

RESEARCH ARTICLE

Droplet spectra and high-speed wind tunnel evaluation of air induction nozzles

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Abstract A series of air induction nozzles were tested in a high-speed wind tunnel. Droplet size spectra were measured for four air induction nozzles (IDK-120-01, IDK-120-02, IDK-120-03 and IDK-120-04) each at three spray pressures (0.3, 0.4 and 0.5 MPa) and seven different air velocities (121.7, 153.4, 185.5, 218.4, 253.5, 277.5 and 305.5 km·h⁻¹). The measurement distance (0.15, 0.25 and 0.35 m) from the nozzle orifice was found to be important for the atomization of the droplets. The response surface method was used to analyze the experimental data. The results indicated that $D_{V_{0.1}}$ and $D_{V_{0.5}}$ of the droplets decreased quasi-linearly with increased wind speed, while $D_{V_{0.9}}$ was affected by the quadratic of wind speed. $D_{V_{0.1}}$, $D_{V_{0.5}}$ and $D_{V_{0.9}}$ of the droplets were all proportional to the orifice size, and were not markedly influenced by the spray pressure. The percentage of the spray volume consisting of droplets with a diameter below 100 μm ($\% < 100 \mu\text{m}$) was found to be quadratically related to wind speed, and was not markedly influenced by the spray pressure and orifice size. However, the effect of the orifice size on the $\% < 200 \mu\text{m}$ could not be ignored.

Keywords air induction nozzle, wind tunnel, aerial spray, droplet size spectra

1 Introduction

With its low cost and high efficient performance, aerial spraying has become the most common method for pesticide application in large fields^[1]. However, aerial spraying can easily cause droplet drift and off-target damage to the environment or public health^[2,3]. The cross wind speed and spray droplet size have long been

considered as two of the dominant factors influencing drift^[4–6]. When the great losses of small droplets were taken into consideration, the droplet size distribution was found more important than average droplet size after the original publication of ASAE S572^[7,8]. Aerial spray droplet size and spectra were influenced by many parameters such as nozzle type, size, spray pressure, and so on^[9,10].

However, the initial droplet size distribution in aerial spray is still very hard and expensive to obtain directly in the aircraft. It is also hard to make a ground test, because the application speed of the airplane is very high and the air shear will smash the droplets immediately when they come out of the nozzle^[11]. Thus, wind tunnels have been used to simulate a real flight-speed environment to estimate the air shear effect on the droplets generated by the aerial spray nozzles. Kirk and Hewitt studied the influence of wind speed, spray pressure, orientation angle of the nozzle and nozzle orifice size on aerial spray droplet size spectra in various wind tunnel experiments^[8,12]. These four parameters were used to assess the spray droplet size spectra of the flat fan nozzles. The response surface method has also been used to design experiments.

Subsequently, a series of experimental studies of the performance of the flat fan nozzles were made by Frits et al. in high-speed wind tunnels at USDA-ARS, University of Queensland and University of Nebraska-Lincoln^[13–15]. The measurement systems had been upgraded with more modern technology. A central composite design response surface method was used to design the experiments instead of the Box-Behnken design method. The current USDA-ARS aerial spray nozzle atomization models have been updated through all of these efforts^[16].

In addition to flat fan nozzles, which have been studied carefully under all operating conditions, air induction nozzles have been recommended over the past 20 years by

Received June 7, 2017; accepted August 18, 2017

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some nozzle manufacturers and researchers to reduce spray drift by generating droplets filled with air. Its performance has been widely studied under low speed conditions^[9,17–22]. However, the application efficiency of this kind of nozzle still remains controversial^[23,24].

So far, few experiments have examined the performance of this kind of nozzle under high speed conditions. Commonly it is believed that the strong air shear under high speed conditions will break the bubbles generated by the air induction nozzles rendering them useless. However, Tang et al.^[25] found that under high speed conditions, air induction nozzles perform better than flat fan nozzles at the same flow rate. They have a lower RS, higher $Dv_{0.5}$, and are insensitive to spray pressure changes. In this study, a series of air induction nozzles were tested in a newly designed high-speed wind tunnel at National Research Center of Intelligent Equipment for Agriculture (NRCIEA). The spray droplets were measured with varying orifice size, spray pressure and wind speed. A response surface method was used to analyze the experimental data. A simplification of the fitted equations of the atomization parameters was used to find the factors influencing atomization and spray droplet size from spray nozzles on agricultural aircraft.

2 Materials and methods

The nozzle test was conducted in the IEA-I high-speed wind tunnel at NRCIEA, Beijing, China. The spray pressure and flow rate of the nozzles were adjustable with a spray control system. Droplet size and spectra measurements were made using a Malvern Spraytec laser diffraction instrument (Malvern Instruments, Malvern, UK) and its diameter distributions were analyzed by the software of Malvern Corporation.

2.1 Test design

The IDK nozzles tested in this paper were produced by Lechler GmbH (Ulmer Street 128, D-72555 Metzingen, Baden-Württemberg, Germany). These kinds of air induction nozzles have a droplet generation principle based on the Venturi effect^[20]. The nozzles were mounted on the tube of the spray control system, and the orifice was about 0.1 m away from the exit of the wind tunnel. The temperature was 20°C, and the relative humidity was 30% during the experiment. Tap water was used as the test medium.

$Dv_{0.1}$, $Dv_{0.5}$, $Dv_{0.9}$, RS, % < 100 μm and % < 200 μm of the droplets were analyzed. The atomization parameters were defined as follows:

$Dv_{0.1}$ = droplet size such that 10% of the spray volume is droplets smaller than $Dv_{0.1}$.

$Dv_{0.5}$ = droplet size such that 50% of the spray volume is droplets smaller than $Dv_{0.5}$.

$Dv_{0.9}$ = droplet size such that 90% of the spray volume is droplets smaller than $Dv_{0.9}$.

RS = relative span of the droplets, which is defined by the formula $(Dv_{0.9} - Dv_{0.1})/Dv_{0.5}$. It is a measure of the range of droplet size spectrum in the spray, with smaller numbers indicating a narrower range of droplet sizes, accounting for the mid 80% of the spray volume.

% < 100 μm = percentage of the spray volume contained in droplets with a diameter below 100 μm .

% < 200 μm = percentage of the spray volume contained in droplets with a diameter below 200 μm .

Each case was replicated three times and each acquisition time lasted 50 s. The final result of the case was the mean value of the three measurements. The droplet size spectra measured by the Malvern Spraytec laser diffraction instrument were carefully analyzed. $Dv_{0.5}$ and RS of the droplets were extracted from the experimental data.

The test parameters are listed below:

- (1) The air induction nozzle types IDK-120-01, IDK-120-02, IDK-120-03 and IDK-120-04 (Fig. 1) were tested.
- (2) The distances from the nozzle orifice to the measurement point were 0.15, 0.25 and 0.35 m.
- (3) The wind speeds were 121.7, 153.4, 185.5, 218.4, 253.5, 277.5 and 305.5 $\text{km}\cdot\text{h}^{-1}$.
- (4) The flow rate of the nozzles depends on the spray pressure and their types, as shown in Table 1.



Fig. 1 The IDK nozzles with different orifice sizes

Table 1 The flow rate of the nozzles at different spray pressures

Nozzle type	Spray pressure/MPa	Flow rate/(L·min ⁻¹)
IDK-120-01	0.3	0.39
	0.4	0.45
	0.5	0.51
IDK-120-02	0.3	0.80
	0.4	0.92
	0.5	1.03
IDK-120-03	0.3	1.19
	0.4	1.37
	0.5	1.53
IDK-120-04	0.3	1.58
	0.4	1.82
	0.5	2.04

2.2 Wind tunnel facility

The IEA-I high-speed wind tunnel, built in 2015, at the aerial spray laboratory of NRCIEA, was used. It was a blow down wind tunnel with a maximum wind speed of $350 \text{ km} \cdot \text{h}^{-1}$, which could cover the highest speed of fixed-wing agricultural aircraft. This tunnel contained a carefully designed setting chamber with honeycomb and screen meshes, which could greatly improve the flow quality of the test section. A detailed structure diagram of the IEA-I high-speed wind tunnel is given in Fig. 2.

The operational conditions of the IEA-I high-speed wind tunnel are listed in Table 2. More details about the design and test of the wind tunnel are shown in reference^[26].

2.3 Spray control system

The spray control system was designed to control and record the pressure and flow rate in the tube. It had a water storage tank, a diaphragm pump, a buffer tank, a reducing

valve, a pressure sensor, a flow meter and a spray nozzle. The pressure transducer was mounted at the same height with the nozzle. The flow rate and spray pressure was controlled and recorded accurately by adjusting the reducing valve. The pressure sensor was mounted at the same height with the nozzle.

A schematic of the spray control system is given in Fig. 3.

2.4 Data acquisition

A Malvern Spraytec laser diffraction instrument was used to measure the spectra of droplet size. It was an automated, real-time and high-speed measuring system. Its acquisition rate was about 10 kHz, with a size measuring range of $0.1\text{--}900 \mu\text{m}$.

The nozzle was fixed on an optimal platform and could be twisted to adjust the atomization zone. The nominal spray angle of the nozzle is 120 degree, but influenced by the high speed air flow, the real angle of the plume is less

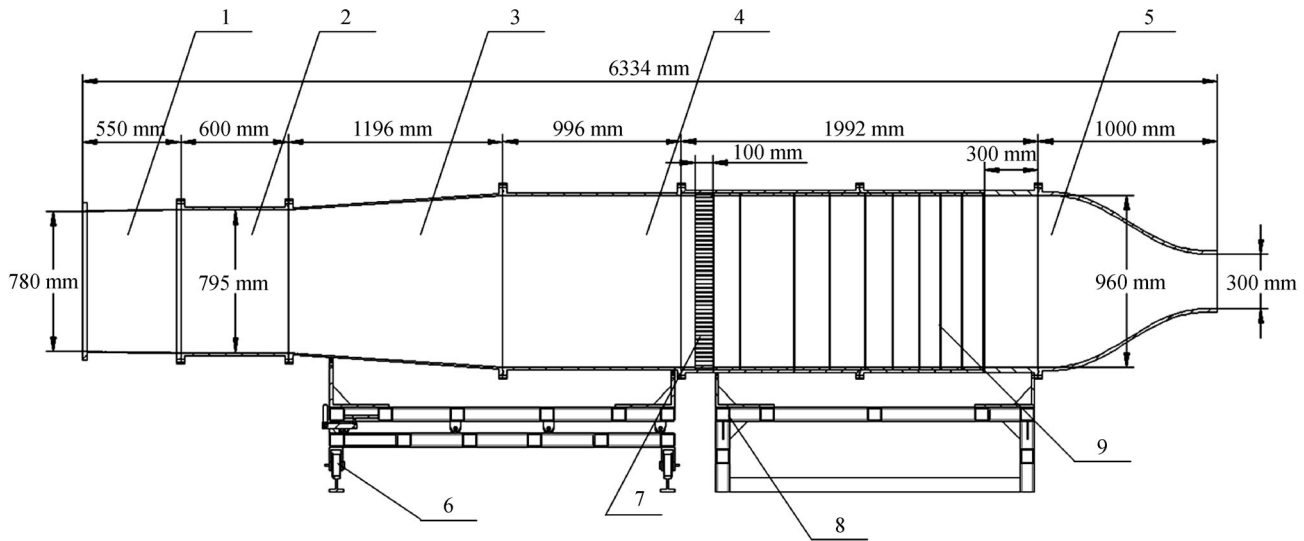


Fig. 2 Structure diagram of the IEA-I high-speed wind tunnel^[26]. 1, Adapter; 2, shock absorber; 3, diffuser; 4, settling chamber; 5, contraction section; 6, rail; 7, honey comb; 8, fixed support; 9, screen meshes.

Table 2 Parameters of the IEA-I high-speed wind tunnel

Parameter	Technical index
Form of structure	Open-circuit blow-down wind tunnel
Test section diameter	300 mm
Wind speed	$24\text{--}350 \text{ km} \cdot \text{h}^{-1}$
Turbulent intensity	$< 1.0\%$
Coefficient of variation	$< 0.5\%$
Dynamic pressure stability coefficient	$< 2.0\%$
Inclined angle	$< 0.5 \text{ deg}$
Normalized axial static pressure gradient	0.02 (0–0.46 m outside the exit)

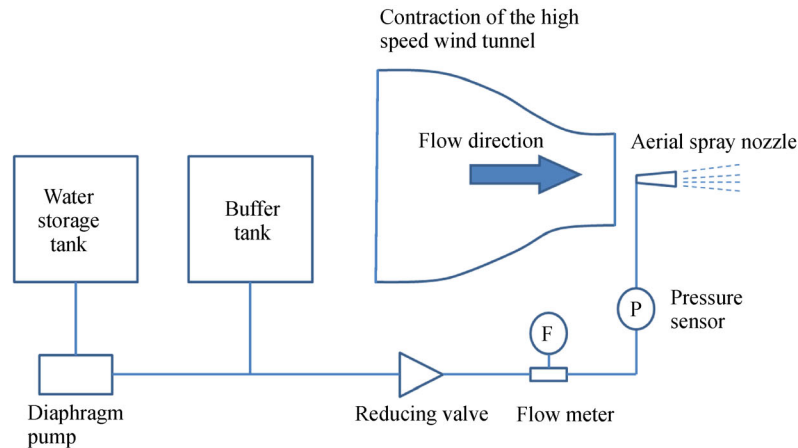


Fig. 3 Schematic diagram of the spray control system

than 45 degree. The laser diffraction instrument was installed on an electric lifting platform, which could be traversed vertically such that the entire spray plume could be sampled within a given replicated measurement. The speed of the platform was set to $5 \text{ mm} \cdot \text{s}^{-1}$, and the scanning distance was about 250 mm. This scanning distance is in the range of the exit diameter of the test section, it is also large enough to sample the entire spray plume of the nozzle. The leeward view of the measuring schematic is shown in Fig. 4.

The Malvern analyzer operates on the basis of light scattering and there were concerns that the internal structures of droplets with air inclusions may influence the values obtained when measuring droplet size distributions from air induction nozzles with this instrument. However, Powell et al.^[18] found that the Malvern analyzer can be used to measure droplet size distribution in sprays from air induction nozzles with reasonable confidence over a range of relevant conditions.

3 Results and discussion

3.1 Effect of the measuring distance

First, the study focused on the effect of the measuring point on the atomization of the droplets. The droplets size data for the IDK120-03 nozzle at spray pressure of 0.4 MPa measured using laser diffraction at each measurement distance and air speed are shown in Table 3.

Figure 5 shows that spectra of the droplet size were influenced both by distance of the measuring point from the nozzle orifice and wind speed. When wind speed was less than $150 \text{ km} \cdot \text{h}^{-1}$, $Dv_{0.5}$, RS, % < $100 \mu\text{m}$ and % < $200 \mu\text{m}$ of the droplets were almost the same at 0.15, 0.25 and 0.35 m from the nozzle orifice. However, when wind speed was increased, the measuring distance had an impact.

As shown in Fig. 5a, when the measuring point was 0.15 m from the nozzle orifice, $Dv_{0.5}$ of droplets was about

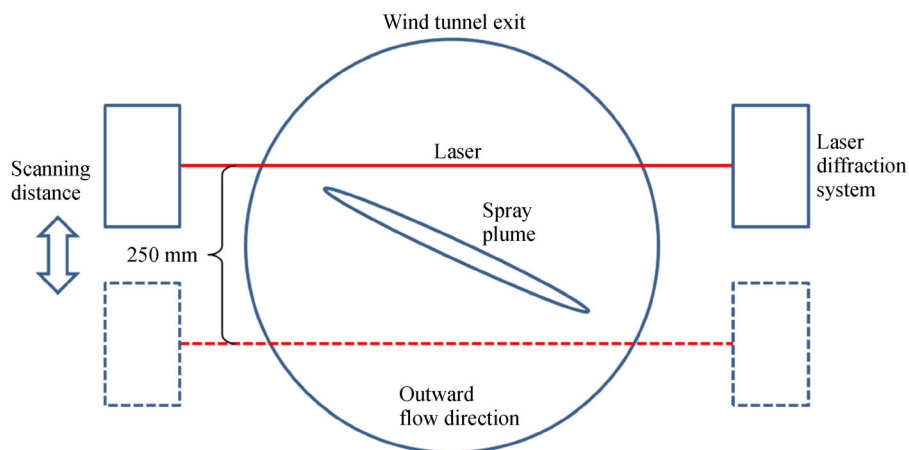


Fig. 4 Schematic diagram of the spray measurement from the leeward view

Table 3 Droplet size data measured using the Malvern laser diffraction system for IDK120-03 nozzle operating at 0.4 MPa

Distance from the orifice/m	Wind speed/(km · h ⁻¹)	Dv _{0.5} /μm	Dv _{0.1} /μm	Dv _{0.9} /μm	RS	% < 100 μm	% < 200 μm
0.15	121.7	426.8	210.5	740.5	1.242	1.56	8.62
	153.4	403.6	195.1	722.8	1.308	1.70	10.74
	185.5	367.6	172.5	692.0	1.414	2.28	14.89
	218.4	312.6	141.7	636.6	1.583	3.75	23.23
	253.5	257.2	115.9	555.5	1.709	6.68	34.13
	277.5	212.7	95.0	477.6	1.797	11.42	46.05
	305.5	175.7	78.1	402	1.843	18.32	58.17
0.25	121.7	428.6	215.3	740.7	1.226	1.44	7.98
	153.4	401.3	196.1	719.2	1.303	1.72	10.60
	185.5	354.2	167.0	676.6	1.439	2.39	16.28
	218.4	292.2	136.3	595.6	1.572	4.16	25.98
	253.5	234.1	110.4	477.5	1.568	7.58	39.14
	277.5	188.4	87.4	375.4	1.528	14.13	54.21
	305.5	157.6	73.3	307.7	1.487	21.39	66.88
0.35	121.7	424.3	213.3	737.0	1.234	1.49	8.19
	153.4	397.5	195.0	714.6	1.307	1.79	10.76
	185.5	348.6	168.5	663.5	1.420	2.47	16.09
	218.4	282.4	136.1	558.2	1.495	4.35	26.69
	253.5	225.8	110.1	428.3	1.410	7.69	40.96
	277.5	184.7	87.9	343.0	1.381	13.85	56.05
	305.5	154.9	72.6	290.3	1.405	21.69	68.87

10% larger than when measured 0.25 and 0.35 m from the nozzle orifice over a wind speed range of 180–300 km · h⁻¹, which indicates that 0.15 m is not long enough for the droplets to be atomized sufficiently. It is easy to imagine that when the wind speed increases, the liquid will move a greater distance before it is fully atomized.

Figure 5b shows that RS of droplets increased with wind speed at the measuring point of 0.15 m. It was also evident that at the measuring points of 0.25 and 0.35 m, RS stopped increasing when wind speed exceeded 220 km · h⁻¹. However, RS of droplets is not a direct physical parameter and it is difficult to analyze it in this figure.

Figure 5c and Figure 5d could be utilized to explain this phenomenon, for RS is defined by the formula $(Dv_{0.9} - Dv_{0.1})/Dv_{0.5}$. When the measuring distance was increased, small droplets did not change much, but the size of large droplets decreased greatly. A possible reason is that the instrument measures the droplet size by calculating the numbers of droplets across the laser spot in a unit time. When the wind speed increased, big droplets are easily calculated repetitively comparing with the smaller ones because of their lower speed and big inertia, which may cause an over-predicted value of droplet size^[15,27,28]. Another possible reason is that large droplets need to take longer time and distance to break up into smaller droplets. In Fig. 5d it could be seen that there is a great difference of

$Dv_{0.9}$ between the measuring distance of 0.15 m and 0.25 m. There was also a smaller difference of $Dv_{0.9}$ between the measuring distance of 0.25 m and 0.35 m, which indicates that at the measuring distance of 0.35 m the large droplets still may not be fully atomized.

Figure 5e and Figure 5f show little difference between the measuring points at 0.25 and 0.35 m for % < 100 μm and % < 200 μm, which were larger than the results at the measuring point at 0.15 m. This also indicates that 0.15 m was insufficient to obtain fully atomized droplets.

As shown in Fig. 5, it is obvious that the further the measuring point was away from the nozzle orifice, the more the droplets were atomized. However, flow field quality outside the exit of the wind tunnel should not be ignored^[26]. When the measuring point was too far away from the exit of the wind tunnel, the flow field (wind speed/fluctuations) changed. The spray plume may also exceed the measuring range of the laser diffraction instrument and the uniform flow field of the wind tunnel test section. As a tradeoff of the above situations, a measuring point of 0.35 m was chosen for the following analysis.

3.2 Effect of the nozzle type, spray pressure and wind speed

The droplet size data for different orifice sizes, wind speeds and spray pressures were measured systematically and the

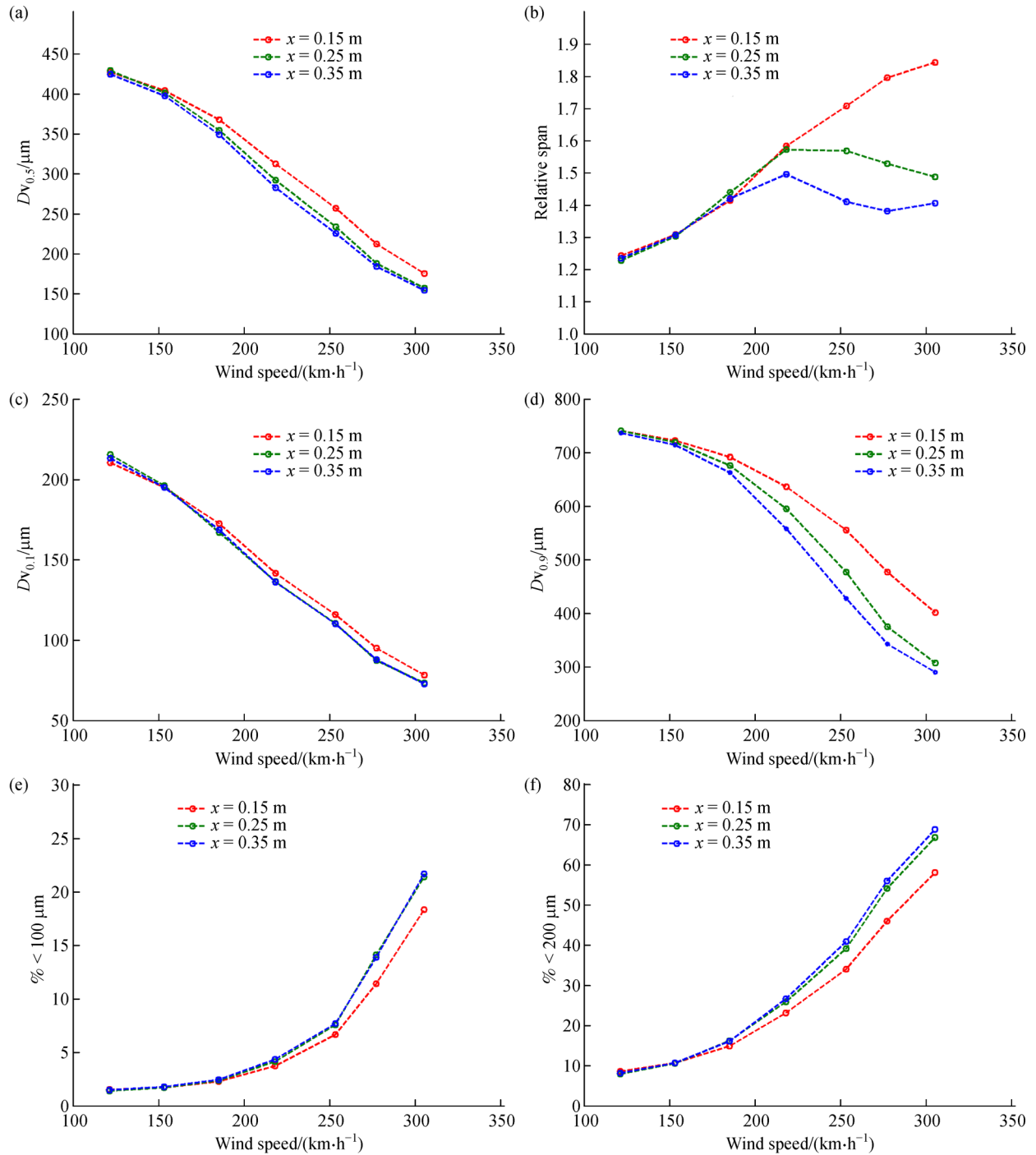


Fig. 5 $Dv_{0.5}$ (a), RS (b), $Dv_{0.1}$ (c), $Dv_{0.9}$ (d), % < 100 μm (e) and % < 200 μm (f) measured at 0.15, 0.25 and 0.35 m from the nozzle orifice

detailed results are shown in Table 4.

The response surface method was used to analyze the above results. Similar to Kirk^[8] and Fritz & Hoffmann^[16], second-order response relationships were fitted using Eq. (1) for data collected for each nozzle and model type evaluated:

$$Y = AX_1 + BX_2 + CX_3 + DX_1^2 + EX_2^2 + FX_3^2 + GX_1X_2 + HX_2X_3 + IX_1X_3 \quad (1)$$

where Y is the predicted atomization parameter based on specification of inputs X_1 to X_3 ($Dv_{0.5}$, $Dv_{0.1}$, $Dv_{0.9}$, RS, % < 100 μm and % < 200 μm), X_1 is the airspeed ($\text{km}\cdot\text{h}^{-1}$), X_2 is the spray pressure (MPa), X_3 is the orifice size (unitless, specific orifice number for each nozzle based on the flow rate at fixed spray pressure^[29]), and A to I are the coefficients for respective terms of the equation.

Coefficients of the response surface equations for IDK nozzle are shown in Table 5. A quadratic process and a

Table 4 Droplet sizes data measured using Malvern laser diffraction system at 0.35 m

Spray pressure/MPa	Nozzle type	Wind speed/(km·h ⁻¹)	Dv _{0.5} /μm	Dv _{0.1} /μm	Dv _{0.9} /μm	RS	% < 100 μm	% < 200 μm	
0.3	IDK-120-01	121.7	414.2	205.7	728.7	1.263	1.53	9.193	
		153.4	373.6	185.6	687.0	1.343	1.97	12.51	
		185.5	315.8	159.2	603.3	1.406	2.68	19.36	
		218.4	255.2	131.6	471.9	1.334	4.32	31.43	
		253.5	209.0	107.2	375.0	1.282	8.12	46.44	
		277.5	175.3	88.5	317.5	1.307	14.16	60.61	
		305.5	151.4	76.4	285.5	1.381	21.17	71.09	
	IDK-120-02	121.7	408.2	204.3	722.4	1.270	1.48	9.37	
		153.4	375.6	185.3	690.5	1.345	1.92	12.52	
		185.5	322.9	160.4	618.7	1.419	2.69	18.69	
		218.4	265.2	135.8	498.7	1.369	3.92	29.03	
		253.5	214.2	106.8	393.3	1.337	8.27	44.66	
		277.5	178.7	87.9	330.5	1.357	14.16	58.78	
		305.5	154.1	74.3	306.0	1.504	21.43	68.90	
	IDK-120-03	121.7	442.9	233.7	746.4	1.158	0.99	5.73	
		153.4	408.1	203.3	723.6	1.275	1.71	9.52	
		185.5	350.7	169.8	666.7	1.417	2.42	15.83	
		218.4	280.4	136.9	552.8	1.483	4.07	26.89	
		253.5	221.3	107.9	419.6	1.408	8.07	42.46	
		277.5	181.9	87.4	338.0	1.378	14.25	57.18	
		305.5	152.8	71.5	286.3	1.406	22.44	69.73	
	IDK-120-04	121.7	471.6	257.9	767.5	1.081	0.87	3.74	
		153.4	434.1	221.7	743.8	1.203	1.49	7.23	
		185.5	367.9	181.4	682.2	1.362	2.17	13.29	
		218.4	293.8	144.1	574.2	1.464	3.67	23.98	
		253.5	234.4	114.3	451.1	1.437	6.95	38.30	
		277.5	190.6	92.1	359.5	1.404	12.43	53.68	
		305.5	160.5	76.7	308.2	1.443	19.60	66.30	
	0.4	IDK-120-01	121.7	383.1	186.6	703.0	1.348	1.47	12.30
			153.4	350.3	171.9	663.9	1.405	1.84	15.59
			185.5	303.5	153.6	583.5	1.417	2.50	21.49
			218.4	251.7	129.6	472.6	1.363	4.24	32.62
			253.5	208.2	105.0	384.0	1.341	8.64	46.88
			277.5	177.3	90.3	325.0	1.324	13.59	59.52
			305.5	151.2	75.7	283.1	1.372	21.59	71.04
		IDK-120-02	121.7	389.9	196.6	704.3	1.306	1.52	10.81
153.4			359.2	177.0	671.6	1.377	2.01	14.28	
185.5			317.2	157.0	611.4	1.433	2.74	19.74	
218.4			263.4	132.0	500.7	1.401	4.46	29.97	
253.5			215.7	108.0	395.4	1.332	8.01	44.11	
277.5			180.4	89.2	330.1	1.336	13.69	58.14	
305.5			153.8	74.8	287.7	1.385	21.17	69.81	
IDK-120-03		121.7	424.3	213.3	737.0	1.234	1.49	8.19	
		153.4	397.5	195.0	714.6	1.307	1.79	10.76	
		185.5	348.6	168.5	663.5	1.420	2.47	16.09	
		218.4	282.4	136.1	558.2	1.495	4.35	26.69	
		253.5	225.8	110.1	428.3	1.410	7.69	40.96	
		277.5	184.7	87.9	343.0	1.381	13.85	56.05	
		305.5	154.9	72.6	290.3	1.405	21.69	68.87	
IDK-120-04		121.7	445.3	235.3	749.2	1.155	1.09	5.66	
		153.4	414.5	209.0	727.0	1.249	1.51	8.67	
		185.5	360.8	178.7	672.5	1.369	2.15	13.93	
		218.4	290.2	143.6	560.3	1.436	3.70	24.38	
		253.5	230.9	114.1	428.1	1.360	6.97	39.08	
		277.5	190.4	95.2	349.4	1.343	11.96	53.86	
		305.5	160.1	77.0	295.9	1.368	19.46	66.95	

(Continued)

Spray pressure/MPa	Nozzle type	Wind speed/(km·h ⁻¹)	D _{v0.5} /μm	D _{v0.1} /μm	D _{v0.9} /μm	RS	% < 100 μm	% < 200 μm
0.5	IDK-120-01	121.7	361.8	173.6	683.0	1.408	1.85	14.94
		153.4	330.0	161.2	634.1	1.433	2.50	18.25
		185.5	289.2	145.2	554.0	1.414	3.29	24.25
		218.4	248.9	128.6	465.9	1.356	4.23	33.39
		253.5	207.8	108.0	375.2	1.286	7.76	46.93
		277.5	176.6	90.2	320.8	1.307	13.66	59.96
		305.5	151.6	76.6	282.2	1.356	21.21	71.00
	IDK-120-02	121.7	367.2	182.4	680.9	1.358	1.70	13.19
		153.4	348.4	170.3	659.9	1.406	2.20	15.80
		185.5	314.8	154.1	612.2	1.456	2.88	20.49
		218.4	269.6	132.5	530.4	1.476	4.35	29.12
		253.5	220.3	109.2	413.9	1.383	7.76	42.64
		277.5	184.6	90.6	347.3	1.390	13.10	56.15
		305.5	157.6	76.3	308.2	1.472	20.27	67.43
	IDK-120-03	121.7	423.2	210.3	736.3	1.243	1.83	8.64
		153.4	403.5	196.8	720.3	1.298	2.03	10.47
		185.5	359.5	169.2	679.1	1.418	2.88	15.50
		218.4	295.2	136.9	591.6	1.540	4.55	25.09
		253.5	233.1	108.9	460.4	1.509	8.02	39.22
		277.5	185.8	85.9	353.4	1.440	14.48	55.41
		305.5	154.2	71.2	293.8	1.440	22.44	68.73
	IDK-120-04	121.7	429.2	222.3	736.3	1.198	0.99	6.96
		153.4	409.2	206.8	720.6	1.408	1.85	14.94
		185.5	364.0	175.2	684.8	1.433	2.50	18.25
		218.4	300.2	144.9	597.9	1.414	3.29	24.25
		253.5	236.1	116.2	447.4	1.356	4.23	33.39
		277.5	193.2	93.8	357.4	1.286	7.76	46.93
		305.5	162.0	77.6	300.1	1.307	13.66	59.96

modified process were used to find the dominant factors affecting droplet size spectra.

The quadratic model was applied to the $Dv_{0.5}$ result (Fig. 6), which was inversely proportional to the wind speed. The $Dv_{0.5}$ of the droplets was also found proportional to the orifice size. Meanwhile, increasing spray pressure could slightly reduce $Dv_{0.5}$ under low speed conditions and slightly increase $Dv_{0.5}$ under high speed conditions.

The simplified equation of $Dv_{0.5}$ is:

$$Dv_{0.5} = 566.9 - 1.49X_1 + 143.3X_3 (\mu\text{m}) \quad (2)$$

As indicated by Guler et al.^[23], the generation of the droplets by air induction nozzle originates from the breakdown of the liquid sheet. The breakdown process of the liquid sheet is accelerated by the bubbles generated by the air induction nozzle. The bubbles experience a sudden pressure relaxation and expand rapidly, thereby shattering the liquid into drops. A typical breakdown process of the liquid sheet was mentioned by Dombrowski & Johns^[30].

Based on the linear stability theory of the inviscid liquid sheet break down process, the droplet size is controlled by

the equations^[31,32]:

$$Dv_{0.5} = \text{const} \left(\frac{1}{f} \right)^{1/3} \left[\frac{C^2 \sigma_l^2}{\rho_g \rho_l (U_g - U_l)^4} \right]^{1/6} \quad (3)$$

$$f = \ln \frac{\eta_b}{\eta_0} = We^{0.37} Re^{0.07} = \frac{\alpha^{0.44} \rho_l^{0.44} U_l^{0.81}}{\mu_l^{0.07} \sigma_l^{0.37}} \quad (4)$$

where α is the thickness of the liquid sheet, ρ_g is the air density and ρ_l is the liquid density, η_b is the wave amplitude when the liquid sheet breakdown and η_0 is the initial wave amplitude. C is a constant proportional to the size of the nozzle orifice, σ_l is the surface tension of the liquid, U_g is the air speed and U_l is the liquid sheet speed.

From the Eq. (3) it can easily be derived that the $Dv_{0.5}$ of the droplets is proportional to the nozzle orifice size. Based on the test speed range of this paper, the air speed U_g is much larger than the liquid sheet speed U_l , the increase of the wind speed will reduce the $Dv_{0.5}$ of the droplets. Ignoring the linear loss of the tube flow, we obtained $\Delta\rho \propto U_l^2$. When the spray pressure increases, the breakup parameter f increases, but the velocity difference $U_g - U_l$

Table 5 Coefficients of the response surface equations for IDK nozzle

IDK nozzle	Factors	Quadratic	Modified
$Dv_{0.5}/\mu\text{m}$	Intercept	+ 667.33268	+ 566.90032
	X_1	- 1.54002	- 1.48646
	X_2	- 548.47754	NA
	X_3	+ 313.86764	+ 143.31905
	X_1X_2	+ 1.11966	NA
	X_1X_3	- 1.30482	NA
	X_2X_3	+ 201.14286	NA
	X_1^2	- 0.00016	NA
	X_2^2	+ 268.92857	NA
	X_3^2	+ 62.97619	NA
	R^2	0.9892	0.9747
$Dv_{0.1}/\mu\text{m}$	Intercept	+ 349.79038	+ 287.18927
	X_1	- 0.90314	- 0.76261
	X_2	- 287.04831	NA
	X_3	+ 173.97654	+ 69.10476
	X_1X_2	+ 0.74849	NA
	X_1X_3	- 0.98485	NA
	X_2X_3	+ 47.35714	NA
	X_1^2	+ 0.00020	NA
	X_2^2	+ 98.39286	NA
	X_3^2	+ 178.80952	NA
	R^2	0.9926	0.9621
$Dv_{0.9}/\mu\text{m}$	Intercept	+ 8.09386	+ 829.71053
	X_1	- 0.25499	- 0.62237
	X_2	+ 73.32265	NA
	X_3	- 16.54223	+ 220.55714
	X_1X_2	- 0.15258	NA
	X_1X_3	+ 0.040531	NA
	X_2X_3	- 35.50786	NA
	X_1^2	+ 0.00150	- 0.00455
	X_2^2	- 34.67321	NA
	X_3^2	- 4.02024	NA
	R^2	0.9955	0.9738
% < 100 μm	Intercept	+ 19.89198	+ 23.28981
	X_1	- 0.26713	- 0.28134
	X_2	+ 3.77809	NA
	X_3	+ 14.73769	NA
	X_1X_2	- 0.025250	NA
	X_1X_3	- 0.016430	NA
	X_2X_3	- 3.17857	NA
	X_1^2	+ 0.00089	+ 0.00089
	X_2^2	+ 2.87857	NA
	X_3^2	- 26.12976	NA
	R^2	0.9828	0.9780

(Continued)

IDK nozzle	Factors	Quadratic	Modified
% < 200 μm	Intercept	+ 8.09386	+ 29.6513
	X_1	- 0.25499	- 0.30589
	X_2	+ 73.32265	NA
	X_3	- 16.54223	- 23.98043
	X_1X_2	- 0.15258	NA
	X_1X_3	+ 0.040531	NA
	X_2X_3	- 35.50786	NA
	X_1^2	+ 0.00150	+ 0.00150
	X_2^2	- 34.67321	NA
	X_3^2	- 4.02024	NA
	R^2	0.9955	0.9936

decreases. It is hard to say how the spray pressure affects the $Dv_{0.5}$ of the droplets. When the wind speed increases, the spread angle of the flat fan nozzle decreases accordingly. In this condition, increasing the spray pressure will raise the flow rate and enhance the collision and congregation process, which may cause an increase of the $Dv_{0.5}$ of the droplets. In contrast, when the wind speed decreases, the spread angle of the flat fan nozzle increases accordingly. In this condition, increasing the spray pressure will raise the breakup parameter f , which may cause a decrease of the $Dv_{0.5}$ of the droplets. This might be a possible explanation of the phenomenon in Fig. 6b.

In this study, model equations were developed for $Dv_{0.1}$ and $Dv_{0.9}$ along with $Dv_{0.5}$, so RS values were computed with the formula $(Dv_{0.9} - Dv_{0.1})/Dv_{0.5}$.

The simplified equation is:

$$Dv_{0.1} = 287.2 - 0.76X_1 + 69.1X_3 (\mu\text{m}) \quad (5)$$

In Fig. 7, it could be seen that the $Dv_{0.1}$ has the same trends like $Dv_{0.5}$ of the droplets. A slight difference is that increasing the spray pressure will reduce $Dv_{0.1}$ to a certain extent under low speed conditions and slightly increase it under high speed conditions. The $Dv_{0.1}$ of the droplets is found to be more sensitive to the spray pressure at low speed conditions than $Dv_{0.5}$.

$Dv_{0.9}$ was not the same as $Dv_{0.1}$ and $Dv_{0.5}$. It was proportional to the orifice size and influenced by the quadratic of the wind speed. Meanwhile, it was not markedly influenced by the spray pressure, as shown in Fig. 8.

The simplified equation is:

$$Dv_{0.9} = 829.7 - 0.62X_1 + 220.6X_3 - 4.55 \times 10^{-3}X_1^2 (\mu\text{m}) \quad (6)$$

$Dv_{0.9}$ was more likely to be influenced by the quadratic of the wind speed than $Dv_{0.1}$ and $Dv_{0.5}$, which can be interpreted as follows.

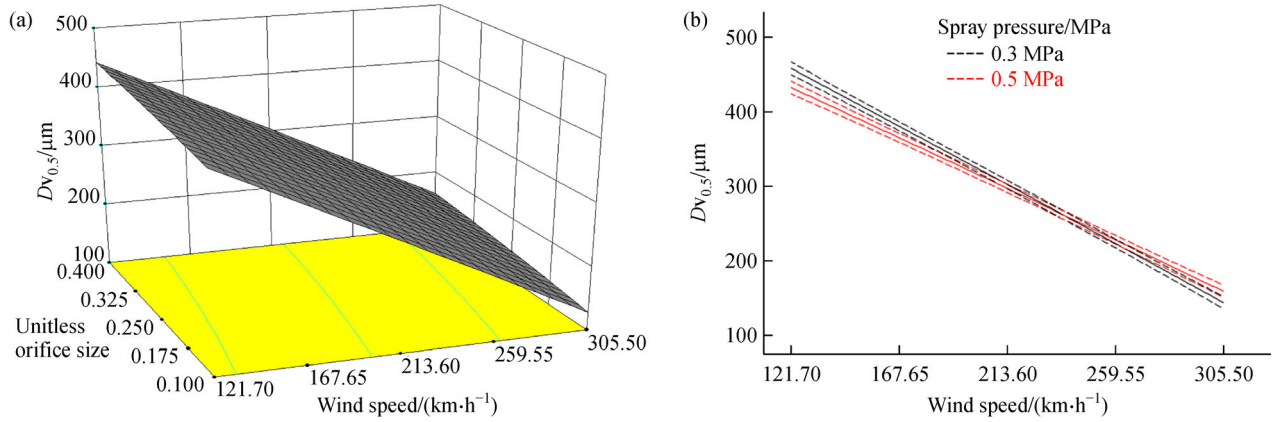


Fig. 6 3D response surface of $DV_{0.5}$ related to the wind speed and orifice size (a) and the effect of the spray pressure and wind speed on $DV_{0.5}$ (b)

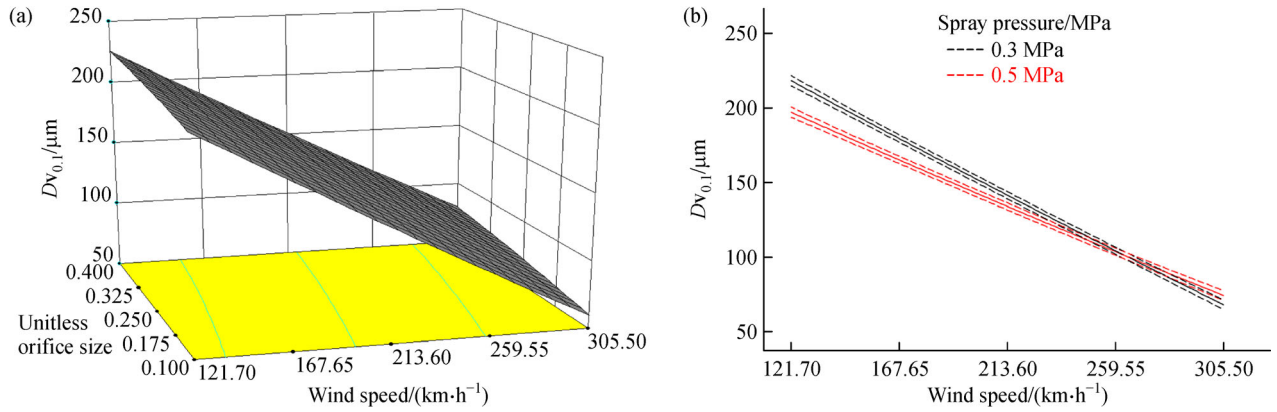


Fig. 7 3D response surface of $DV_{0.1}$ related to the wind speed and orifice size (a) and the effect of the spray pressure and wind speed on $DV_{0.1}$ (b)

The maximum diameter of droplets in shear flow was determined by the equation^[33] below:

$$D_{\max} = \frac{We\sigma_l}{\rho_g\Delta U^2} \quad (7)$$

We is the Weber number, which depends on the breakdown conditions of the droplet. When bag breakup (one of the most important breakup modes) occurs, multiple studies^[34] have shown that $We \approx 11$. D_{\max} is the maximum stable diameter of the droplet; ρ_g is the air density; ΔU is the speed difference between the air and the liquid; σ_l is the surface tension coefficient of the droplet.

From the above equation, it can be seen that the maximum stable diameter of the droplet was inversely proportional to the quadratic of the speed difference between the air and the liquid, which can influence $DV_{0.9}$ to a certain extent.

$\% < 100 \mu\text{m}$ was found only quadratically related to wind speed and not markedly influenced by spray pressure and orifice size, as shown in Fig. 9.

The simplified formula is:

$$\% < 100 \mu\text{m} = 23.29 - 0.28X_1 + 8.88 \times 10^{-4}X_1^2 \quad (8)$$

Since $\% < 100 \mu\text{m}$ is one of the primary parameters indicative of spray drift propensity of aerial applied agricultural materials, the equation indicates that changing spray pressure or nozzle orifice size had limited effect on reducing potential drift losses of small droplets.

$\% < 200 \mu\text{m}$ was similar to $\% < 100 \mu\text{m}$. It was not only influenced by wind speed, but also slightly influenced by nozzle orifice size, as shown in Fig. 10.

The simplified formula is:

$$\% < 200 \mu\text{m} = 29.65 - 0.31X_1 - 23.98X_3 + 1.50 \times 10^{-3}X_1^2 \quad (9)$$

While $\% < 200 \mu\text{m}$ also provides a measure of potential spray drift from aerial sprays. The result indicated that increasing nozzle orifice size can slightly reduce $\% < 200 \mu\text{m}$ and improve drift losses of larger droplets.

Because the common aerial spray application speed of the fixed-wing aircraft is about $150\text{--}260 \text{ km}\cdot\text{h}^{-1}$ (the working speed of Thrush 510G is about $150\text{--}240 \text{ km}\cdot\text{h}^{-1}$, and the Air Tractor 802A is about $210\text{--}260 \text{ km}\cdot\text{h}^{-1}$), the $DV_{0.5}$ of the droplet generated by the IDK nozzles at this speed range could be kept to $224\text{--}330 \mu\text{m}$, which is an

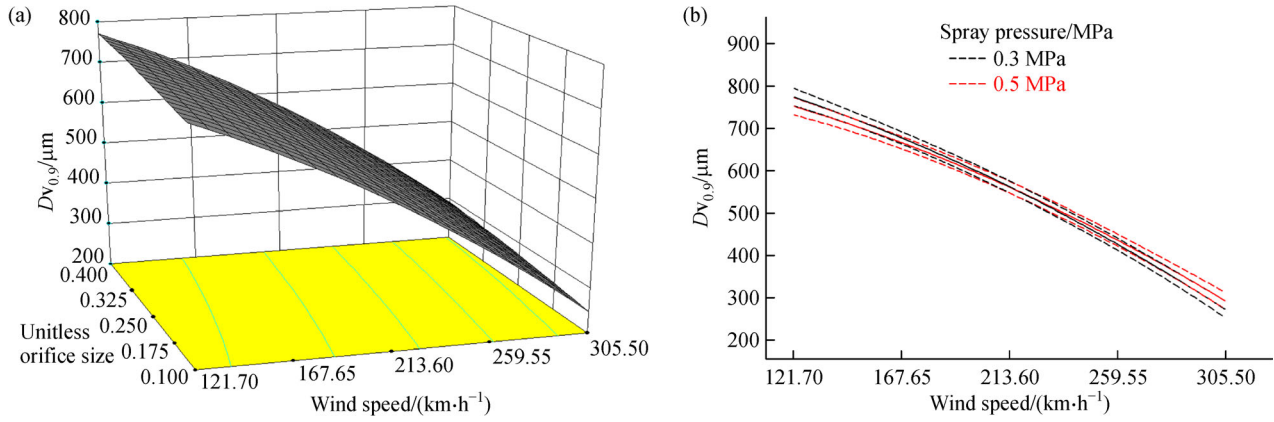


Fig. 8 3D response surface of $Dv_{0.9}$ related to the wind speed and orifice size (a) and the effect of the spray pressure and wind speed on $Dv_{0.9}$ (b)

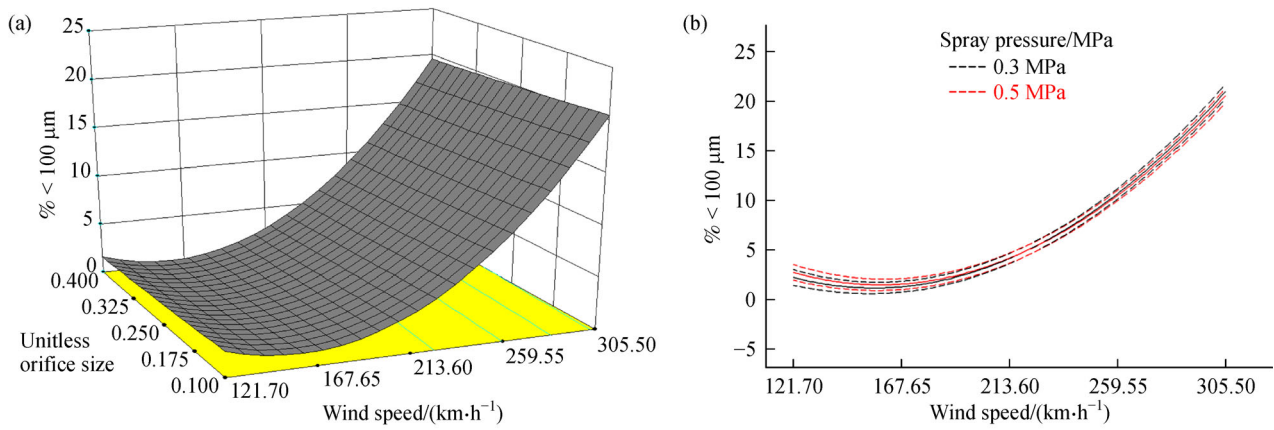


Fig. 9 The 3D response surface of the $\% < 100 \mu\text{m}$ related to the wind speed and orifice size (a) and the effect of the spray pressure and wind speed on the $\% < 100 \mu\text{m}$ (b)

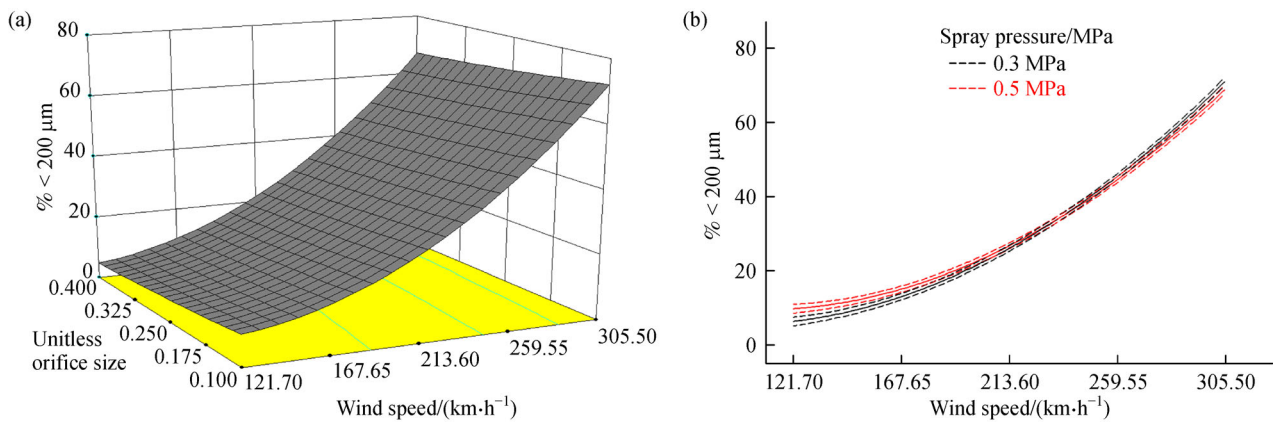


Fig. 10 The 3D response surface of the $\% < 200 \mu\text{m}$ related to the wind speed and orifice size (a) and the effect of the spray pressure and wind speed on the $\% < 200 \mu\text{m}$ (b)

optimal size for weeding. Increasing nozzle orifice size could greatly increase the flow rate and improve drift losses of droplets with diameter between 100 μm and 200 μm .

Based on these results, it could be suggested that the IDK nozzle is applicable for fixed-wing aerial spray weed control. Higher spray pressure and larger orifice size should be chosen to increase the flow rate and improve drift losses of the droplets at a high application speed. For example, when the spray pressure is 0.5 MPa and the IDK-120-04 nozzles have been used in an Air Tractor 802A with application speed of 260 $\text{km}\cdot\text{h}^{-1}$, the $Dv_{0.5}$ of the droplet is about 224 μm , $\% < 200 \mu\text{m}$ is 37.34% and $\% < 100 \mu\text{m}$ is 5.26%. The potential drift losses of the IDK nozzles are still acceptable. Since the IDK nozzles with even larger orifice size (IDK-120-05 to IDK-120-08) were not tested in this paper, but it is believed that the IDK nozzle could perform well at high speed weeding condition. In contrast, in order to improve untargeted deposit losses of the droplets at a low application speed, higher spray pressure and smaller orifice size should be chosen. For example, when the spray pressure is set at 0.5 MPa and the IDK-120-01 nozzles have been used in a Thrush 510G with application speed of 150 $\text{km}\cdot\text{h}^{-1}$, the $Dv_{0.5}$ of the droplet is kept to about 330 μm , $\% < 200 \mu\text{m}$ is 18.25% and $\% < 100 \mu\text{m}$ is 2.5%.

4 Conclusions

This paper tested a series of air induction nozzles at the IEA-I high-speed wind tunnel in NRCIEA. The parameters influencing the droplets distribution, including the wind speed, spray pressure and orifice size have been carefully studied. It was concluded that:

(1) Distance from the measuring point to the nozzle orifice greatly affected the distribution of the droplets. When the measuring point was 0.15 m from the nozzle orifice, the droplets, especially the large ones generated by the nozzle, were not fully atomized. When the measuring points were 0.25 and 0.35 m distant, the atomization of the droplets improved greatly, which indicates 0.35 m was a suitable measuring distance based on the size of the wind tunnel exit. The measuring distance should not be too far downstream from the nozzle, since the flow speed further downstream from the exit of the wind tunnel may be not uniform.

(2) Droplet size was found to be proportional to the orifice size, especially under low speed conditions. $Dv_{0.1}$ and $Dv_{0.5}$ were inversely proportional to wind speed. Relatively, $Dv_{0.9}$ was influenced by the quadratic of the wind speed. Increasing the spray pressure slightly reduced droplet size under low speed conditions, and slightly increased droplet size under high speed conditions. However, the overall effect of spray pressure on droplet size was weak.

(3) $\% < 200 \mu\text{m}$ was found to be influenced by nozzle orifice size and the quadratic of the wind speed, the effect of the spray pressure was indistinct. However, the percentage of the small droplets which dominated the drift losses of small droplets, $\% < 100 \mu\text{m}$, was found to be largely independent of nozzle orifice size and spray pressure. This indicates that under high-speed operating conditions, reducing drift by increasing orifice size of the air induction nozzle or reducing the spray pressure are not suitable approaches.

(4) IDK nozzles could be used for aerial spray weeding, as the $Dv_{0.5}$ of the droplets is in the range of 224–330 μm , at an application speed of 150 $\text{km}\cdot\text{h}^{-1}$ to 260 $\text{km}\cdot\text{h}^{-1}$. At an application speed of 150 $\text{km}\cdot\text{h}^{-1}$, a spray pressure of 0.5 MPa and the IDK-120-01 nozzle should be chosen to improve untargeted deposit losses of the droplets, and the $Dv_{0.5}$ of the droplet could be kept at about 330 μm . At an application speed of 260 $\text{km}\cdot\text{h}^{-1}$, a spray pressure of 0.5 MPa and the IDK-120-04 nozzle should be chosen to improve drift losses of the droplets, and the $Dv_{0.5}$ of the droplet should be kept to about 224 μm .

Acknowledgements This work was supported by the National Natural Science Foundation of China (31601228, 31701315), the Youth Science Fund of the Beijing Natural Science Foundation (6164032), the Youth Science Fund of Beijing Academy of Agriculture and Forestry Sciences (QNJJ201631), and Beijing Talent Program for Ruirui Zhang.

Compliance with ethics guidelines Qing Tang, Liping Chen, Ruirui Zhang, Min Xu, Gang Xu, Tongchuan Yi, and Bin Zhang declare that they have no conflicts of interest or financial conflicts to disclose.

This article does not contain any studies with human or animal subjects performed by any of the authors.

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