 20 cm above the nozzle.

2.2.2. Measurement

In order to simultaneously obtain vertical deposits from nozzles with various working parameters, the nozzles were installed 1.2 m above the floor, and 10 polyethylene lines (V1–V10), with a diameter of 2 mm, were placed horizontally across the wind tunnel 2 m downwind from the nozzle at heights from 0.3 m to 1.2 m at 0.1 m intervals. A tracer (Sodium fluorescein, liquid type, 0.02%, w/w) and a non-ionic surfactant (Tween 20, 0.1%, w/w) were used in the present study. The non-ionic surfactant was used to simulate the real condition when the pesticide was applied. An Excel spreadsheet (Fritz et al., 2011) was used for recording and calculating the calibration equation between the relative fluorescence and the dye concentration. After spraying, the polyethylene lines were washed using 0.1 L of deionized water, and the liquid was collected in order to measure the tracer concentration. The deposit volume at one collector, v(i), was then obtained by the calibration equation.

2.2.3. Information on the investigated nozzles

The nozzle information and relative environmental parameters of the nozzles investigated in the present study are shown in Table 5.

Table 5 Overview of the investigated nozzle-pressure combinations and the environment parameters in the measurement of the relative spray drift

Notation[a]	Liquid flow rate[b], L min^{-1}	Pressure, MPa	Environment parameters[c]		
			Air temperature, ℃	Water temperature, ℃	Relative humidity, %
HS03-0.30	1.16	0.30	22.4	20.6	57.3
ES05-1.00	0.34	1.00	23.7	21.6	50.7
ES05-1.50	0.42	1.50	27.0	22.8	46.7
ES06-1.00	0.49	1.00	25.4	22.0	53.3
ES06-1.50	0.6	1.50	25.6	22.2	43.7
ES07-1.00	0.64	1.00	27.0	22.8	37.7
ES07-1.50	0.79	1.50	21.8	20.7	78.0
ES08-1.00	0.83	1.00	22.2	20.7	71.7
ES08-1.50	1.05	1.50	26.5	22.0	42.7
ES09-1.00	1.04	1.00	25.8	21.2	45.3
ES09-1.50	1.28	1.50	23.1	20.7	42.5
ES10-1.00	1.32	1.00	24.3	21.0	49.0
ES10-1.50	1.66	1.50	17.5	17.6	66.7
ES11-1.00	1.58	1.00	17.4	17.5	70.3
ES11-1.50	1.98	1.50	22.0	19.3	60.0

[a] HS03, Hypro ISO F 110 03 standard flat fan nozzle; ES, YAMAHO KIRINASHI ES nozzle;

[b] Liquid flow rate data were measured by the weighing method; [c] The values of the environment parameters were obtained by averaging the values of three repetitions.

All of the investigated conditions were repeated three times. Besides, the KIRINASHI ES nozzles produce a flat-fan spray jet pattern with 100°spray angle and a spacing of 0.3 m between nozzles on boom sprayers. And the nozzles investigated have been widely used as drift reduction nozzles in Japan, especially in the Hokkaido region (Miyahara, 2012). A Hypro ISO F 110 03 standard flat fan nozzle with a nozzle pressure of 0.3 MPa at a nozzle height of 0.5 m was used as the reference spray following the ISO standard (ISO 22856, 2008). The spray time for the nozzle-pressure combinations was 10 s when liquid flow rate was above 0.8 L/min and was 20 s for the other combinations.

2.2.4. Index calculation and nozzle drift classification

In the present study, the DIXRP value was calculated in order to estimate the drift reduction performance of the investigated nozzle-pressure combinations. The DIX method considered not only the total deposit volume and the weight of the collection height, but also the relationship between the data from wind tunnel test and those from the field test by introducing two parameters (Herbst, 2001). Additionally, RP (Reduction Percentage) was adopted because its value was easy to understand based on the drift reduction performance (Nuyttens et al., 2009). The drift potential index reduction percentage (DIXRP), which is a combination of the reduction percentage and the DIX, were obtained as follows:

$$V = \frac{\sum_{i=1}^{n} v(i)\Delta z_i}{V_N} \quad (1)$$

$$h = \frac{\sum_{i=1}^{n} v(i) z_i \Delta z_i}{\sum_{i=1}^{n} v(i)\Delta z_i} \quad (2)$$

$$DIXRP = \frac{(h_{rs}^{0.88} V_{rs}^{0.78} - h_{is}^{0.88} V_{is}^{0.78})}{h_{rs}^{0.88} V_{rs}^{0.78}} \times 100\% \quad (3)$$

where V: the relative drift potential volume; v(i): the deposit volume at one collector;

Δz_i: the representative height interval of one collector; V_N: the nozzle output; h: the characteristic height of the drift potential cloud; z_i: the collector height; hrs: the characteristic height of the drift potential cloud of the reference spray; V_{rs}: the relative drift potential volume of the reference spray; h_{is}: the characteristic height of the drift potential cloud of the investigated spray; V_{is}: the relative drift potential volume of the investigated spray.

In the calculation process, the nozzle height was 0.5 m for the reference spray, while the nozzle heights were 0.3 m, 0.4 m, 0.5 m, 0.7 m and 0.9 m for ES series nozzles. This allowed the influence of nozzle height on DIXRP values to be investigated. The virtual floors (h = 0 m) in the index calculation were assumed to be 0.2 m, 0.4 m and 0.6 m above the floor of the wind tunnel corresponding to the respective nozzle heights. Thus, the nozzle heights, which were equal to the vertical distance between the nozzle and the lowest polyethylene line, were 0.9 m, 0.7 m and 0.5 m. The nozzle drift classification for nozzle-pressure combinations investigated was carried out by following the methods adopted by the former Federal Biological Research Centre for Agriculture and Forestry (BBA, Germany) (Herbst, 2001).

2.3. Results and discussion

2.3.1. Effect of nozzle size

The influence of nozzle size on the DIXRP value for a nozzle pressure of 1.0 MPa and different nozzle heights is shown (Fig. 8). As shown in the figure, the index exhibited a trend of growth as nozzle size increased for a certain nozzle height and pressure. The index increased rapidly as nozzle size increased from 05 to 06. Considering the standard deviation, indices for nozzle sizes of 06 and 07 were found not to differ at all nozzle heights while the indices for other nozzle sizes showed an increasing trend as the nozzle size increased. The index increased linearly as nozzle size increased from 07 to 09. Finally, the index stopped increasing when nozzle sizes were 10 and 11. The reason why the index increased as nozzle size increased might be that droplet size and liquid flow rate also increased with the increase in nozzle size. However, the droplet size did not experience an increase when nozzle size increased. In this study, a laser analyzer, LDSA-1400A (Nikkiso), was used to measure the volume median diameter (VMD) at 0.3 m below the nozzle. The VMD for all nozzle sizes was in the range from 300 to 400 μm and from 250 to 350 μm for nozzle pressures of 1.0 and 1.5 MPa, respectively. The difference of the VMD for same nozzle size but at different nozzle pressures was about 50 μm while the smallest VMD was found with ES05-1.50. Based on the equation reported by Herbst (2001), relative drift potential volume was divided by the nozzle output. Therefore, the DIXRP value might increase as liquid flow rate increases when the absolute values of drift volume remains the same. The increase rate of liquid flow rate with the increase of nozzle size can be obtained through simple calculation based on Table 5. The maximum growth rate of liquid flow rate was observed when nozzle size increased from 05 to 06. This growth might contribute to the rapid increase in the DIXRP value from 05 to 06.

Generally, all of the index values were positive except for ES 05, 06 and 07 for a nozzle height of 0.7 m at a pressure of 1.0 MPa. The index values at a nozzle height of 0.9 m were all negative and are not shown in the figures. The results indicated that this series of nozzles can reduce the drift under the working conditions considered herein. When nozzle heights were between 0.3 and 0.5 m, the DIXRP values were above 50% with nozzle sizes from 06 to 11. However, only nozzle sizes of 10 and 11 had a drift reduction performance above 50% when nozzle height was increased to 0.7 m. Based on the BBA classification system, nozzles that have a drift reduction performance above 50% can be classified into three categories (50%+, 75%+ and 90%+) of drift reduction nozzles (Herbst, 2001). In addition, when nozzle height was between 0.3 and 0.4 m, all of the nozzles investigated could be classified into the 75%+ category, except for nozzle sizes of 05 and 06. In addition, most of the indices could achieve 90%+ when nozzle size was larger than 07 for a nozzle height of 0.3 m.

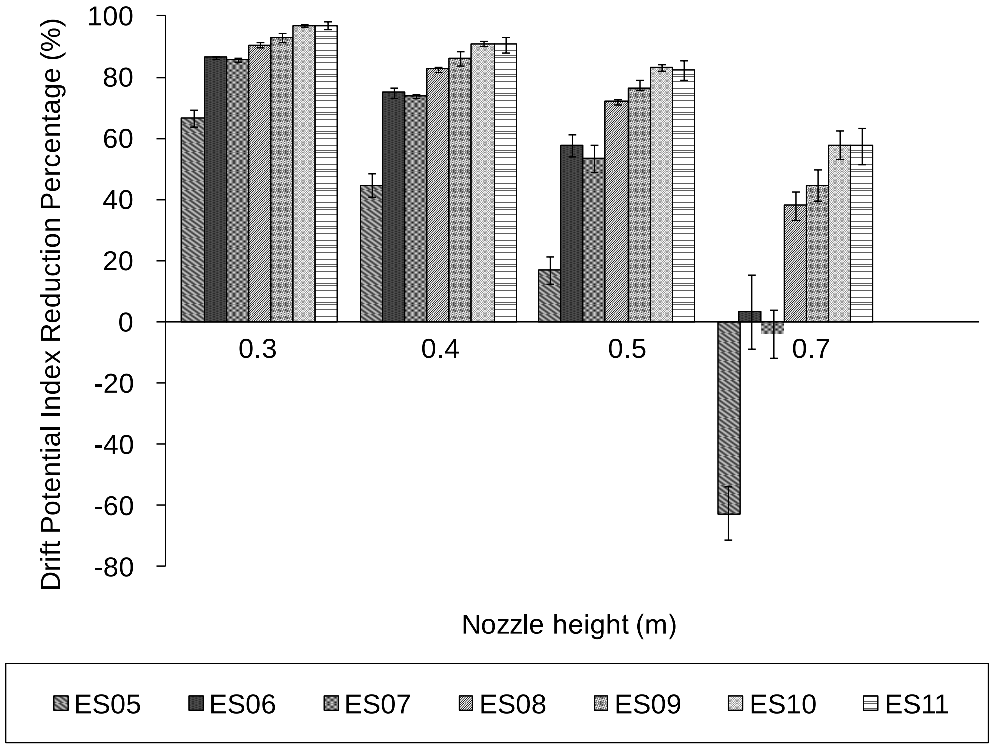

Figure 8 DIXRP values and standard deviations obtained under different nozzle-pressure combinations of ES series nozzle for various nozzle heights ranging from 0.3 to 0.7 m for a nozzle pressure of 1.00 MPa

The influence of nozzle size on the DIXRP value for a nozzle pressure of 1.50 MPa for various nozzle heights and sizes are illustrated (Fig. 9). When nozzle height was between 0.3 and 0.5 m, the DIXRP values were high and were close to the values obtained under 1.00 MPa for nozzle sizes from 06 to 11. However, no index value for the ES nozzles was found to be above 50% at a nozzle pressure of 1.50 MPa when nozzle height was 0.7 m. For a nozzle size of 05, all of the index values were negative for nozzle pressure of 1.50 MPa, which means that 05 nozzle could not be considered as a drift reduction nozzle under these conditions. In addition, the index was -76%, -178%, and -484% for the 05 nozzle at 1.50 MPa for nozzle heights of 0.4, 0.5, and 0.7 m, respectively. Therefore, nozzle height should be restricted to 0.3 m when 05 nozzle is used. The large increase of liquid flow rate was considered to be the important reason

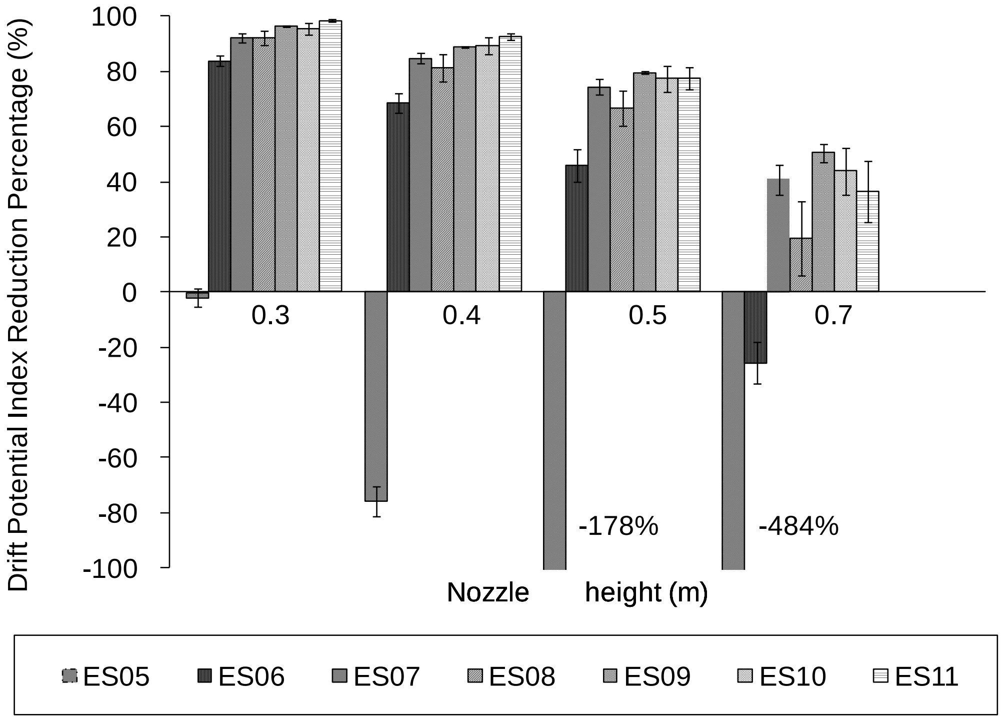

Figure 9 DIXRP values and standard deviations obtained under different nozzle-pressure combinations for ES series nozzles and for different nozzle heights of from 0.3 to 0.7 m for a nozzle pressure of 1.50 MPa

for the increase of DIXRP value from 05 to 06 nozzle.

From the data obtained by Nuyttens et al. (2009), the drift reduction index of air inclusion nozzles (Hardi ISO injet nozzle) increased gradually as nozzle size increased, although the trend was not statistically significant. All of the index values of injet nozzles were above 80%, which indicated good drift reduction performance under the investigated conditions. In the present study, the influence of nozzle size on the index value was found to be statistically significant by one-way analysis of variance (**P < 0.01). In addition, most of the DIXRP values produced by ES series nozzles were above 50% except 05 nozzle when nozzle height was between 0.3 and 0.5 m. It should be stressed that the ISO nozzle code cannot be directly compared with the nozzle size number of ES series nozzle due to the different coding methods. The ISO nozzle number was decided by liquid flow rate under a certain nozzle pressure, where the ES 05 nozzle has a nozzle diameter of 0.5 mm. For example, liquid flow rates of the ISO 03, 04 and 05 nozzles under 0.3 MPa are 1.2 L/min, 1.6 L/min and 2.0 L/min, respectively. Compared with ES nozzles, the ISO nozzles are relatively larger for the same nozzle numbers for ES nozzles. The difference in nozzle sizes indicates that a comparison of drift reduction performance between the two types of air inclusion nozzles for the same nozzle size is not possible. The reason for the existence of this difference may be that the nozzle pressures of ISO nozzles were much lower than those of ES nozzles. Therefore, a larger nozzle size was required in order to obtain a similar liquid flow rate to that of the ES nozzle. However, the drift reduction indices of nozzles investigated and Hardi ISO injet nozzles exhibited a similar trend of gradual growth when nozzle size increases. For the Hardi ISO injet nozzle, the increase in liquid flow rate and VMDs with nozzle size contributed to the increase in the drift reduction index. For the ES series nozzle with an average VMD of about 300 μm, the increase in liquid flow rate may be an important cause of the increase in the DIXRP values. In addition, since VMDs of the injet nozzles were above 500 μm (Nuyttens et al., 2007) while the value of the ES series nozzles were approximately 300 μm, the drift reduction indices of the ES series nozzles were assumed to be much smaller than those of the injet nozzles. However, the potential higher jet velocity due to the much higher nozzle pressure of ES series nozzles might contribute to the improved drift reduction performance because droplet velocity distribution is an important factor which influences the nozzle performance including drift risk (Miller and Butler Ellis, 2000). Therefore, jet velocity should be also investigated in the future.

2.3.2. Effect of nozzle height

When nozzle height increased from 0.3 to 0.7 m, the DIXRP values decreased rapidly (Fig. 8 and 9). In the present study, the influence of nozzle height on the index value was statistically significant by one way analysis of variance (**$P < 0.01$). When nozzle height was between 0.3 and 0.4 m, which was the recommended range of the nozzle height by the manufacturer, most of the index values were above 75% and at least half of the values were above 90%. These results indicated that a good drift reduction performance can be achieved if the users strictly adopt the recommended nozzle height. However, this range might be difficult to be meet in uneven fields or if higher work rates are wanted (Miller et al., 2011). When nozzle height was between 0.3 and 0.5 m, the index values for all the conditions investigated were higher than 50%, except for ES 05. When nozzle height increased to 0.7 m, the index values were negative for nozzle sizes smaller than ES 07, and all of the index values were negative when nozzle height reached 0.9 m. Thus, for a nozzle height of 0.9 m, the ES series nozzles might have no greater drift reduction ability compared with the reference spray because all the DIXRP values at 0.9m nozzle height were smaller than 19% based on the calculation result. Therefore, in order to obtain good drift reduction performance, users are recommended to apply pesticide at a nozzle height of less than 0.5 m.

2.3.3. Effect of nozzle pressure

The DIXRP values for the ES series nozzles under two different nozzle pressures at a nozzle height of 0.3 m are shown (Fig. 10). As shown in the figure, the influence of nozzle pressure on the index values is obvious for the ES 05, but is not clear for nozzle sizes from 06 to 11. The reason why the difference occurred was the drift volumes of ES 05-1.50 were much higher than those from other conditions at each height. The low liquid flow rate and the smallest VMD of ES 05-1.50 should be considered as an important factor that can increase drift risk. Therefore, other drift reduction methods should be applied in order to reduce the potential drift risk, otherwise relatively high drift might occur. For other nozzle heights, very similar conclusions can be obtained, where nozzle pressure did not have an obvious influence on the drift reduction performance of ES series nozzles, except for the ES 05 nozzle. In the present study, the influence of nozzle pressure on DIXRP values was statistically significant (**$P < 0.01$) only for nozzle sizes of 05 and 07 at all nozzle heights by one way analysis of variance.

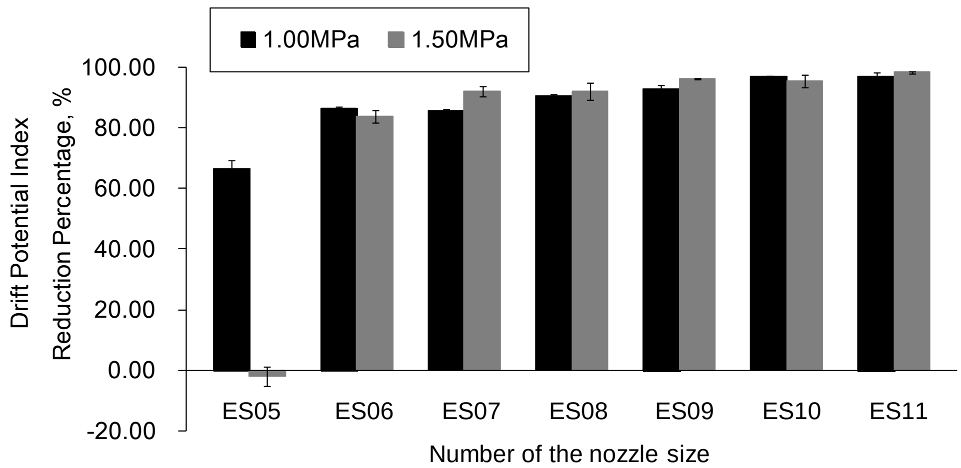

Figure 10 DIXRP values and standard deviations obtained under different nozzle-pressure combinations of ES series nozzle under various nozzle pressures of from 1.00 to 1.50 MPa for a nozzle height of 0.30 m

2.3.4. Drift classification

Based on the nozzle classification system of the drift reduction nozzle by BBA, the drift reduction performance of ES series nozzles of various sizes, pressures and heights was investigated (Table 6). The result revealed that the most important factor influencing the drift reduction performance was the nozzle height, followed by the nozzle size. Based on the above results, nozzle height should be controlled at least 0.3 to 0.5 m or even 0.3 to 0.4 m to achieve the best drift reduction performance of ES series nozzles. Moreover, this classification could help users to estimate the drift reduction level of the entire spray system and decide the buffer zone size with flexibility by combining with other application conditions of the field (Herbst, 2001).

Table 6 Nozzle classification of ES series nozzles based on the relative drift potential

Reference nozzle	**HS03 (0.3MPa nozzle pressure, 0.5m nozzle height)**		
Drift potential reduction percentages[a]	50%	75%	90%
YAMAHO KIRINASHI ES 05	1.00 (0.3) [b]		
YAMAHO KIRINASHI ES 06	1.50 (0.4)	1.00 (0.4)	
	1.00 (0.5)	1.00～1.50 (0.3)	
YAMAHO KIRINASHI ES 07	1.00 (0.4)	1.00 (0.3)	1.50 (0.3)
	1.00～1.50 (0.5)	1.5 (0.4)	
YAMAHO KIRINASHI ES 08	1.00～1.50 (0.5)	1.00～1.50 (0.4)	1.00～1.50 (0.3)
YAMAHO KIRINASHI ES 09		1.00～1.50 (0.4)	1.00～1.50 (0.3)
		1.00～1.50 (0.5)	
YAMAHO KIRINASHI ES 10	1.00 (0.7)	1.50 (0.4)	1.00 (0.4)
		1.00～1.50 (0.5)	1.00～1.50 (0.3)
YAMAHO KIRINASHI ES 11	1.00 (0.7)	1.00～1.50 (0.5)	1.00～1.50 (0.3)
			1.00～1.50 (0.4)

[a] Drift reduction percentage, 50%, 75% and 90%, were DIXRP values.

[b] 1.00(0.3) represented spraying at 1.00 nozzle pressure and 0.3m nozzle height.

Due to the difference in the nozzle pressure range adopted in Japan and other countries, ISO nozzles are not widely used in Japan. In addition, there are far fewer types of drift reduction nozzles in the domestic Japanese market than in the European market. Compared with the established evaluation system for the drift reduction spray system in some European countries, the two reasons described above might limit research and more precise regulations for precise drift governance for the pesticide application.

The present study may be the first investigation of relative drift potential of pesticide nozzles used in Japan. The classification table provides the users with relatively objective and visual information of the drift reduction performance of ES series nozzles. The table can be expanded as more types of drift reduction nozzles become available. Finally, note that, in the present study, the air temperature and the relative humidity cannot be controlled, which means that the results may vary when this test is carried out under different environment parameters.

2.4. Conclusion

In conclusion, the relative drift potential for one series of drift reduction nozzles used in Japan was measured under different combinations of nozzle size, pressure and height. The results reveal that the influence of nozzle height and nozzle size on the index value were statistically significant (**$P < 0.01$), whereas the nozzle pressure has a significant effect (**$P < 0.01$) on the index value only for nozzle sizes of 05 and 07. Compared with the reference spray, the ES series nozzles had drift reduction abilities above 50% when the nozzle height was between 0.3 and 0.5 m, except for the ES 05 nozzle. According to the spray distribution performance, the best nozzle height range is between 0.3m and 0.4m above the crop canopy. The results provided the users objective information for the relative drift reduction performance of ES nozzles and could also be expanded as more types of drift reduction nozzles become available.

Chapter 3 The influence of design parameters on the initial spray characteristics of the high-pressure air inclusion nozzle used in Japan

Abstract

Over 40000 sets of the air inclusion nozzles, KIRINASHI ES series with high nozzle pressure, have being already used as one of the best drift control methods on the boom sprayers in Japan. To get better understanding of the relationship between the key nozzle design parameters and the initial spray characteristics, the influence of the key design parameters and nozzle pressure of KIRINASHI ES series nozzles on the droplet size characteristics, spray angle, liquid flow rate and included air within droplets was investigated. The results show that the nozzle pressure and the pre-orifice diameter had negative correlations with the volume median diameter ($D_{v0.5}$) while the nozzle tip area had a positive effect on the $D_{v0.5}$. In addition, the nozzle pressure and the pre-orifice diameter had positive correlations with the spray angle. The pre-orifice diameter and the nozzle tip area significantly influence the spray liquid density which could indicate the quantity of included air within droplets. The corresponding multivariate regression analysis was carried out and relative high values of the coefficient of determinations (R2) were obtained between several nozzle parameters and the $D_{v0.5}$, the spray liquid density and the liquid flow rate.

3.1. Introduction

Spray drift control of the pesticide application has caused much attention all over the world because the drift could not only do harm to the human health but also lead to the environmental pollution. In the field of the drift reduction technology for boom sprayers, air inclusion nozzles which can produce large droplet with included air within droplets have been commercially popularized for users to control spray drift. In the UK, the pesticide nozzles with air-injection designs now account for a substantial proportion in the sale market of new agricultural nozzle (Miller et al., 2011). In Japan, approximately 400,000 sets of air inclusion nozzles for boom sprayers have been sold (Miyahara, 2012).

Initial spray characteristics of nozzles are very important due to their influence on the different aspects of spray performance. Droplet size was proved to be a vital factor because it has strong relationship with the spray drift, droplet velocity and also coverage rate (Butler Ellis et al., 2002; Nuyytens et al., 2007). Liquid flow rate of the individual nozzle might have strong effect on the forward speed of the boom sprayer if spray drift level is acceptable at higher forward speed. A shorter working time means lower labor cost and energy consumption. For the boom sprayer, the combined spray pattern of the nozzles might be uneven when the spray angle is too narrow at low nozzle height.

The included air within droplets produced by air inclusion nozzles is another important feature to improve spray performance. Almost all the manufactures claim that the air inclusion nozzle could produce droplet with included air within droplets which improve the deposit efficiency of the droplets. The presence of air within droplets influences droplet size and velocity, impaction, retention, and spray drift (Combellack & Miller, 2001). However, the quantitative study of the included air within droplets produced by air inclusion nozzles was limited. Butler Eillis et al. (2002) obtained the spray liquid density by matching the droplet velocities between the calculated and measured values. However, no deeper analysis between nozzle design parameters and spray liquid density was carried out. Faggion, Miller and Butler Ellis (2006) compared two different methods for measuring the quantity of included air and concluded that the measurement of the density of collected spray by a cylinder (Hereafter, cylinder method) could discriminate between different air inclusion nozzle designs while the measurement of impact force could only discriminate the quantity of included air between an air inclusion nozzle and a conventional nozzle. Using cylinder method, Dorr et al. (2013) found that spray mixtures significantly affect the spray liquid density of air inclusion nozzles. The spray liquid density was approximately 1000kg m-3 when only water was sprayed which means no included air was found. This might be the reason that Guler et al. (2007) doubted the existence of the included air within droplets.

With the development and application of air inclusion nozzles, several researches were carried out to investigate the influence of the nozzle design parameters, nozzle pressure, and the properties of the spray liquid on the spray characteristics including droplet characteristics, spray angle, spray liquid density, liquid flow rate and spray drift (Butler Ellis et al., 2002; Dorr et al., 2013; Guler et al., 2007; Miller & Butler Ellis, 2000; Nuyttens et al., 2007). However, no deeper analysis and the regression relationships were obtained between key design parameters and the droplet size characteristics in the studies above. Among the influential factors above, the nozzle design parameters should play very important roles. However, only a few deep researches were found. Butler Ellis et al. (2002) manufactured an air inclusion nozzle to investigate the influence of Venturi injector diameter, Venturi throat diameter, nozzle tip size, air inlet size on the spray performance. The result showed that (1) liquid flow rate was only controlled by Venturi injector diameter; (2) The estimated quantity of included air within droplets increased with the increasing of the air flow rate from air inlet, however, was independent of the nozzle tip size; and (3) the droplet size was controlled by nozzle tip size. However, only 2 liquid flow rates were available and 2 nozzle tips were compared in the measurement of the droplet size. Therefore, no further analysis was able to carry out. Nuyttens et al. (2007) found that the volume median diameter ($D_{v0.5}$) of the investigated air inclusion nozzles (Hardi Injet) was directly proportional to the International Standard Organisation (ISO) nozzle size. However, when nozzle size increases for the investigated nozzle, the sizes of the pre-orifice, air inlet and finial orifice increase at the same time. Therefore, the independent influence of these key design parameters could not be obtained.

The different design and working parameters of air inclusion nozzles from different manufactures might also result in different relationship between key design parameters and droplet size characteristics. The nozzle pressure of air inclusion nozzles on boom sprayers is normally between 1.0-1.5 MPa in Japan, which is much higher than the nozzle pressure used in other regions, such as Europe. Therefore, it is necessary to investigate the influence of the key design parameters on the droplet size characteristics, spray angle, liquid flow rate and included air within droplets of the high-pressure nozzle used in Japan.

The objectives of the present study were to investigate the influence of the pre-orifice diameter, the nozzle tip area and the nozzle pressure on the initial spray characteristics including droplet size characteristics, liquid flow rate, spray angle and included air within droplets by multivariate regression analysis.

3.2. Material and methods

3.2.1. Spray nozzles

The design of KIRINASHI ES series nozzle (YAMAHO) follows the common design principles of air inclusion flat fan nozzles. As shown in Fig. 1, the spray liquid goes through the pre-orifice and mixed with the induced air entering from the air inlet by Venturi effect to form a liquid jet with included air. A mixing chamber was created at the downstream of the mixing throat by a two-hole washer to provide sufficient mixing of the air and liquid. Finally, the air included droplets spray out from a rectangular shaped nozzle tip.

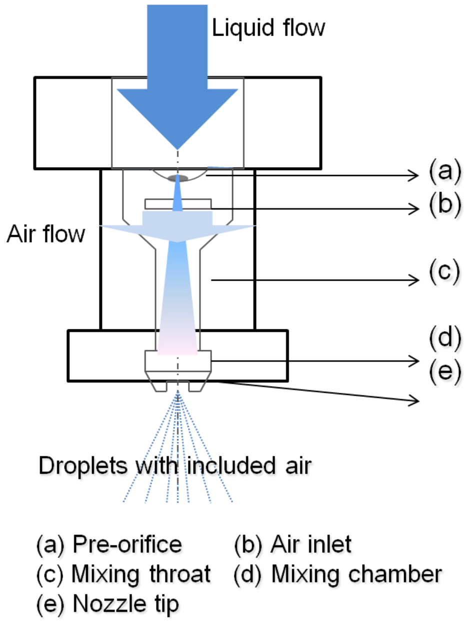

Figure 11 Design features of KIRINASHI ES series nozzles. The range of the pre-orifice diameter is 0.5 -1.1mm with a 0.1mm interval; the size of the air inlet and the diameter of the mixing throat keep consistent; the corresponding range of the nozzle tip area is 0.57-2.19 mm^2

The nozzle pressure of the ES series nozzle was from 1.0 to 1.5MPa, which is much higher than that of the air inclusion flat fan nozzles being used on the boom sprayer in other countries. Hardi Inject nozzle (HARDI) was compared as a typical low-pressure air inclusion nozzle as follows. Compared with the pre-orifice diameter of Hardi Injet nozzles, the pre-orifice diameter of KIRINASHI ES series nozzles is much smaller for controlling the liquid flow rate with similar values when higher nozzle pressure was used. In addition, the shape of the air inlet and the nozzle tip of KIRINASHI ES series nozzles are rectangle while Hardi Injet nozzles have a circular air inlet and a nozzle tip with ellipse shape. When the nozzle size increases, the size of the air inlet and the nozzle tip increase with pre-orifice diameter for Hardi Injet nozzles, which is not the case for KIRINASHI ES series nozzles. For KIRINASHI ES series nozzle, the sizes of the air inlet remain the same as the size of the pre-orifice and the nozzle tip increase. There are 7 and 6 different sizes of pre-orifice and the nozzle tip, respectively. Besides, the pre-orifice and the nozzle tip could be taken apart with each other which mean 42 potential combinations of the pre-orifice and nozzle tip were obtained while the size of the air inlet kept constant. Table 7 shows the detail information of the nozzle tip area, the pre-orifice diameter and the investigated nozzle pressure. The influence of the two design parameters on the initial spray characteristics was investigated under different nozzle pressures.

The nozzle tip area were measured by image processing method with a CCD camera (DFK 31BF03, The Imaging Source), MATLAB software (MATLAB 2012, Mathworks) and a computer. In addition, there are 7 different pre-orifice diameters with the range from 0.5 to 1.1mm.

Table 7 Investigated design and working parameters included the nozzle tip areas, the diameter of pre-orifice and the nozzle pressure

	Nozzle tip	**Pre-orifice**		**Pressure**
Notation[a]	Area of the nozzle tip[b], mm^2	Number[c]	Diameter of the pre-orifice, mm	Nozzle pressure, MPa
SR1A	0.57	05	0.5	1.00
KS8	1.01	06	0.6	1.25
KS9	1.08	07	0.7	1.50
KS10	1.40	08	0.8	
KS11	1.63	09	0.9	
SR4	2.19	10	1.0	
		11	1.1	

[a]: Notations are from Company data sheet; [b]: Area of the nozzle tip was obtained by image processing technique; [c]: Numbers are from Company data sheet.

3.2.2. Measurement of droplet size characteristics, liquid flow rate and fan angle

The measurement of droplet size characteristics under all available combinations of pre-orifice and nozzle tip at three nozzle pressures were carried out (Table 8). A laser diffraction analyser, LDSA-1400A (Nikkiso), was used in this study to measure the droplet size characteristics. Using the accessory software, the volume distribution of droplet sizes can be determined, in addition to important characteristics of droplet size including volume diameters below which smaller droplets constitute 10%, 50% and 90% of the total volume ($D_{v0.1}$, $D_{v0.5}$ and $D_{v0.9}$), relative span factor indicating the uniformity of the droplet size distribution (RSF), arithmetic mean diameter (D_{10}), surface mean diameter (D_{20}), volume mean diameter (D_{30}), Sauter mean diameter (D_{32}), the volume percentage of droplets smaller than 50μm (V_{50}), 100μm (V_{100}), 150μm (V_{150}), 200μm (V_{200}) and 250μm (V_{250}), respectively (Nuyttens et al., 2007). The calculation equations for RSF, D_{10}, D_{20}, D_{30} and D_{32} were shown in the equations as below (Eq. (4)-(8)).When measuring the droplet size characteristics, the vertical distance between the nozzle and the laser beam was 0.3m. For each combination of the nozzle size and nozzle pressure, the measurement was repeated five times. Tween 20 used in the measurement of the relative spray drift was also applied to tap water to obtain a 0.1% w/w solution with similar physical properties to those of real pesticide (Nuyttens, 2007). One automatic hygrothermograph was placed near the spray nozzle to record the environment parameters during the experiment. During the measurement, the average air temperature and the relative humidity were 30℃ and 70%, respectively. Liquid flow rates were recorded by mass method and repeated 3 times.

$$RSF = \frac{D_{v0.9} - D_{v0.1}}{D_{v0.5}} \tag{4}$$

$$D_{10} = \frac{\sum_{i=1}^{n} d_i}{n} \tag{5}$$

$$D_{20} = \sqrt{\frac{\sum_{i=1}^{n} d_i^2}{n}} \tag{6}$$

$$D_{30} = \sqrt[3]{\frac{\sum_{i=1}^{n} d_i^3}{n}} \tag{7}$$

$$D_{32} = \frac{\sum_{i=1}^{n} d_i^3}{\sum_{i=1}^{n} d_i^2} \tag{8}$$

Where d_i: the diameter of droplet i, μm; n: the total number of droplets.

Table 8 Pre-test result of spray stability under all possible combinations of nozzle tip areas and pre-orifice diameters

	Nozzle tip number					
Pre-orifice number	**SR1A**	**KS8**	**KS9**	**KS10**	**KS11**	**SR4**
05	○	○	○	●	●	●
06	○	○	○	○	○	○
07	※	○	○	●	●	●
08	※	○	○	○	○	○
09	※	※	○	●	●	●
10	※	※	※	○	○	○
11	※	※	※	※	●	●

※: Combinations which produce unstable spray; ○: Combinations which produced stable sprays and the measurement of droplet size characteristics, spray angle and liquid flow rate were carried out under the combinations; ●: Combinations which produced stable sprays and the measurement of droplet size characteristics, spray angle, liquid flow rate and the included air within droplet were carried out under the combinations.

The measurement of the spray angle under same combinations of design parameters at three nozzle pressures were carried out (Table 8). One digital camera (FinePix F200EXR, Fujifilm) was used to take the photo of the spray sheet at the area of the nozzle tip after adjusting the nozzle pressure and before and measurement of the droplet size measurement. Image analysis software (IrfanView, Irfan Skiljan, Graduate of Vienna University of Technology) was used to measure the fan angle of the spray sheet by manually drawing 2 straight lines at the boundary between spray sheet and air. The measurement by the software was repeated 5 times under each spray.

3.2.3. Measurement of included air within droplets

Fig. 12 shows the sketch of the measurement of the spray liquid density (Faggion et al., 2006; Dorr et al., 2013). 11 combinations which covered the whole range of the pre-orifice diameter were investigated under nozzle pressures of 1.0 and 1.5MPa (Table 8). A higher spray liquid density indicates less quantity of included air exists within droplets. Black curtains were used to create a relative static environment without any potential air flow turbulence during the experiment. A 250ml glass cylinder (2ml resolution) was placed right below the nozzle tip of the investigated nozzle to collect the spray droplet with included air with a vertical distance of 1.0m between the nozzle tip and the bottom of the cylinder. An automatic hygrothermograph was placed near the spray nozzle to record the air temperature and the relative humidity during the experiment.

The spraying was then carried out and a foam layer above the liquid surface with a certain thickness was observed in the cylinder. In the previous study, liquid was sprayed until the cylinder was approximately three quarters full (Faggion et al., 2006; Dorr et al., 2013). However, it took too long time to achieve three quarters full for small pre-orifice diameters (0.5 and 0.7mm) and the thickness of the foam layer decreases when collecting time passed based on the pre test. Therefore, a fix spray duration of 10min was set for the pre-orifice diameters of 0.5 and 0.7mm. After 10min spray, approximate 100ml of the foam and liquid was collected by the cylinder for 0.7mm pre-orifice diameter. In addition, a fix spray duration of 6min was set for large pre-orifice diameters (0.9 and 1.1mm) to collect approximate 100ml by the cylinder. After spraying, the cylinder was removed on a flat surface nearby as soon as possible. Then, the scale on the top of the foam was recorded to estimate the volume of spray. The weight of the collected liquid was then measured by an electrical scale. The density of the spray liquid and the average percentage of air within spray droplets were calculated based on the Eq. (9) (Dorr et al., 2013).

$$\rho_s = \frac{w}{V_f} \times 1000 \tag{9}$$

Where ρ_s: spray liquid density, kg m^{-3}; V_f: volume of spray, L; w: weight of spray, kg.

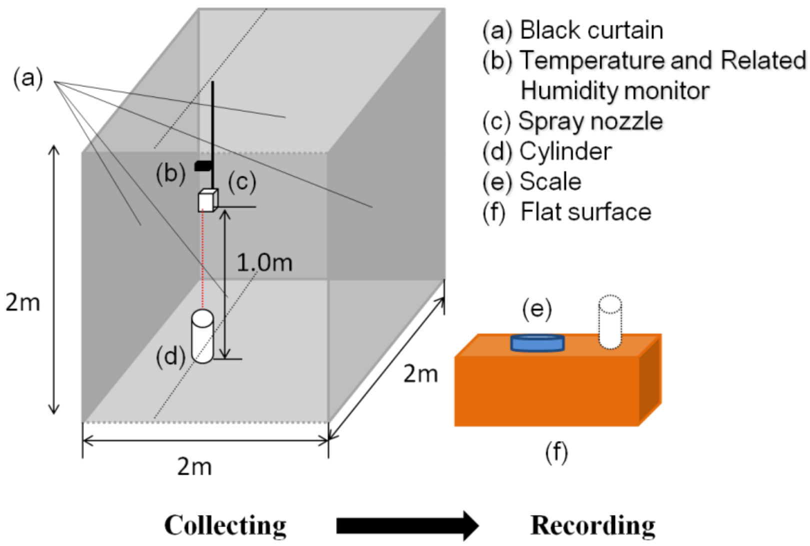

Figure 12 Sketch of the measurement of the spray liquid density

3.3. Results and Discussion

3.3.1. The influence of nozzle design parameters on the droplet size characteristics

Fig. 13 and Table 9 show the volume accumulation of droplet size and the result of the droplet size characteristics under same investigated conditions. 18 of 31 investigated combinations of the pre-orifice, nozzle tip and nozzle pressure were given to demonstrate the influence of the three factors on the droplet size characteristics.

The influence of nozzle pressure on the droplet size characteristics was obtained. The volume accumulation line of droplet size moved rightwards as nozzle pressure decreased which means that the droplet size increased as nozzle pressure decreased from 1.5MPa to 1.0MPa while the size of the pre-orifice and the nozzle tip kept constant. Table 9 shows the specific change of the droplet size characteristics. $D_{v0.5}$ was the most frequently and widely used indicator representing the droplet size characteristics. Besides, the whole droplet size distribution characteristics could be obtained by introducing $D_{v0.1}$, $D_{v0.5}$ and $D_{v0.9}$. The RSF is an indicator calculated from the three characteristics to estimate the uniformity of the droplet size distribution (Nuyttens et al., 2007). The volume percentage of droplets smaller than a certain diameter was found to be the best indicator of the spray drift index with a range from 75 to 200μm (Donkersley & Nuyttens, 2011). Therefore, these droplet size characteristics were also shown. The relationship among the droplet size characteristics will be discussed later in this study. Table 9 shows that $D_{v0.1}$, $D_{v0.5}$ and $D_{v0.9}$ increased as nozzle pressure decreased with the maximum increase of 30, 44 and 62μm, respectively, when nozzle pressure decreased from 1.5 to 1.0MPa at all the investigated conditions. The result also indicated that the influence of the nozzle pressure was relative small. In addition, the effect of the nozzle pressure on the droplet size characteristics of the investigated flat fan nozzles was found to be very limited when comparing with the effect of nozzle size and type (Nuyttens et al., 2007).

The influence of the nozzle tip area on the droplet size characteristics was investigated. When the nozzle tip area increased from SR1A (0.57mm2) to SK11 (1.63mm2) with a constant pre-orifice diameter of 0.5mm and a nozzle pressure of 1.0MPa, the volume accumulation line of droplet size moved rightwards and $D_{v0.1}$, $D_{v0.5}$ and $D_{v0.9}$ increased from 166.5, 269.1 and 372.5μm to 243.4, 395.8 and 550.6μm, respectively. The same trend was also found under other nozzle pressures and pre-orifice diameters. These trends indicated that the nozzle tip area was proportional to the droplet size for ES nozzles. Miller et al (2002) concluded that the nozzle tips dominated the influence of the design factors on the droplet size for the investigated air inclusion nozzle. However, only 2 nozzle tips were tested and only qualitative result was obtained.

Except Miller et al (2002), little literature was found which studied the independent influence of the nozzle tip area on the droplet size without changing other key design parameters, such as pre-orifice diameter. Based on the previous studies, the droplet size characteristics of air inclusion nozzles increased when nozzle size increased (Guler et al., 2007; Nuyytens et al., 2007). However, with the increase of the nozzle size, the size of the pre-orifice, the air inlet and the nozzle tip increased simultaneously which means that it was difficult to investigate the independent influence of the key design parameters on the droplet size characteristics due to the lack of the available combinations of these parameters. Therefore, the potential reason why $D_{v0.5}$ increased in the previous study might be that the influence of the nozzle tip area surpassed the opposite influence of the pre-orifice diameter. In this study, $D_{v0.1}$, $D_{v0.5}$ and $D_{v0.9}$ decreased from 243.4, 395.8 and 550.6μm to 148.0, 256.6 and 369.7μm when the pre-orifice diameter increased from 0.5 to 1.1mm under a nozzle pressure of 1.0MPa and a KS11 nozzle tip (Table 9). The similar trends between the pre-orifice diameter and the droplet size characteristics were also found under other combinations of nozzle tip area and nozzle pressure.

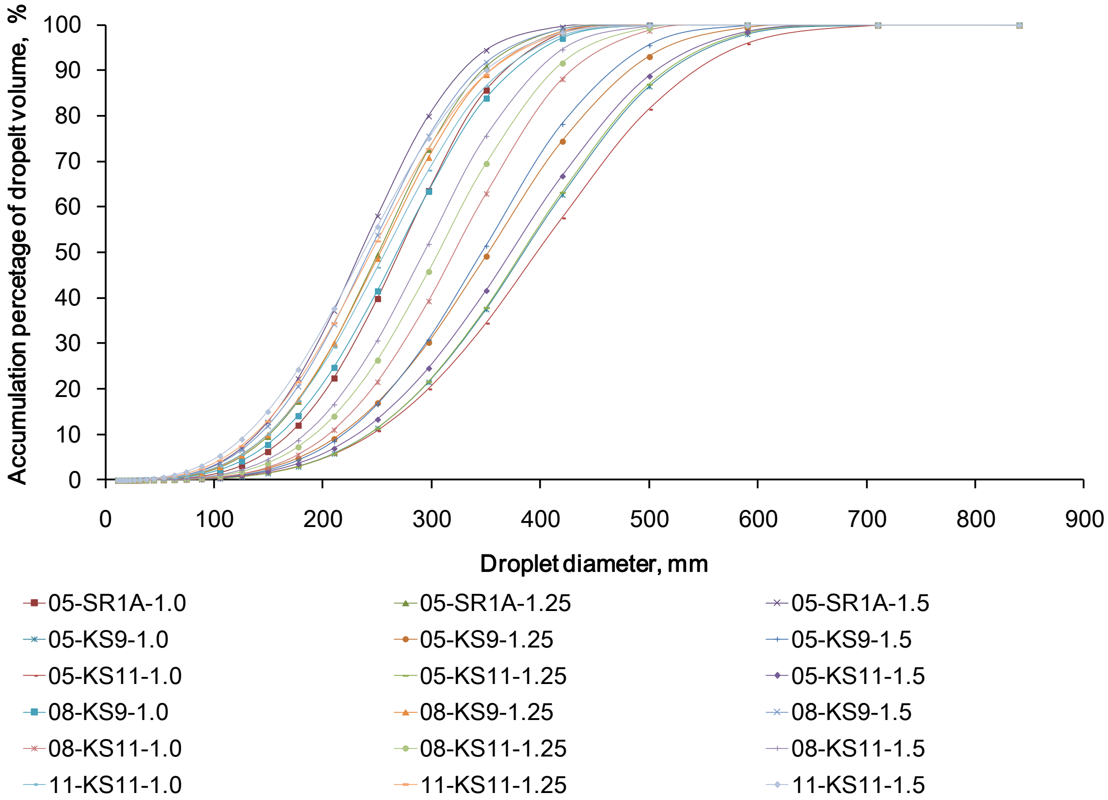

Figure 13 Accumulation percentage of the droplet volume (Part of the investigated data). The notation 05-SR1A-1.0 means the measurement of the droplet size was carried out with a pre-orifice diameter of 0.5mm, a nozzle tip of SR1A with an area of $0.57mm^2$ and a nozzle pressure of 1.0MPa

Table 9 Droplet size characteristics under different combinations of pre-orifice diameter, nozzle tip area and nozzle pressure with the average values from 5 repetitions and the corresponding standard deviations (Part of the investigated data)

Samples	$D_{v0.1}$	$D_{v0.5}$	$D_{v0.9}$	RSF	D_{10}	D_{20}	D_{30}	D_{32}	D_{50}	D_{100}	D_{150}	D_{200}	D_{250}
05-SR1A-1.0[a]	166.5±2.5	269.1±1.9	372.5±5.2	0.8±0.0	166.5±2.5	201.7±2.3	226.5±1.7	240.8±2.0	0.1±0.0	1.4±0.1	6.5±0.4	19.5±0.7	39.9±0.9
05-SR1A-1.25	149.8±9.9	250.4±8.0	347.8±5.4	0.8±0.1	149.8±9.9	183.6±9.1	208.8±9.3	220.6±10.2	0.2±0.1	2.4±0.9	9.9±2.4	26.4±3.8	49.5±4.0
05-SR1A-1.5	137.0±3.1	233.7±1.9	332.7±3.5	0.8±0.0	137.0±3.1	169.8±3.0	193.3±2.3	204.7±2.7	0.3±0.1	3.3±0.4	13.1±0.9	33.0±1.0	58.1±1.0
05-KS9-1.0	241.3±18.1	383.0±16.7	523.4±19.1	0.7±0.0	241.3±18.1	290.0±18.5	325.2±17.5	344.5±19.5	0.0±0.0	0.3±0.2	1.6±0.8	5.0±1.9	11.4±3.5
05-KS9-1.25	214.4±9.3	351.5±10.6	485.3±8.6	0.8±0.0	214.4±9.3	260.6±9.4	294.9±10.7	312.0±11.4	0.0±0.0	0.6±0.2	2.6±0.6	7.9±1.4	17.0±2.5
05-KS9-1.5	216.7±0.9	345.9±2.5	472.7±3.2	0.7±0.0	216.7±0.9	260.3±1.2	293.9±2.0	310.3±1.7	0.0±0.0	0.4±0.0	2.3±0.1	7.3±0.2	16.7±0.3
05-KS11-1.0	243.4±9.3	395.8±8.0	550.6±12.3	0.8±0.0	243.4±9.3	296.0±8.4	332.9±8.2	352.7±8.3	0.0±0.0	0.4±0.1	1.6±0.4	4.9±0.8	10.8±1.4
05-KS11-1.25	240.0±7.7	381.8±5.6	522.5±5.5	0.7±0.0	240.0±7.7	289.3±7.7	323.3±6.3	343.5±7.0	0.0±0.0	0.3±0.1	1.5±0.3	5.0±0.7	11.4±1.3
05-KS11-1.5	229.0±9.5	371.9±9.2	510.7±13.8	0.8±0.0	229.0±9.5	277.5±10.2	313.2±8.9	332.0±10.3	0.0±0.0	0.4±0.1	1.9±0.4	6.0±1.0	13.4±1.8
08-KS9-1.0	158.1±1.7	267.2±3.6	380.2±8.3	0.8±0.0	158.1±1.7	194.5±2.2	221.8±2.4	234.9±2.7	0.2±0.0	2.0±0.1	8.1±0.3	21.8±0.8	41.6±1.5
08-KS9-1.25	148.7±2.5	252.4±3.4	356.2±6.1	0.8±0.0	148.7±2.5	182.8±2.2	209.4±3.2	220.3±3.1	0.2±0.0	2.6±0.2	10.3±0.5	26.6±1.1	48.7±1.6
08-KS9-1.5	140.1±3.5	241.6±3.9	343.4±3.4	0.8±0.0	140.1±3.5	174.7±3.8	199.1±3.7	210.4±3.8	0.3±0.0	3.2±0.3	12.2±0.9	30.4±1.5	53.8±1.9
08-KS11-1.0	203.2±2.4	319.8±1.9	433.0±3.5	0.7±0.0	203.2±2.4	243.6±2.4	271.3±1.9	288.8±2.1	0.0±0.0	0.6±0.0	2.9±0.1	9.5±0.4	21.6±0.6
08-KS11-1.25	189.8±4.6	305.7±5.3	414.2±4.3	0.7±0.0	189.8±4.6	228.7±5.0	258.3±4.6	273.7±5.8	0.0±0.0	0.8±0.1	3.9±0.5	12.1±1.2	26.4±2.0
08-KS11-1.5	181.9±1.7	292.5±4.9	401.5±5.8	0.8±0.0	181.9±1.7	219.0±2.5	247.7±3.6	261.7±3.6	0.1±0.0	1.0±0.0	4.7±0.2	14.4±0.6	30.7±1.4
11-KS11-1.0	148.0±4.9	256.6±2.9	369.7±4.7	0.9±0.0	148.0±4.9	183.8±3.8	211.4±3.7	222.2±4.5	0.3±0.1	2.7±0.4	10.3±1.1	25.9±1.5	46.8±1.5
11-KS11-1.25	135.4±3.0	243.9±2.1	355.8±3.7	0.9±0.0	135.4±3.0	171.5±3.2	197.8±2.6	208.2±2.9	0.4±0.1	3.9±0.3	13.3±0.8	30.8±1.0	52.6±0.9
11-KS11-1.5	128.6±2.6	236.5±2.5	349.7±1.3	0.9±0.0	128.6±2.6	163.4±3.0	190.3±2.8	199.7±3.3	0.6±0.1	4.8±0.4	15.4±0.9	33.9±1.2	55.7±1.0

[a]:The notation 05-SR1A-1.0 means the measurement of the droplet size was carried out with the pre-orifice size of 05 which means a diameter of 0.5mm, a nozzle tip of SR1A with an area of $0.57mm^2$ and a nozzle pressure of 1.0MPa

After obtaining different droplet size characteristics, the correlation analysis among the droplet size characteristics were carried out (Table 10). The investigated droplet size characteristics were as same as that of Table 9 and the correlation coefficient (R) between different droplet size characteristics were shown. The R values show that the diameter characteristics ($D_{v0.1}$, $D_{v0.5}$, $D_{v0.9}$, D_{10}, D_{20}, D_{30} and D_{32}) have negative correlation with characteristics of volume percentages ($D_{50,}$ D_{100}, D_{150}, D_{200} and D_{250}). Besides, RSF has negative correlation with diameter characteristics and positive correlation with volume percentages. In addition, the average value of the absolute values of R (ABS) for each droplet size characteristic was obtained to estimate whether it could represent other droplet size characteristics. The result shows that most of the characteristics had relative high average values which mean they could be used to represent other characteristics except the volume percentage of droplet size smaller than 50μm and RSF. Therefore, $D_{v0.5}$ was used to carry out the regression analysis between key design parameters and the droplet size characteristics under different nozzle pressures.

Eq. (10) shows the result of the multivariate regression analysis between the key nozzle design parameters and $D_{v0.5}$ under different nozzle pressures. The nozzle tip area, pre-orifice diameter and nozzle pressure were found to have significantly effect on the $D_{v0.5}$ ($P<0.05$) with a coefficient of determination (R2) of 0.81. Previous study showed that the nozzle tip area controlled the droplet size due to the atomization (Butler Ellis et al., 2002). In this study, the positive proportion relation between the nozzle tip area and the $D_{v0.5}$ was also found. In addition, Eq. (10) also shows that the pre-orifice diameter was negative proportional with the $D_{v0.5}$ and this trend was not reported in the previous study. The reason of the above relationship between the pre-orifice diameter and the $D_{v0.5}$ might be the variation of the mixing condition in the mixing chamber by varying the liquid flow rate controlled by the pre-orifice diameter when the nozzle pressure and the nozzle tip area were kept constant. However, the relative mechanism needs to be

Table 10 Values of correlation coefficients (R) obtained in the correlation analysis of droplet size characteristics

	$D_{v0.1}$	$D_{v0.5}$	$D_{v0.9}$	RSF	D_{10}	D_{20}	D_{30}	D_{32}	D_{50}	D_{100}	D_{150}	D_{200}	D_{250}
$D_{v0.1}$		0.99	0.98	-0.89	1.00	1.00	1.00	1.00	-0.80	-0.87	-0.91	-0.95	-0.98
$D_{v0.5}$	0.99		1.00	-0.84	0.99	1.00	1.00	1.00	-0.77	-0.84	-0.89	-0.94	-0.97
$D_{v0.9}$	0.98	1.00		-0.79	0.98	0.99	0.99	0.99	-0.73	-0.81	-0.87	-0.92	-0.96
RSF	-0.89	-0.84	-0.79		-0.89	-0.87	-0.86	-0.86	0.88	0.92	0.93	0.92	0.91
D_{10}	1.00	0.99	0.98	-0.89		1.00	1.00	1.00	-0.80	-0.87	-0.91	-0.95	-0.98
D_{20}	1.00	1.00	0.99	-0.87	1.00		1.00	1.00	-0.79	-0.86	-0.91	-0.95	-0.98
D_{30}	1.00	1.00	0.99	-0.86	1.00	1.00		1.00	-0.78	-0.85	-0.90	-0.95	-0.98
D_{32}	1.00	1.00	0.99	-0.86	1.00	1.00	1.00		-0.78	-0.86	-0.91	-0.95	-0.98
V_{50}	-0.80	-0.77	-0.73	0.88	-0.80	-0.79	-0.78	-0.78		0.99	0.96	0.92	0.86
V_{100}	-0.87	-0.84	-0.81	0.92	-0.87	-0.86	-0.85	-0.86	0.99		0.99	0.97	0.93
V_{150}	-0.91	-0.89	-0.87	0.93	-0.91	-0.91	-0.90	-0.91	0.96	0.99		0.99	0.96
V_{200}	-0.95	-0.94	-0.92	0.92	-0.95	-0.95	-0.95	-0.95	0.92	0.97	0.99		0.99
V_{250}	-0.98	-0.97	-0.96	0.91	-0.98	-0.98	-0.98	-0.98	0.86	0.93	0.96	0.99	
ABS Values	0.87	0.86	0.85	0.81	0.87	0.87	0.87	0.87	0.77	0.83	0.86	0.88	0.88

investigated in the future by simulation or experiment.

The influence of the air inlet area on $D_{v0.5}$ might be ignored because it was found that covering or restricting the air inlet port on the air inclusion nozzle had little impact on the overall droplet spectrum (Derksen et al., 1999). In addition, the nozzle pressure was found to be negative proportional to the $D_{v0.5}$ due to the more sufficient atomization under higher nozzle pressure.

$$D_{V0.5} = -57.48P - 221.02D + 73.43A + 424.22 (R^2 = 0.81) \quad (10)$$

Where *P*: Nozzle pressure, MPa; *D*: Pre-orifice diameter, mm; *A*: Nozzle tip area, mm^2.

3.3.2. The influence of nozzle design parameters on the spray angle and liquid flow rate

The influence of the key nozzle design parameters on the spray angle and liquid flow rate were investigated by the multivariate regression analysis (Eq. (11)). The influence of the nozzle pressure and pre-orifice diameter on the spray angle were significant while the effect of nozzle tip area was not ($P<0.05$). The result also shows that when the nozzle was operated at lower pressure of 1.0 and 1.25MPa, the spray angle tended to be narrower than 100°, which means the expected spray angle (100°) might not be achieved when the nozzle pressure was lower than 1.5MPa. Derksen et al. (1999) found that for the investigated air inclusion nozzles, lower nozzle pressure led to the nearly 20° decrease of the spray angle. Dorr et al. (2013) also found that increase of the nozzle pressure significantly increased the spray angle for all of the investigated flat fan nozzles. A higher pressure led to a better mixing which might lead to a wider spray angle. The influence of the variation of the spray angle on the coverage rate and application distribution should be carried out because the spray angle plays an important role in the determination of nozzle height to provide the acceptable coverage rate and uniform application distribution of pesticide. In addition, the pre-orifice diameter was found to be positive proportional to the spray angle which means that the spray angle became larger as the pre-orifice diameter increased under the constant nozzle pressure and nozzle tip area. It might be that the increase of the liquid flow rate is the reason why the increase of the nozzle pressure and pre-orifice diameter lead to the increase of the spray angle. Under a certain nozzle tip area, a larger liquid flow rate led to more liquid existed in the mixing chamber at a certain time interval and then led to a wider spray angle. In addition, the influence of the nozzle tip area on the spray angle was found to be not significant in this study and low R2 was obtained in the regression equation.

$$SA = 15.67P + 23.09D + 52.56(R^2 = 0.25) \tag{11}$$

Where SA: spray angle, degree.

Eq. (12) shows the results of the multivariate regression analysis between the key nozzle design parameters, nozzle pressures and the liquid flow rate. The regression equation validated that the nozzle pressure and the pre-orifice diameter significantly influenced the liquid flow rate with a R2 value of 0.98. Meanwhile, the nozzle tip area has no significant influence on the liquid flow rate. When the nozzle pressure increased, the liquid was speeded up which led to the increasing of the liquid flow rate. Besides, the increasing of the pre-orifice diameter resulted in the increasing of the area of the narrowest cross-section of the nozzle flow passage, which also led to the increasing of the liquid flow rate. The main reason why the nozzle tip area had no significant influence on liquid flow rate should be that the pre-orifices areas were always smaller than that of the nozzle tips under all the available combinations in the study (Table 7). In addition, the spray liquid runs out from the air inlet which was considered as an unstable spray when the pre-orifice area was bigger than that of the nozzle tip.

$$Q = 382.69P + 2282.64D - 1299.03(R^2 = 0.98) \tag{12}$$

Where Q: liquid flow rate, ml/min.

3.3.3. The influence of nozzle design parameters on the quantity of the included air within droplet

Eq. (13) shows the results of the multivariate regression analysis between the key nozzle design parameters and the spray liquid density with a R2 of 0.70. The pre-orifice diameter and the nozzle tip area had significant influence on the spray liquid density. Based on the inverse relationship between the pre-orifice diameter and droplet size, the increase of the pre-orifice diameter led to smaller droplet size (Eq. 13). Therefore, small droplets which might have less included air within droplets resulted in the increase of the spray liquid density. In addition, the increase of the pre-orifice diameter also led to the growth of liquid flow rate, which might lead to higher spray liquid density due to the increase of the ratio of the liquid flow rate to the included air flow rate. When the nozzle tip area increased, the droplet size increased (Eq. 13). The larger droplet size might have more included air within droplets which lead to the decrease of the spray liquid density.

$$\rho_s = 273.58D - 100.05A + 559.95 (R^2 = 0.70) \tag{13}$$

3.4. Conclusions

In conclusion, the influence of the key nozzle design parameters for high-pressure air inclusion nozzles, which includes pre-orifice diameter and nozzle tip area on the droplet size characteristics, spray angle, included air within droplet and liquid flow rate were investigated under different nozzle pressures. The combinations of 7 pre-orifice diameters, 6 nozzle tip areas and 3 nozzle pressures, were tested in the pre-test and 93 stable spray conditions were chosen to carry out the measurement of droplet size characteristics, spray angle and liquid flow rate. The correlation analysis among important droplet size characteristics were carried out. The result shows that most of the characteristics had relative high average values which mean they could be used to represent other characteristics. Therefore, $D_{v0.5}$ was used to carry out the regression analysis between key design parameters and the droplet size characteristics under different nozzle pressures.

The result of the multivariate regression analysis between the key nozzle design parameters and $D_{v0.5}$ under different nozzle pressures shows that nozzle tip area, pre-orifice diameter and nozzle pressure were found to have significantly effect on the $D_{v0.5}$ ($P<0.05$) with a coefficient of determination (R2) of 0.81. The positive proportion relation between the nozzle tip area and the $D_{v0.5}$ was found. In addition, pre-orifice diameter was negative proportional with the $D_{v0.5}$ and this trend was not reported in the previous study. The further investigation should be carried out to explain the result. In addition, nozzle pressure was found to be negative proportional to the $D_{v0.5}$ due to the more sufficient atomization under higher nozzle pressure.

The results of the multivariate regression analysis between the key nozzle design parameters and spray angle under different nozzle pressures shows that the influence of nozzle pressure and pre-orifice diameter on the spray angle were significant while the effect of nozzle tip area was not ($P<0.05$). In addition, pre-orifice diameter and nozzle pressure were found to be positive proportional to the spray angle. The result shows that the nozzle pressure and pre-orifice diameter controlled the liquid flow rate with a R2 value of 0.98. From 22 investigated sprays, the regression equation between the key nozzle design parameters and the spray liquid density was obtained. The pre-orifice diameter and nozzle tip area significantly affect the spray liquid density. The influence of the pre-orifice diameter and nozzle tip on droplet size characteristics might be the main reason why the two design parameters significantly influence the spray liquid density.

Chapter 4 The influence of the air inlet design on the spray performance of the air inclusion nozzle used in Japan

Abstract

The application of air inclusion nozzles was proved to be one of the most effective ways to decrease the spray drift because the nozzle could produce much larger droplet than that produced by the conventional spray nozzles. However, the effect of the air inlet on spray performance of the air inclusion nozzle and whether this kind of nozzle could be replaced by other cheaper nozzles has been debated. Besides, the nozzle pressure and the corresponding nozzle deign parameters of the air inclusion nozzles used in Japan are different from other regions. Therefore, the influence of the air inlet design on the spray performance of one series of air inclusion nozzles used on boom sprayers in Japan was carried out. The result showed that sealing of the air inlet significantly decreased the quantity of the included air within droplets under the investigated conditions. The included air quantity of KIRINASHI ES series nozzles was slightly higher, comparing with that of low pressure air inclusion nozzles. No significant difference of volume median diameter ($D_{v0.5}$) was found between the unsealed and sealed group. The existence of the air inlet led to a more uniform distribution of the droplet size based on its influence on the RSF and might result in a better drift control due to less volume proportion of small droplets it produced. The sealing of the air inlet slightly increased the liquid flow rate but not significantly. No significant difference of the spray angle, deposit weight of spray liquid and coverage rate were found between the two groups. It could be concluded that the unsealed group might have the potential to decrease the volume proportion of small droplets which indicated a better drift control while keeping the coverage rate as same as the sealed group.

4.1. Introduction

Spray drift control is one of the most important tasks during pesticide spray. Among all the drift control methods, the application of the air inclusion nozzle was proved to be one of the most effective ways to decrease the spray drift because the nozzle could produce much larger droplet than that produced by the conventional spray nozzles (Derksen et al., 1999; Nuyttens, et al., 2010). The sales of the air inclusion nozzle are also increasing in the market (Miller et al., 2011; Miyahara, 2012). For the working mechanism of the air inclusion nozzle, a Venturi design near the pre-orifice section was applied to inhale the outside air from an air inlet into the liquid flow passage. Then, the air and liquid mix with each other in the mixing chamber and produce larger droplet after leaving the nozzle tip.

The effect of the air inlet on spray performance of the air inclusion nozzles and whether this kind of nozzle could be replaced by other cheaper nozzles has been debated. On one hand, Derksen et al (1999) used tape to cover the air inlet to investigate the influence of covering or restricting the air inlet on the droplet size characteristics, liquid flow rate and drift deposit. The result showed that covering the air inlet increased the liquid flow rate slightly, decreased the volume median diameter ($D_{v0.5}$) by less than 8.5%, decreased the volume percentage of droplets smaller than 100μm (V_{100}) by less than 1% and might affect other nozzle spray performance, such as spray coverage which the test was not carried out. Therefore, the drift reduction ability which has a close relationship with the volume of small droplets was not significantly affected by covering or restricting the air inlet. Guler et al (2007) also investigated the droplet size, spray pattern width, spray coverage and also the drift deposit of different types of nozzles. They concluded that the spray performance of the air inclusion nozzles could be achieved by normal flat fan nozzles with similar size of the nozzle tip with air inclusion nozzles under reduced nozzle pressure. They also found that the spray of the air inclusion nozzles with sealed air inlet and reduced nozzle pressure could achieve spray performance which was similar to that produced by the same nozzle with unsealed air inlet and normal nozzle pressure.

On the other hand, almost all the manufactures claim that the air inclusion nozzle could produce droplet with included air within droplets which improve the deposit efficiency of the droplets. Miller and Butler Ellis (2000) said that air inclusions within droplets are probably crucial to modifying the droplet behaviour on impact with a target surface, resulting in retention characteristics much closer to that of a finer spray. Other research also brought forward that the presence of air within droplets influences droplet size and velocity, impaction, retention, and spray drift (Combellack & Miller, 2001).

In addition, the quantitative study of the included air within droplets produced by air inclusion nozzles was limited. Based on reviewed literatures, the cylinder method was proved to be a better method to indirectly estimate the included air quantity within droplets. Butler Eillis et al., (2002) obtained the spray liquid density by matching the droplet velocities between the calculated and measured value. The result showed that the quantity of included air depended on the air flow rate into the nozzle and the quantity did not significantly affect the droplet size. However, this method was established by the assumptions of droplet movement simulation and also needs the measurement of the droplet velocity. Faggion et al., (2006) compared two different methods for measuring the quantity of included air and concluded that the measurement of the density of collected spray by a cylinder (Hereafter, cylinder method) could discriminate differences between different air inclusion nozzle designs while the measurement of impact force could only discriminate differences between an air inclusion nozzle and a conventional nozzle. Using cylinder method, Dorr et al (2013) found that spray mixtures significantly affect the spray liquid density of air inclusion nozzles. The spray liquid density was approximately 1000kg m^{-3} when only water was sprayed, which means no included air was found. This might be the reason that Guler et al., (2007) doubts the existence of the included air within droplets.

Besides, the nozzle design and working parameters of the air inclusion nozzles are different from each other between different manufactures and regions. Comparing with the air inclusion nozzles used in other regions, the nozzle parameters which include key nozzle design parameters and nozzle pressure of air inclusion nozzles used in Japan are different. Therefore, the influence of the air inlet on the spray performance might also be different.

The objective of this study were to investigate the influence of the air inlet design on the spray performance of the air inclusion nozzle on boom sprayers used in Japan by carrying out the measurement of the included air quantity, droplet size characteristics, liquid flow rate, spray angle, deposit weight of spray liquid and also coverage rate.

4.2. Materials and methods

4.2.1. Spray nozzles

The design of KIRINASHI ES series nozzle (YAMAHO) follows the common design principles of air inclusion flat fan nozzles. As shown in Fig. 14, the spray liquid goes through the pre-orifice and mixed with the induced air entering from the air inlet by Venturi effect to form a liquid jet with included air. A mixing chamber was created at the downstream of the mixing throat by a two-hole washer to provide sufficient mixing of the air and liquid. Finally, the air included droplets spray out from a rectangular shaped nozzle tip.

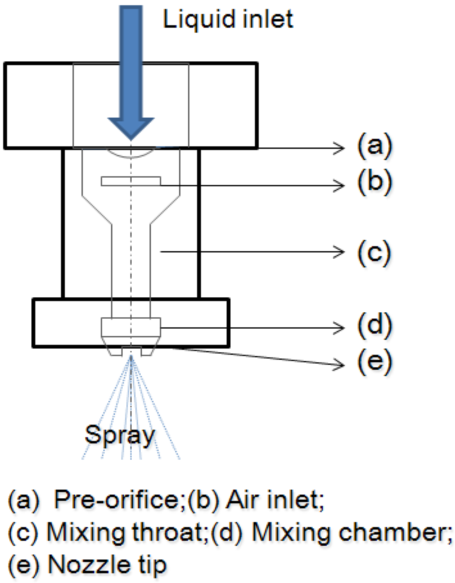

Figure 14 Design features of KIRINASHI ES series nozzles. The range of the pre-orifice diameter is 0.5 -1.1mm with a 0.1mm interval; the size of the air inlet and the diameter of the mixing throat keep consistent; the corresponding range of the nozzle tip area is 0.57-2.19 mm^2

The nozzle pressure of the ES series nozzle was from 1.0 to 1.5MPa, which is much higher than that of the air inclusion flat fan nozzles being used on the boom sprayer in other countries. Hardi Inject nozzle (HARDI) was compared as a typical low-pressure air inclusion nozzle as follows. Compared with the pre-orifice diameter of Hardi Injet nozzles, the pre-orifice diameter of KIRINASHI ES series nozzles is much smaller for controlling the liquid flow rate with similar values when higher nozzle pressure was used. In addition, the shape of the air inlet and the nozzle tip of KIRINASHI ES series nozzles are rectangle while Hardi Injet nozzles have a circular air inlet and a nozzle tip with ellipse shape. When the nozzle size increases, the size of the air inlet and the nozzle tip increase with pre-orifice diameter for Hardi Injet nozzles, which is not the case for KIRINASHI ES series nozzles. For KIRINASHI ES series nozzle, the sizes of the air inlet remain the same as the size of the pre-orifice and the nozzle tip increase.

There are 7 different nozzle numbers in the whole series of KIRINASHI ES nozzle from No. 05 to 11. The nozzle number indicates the pre-orifice diameter of the nozzle which means No. 05 nozzle has a 0.5mm diameter pre-orifice diameter. Besides, the nozzle tip area increases when the pre-orifice diameter increases. In this study, 4 nozzle numbers covering the whole series (No. 05, 07, 09, 11) were investigated under the nozzle pressure of 1.0 and 1.5MPa for the measurements of included air quantity, droplet size characteristics, liquid flow rate, spray angle, deposit weight of spray liquid and coverage rate. A silicone sealant was used to seal the air inlet. The unsealed and sealed groups were investigated to study the influence of the air inlet on the above spray characteristics. The general information of the investigated nozzle in this study is shown in Table 11. During the whole measurement, the average air temperature and the relative humidity were 30℃ and 70%, respectively.

Table 11 General information of the investigated nozzle, including the nozzle number, nozzle pressure and the processing of the air inlet

Nozzle number	Nozzle pressure, MPa	Processing of the air inlet
ES05[a]	1.00	Unsealed
ES07	1.50	Sealed[b]
ES09		
ES11		

[a] ES05, KIRINASHI ES series nozzle with the nozzle number of 05; [b] Sealed, the air inlet was sealed by the silicone sealant.

4.2.2. Measurement of included air within droplets

Fig. 15 shows the sketch of the measurement of the spray liquid density (Faggion et al., 2006; Dorr et al., 2013). A higher spray liquid density indicates less quantity of included air exists within droplets. Black curtains were used to create a relative static environment without any potential air flow turbulence during the experiment. A 250ml glass cylinder (2ml resolution) was placed right below the nozzle tip of the investigated nozzle to collect the spray droplet with included air with a vertical distance of 1.0m between the nozzle tip and the bottom of the cylinder. An automatic hygrothermograph was placed near the spray nozzle to record the air temperature and the relative humidity during the experiment.

The spraying was then carried out and a foam layer above the liquid surface with a certain thickness was observed in the cylinder. In the previous study, liquid was sprayed until the cylinder was approximately three quarters full (Faggion et al., 2006; Dorr et al., 2013). However, it took too long time to achieve three quarters full for small pre-orifice diameters (0.5 and 0.7mm) and the thickness of the foam layer decreases when collecting time passed based on the pre test. Therefore, a fix spray duration of 10min was set for the pre-orifice diameters of 0.5 and 0.7mm. After 10min spray, approximate 100ml of the foam and liquid was collected by the cylinder for 0.7mm pre-orifice diameter. In addition, a fix spray duration of 6min was set for large pre-orifice diameters (0.9 and 1.1mm) to collect approximate 100ml by the cylinder. After spraying, the cylinder was removed on a flat surface nearby as soon as possible. Then, the scale on the top of the foam was recorded to estimate the volume of spray. The weight of the collected liquid was then measured by an electrical scale. The density of the spray liquid and the average percentage of air within spray droplets were calculated based on the equations (14)-(15) (Dorr et al., 2013).

$$\rho_s = \frac{w}{V_f} \times 1000 \tag{14}$$

$$a_d = \frac{V_f - \dfrac{w}{\rho_l}}{V_f} \times 100 \tag{15}$$

Where ρ_s: spray liquid density, kg m^{-3}; V_f: volume of spray, L; w: weight of spray, kg;

ad: percentage of air quantity in spray, %; ρ_l: density of spray liquid before spraying, 1000kg m^{-3}.

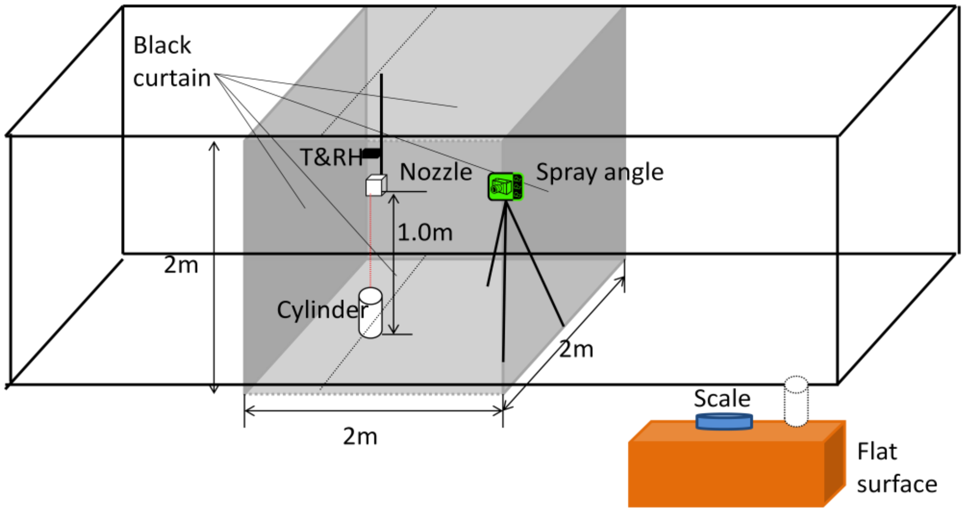

Figure 15 Sketch of the measurement of the spray liquid density. T&RH: a automatic hygrothermograph used to record the air temperature and relative humidity

4.2.3. Measurement of droplet size characteristics

A laser diffraction analyser, LDSA-1400A (Nikkiso), was used in this study to measure the droplet size characteristics. Using the accessory software, the volume distribution of droplet sizes can be determined, in addition to important characteristics of droplet size including volume diameters below which smaller droplets constitute 10%, 50% and 90% of the total volume ($D_{v0.1}$, $D_{v0.5}$ and $D_{v0.9}$), relative span factor indicating the uniformity of the droplet size distribution (RSF), arithmetic mean diameter (D_{10}), surface mean diameter (D_{20}), volume mean diameter (D_{30}), Sauter mean diameter (D_{32}), the volume percentage of droplets smaller than 50μm (V_{50}), 100μm (V_{100}), 150μm (V_{150}), 200μm (V_{200}) and 250μm (V_{250}), respectively (Nuyttens et al., 2007). The calculation equations for RSF, D_{10}, D_{20}, D_{30} and D_{32} were shown in the equations as below (Eq. (16)-(20)).When measuring the droplet size characteristics, the vertical distance between the nozzle and the laser beam was 0.3m. For each combination of the nozzle size and nozzle pressure, the measurement was repeated five times. Tween 20 used in the measurement of the relative spray drift was also applied to tap water to obtain a 0.1% w/w solution with similar physical properties to those of real pesticide (Nuyttens, 2007). One automatic hygrothermograph was placed near the spray nozzle to record the environment parameters during the experiment. During the measurement, the average air temperature and the relative humidity were 30℃ and 70%, respectively. Liquid flow rates were recorded by mass method and repeated 3 times.

$$RSF = \frac{D_{v0.9} - D_{v0.1}}{D_{v0.5}} \tag{16}$$

$$D_{10} = \frac{\sum_{i=1}^{n} d_i}{n} \tag{17}$$

$$D_{20} = \sqrt{\frac{\sum_{i=1}^{n} d_i^2}{n}} \tag{18}$$

$$D_{30} = \sqrt[3]{\frac{\sum_{i=1}^{n} d_i^3}{n}} \tag{19}$$

$$D_{32} = \frac{\sum_{i=1}^{n} d_i^3}{\sum_{i=1}^{n} d_i^2} \tag{20}$$

Where d_i: the diameter of droplet i, μm; n: the total number of droplets.

4.2.4. Measurement of spray angle

One digital camera (FinePix F200EXR, Fujifilm) was used to take the photo of the spray sheet at the area of the nozzle tip after adjusting the nozzle pressure and before and measurement of the droplet size measurement. Image analysis software (IrfanView, Irfan Skiljan, Graduate of Vienna University of Technology) was used to measure the fan angle of the spray sheet by manually drawing two straight lines at the boundary between spray sheet and air. The measurement by the software was repeated 5 times at each spray.

4.2.5. Measurement of coverage rate

Fig. 16 shows the sketch of the measurement of the spray coverage rate. A wind tunnel was used to conduct the test. The investigated nozzle was installed on an automatic track with an average travel speed of 0.85m s^{-1}. The spray coverage at 1.0m below the nozzle tip was obtained by using water-sensitive paper (WSP, 52×76mm, Spraying system) to collect the spray deposit. The placement of 4 WSPs is also shown in Fig. 16. 4 culture dishes were used to measure the deposit weight of the spray liquid. WSPs were dried and scanned by a portable scanner. Then a image processing software was used to calculate the coverage rate of each spray (Coverage rate measurement software, NARO).

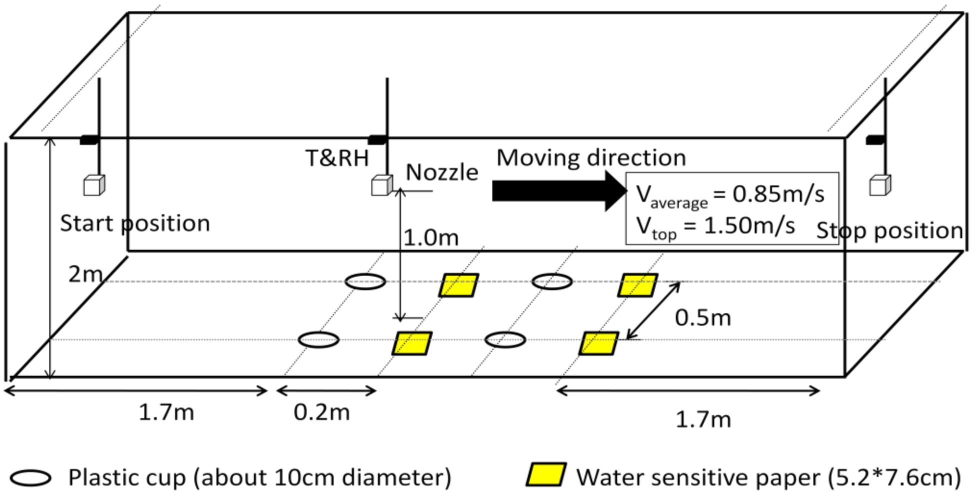

Figure 16 Sketch of the measurement of the spray coverage rate

4.3. Results and Discussions

4.3.1. Included air within droplets

Fig. 17 and 18 show the comparisons of the spray liquid density and the percentage of air quantity produced by the investigated nozzles between the unsealed and sealed nozzles under two nozzle pressures. The ranges of the spray density were 599-729kg m^{-3} and 845-953kg m^{-3} for the unsealed and sealed nozzle group, respectively. Besides, the ranges of the percentage of air quantity were 27.12-40.13% and 4.74-15.49%, respectively. The spray liquid density and the percentage of air quantity were significantly different between the two groups (t-test, $P<0.05$). Therefore, it could be concluded that sealing of the air inlet significantly decreased the quantity of the included air within droplets under the investigated conditions. In addition, Faggion et al (2006) showed that the included air quantity of air inclusion nozzles varied from 14-36% by different measuring methods. Comparing with the above result, the included air quantity of KIRINASHI ES series nozzles was slightly higher. The reason might be that the nozzle pressure used by KIRINASHI ES series nozzles was much higher than that of other investigated air inclusion nozzles, which led to a much smaller pre-orifice to control the liquid flow rate. Therefore, the diameter difference between the flow passage prior to pre-orifice and the pre-orifice were larger than that of low pressure nozzles. Based on the Venturi theory, the pressure differential, which controls the included air quantity entering from the air inlet, is decided by the difference of the liquid flow speed at the wider and narrower place. Because the larger diameter difference means a larger difference of the liquid flow speed, it is possible that the KIRINASHI ES series nozzle could produce the droplet with more included air quantity, compared to the low pressure air inclusion nozzles.

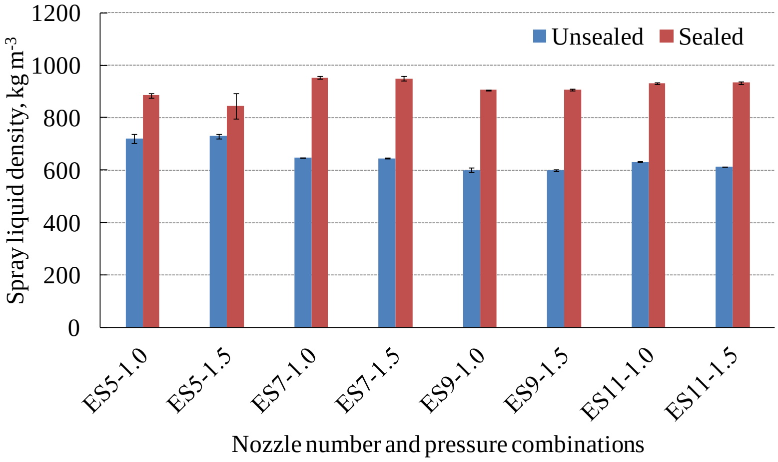

Figure 17 Spray liquid density and the corresponding standard deviations of KIRINASHI ES series nozzles (unsealed and sealed groups) under different nozzle number and pressure combinations. ES5-1.0: KIRINASHI ES series nozzles with the nozzle number of 5 and the nozzle pressure of 1.0MPa

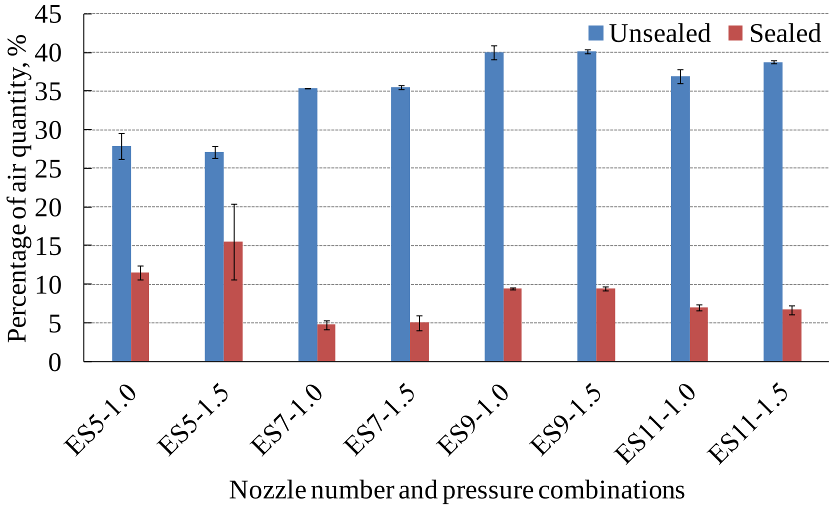

Figure 18 Included air quantity and the corresponding standard deviations of KIRINASHI ES series nozzles (unsealed and sealed groups) under different nozzle number and pressure combinations. ES5-1.0: KIRINASHI ES series nozzles with the nozzle number of 5 and the nozzle pressure of 1.0MPa

4.3.2. Droplet characteristics and liquid flow rate

Fig. 19 shows the $D_{v0.5}$ of unsealed and sealed groups under different nozzle number and pressure combinations. Though the $D_{v0.5}$ of unsealed group were relative larger than that of sealed group except ES07 based on the average values, no significant difference was found between the results of the two groups (t-test, $P<0.05$). Derksen et al (1999) found that covering the air inlet increased the liquid flow rate slightly, decreased the volume median diameter ($D_{v0.5}$) by less than 8.5%, decreased the volume percentage of droplets smaller than 100μm (V_{100}) by less than 1%. The high nozzle pressure might be the reason why there was no significant difference of $D_{v0.5}$ between the two groups for KINASHI ES series nozzles.

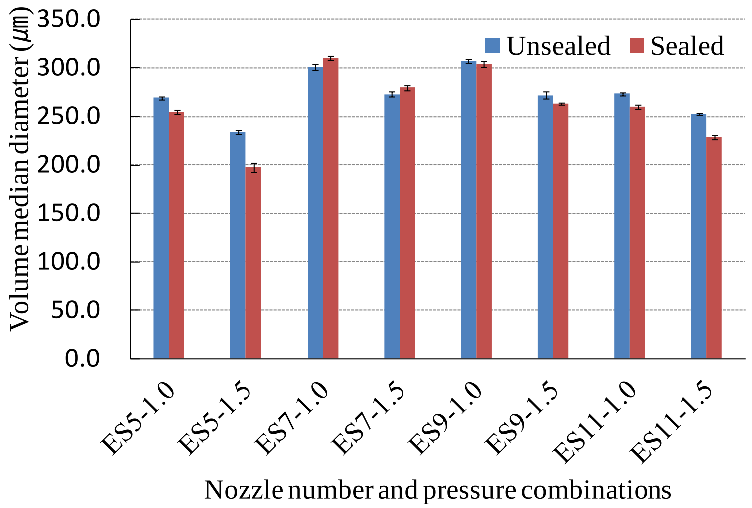

Figure 19 Volume median diameter ($D_{v0.5}$) and the corresponding standard deviations of KIRINASHI ES series nozzles (unsealed and sealed groups) under different nozzle number and pressure combinations. ES5-1.0: KIRINASHI ES series nozzles with the nozzle number of 5 and the nozzle pressure of 1.0MPa

Table 12 shows the droplet size characteristics of the investigated sprays. The one way ANOVA analysis was carried out for each droplet size characteristic between unsealed and sealed groups. The analysis result shows that RSF, D_{50} and D_{100} of the two groups are significantly different if it is assumed that sealing of the air inlet only lead to smaller droplets. Single-sided t-test was used under the assumption. The RSF is the only significantly different characteristic if double-sided t-test was used. Therefore, the existence of the air inlet led to a more uniform droplet size distribution based on its influence on the RSF and might lead to a better drift control due to a less volume proportion of small droplets. In addition, the sealing of air inlet slightly increased the liquid flow rate but not significantly (t-test, $P<0.05$).

4.3.3. Spray angle

Fig. 20 shows the spray angles of the two groups. No significant difference was found between the two groups (t-test, $P<0.05$). Although the manufactures claim that the spray angle is 100°, the range of the spray angles were 69-104° and 71-106°for the unsealed and sealed group, respectively. Other researchers also found that the spray angle varies (Derksen et al., 1999; Dorr et al., 2013).

4.3.4. Deposit weight and coverage rate

Fig. 21 shows the deposit weight of spray liquid of the two groups. No significant difference was found between the two groups (t-test, $P<0.05$). However, the deposit weight of sealed group was slightly higher than that of unsealed group when the nozzle number increased. The slight increase of the liquid flow rate of the sealed group should be the reason.

Table 12 Droplet size characteristics and the corresponding standard deviations of KIRINASHI ES series nozzles (unsealed and sealed groups) under different nozzle number and pressure combinations with the average values from 5 repetitions. ES5-1.0-U: KIRINASHI ES series nozzles with the nozzle number of 5 and the nozzle pressure of 1.0MPa with unsealed air inlet; ES5-1.0-S: KIRINASHI ES series nozzles with the nozzle number of 5 and the nozzle pressure of 1.0MPa with sealed air inlet

Samples	**$D_{v0.1}$**	**$D_{v0.5}$**	**$D_{v0.9}$**	**RSF**	**D_{10}**	**D_{20}**	**D_{30}**	**D_{32}**	**D_{50}**	**D_{100}**	**D_{150}**	**D_{200}**	**D_{250}**
ES5-1.0-U	166.5±2.5	269.1±1.9	372.5±5.2	0.8±0.0	166.5±2.5	201.7±2.3	226.5±1.7	240.8±2.0	0.1±0.0	1.4±0.1	6.5±0.4	19.5±0.7	39. 9±0.9
ES5-1.0-S	133.8±4.0	254.9±2.0	388.8±9.4	1.0±0.0	133.8±4.0	173.3±3.5	202.9±2.4	211.4±3.2	0.6±0.1	4.4±0.6	13.5±0.9	29.0±0.8	47.9±0.8
ES5-1.5-U	137.0±3.1	233.7±1.9	332.7±3.5	0.8±0.0	137.0±3.1	169.8±3.0	193.3±2.3	204.7±2.7	0.3±0.1	3.3±0.4	13.1±0.9	33.0±1.0	58.1±1.0
ES5-1.5-S	90.8±6.8	197.7±4.9	328.0±3.3	1.2±0.1	90.8±6.8	124.0±7.0	150.4±6.5	152.0±8.8	2.5±0.8	12.5±2.0	29.7±2.6	50.9±1.9	70.4±0.8
ES7-1.0-U	177.8±3.2	300.6±3.2	421.3±5.1	0.8±0.0	177.8±3.2	218.0±3.1	249.7±3.3	262.9±3.7	0.1±0.0	1.4±0.2	5.5±0.5	15.1±0.9	29.9±1.2
ES7-1.0-S	189.7±1.8	310.3±2.3	424.8±4.1	0.8±0.0	189.7±1.8	230.1±2.1	260.6±2.0	276.4±2.4	0.1±0.0	0.9±0.0	4.0±0.2	12.0±0.4	25.6±0.8
ES7-1.5-U	160.9±2.6	272.9±2.9	389.2±6.1	0.8±0.0	160.9±2.6	198.6±2.6	226.1±2.3	239.6±2.6	0.2±0.0	1.9±0.2	7.6±0.5	20.4±0.8	39.2±1.1
ES7-1.5-S	161.8±1.7	279.6±2.6	401.3±4.9	0.9±0.0	161.8±1.7	201.5±1.7	230.1±1.7	243.5±1.8	0.2±0.0	1.9±0.1	7.5±0.3	19.6±0.5	37.1±0.8
ES9-1.0-U	187.0±1.6	307.2±2.4	420.6±3.4	0.8±0.0	187.0±1.6	227.1±2.0	257.8±1.9	272.9±2.3	0.1±0.0	0.9±0.0	4.2±0.2	12.7±0.4	26.7±0.8
ES9-1.0-S	182.0±1.7	304.0±3.0	422.0±5.7	0.8±0.0	182.0±1.7	222.1±2.2	253.8±2.3	267.7±2.8	0.1±0.0	1.1±0.1	4.9±0.2	14.0±0.5	28.4±0.9
ES9-1.5-U	161.7±2.7	272.1±3.2	386.5±4.3	0.8±0.0	161.7±1.7	199.0±3.2	226.0±2.9	239.7±3.3	0.1±0.0	1.8±0.2	7.4±0.5	20.3±1.0	39.4±1.4
ES9-1.5-S	143.0±1.6	263.0±1.1	393.7±3.4	1.0±0.0	143.0±2.7	182.2±0.9	212.6±0.8	222.0±1.1	0.4±0.0	3.4±0.2	11.3±0.3	25.8±0.3	44.4±0.4
ES11-1.0-U	159.7±2.6	273.3±1.7	391.9±2.8	0.8±0.0	159.7±2.6	197.8±2.6	225.7±2.1	239.1±2.5	0.2±0.0	2.0±0.2	7.8±0.5	20.7±0.8	39.2±0.8
ES11-1.0-S	136.6±1.7	259.8±1.9	395.4±3.3	1.0±0.0	136.6±1.7	177.4±1.6	207.8±2.0	215.9±1.9	0.5±0.0	4.1±0.2	12.7±0.4	27.6±0.6	46.0±0.7
ES11-1.5-U	142.1±1.8	252.6±1.0	368.5±2.9	0.9±0.0	142.1±1.8	179.1±1.1	206.3±1.4	216.6±1.4	0.3±0.0	3.2±0.2	11.6±0.4	27.8±0.5	48.7±0.5
ES11-1.5-S	112.2±1.7	228.5±1.9	362.6±2.3	1.1±0.0	112.2±1.7	149.6±1.8	178.4±1.8	183.0±2.3	1.2±0.1	7.4±0.3	20.1±0.6	38.6±0.8	58.3±0.7

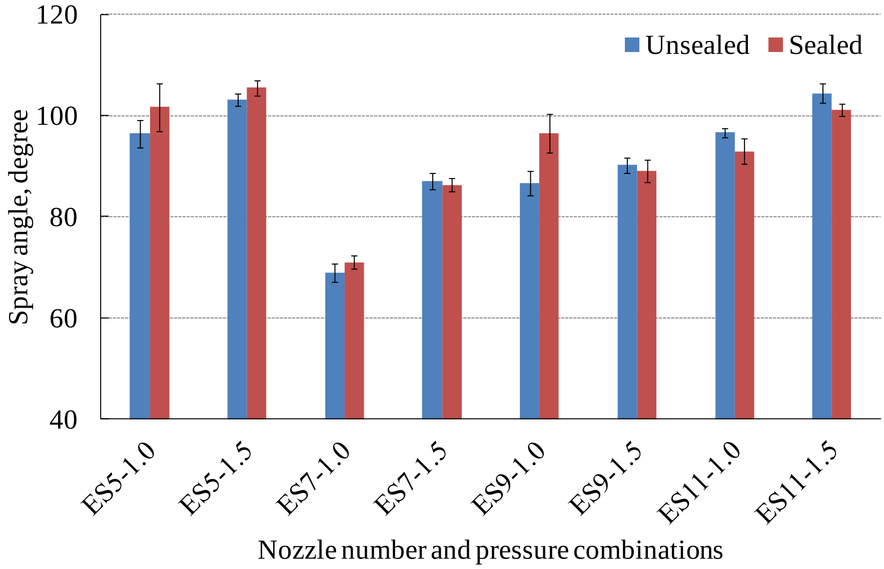

Figure 20 Spray angle and the corresponding standard deviations of KIRINASHI ES series nozzles (unsealed and sealed groups) under different nozzle number and pressure combinations. ES5-1.0: KIRINASHI ES series nozzles with the nozzle number of 5 and the nozzle pressure of 1.0MPa

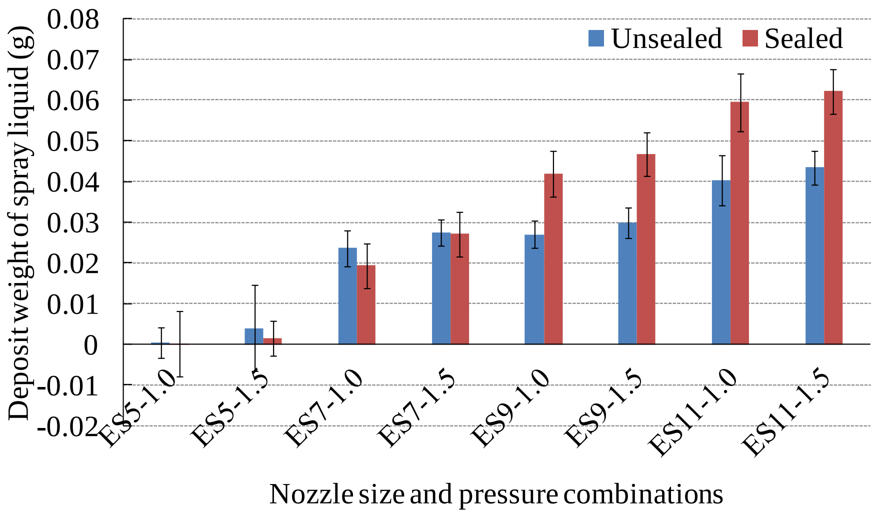

Figure 21 Deposit weight of spray liquid and the corresponding standard deviations of KIRINASHI ES series nozzles (unsealed and sealed groups) under different nozzle number and pressure combinations. ES5-1.0: KIRINASHI ES series nozzles with the nozzle number of 5 and the nozzle pressure of 1.0MPa

Fig. 22 shows the coverage rate of the two groups. It was expected that the coverage rate of the unsealed group could be significantly higher than that of sealed group due to the significantly higher quantity of included air when the $D_{v0.5}$, liquid flow rate, deposit weight of spray liquid and spray angle had no significantly difference between the two groups. However, no significant difference was found between the two groups (t-test, $P<0.05$). In addition, Fig. 21 and 22 also indicated that higher deposit weights of spray liquid might result in higher coverage rates. Besides, because the results of the D_{50} and D_{100} indicated that the unsealed group had the potential to decrease the volume proportion of small droplets, using unsealed group might have a better drift control while keeping the coverage rate as same as the sealed group.

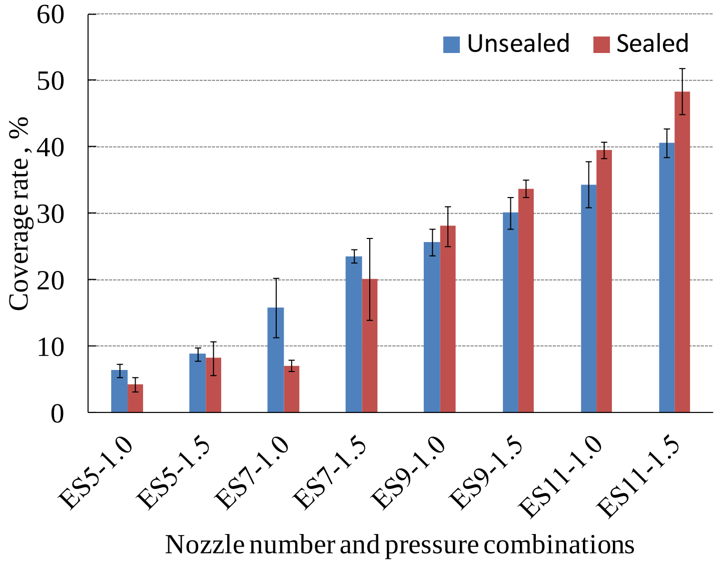

Figure 22 Coverage rate and the corresponding standard deviations of KIRINASHI ES series nozzles (unsealed and sealed groups) under different nozzle number and pressure combinations. ES5-1.0: KIRINASHI ES series nozzles with the nozzle number of 5 and the nozzle pressure of 1.0MPa

4.4. Conclusion

To get a better understanding of the role air inlet design plays in the air inclusion nozzle, the influence of the air inlet design on the included air within droplets, droplet size characteristics, liquid flow rate, spray angle, deposit weight of spray liquid and coverage rate of the KIRINASHI ES series air inclusion nozzle was carried out.

The result showed that the quantity of the included air within droplets was significantly different between the unsealed and sealed group. In addition, the sealing of the air inlet significantly decreased the quantity of the included air within droplets under the investigated conditions. Besides, the included air quantity of KIRINASHI ES series nozzles was slightly higher, comparing with that of low pressure air inclusion nozzles based on previous research. No significant difference of $D_{v0.5}$ was found between the results of the two groups. The existence of the air inlet led to a more uniform droplet size distribution based on its influence on the RSF and might lead to better drift control due to a less volume proportion of small droplets. In addition, the sealing of air inlet slightly increased the liquid flow rate but not significantly. For the spray angle, no significant difference of the spray angle was found between the two groups. Although the manufacture claims that the spray angle is 100°, the range of the spray angle varies under different nozzle number and pressure combinations. For the deposit weight of spray liquid, no significant difference were found between the two groups. However, the deposit weight of sealed group was slight higher than that of unsealed group when the nozzle number increased. The test of the coverage rate of the two groups showed that no significant difference was found between the two groups. However, based on the results of the D_{50} and D_{100}, it could be concluded that the unsealed group might have the potential to decrease the volume proportion of small droplets and have a better drift control while keeping the coverage rate as same as the sealed group.

Chapter 5 Summary

5.1. Characteristics and classification of Japanese nozzles based on relative spray drift potential

In conclusion, the relative drift potential for one series of drift reduction nozzles used in Japan was measured under different combinations of nozzle size, pressure and height. The results reveal that the influence of nozzle height and nozzle size on the index value were statistically significant (**P < 0.01), whereas the nozzle pressure has a significant effect (**P < 0.01) on the index value only for nozzle sizes of 05 and 07. Compared with the reference spray, the ES series nozzles had drift reduction abilities above 50% when the nozzle height was between 0.3 and 0.5 m, except for the ES 05 nozzle. According to the spray distribution performance, the best nozzle height range is between 0.3m and 0.4m above the crop canopy. The results provided the users objective information for the relative drift reduction performance of ES nozzles and could also be expanded as more types of drift reduction nozzles become available.

5.2. The influence of nozzle parameters on the droplet size characteristics, spray angle, liquid flow rate and included air within droplers for the high pressure air inclusion nozzle used in Japan

In conclusion, the influence of the key nozzle design parameters for high-pressure air inclusion nozzles, which includes pre-orifice diameter and nozzle tip area on the droplet size characteristics, spray angle, included air within droplet and liquid flow rate were investigated under different nozzle pressures. The combinations of 7 pre-orifice diameters, 6 nozzle tip areas and 3 nozzle pressures, were tested in the pre-test and 93 stable spray conditions were chosen to carry out the measurement of droplet size characteristics, spray angle and liquid flow rate. The correlation analysis among important droplet size characteristics were carried out. The result shows that most of the characteristics had relative high average values which mean they could be used to represent other characteristics. Therefore, $D_{v0.5}$ was used to carry out the regression analysis between key design parameters and the droplet size characteristics under different nozzle pressures.

The result of the multivariate regression analysis between the key nozzle design parameters and $D_{v0.5}$ under different nozzle pressures shows that nozzle tip area, pre-orifice diameter and nozzle pressure were found to have significantly effect on the $D_{v0.5}$ ($P<0.05$) with a coefficient of determination (R2) of 0.81. The positive proportion relation between the nozzle tip area and the $D_{v0.5}$ was found. In addition, pre-orifice diameter was negative proportional with the $D_{v0.5}$ and this trend was not reported in the previous study. The further investigation should be carried out to explain the result. In addition, nozzle pressure was found to be negative proportional to the $D_{v0.5}$ due to the more sufficient atomization under higher nozzle pressure.

The results of the multivariate regression analysis between the key nozzle design parameters and spray angle under different nozzle pressures shows that the influence of nozzle pressure and pre-orifice diameter on the spray angle were significant while the effect of nozzle tip area was not ($P<0.05$). In addition, pre-orifice diameter and nozzle pressure were found to be positive proportional to the spray angle. The result shows that the nozzle pressure and pre-orifice diameter controlled the liquid flow rate with a R2 value of 0.98. From 22 investigated sprays, the regression equation between the key nozzle design parameters and the spray liquid density was obtained. The pre-orifice diameter and nozzle tip area significantly affect the spray liquid density. The influence of the pre-orifice diameter and nozzle tip on droplet size characteristics might be the main reason why the two design parameters significantly influence the spray liquid density.

5.3. The influence of the air inlet design on the spray performance of the air inclusion nozzle used in Japan

To get a better understanding of the role air inlet design plays in the air inclusion nozzle, the influence of the air inlet design on the included air within droplets, droplet size characteristics, liquid flow rate, spray angle, deposit weight of spray liquid and coverage rate of the KIRINASHI ES series air inclusion nozzle was carried out.

The result showed that the quantity of the included air within droplets was significantly different between the unsealed and sealed group. In addition, the sealing of the air inlet significantly decreased the quantity of the included air within droplets under the investigated conditions. Besides, the included air quantity of KIRINASHI ES series nozzles was slightly higher, comparing with that of low pressure air inclusion nozzles based on previous research. No significant difference of $D_{v0.5}$ was found between the results of the two groups. The existence of the air inlet led to a more uniform droplet size distribution based on its influence on the RSF and might lead to better drift control due to a less volume proportion of small droplets. In addition, the sealing of air inlet slightly increased the liquid flow rate but not significantly. For the spray angle, no significant difference of the spray angle was found between the two groups. Although the manufacture claims that the spray angle is 100°, the range of the spray angle varies under different nozzle number and pressure combinations. For the deposit weight of spray liquid, no significant difference were found between the two groups. However, the deposit weight of sealed group was slight higher than that of unsealed group when the nozzle number increased. The test of the coverage rate of the two groups showed that no significant difference was found between the two groups. However, based on the results of the D_{50} and D_{100}, it could be concluded that the unsealed group might have the potential to decrease the volume proportion of small droplets and have a better drift control while keeping the coverage rate as same as the sealed group.

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