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Airspeed and pressure affect spray droplet spectrum from an aerial nozzle for fixed-wing applications

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Abstract. *The atomization of the droplets generated by a flat fan nozzle has been studied in the IEA-I high speed wind tunnel at NERCIEA with Marvern Spraytec Laser Diffraction system. The measurement point is set at 0.15m, 0.25m and 0.35m away from the orifice of the nozzle. The wind speed range is from 150km/h to 305km/h, and the tube pressure is set about 0.3MPa, 0.4MPa and 0.5MPa. The measuring distance from the orifice of the nozzle is found important to the diameter and relative span of the droplets. In our results, 0.35m away from the orifice of the nozzle is found to be a proper measuring point, where the droplets are fully atomized and the flow quality of the wind tunnel is good enough for the test. The effect of airspeed and pressure has been analyzed with response surface method, and the results showed that when the wind speed increase from 120km/h to 305km/h, the Dv0.5 of the droplets decreased from 220μm to 130μm. The increasement of the tube pressure will strongly decrease the droplet diameter at a lower wind speed and slightly increase the droplet diameter at a higher wind speed.*

Keywords. *Aerial spray, Flat fan nozzle, High speed wind tunnel, Droplet characteristics, Response surface method*

Introduction

The droplet drift reduction is an important task in aerial spray application. The factors considered in these studies included the spray droplet size, cross wind speed, spray conditions (type of the aircraft and its flying height), physical chemistry (viscosity, specific gravity, and surface tension), and atmospheric conditions [1,2]. Spray droplet size have long been considered as one of the dominant factors [3-13]. However, the importance of the droplet distribution spectra is taken into consideration after the original publication of ASAE S572 [14,15].

The aerial spray droplet size and spectra are not only influenced by nozzle type, size, and spray pressure [16,17], but also by the air shear layer atomization [8]. Hewitt and Kirk studied the influence of the wind speed, spray pressure, orientation angle of the nozzle and nozzle orifice size to the aerial spray droplet spectra by varies of wind tunnel experiments [15,18]. These four significant parameters were introduced to assess the spray droplet spectra of the flat fan nozzles and a BBD response surface method has been used to design the experiment.

Then, a serial of experimental studies have been taken by Frits in high speed wind tunnels at USDA-ARS, University of Queensland and University of Nebraska-Lincoln [19-21]. The measurement systems have been upgraded with more modern technologies. A CCD response surface method has been used to design the experiment instead of the BBD method. The current USDA-ARS aerial spray nozzle atomization models have been updated by all of these efforts.[22]

Some other types of nozzles have also been tested in high speed wind tunnels. Martin studied the effect of airspeed and orifice size to the spray droplet spectrum from an aerial electrostatic nozzle [23] The spray droplet spectrum from a rotary atomizer has been measured with varies of tank mix, flow rate, wind speed, and blade angle [24].

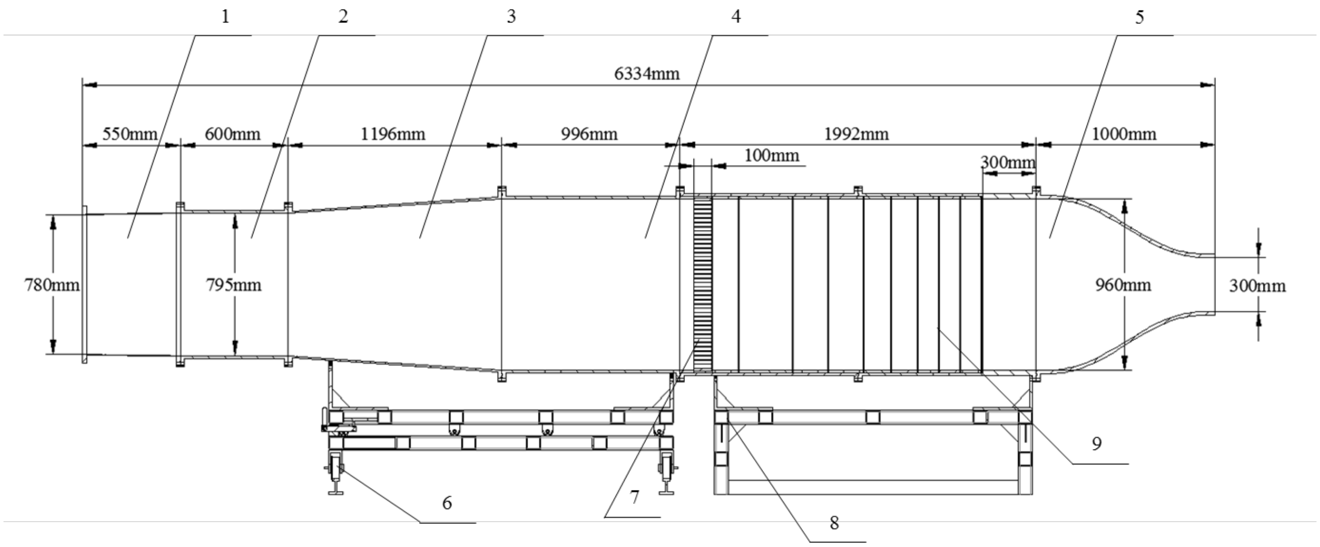
In this paper, a flat-fan nozzle has been tested in a new designed high speed wind tunnel at NERCIEA. The spray droplets generated by this kind of nozzle have been measured with varies of tube pressure, wind speed, and measuring points. The response surface method has been used to analyze the experimental results.

Materials and Methods

The nozzle test was conducted in the IEA-I high speed wind tunnel at NERCIEA, Beijing, China. The spray pressure and flow rate of the nozzle are adjustable with a spray control system. Droplet size and spectra measurements were made using a Marvern Spraytec Laser diffraction instrument and its diameter distributions are analyzed by the software of Marvern Corporation.

Wind Tunnel Facility

The IEA-I high speed wind tunnel has been built in 2015, at the aerial spray lab of NERCIEA, Beijing. It is a blow down wind tunnel with a maximum wind speed of 98m/s, which could cover the highest speed of the fixed-wing agricultural aircraft. This tunnel contains a carefully designed setting chamber with honeycomb and screen meshes, which could greatly improve the flow quality of the test section. The detailed structure diagram of the IEA-I high speed wind tunnel has been shown in Figure 1.



1. Adapter 2.Shock absorber 3.Diffuser 4.Settling chamber 5.Contraction section 6.Rail 7.Honey comb 8.Fixed support 9. Screen meshes

Figure 1. Structure diagram of the IEA-I high speed wind tunnel

The operational conditions of the IEA-I high speed wind tunnel has been listed in table 1. Some more details about the design and test of the wind tunnel were shown in the previous work of the authors [25].

Table 1. The operational conditions of the IEA-I high speed wind tunnel.

Parameters	Technical index
Test section diameter	300mm
Wind speed	6.7-98 m/s
Turbulent intensity	<1.0%
Coefficient of Variation	<0.5%
Dynamic pressure stability coefficient	<2.0%
Inclined angle	$\alpha < 0.5°$

Spray Control System

The spray control system was designed to control and record the pressure and flow rate in the tube. It is containing 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 is mounted at the same height with the nozzle. The flow rate and spray pressure could be controlled and recorded accurately by adjusting the reducing valve.

The schematic diagram of the spray control system is shown in Figure 2.

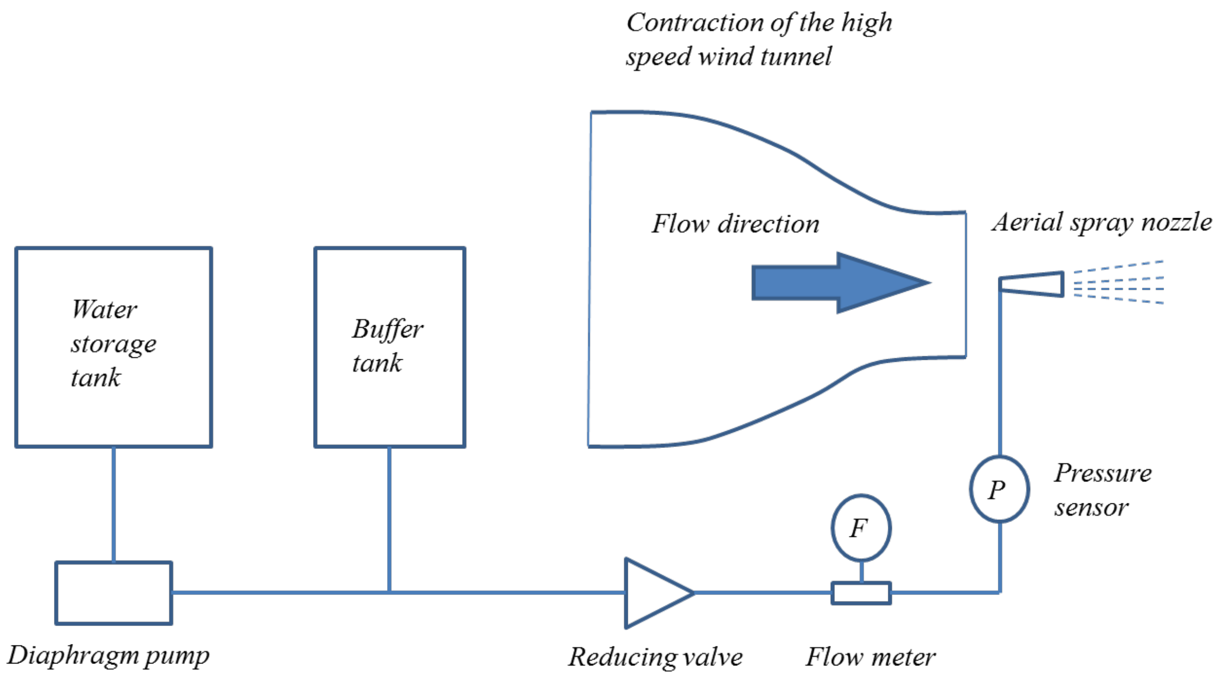


Figure 2. Schematic diagram of the spray control system

Data Acquisition

A Malvern Spraytec Laser diffraction instrument was used to measure the droplets spectra generated by the nozzle. It is a kind of automated, real-time, and high-speed measuring system. Its acquisition rate is about 10 kHz, and its size measuring range is 0.1-900 μm.

The Spraytec system was fixed on an optimal platform and the nozzle was installed on an electric lifting platform which could be traversed vertically such that the entire spray plume is sampled within a given replicated measurement. The moving speed of the platform is in the range of 0-20mm/s, and the travelling distance is about 600mm. At least 3 replications for each nozzle/pressure tested were taken until the standard deviation of DV0.5 is less than or equal to 5% of the mean. The whole spray measurement setup in the wind tunnel is shown in Figure 3.

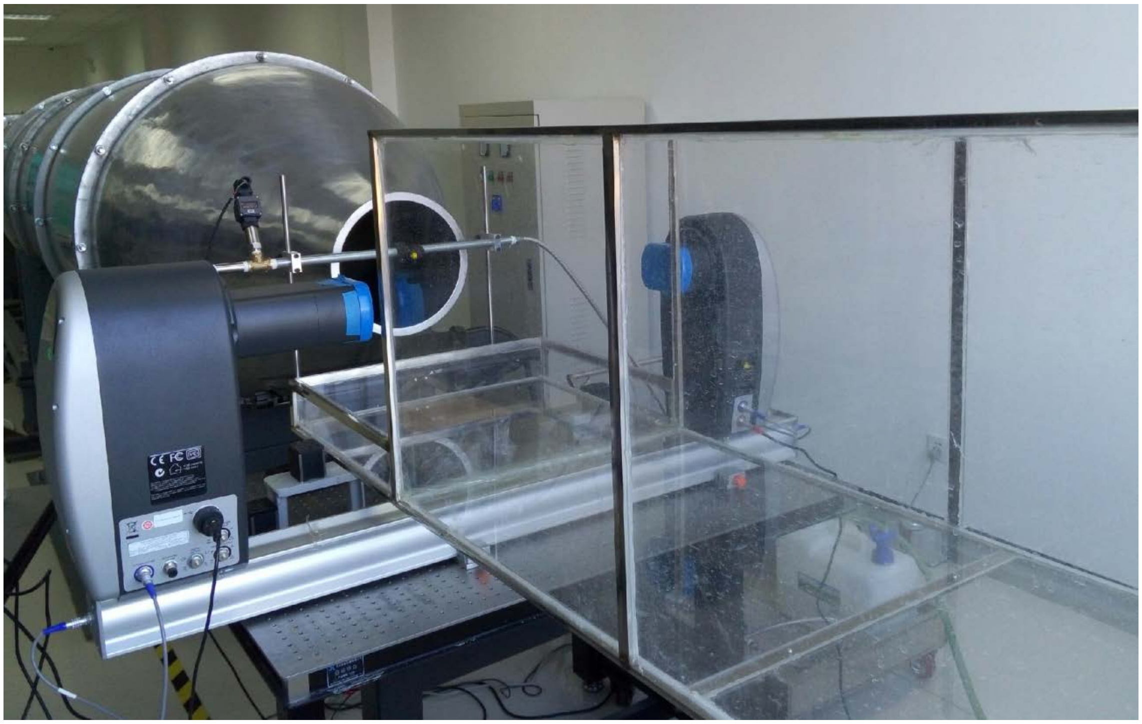


Figure 3. The spray measurement setup in the wind tunnel

The detailed droplet spectra information could be recorded by this system. Dv0.5 and the relative span of the droplets are measured and compared with the wind speed, tube pressure and measuring distances.

Test Design

The LU-120-03 flat fan nozzle is mounted on the tube of the spray control system, and the orifice is about 10 cm away from the exit of the wind tunnel contraction section. The temperature is 20°C and relative humidity is 30% in the experiment. Tap water has been used as a test medium.

Every case is replicated 3 times and each acquisition time lasts 40 s. The final result of the case is the mean value of 3 times measurements and the standard deviation of Dv0.5 should be less than 5%. The droplets spectra measured by the Malvern Spraytec Laser diffraction instrument are carefully analyzed. The dv0.5 and relative span of the droplets are extracted from the experimental results.

The test process is listed below:

1. The distance from the orifice of the nozzle to the measurement point is 15cm, 25cm and 35cm.

2. The wind speed is changed from 121.7 km/h to 305 km/h.

3. The spray pressure is set 3 bar, 4 bar and 5 bar.

4. The Dv0.5 and the relative span of the droplets of all the above cases are analyzed.

Results and Discussion

The LU-120-03 nozzle produced by Lechler Corporation is a kind of flat fan nozzle with simple shape and design.

In the range of 460 mm out of the contraction exit, the normalized axial static pressure gradient is found less than 0.02(Tang, 2016) and the flow quality is considered to be good enough to do the test.

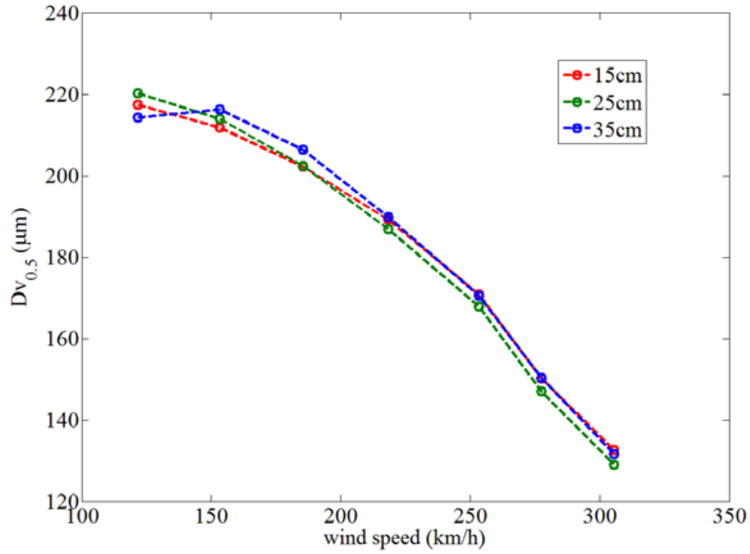
We set the nozzle orifice at x=100mm out of the wind tunnel exit. The measurement points were chosen at x=150mm, x=250mm, and x=350mm.

The detailed test cases have been listed in Table 2.

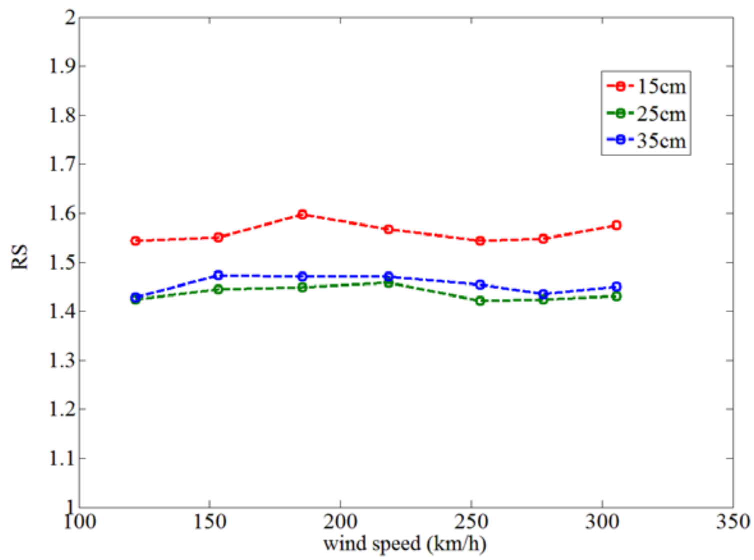
Table 2 The droplet size distribution of LU-120-03 nozzle at different wind speed, measurement distance, and spray pressure

Distance (m)	Wind speed(km/h)	Tube pressure 0.3MPa		Tube pressure 0.4MPa		Tube pressure 0.5MPa	
		Dv0.5(μm)	RS	Dv0.5(μm)	RS	Dv0.5(μm)	RS
0.15	121.7	217.5	1.544	194.3	1.573	190.2	1.488
	153.4	211.9	1.550	193.4	1.574	185.8	1.501
	185.5	202.2	1.597	186.9	1.579	181.2	1.504
	218.4	189.2	1.567	176.9	1.623	174.1	1.510
	253.5	170.9	1.543	165.8	1.618	164.1	1.563
	277.5	150.1	1.548	150.5	1.650	151.2	1.596
	305.5	132.7	1.575	134.6	1.654	137.0	1.670
0.25	121.7	220.3	1.423	197.0	1.349	182.5	1.387
	153.4	214.0	1.444	198.6	1.361	187.0	1.402
	185.5	202.4	1.449	193.2	1.403	183.5	1.440
	218.4	186.8	1.458	184.0	1.429	174.9	1.462
	253.5	167.8	1.421	170.7	1.417	164.3	1.485
	277.5	147.1	1.423	154.7	1.451	151.3	1.489
	305.5	129.0	1.431	137.8	1.473	134.8	1.518
0.35	121.7	214.3	1.428	192.7	1.352	178.9	1.361
	153.4	216.3	1.473	199.9	1.340	190.0	1.353
	185.5	206.3	1.470	194.8	1.396	187.7	1.369
	218.4	189.8	1.470	182.2	1.430	177.3	1.439
	253.5	170.5	1.454	168.0	1.430	166.5	1.458
	277.5	150.4	1.435	150.5	1.433	151.7	1.490
	305.5	131.7	1.450	132.8	1.471	135.6	1.458

Firstly, we focus on the effect of the measuring point to the Dv0.5 of the droplets. In Figure 4, the tube pressure was set to 0.3MPa and we could see in Figure 4a that the Dv0.5 of the droplets is not quite influenced by the distance of the measuring point from the orifice of the nozzle. Most of the differences are less than 2% except a few points reach 5%. However, the relative span of the droplets is greatly influenced by the distance of the measuring point from the orifice of the nozzle, as shown in Figure 4b. When the measuring point is at 0.15m from the orifice of the nozzle, the relative span of the droplets (1.5-1.6) is about 10% larger comparing with the 0.25m and 0.35m cases (1.4-1.5), the latter two have little differences. Our measuring result indicates that when the measuring point is at 0.15m from the orifice of the nozzle, the droplets generated by the nozzle is not fully atomized although the Dv0.5 of the droplets changes little. Meanwhile, the similarity of the Dv0.5 and the relative span of the droplets between the measuring point of 0.25m and 0.35m indicate that the droplets are fully atomized when they are 0.25m away from the orifice of the nozzle.



a



b

Figure 4. a) The Dv0.5 and b) the relative span of the droplets when the measurement point is about 0.15m,0.25m and 0.35m from the orifice of the nozzle.

Secondly, the relationship between the droplet size distribution and the wind speed is taken into account. Based on our previous result, the droplets are fully atomized at 0.25m away from the orifice of the nozzle. Conservatively, we choose the measuring point at 0.35m for example. The response surface method has been used to analyze the above results. Similar to Kirk (2007) and Fritz(2014), second-order response relationships were fitted following the format of equation 1 to the data collected for each nozzle and model type evaluated:

$$\mathrm{Y} = \mathrm{A}X_1 + \mathrm{B}X_2 + \mathrm{C}X_1X_2 + \mathrm{D}\mathrm{X}_1^2 + \mathrm{E}\mathrm{X}_2^2 \quad (1)$$

Where

Y= atomization parameter to be predicted based on input combination of X1 and X2 (Dv0.5, relative span, etc.)

X1= airspeed (km/h)

X2= spray pressure (MPa)

A to E= constant coefficients for each term of the prediction expression.

A second order response surface method has been used to analyze the experimental results. The coefficients of the fitted equation of Dv0.5 are listed in table 3. From this table we could see that the response surface equations had high R^2 values for Dv0.5 modeling.

Table 3. The coefficients of the response surface equations for Dv0.5.

Factors	Droplet Spectrum Parameters
	Dv0.5 (μm)
Intercept	+290.8432
X1	+0.3349
X2	-444.3229
X1X2	+1.0850
X1^2	-0.002641
X2^2	+180.0000
R^2	0.9924

The comparison of the multiple regression prediction and the measured value of Dv0.5 were shown in Figure 5. The wind speed and spray pressure were used to form the regression. From this figure it could be seen that the predicted Dv0.5 fits well with the measured Dv0.5.

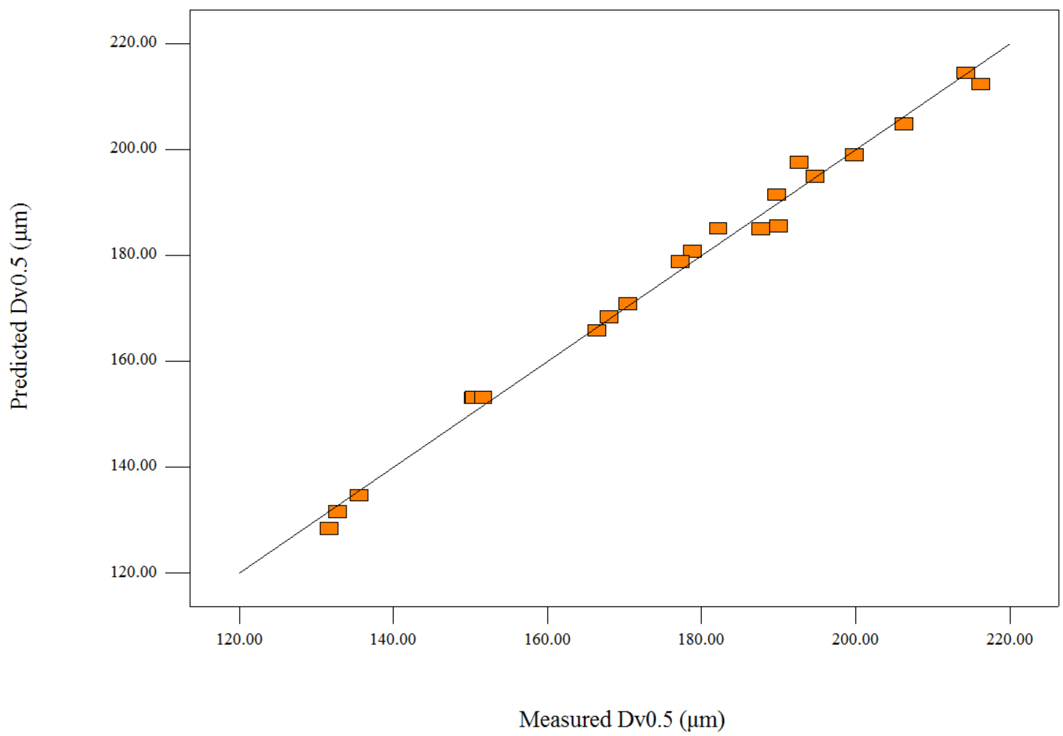


Figure 5 the comparison of the multiple regression prediction for DV0. 5 with the measured DV0.5, for LU-120-02 nozzle, with wind speed and spray pressure. All measured data were used to form the regression.

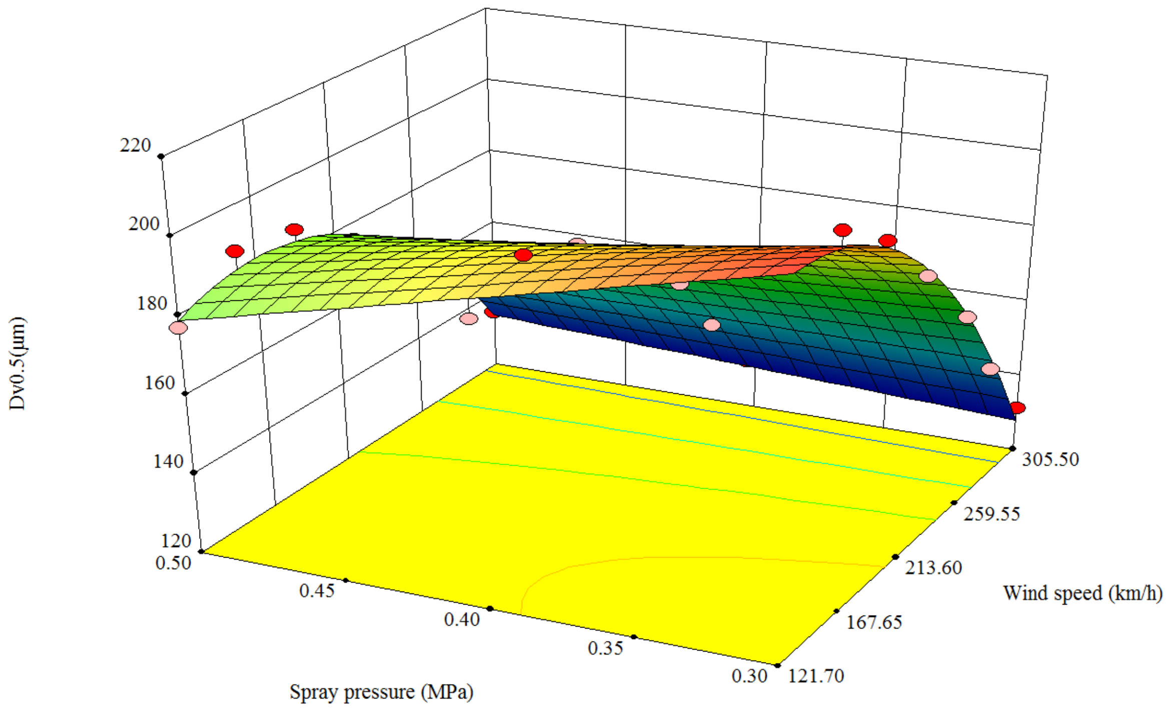


Figure 6 The 3D surface of the dv0.5 related to the windspeed and spray pressure.

The predicted 3D surface of the Dv0.5 could show the effect of wind speed and spray pressure clearly. Figure 6 shows the effect of wind speed and spray pressure to the Dv0.5. The droplet diameter generated by the fan nozzle has a quadratic relationship with the wind speed. The Dv0.5 of the droplet is much larger at lower wind speed. When the wind speed is at 153.4km/h, the Dv0.5 of the droplet reaches its maximum value, which is about 50% larger than the Dv0.5 of the droplet when the wind speed exceeds 253.5km/h, as indicated in table 2. The possible reasons of this phenomenon are listed below:

1. The formation of the droplets generated by the flat fan nozzle mainly depends on the break process of the planar liquid film. Meanwhile, the break of the planar liquid film is influenced by the growth rate of the surface wave. The larger the growth rate of the surface wave is, the easier the planar liquid film becomes unstable and breakdown. The growth rate of the surface wave is in direct proportional to the shear strength between the planar liquid film and the air [26].

$$\omega_r \propto \left| U_l - U_g \right| \quad (2)$$

   Since the jet speed of the nozzle is a fixed value, the growth rate of the surface wave is decreasing firstly and then increasing with the increasement of the wind speed.

2. With the increasement of the wind speed, the spread angle of the flat fan nozzle decreased, which will cause the collision and congregation of the droplets and increase the Dv0.5 of the droplets. When the wind speed exceeds a certain critical value that the atomization effect caused by the strong shear overwhelms the collision and congregation of the droplets, the Dv0.5 of the droplets will decrease again.

3. In the breakdown process of the droplets caused by the shear stress of the flow, the maximum stable diameter of the droplets can be described by the flowing equation [27]:

$$D_{\max} = \frac{8\sigma_l}{C_D \rho_g \left| U_l - U_g \right|^2} \quad (3)$$

where C_D is a constant depending on the breakdown conditions, ρ_g is the air density, σ_l is the coefficient of the droplet surface tension. From this equation it could be seen that the maximum stable diameter of the droplets is in inverse square proportional to the speed difference between the liquid and air. This means that the droplet diameter will first increase then decrease with the increasement of the wind speeds while the jet speed is kept constant.

4. The bias caused by the special particle statistical method of the Laser Diffraction system. When the wind speed is very high, the smaller droplets will accelerate more quickly than the larger droplets. This will result in a larger concentration of larger droplets downstream of the nozzle and therefore spatially derived droplet size data tend to yield larger mean diameters than temporally derived. When the wind speed is very low, the results are opposite. [28-30]

The 2nd and 3rd points are considered to be the dominate factor to the variation of the fully atomized droplets' diameter. For the 1st point mainly influenced the breakdown process of the planar liquid film which is before the droplets atomization, and the 4th point have been proved to be have little effect when the wind speed exceeds 12m/s. [28-30]

In figure 6 we could also found that the spray pressure has nearly a linear relationship with the Dv0.5 of the droplets, for the liquid sheet velocity $U_l \propto \sqrt{P}$, based on Bernoulli's principle. Thus, we could simplify the fitted equations; the quadratic terms of spray pressure should be ignored. The coefficients of the simplified equation are listed in table 4, from which we could see that the R^2 of the simplified model of Dv0.5 is similar with the original model.

Table 4. The coefficients of the simplified response surface equations for Dv0.5.

Factors	Droplet Spectrum Parameters
	Dv0.5 (μm)
Intercept	+263.2432
X1	+0.3349
X2	-300.3229
X1X2	+1.0850
X1^2	-0.0026
X2^2	NA
R^2	0.9912

The effect of the spray pressure to the Dv0.5 is also found strongly depends on the wind speed. The higher pressure of the spray system will decrease the droplet diameter, but this kind of effect reverses when the wind speed increases. When the wind speed exceeds a critical value, the droplet diameter will decrease with the increasement of the spray pressure as well. A possible reason is that the shear stress is the main atomization factor when the wind speed is very high. In this case, the high flow rate caused by the high tube pressure may weaken this effect.

The coefficients of the fitted equation of relative span are listed in table 5. From this table we could see that the response surface equations had lower R^2 values than the Dv0.5 modeling.

Table 5. The coefficients of the response surface equations for the relative span.

Factors	Droplet Spectrum Parameters
	RS
Intercept	+2.1075
X1	-0.0004
X2	-3.3407
X1X2	+0.0039
X1^2	$-1.7*10^{-6}$
X2^2	+2.8857

R^2	0.8245

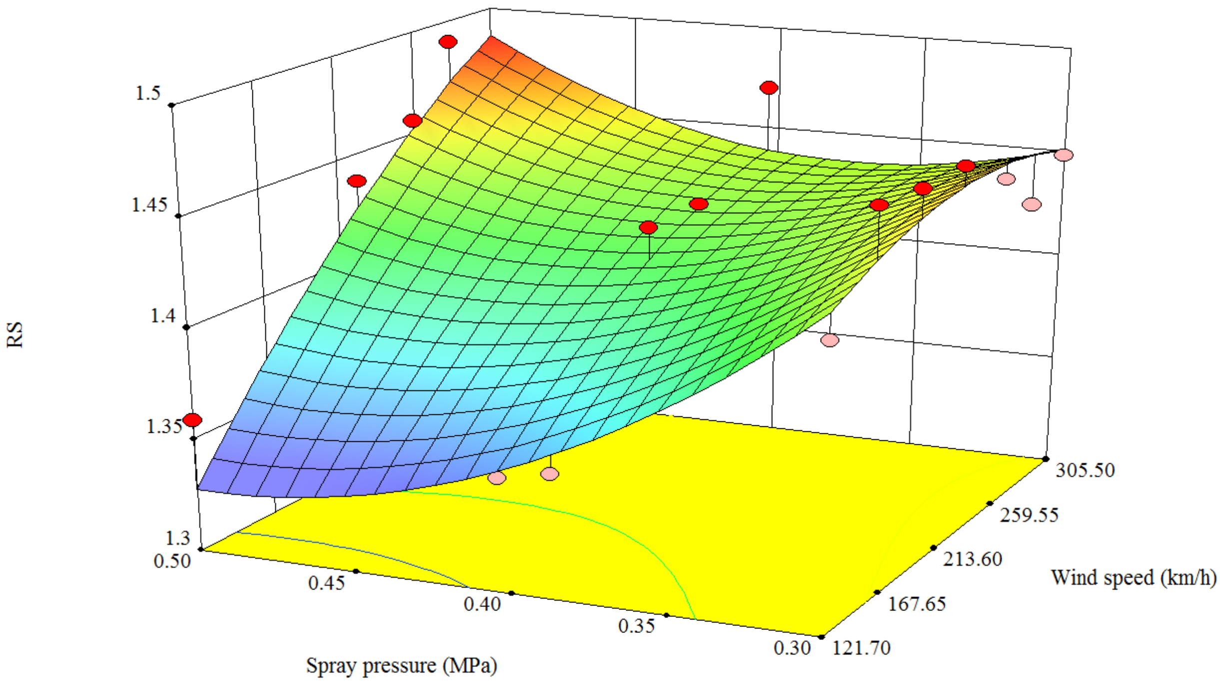


Figure 7 The 3D surface of the dv0.5 related to the windspeed and spray pressure.

The predicted 3D surface of the relative span of the droplet in figure 7 could show the effect of wind speed and spray pressure to the relative span clearly. The relative span of the droplets is not quite influenced by the wind speed when the tube pressure is 0.3MPa. However, when the tube pressure is set to 0.4MPa and 0.5MPa, the relative span of the droplets is increased with the wind speed, up to 10%.

Conclusion

The Dv0.5 of the droplets generated by the LU-120-03 flat fan nozzle is decreasing when the wind speed increases. When the wind speed is 305km/h, the Dv0.5 of the droplets is about 130μm, while the Dv0.5 of the droplets is about 220μm when the wind speed is 120km/h. In most of the wind speed range, the increasement of the tube pressure could decrease the Dv0.5 of the droplets. However, when the wind speed exceeds 250km/h, it is just the opposite. When the tube pressure is larger than 0.4MPa, the relative span of the droplets slightly increases with the wind speed.

The distance from the measuring point to the orifice of the nozzle has great effect to the distribution of the droplets. When the measuring point is at 0.15m from the orifice of the nozzle, the droplets generated by the nozzle is not fully atomized. When the measuring point is at 0.25m and 0.35m, the distribution of the droplets does not change a lot, which indicates 0.35m a suitable measuring distance from the orifice of the nozzle in our experiment.

The quadratic response surface equations had a R^2=0.9924 for Dv0.5 modeling and a R^2=0.8245 for relative span modeling. When the quadratic term of spray pressure is removed, the R^2 decreases from 0.9924 to 0.9912 for Dv0.5 modeling, which indicates the spray pressure has a linear relationship with the Dv0.5 of the droplets.

Acknowledgements

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