

Defocused Shadowgraphy Imaging for Cloud Particle Measurement in Icing Wind Tunnel

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ABSTRACT

Icing experiments in cloud particle environments are a critical component of airworthiness certification, with icing wind tunnels serving as the primary platform for such tests. To accurately simulate cloud characteristics under flight conditions, quantitative evaluation of key parameters of the particle field generated in icing wind tunnels is essential, including particle size distribution, uniformity, liquid water content (LWC), ice water content (IWC), and total water content (TWC). In this study, a Defocused Shadowgraph Particle Imager (DSPI) was developed to meet the measurement requirements of particle size and concentration for high-speed ice crystals and supercooled droplets in icing wind tunnels. Through experimental validation, the instrument has successfully demonstrated its measurement capability for particle sizes from 10 to 1000 μm , airspeeds from 0 to 130 m/s, and total water content (TWC) from 0 to 10 g/m³.

1. Introduction

Icing of aero-engines is a major safety problem for aircraft operating in cold weather, directly threatening flight safety ^{[1][2]}. Its formation is closely related to the characteristics of supercooled droplets in atmospheric clouds and the operating environment of the engine. When an aircraft passes through clouds or freezing fog containing supercooled droplets, the droplets impinge on low-temperature surfaces such as the engine inlet and compressor blades, rapidly freezing and accumulating to form ice layers. The Cloud Particle Size Distribution (PSD) and Liquid Water Content (LWC) in clouds are key factors affecting icing rate, icing morphology, and ice layer coverage. High LWC accelerates ice accumulation, altering the shape of critical engine components in a short period ^{[3][4]}.

Icing wind tunnels are the only controllable and repeatable facilities for reproducing in-flight icing meteorological conditions on the ground. Their necessity is reflected in basic calibration, extreme condition testing, and standard alignment. During the initial stage of developing water-ice detection systems, strict calibration and testing of core indicators, including water content measurement range, particle size measurement range, particle size resolution, and water content

measurement accuracy, must be conducted in the benchmark environment of an icing wind tunnel [5].

Currently, several methods and instruments are applied for the online measurement of cloud particle size and concentration including ice crystals and droplets. The mainstream methods include *forward light scattering* [8][9], *side-scatter imaging* [10], *linear optical array imaging* [11][12], *shadowgraph imaging* [13][14], *holographic imaging* [15][16], *interferometric imaging* [17], *phase doppler interferometry* [18], *oil slide technique* and *rotating multi-cylinder* [5][6][19]. Among these, imaging-based methods offer advantages such as direct imaging, intuitive results, and high accuracy. However, limited by the depth of field (DOF) of measurement, they are generally not directly used for particle concentration measurement. The *Defocused Shadowgraphy Imaging (DSI)* method, a type of *Depth-from-Defocus (DFD)* technique proposed by Zhou et al. [20][21][22][23][24][25], leverages the image blurring characteristics of particles deviated from the focal plane. By establishing a correlation between particle size and spatial position through optical imaging geometric relationships and image convolution models, DSI enables simultaneous acquisition of the true particle size and axial position of particles in a single frame image. This method expands the DOF for particle identification, thereby achieving synchronous quantitative measurement of particle size and concentration. Furthermore, DSI does not inherently require a spherical assumption and can realize phase identification of cloud particles through shape differentiation, making it particularly suitable for measuring the particle size and concentration of ice crystals and droplets in icing wind tunnel environments.

This paper mainly introduces the *Defocused Shadowgraph Particle Imager (DSPI)* developed by our team based on the DSI method. Integrating core technologies including laser source decoherence homogenization, piecewise-fitting calibration method, particle phase identification algorithms, and particle size and concentration calibration, the DSPI was successfully used to measure the cloud particle size (10–1000 μm) and concentration (converted to Total Water Content (TWC) of 0–10 g/m^3) in the icing wind tunnel under high-speed airflow (0–130 m/s).

2. Methodology

2.1 Composition of the DSPI

The DSPI (**Figure 1**) mainly consists of four modules: an imaging module (including a camera and telecentric lens), a lighting module (providing an incoherent pulsed laser), a 3D displacement module (achieving submillimeter-level positioning), and an electrical interface module (ensuring

power supply and data transmission).



Figure 1 The DSPI in the icing wind tunnel

The main parameters of the DSPI are listed in **Table 1**. The DSPI provides a single-measurement field of view of approximately 3.71 mm $\times$ 2.78 mm. The effective measurement depth is linearly correlated with particle size. For instance, the effective depth of field for particles with a diameter of 100 μ m is about 5 mm. The measurement frequency is 50 Hz.

Table 1. The main parameters of the DSPI

Parameter	Value
Pixel size	3.45 μ m
Resolution	1440 $\times$ 1080
Magnification	1.34
Working distance	470 mm
Laser wavelength	532 nm
Laser pulse energy	250 μ J
Laser pulse duration	10 ns
Frequency	50 Hz

2.2 Principle of the DSPI

According to the theory of Depth from Defocus, the in-focus image of a particle can be expressed as $f(x, y)$. When the particle deviates from the focal plane by a depth, Δz , the defocused

blur image formed at that position can be described as the convolution of the focused image with a blur kernel.

$$g_t(x,y)=f(x,y)\otimes h(x,y) \quad (1)$$

where $h(x,y)$ is the point spread function (PSF) of the optical system, which can be approximated as a Gaussian blur kernel.

$$h(x,y)=\frac{1}{2\pi\sigma^2}\exp\left(-\frac{x^2+y^2}{2\sigma^2}\right) \quad (2)$$

where σ represents the diameter of the blur kernel, and it is linearly related to the defocus distance Δz of the particle.

$$\sigma = \beta|\Delta z| \quad (3)$$

where β is a system constant determined by the optical geometry, and is obtained through calibration using a dot calibration target in experiments. Therefore, as long as σ can be extracted from the blurred image, the relative position Δz of the particle can be determined.

Rao et al.^[26] further derived dimensionless formulas based on the above theory, defining the dimensionless grayscale gradient $\tilde{G}$, the dimensionless defocus blur kernel $\tilde{\sigma}$, and the dimensionless particle size $\tilde{\rho}_t$, and obtained the theoretical relationship among these three parameters, as shown in **Figure 2**. Therefore, by using image processing techniques to obtain $\tilde{G}$ at a grayscale threshold $g_t = 0.5$, the corresponding $\tilde{\sigma}$ can be found from **Figure 2a**, and then the corresponding $\tilde{\rho}_t$ from **Figure 2b**. Since r_t (the threshold radius obtained from image processing) is known, the true particle diameter d_0 can be derived. Subsequently, using the dimensionless defocus blur kernel $\tilde{\sigma} = 0.35$ as the criterion for the blurriness that allows accurate particle analysis^{[24][26]}, and substituting it into Equation 3, the measurement depth range $D_i = 2 \Delta z_i$ corresponding to each particle size can be obtained. Correspondingly, the volume of the particle measurement region is,

$$V_{di} = D_i \times H \times W \quad (4)$$

where W and H denote the width and height of the field of view.

The volume of the i^{th} particle is calculated based on its particle size (d_i):

$$V_i = \frac{\pi d_i^3}{6} \quad (5)$$

To obtain the volume concentration from these discrete particle data, assuming there is a total

of N particles, hence, the corresponding volume concentration is,

$$C_v = \sum_{i=1}^N \frac{V_i}{V_{di}} \quad (6)$$

Further multiplication by the density, ρ , yields the mass concentration.

$$C_m = \rho \times C_v \quad (7)$$

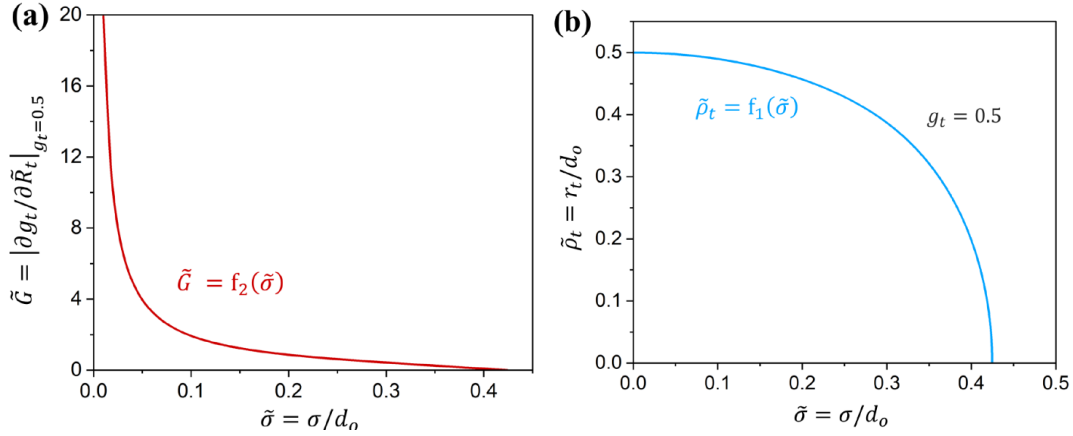


Figure 2 Dimensionless curves of (a) grayscale gradient versus defocus degree and (b) particle size versus defocus degree (normalized grayscale threshold = 0.5)

In summary, the standard procedure for particle size and concentration measurement using the DSPI is as illustrated in **Figure 3**.

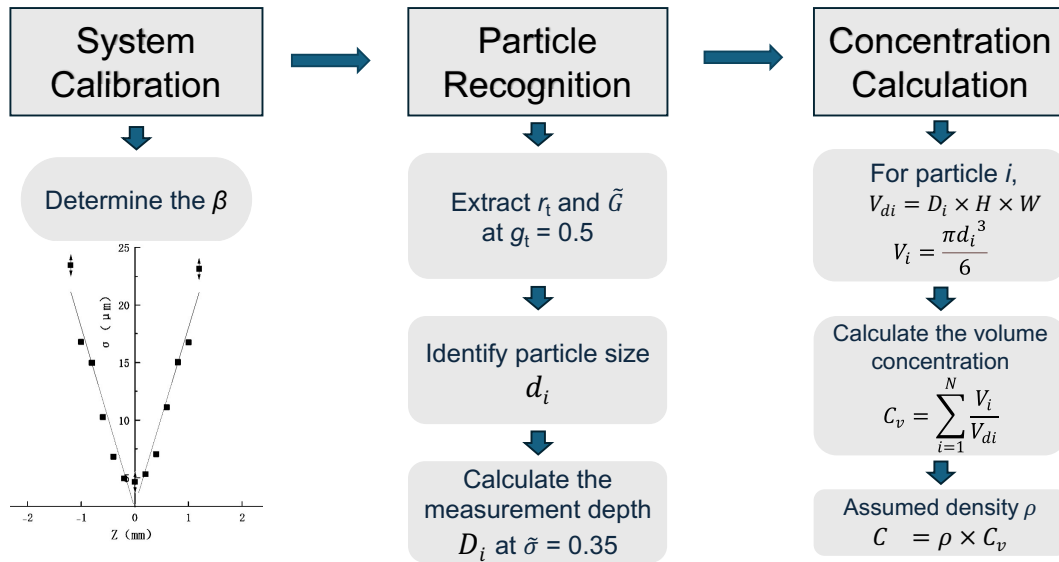


Figure 3 The DSPI working flow

2.3 Experimental Details in the Icing Wind Tunnel

As shown in **Figure 4a**, the optical windows were installed on both sides of the icing wind

tunnel, and the lighting module and imaging module of the DSPI are positioned on the two sides of the wind tunnel respectively. Measurement points were set up at different height positions (above the horizontal center of the wind tunnel) and different spanwise positions. Point-by-point measurement, as displayed in **Figure 4b**, can be achieved through the 3D displacement control system.

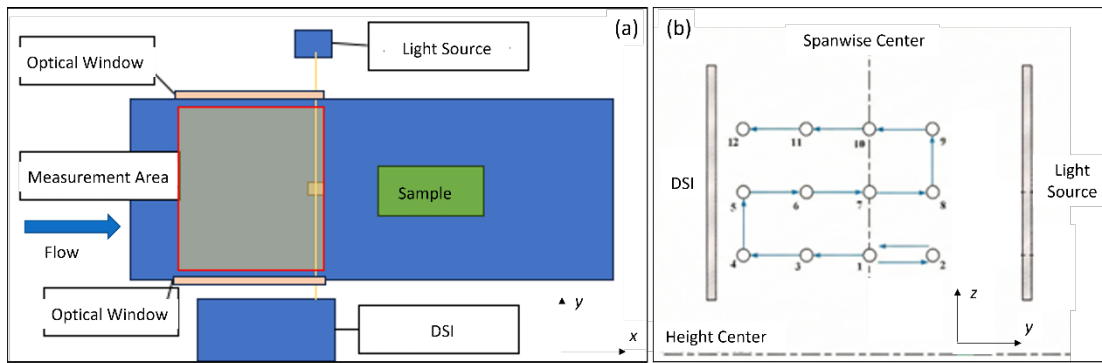


Figure 4 Schematic

diagram of the experimental system

(a) Wind Tunnel Layout (b) Measurement Point Layout

3. Results and Discussion

3.1 Decoherence Effect of the Laser

After adopting the custom-optimized Fresnel lens and integrating sphere homogenization module, the coherence of the laser is significantly reduced, improving the background uniformity of imaging, as seen in **Figure 5a** and **5b**. The relative grayscale deviation (RGD) before and after decoherence process are shown in **Figure 5c** and **5d**. The standard deviation of RGD decreases from 0.26 to 0.09 after decoherence. However, the averaged grey level is remarkably weakened by 35.8% from 181.3 to 116.5, which decreases the contrast of particle images and poses significant challenges for particle recognition, grayscale extraction, and grayscale gradient information acquisition. This issue needs to be further addressed by optimizing the image processing algorithm.

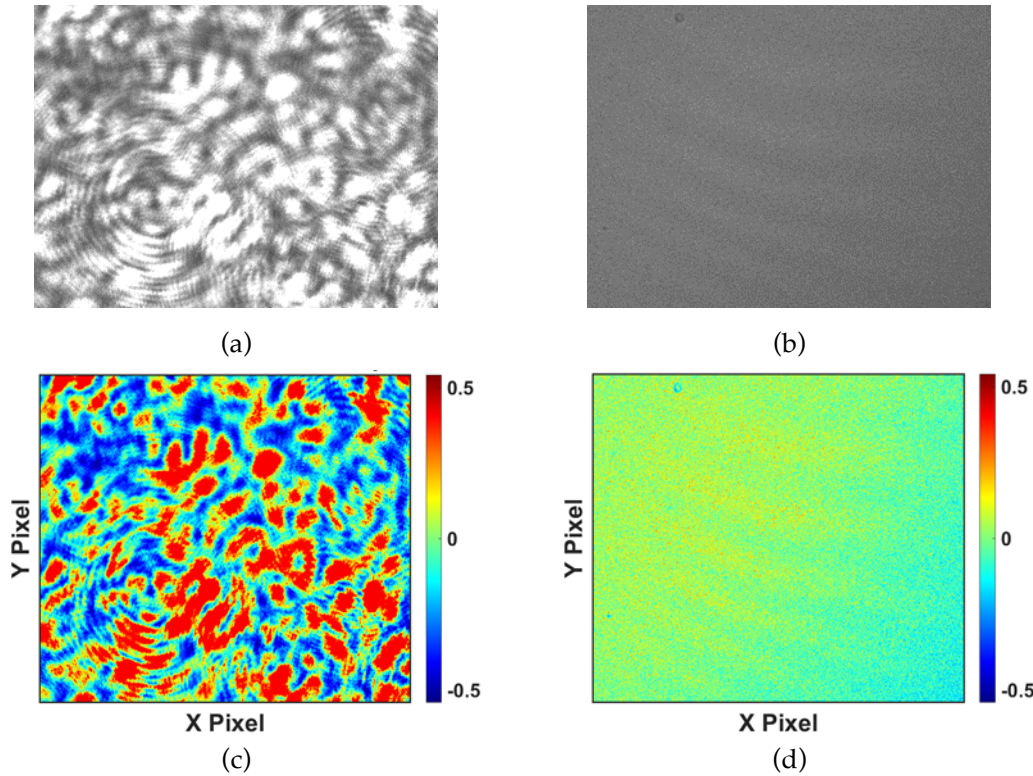


Figure 5 Evaluation of the laser illumination quality.

The images (a) before and (b) after the decoherence process.

The relative grayscale deviation (c) before and (d) after the decoherence process.

3.2 Defocus-Particle Position Calibration Curve

Due to the aberrations of the actual imaging system and insufficient image signal-to-noise ratio (SNR), the linear relationship between the blur kernel (σ) and defocus distance (ΔZ) near the focal plane does not hold. However, the symmetry of forward and backward defocus is still maintained. Therefore, piecewise fitting is adopted: quadratic fitting is used for the calibration results near the focal plane, and linear fitting is applied to those far from the focal plane. The obtained defocus characteristic curve is shown in **Figure 6a**, and the corresponding calculated particle size and position distribution are presented in **Figure 6b**. Compared with the particle size and position distribution obtained by linear function fitting (see **Figure 6c**), and the corresponding results in **Figure 6d**, the spatial distribution of particles via piecewise fitting is more uniform, which is more consistent with the actual situation. Thus, it can be concluded that the three-piece fitting method can obtain more accurate particle size and position information.

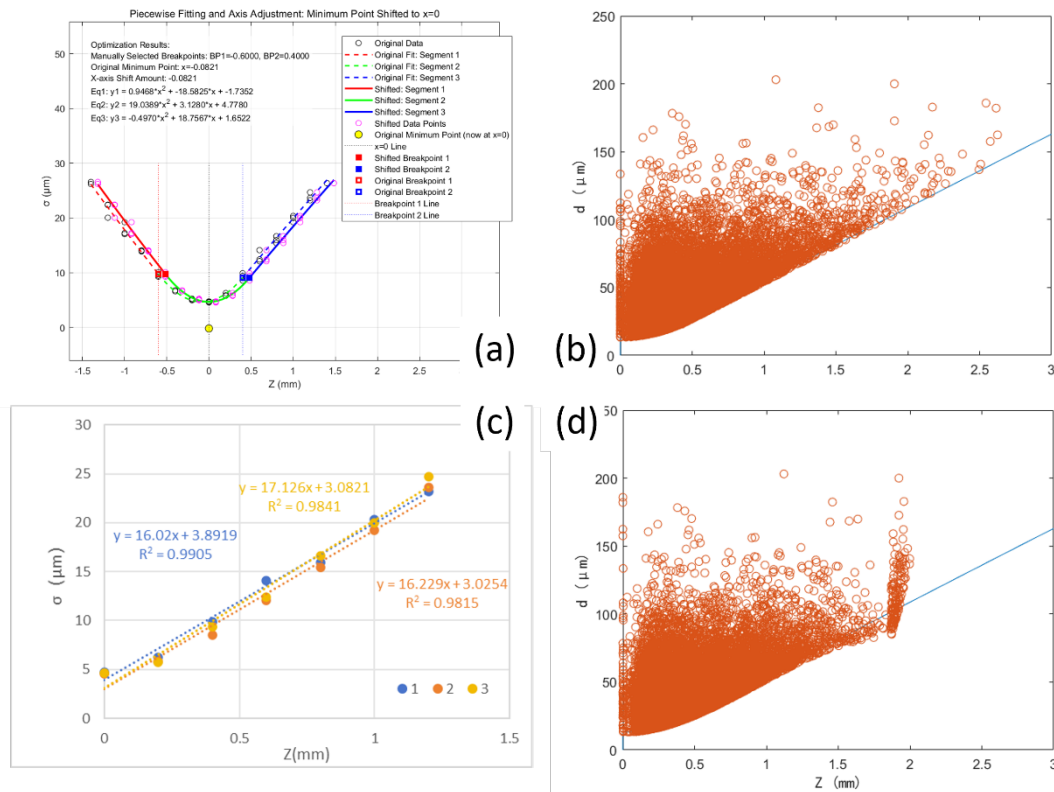


Figure 6 Influence of calibration curve fitting on particle measurement (a) Three-piece fitting function and (b) the results, and (c) Linear fitting function and (d) the results

3.3 Particle Phase Recognition Algorithm

The support vector machine (SVM) model was chosen for particle phase discrimination. The labeled experimental images of pure supercooled water droplets (8732 samples in total) and pure ice crystals (283187 samples in total) were used as the dataset, where 80% of the data was allocated for training and 20% for testing. The labeled parameters, including the equivalent area diameter and circularity, are obtained by following the method provided in Ref. 23. The statistic results are illustrated in **Figure 7**.

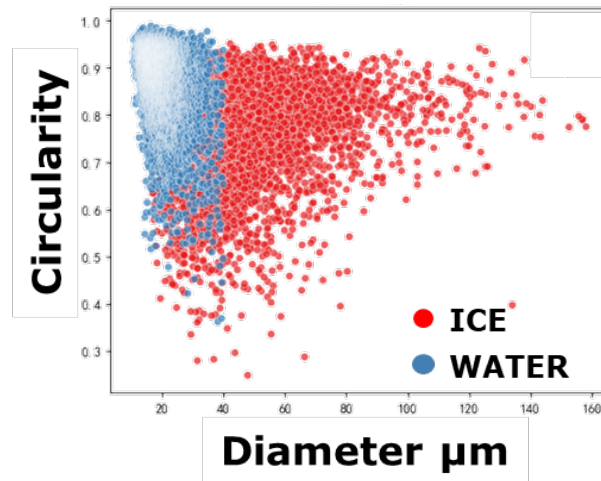


Figure 7 Particle feature distribution map

After all, the recognition accuracy of the optimized model reached 0.90. **Figure 8** presents a typical image of the mixed-phase operating condition, from which it can be observed that the model has successfully distinguished ice crystals from water droplets. However, it is still necessary to further improve the imaging quality to ensure that defocused particles, small particles, and quasi-spherical particles can be more accurately identified as water droplets or ice crystals, and even enable further classification of ice crystal types.

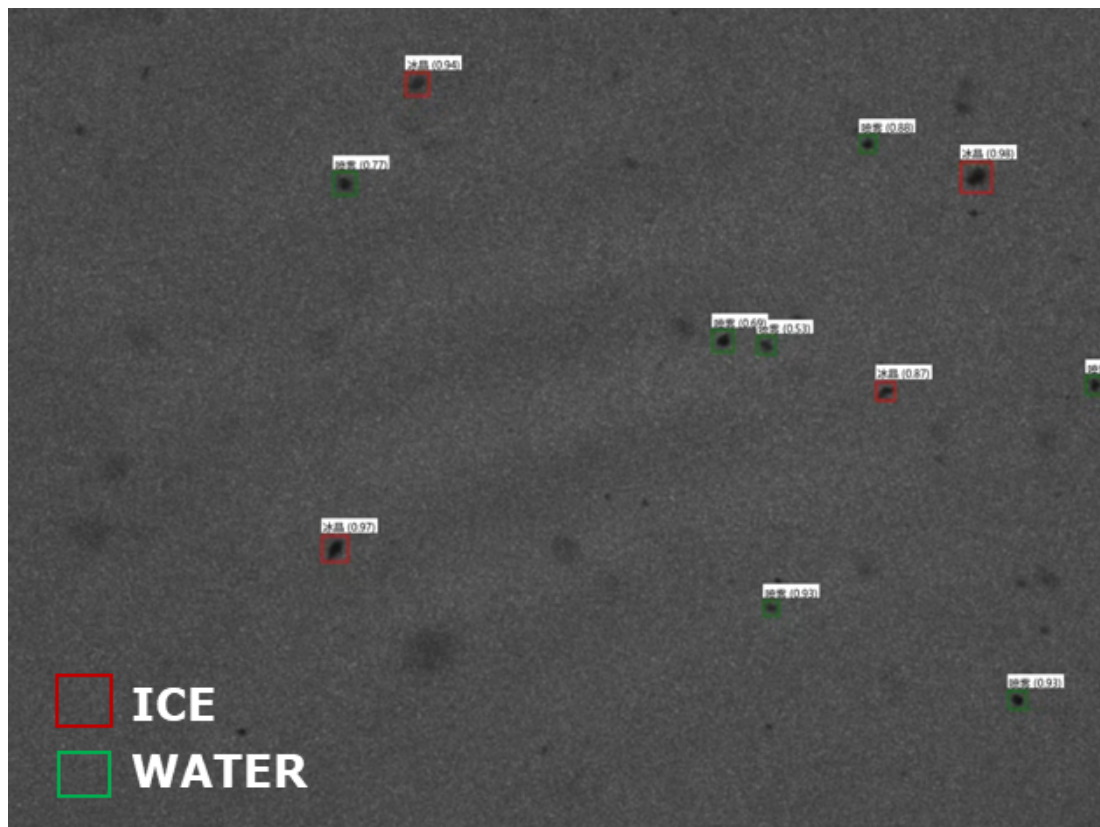


Figure 8 A typical image for particle phase state recognition

3.4 Calibration for Particle Size and Concentration Measurement

The Standard particle samples (Certificated Reference Materials, CRM) with diameters of 10 μm , 30 μm , 60 μm , and 1000 μm were respectively prepared in cuvettes and sealed. Each cuvette was shaken to disperse the particles, and then a single image was quickly captured by the DSPI. This process was repeated 20 times to ensure that the total number of counted particles exceeded 2000, and the particle sizes in the images were statistically analyzed. The above experiment was repeated six times to evaluate the reliability of the particle size measurement results. As shown in **Table 2**, the absolute diameter error is all small, indicating the reliable size measurement ability in the range of 10 to 1000 μm .

Table 2 Calibration results for particle size measurement

	Dmax (μm)	Dn50 (μm)	Dv50 (μm)	Concentration (g/m^3)	Particle Number	Absolute Error (μm)
CRM1: Dv50 = 10.0 μm						
Rep1	19.19	11.46	11.87	65.86	2401.00	1.87
Rep2	20.95	11.44	11.79	67.47	2492.00	1.79
Rep3	19.08	11.61	11.91	67.36	2506.00	1.91
Rep4	19.94	11.49	11.89	67.31	2494.00	1.89
Rep5	19.72	11.73	12.16	67.18	2446.00	2.16
Rep6	21.18	11.41	12.02	67.68	2468.00	2.02
Ave	20.01	11.52	11.94	67.14	2467.83	1.94
CRM2: Dv50 = 28.2 μm						
Rep1	44.56	30.47	31.00	156.58	2316.00	2.80
Rep2	47.96	30.24	30.56	167.59	2497.00	2.36
Rep3	50.37	30.21	30.59	166.04	2473.00	2.39
Rep4	47.32	30.11	30.65	156.82	2350.00	2.45
Rep5	42.30	30.35	30.68	157.31	2342.00	2.48
Rep6	54.18	30.04	30.48	160.21	2390.00	2.28
Ave	47.78	30.24	30.66	160.76	2394.67	2.46
CRM3: Dv50 = 60.1 μm						
Rep1	107.26	56.60	58.49	640.47	2552.00	-2.68
Rep2	102.28	56.16	57.82	616.01	2489.00	-3.79
Rep3	103.69	56.41	58.50	577.55	2298.00	-2.66

Rep4	120.72	56.00	58.00	640.78	2561.00	-3.49
Rep5	103.49	57.05	59.47	580.97	2280.00	-1.05
Rep6	106.02	55.66	58.41	534.95	2202.00	-2.81
Ave	107.24	56.31	58.45	598.46	2397.00	-2.75
CRM4: Dv50 = 1055.0 μm						
Rep1	1188.58	1109.00	1138.78	949.91	28.00	7.94
Rep2	1220.23	1035.39	1074.45	1241.49	43.00	1.84
Rep3	1190.72	1052.85	1070.09	1956.60	64.00	1.43
Rep4	1194.00	1064.98	1081.68	1742.06	56.00	2.53
Rep5	1197.08	1078.12	1084.72	1891.97	58.00	2.82
Rep6	1209.14	1090.39	1123.41	2020.88	60.00	6.48
Ave	1199.96	1071.79	1095.52	1633.82	51.50	3.84

Three standard samples of 25 μm particles with known number concentrations (CRM) were separately prepared in cuvettes and sealed. Each cuvette was shaken to disperse the particles, and then a single image was quickly captured. This process was repeated 100 times to ensure that the total number of counted particles exceeded 1000, and the particle number concentration in the images was statistically determined. The above experiment was repeated six times to evaluate the reliability of the concentration measurement results. As shown in **Table 3**, the absolute concentration error is all small, indicating the reliable concentration measurement ability up to 10 g/m^3 .

Table 3. Calibration results for particle concentration measurement

	Dmax (μm)	Dn50 (μm)	Dv50 (μm)	Concentration (g/m^3)	Particle Number	Relative Error (%)
CRM5: Concentration = 11.22 g/m^3						
Rep1	29.98	27.2	27.33	9.78	936	-12.83
Rep2	29.99	27.15	27.29	9.81	945	-12.57
Rep3	29.96	27.17	27.33	11.48	1102	2.3
Rep4	29.99	27.21	27.34	11.62	1114	3.6
Rep5	29.93	27.16	27.31	11.67	1116	4
Rep6	29.98	27.36	27.48	11.26	1077	0.4
Ave	29.97	27.21	27.35	10.94	1048.33	-2.52
CRM5: Concentration = 11.22 g/m^3						
Rep1	29.96	26.86	27.25	10.68	1046	-4.8
Rep2	29.93	26.98	27.37	10.22	1004	-8.9
Rep3	29.99	26.98	27.3	11.02	1088	-1.8
Rep4	29.99	26.92	27.35	11.33	1110	0.9
Rep5	29.99	27.08	27.54	11.54	1126	2.8
Rep6	29.95	26.93	27.42	10.61	1026	5.5

Ave	29.97	26.96	27.37	10.90	1066.67	-1.05
CRM5: Concentration = 11.22 g/m ³						
Rep1	29.99	26.99	27.32	11.94	1160	6.4
Rep2	29.99	27.33	27.48	9.23	874	-17.74
Rep3	29.99	27.15	27.31	10.82	1042	-3.6
Rep4	29.99	27.29	27.41	11.23	1068	0.1
Rep5	29.95	27.3	27.45	10.75	1020	-4.2
Rep6	29.96	27.31	27.46	11.61	1105	3.5
Ave	29.98	27.23	27.41	10.93	1044.83	-2.59

3.5 Typical results in the icing wind tunnel

The design operating conditions for aircraft icing wind tunnel tests must be formulated in strict accordance with airworthiness regulations and industry standards. Core reference documents include 14 CFR Part 25 Appendix C (Normal Icing) and Appendix O (Supercooled Large Droplet (SLD) Icing), which define the atmospheric icing envelope, as well as SAE ARP 5905, which specifies wind tunnel calibration methods and flow field quality requirements. Test parameters typically cover an ambient temperature range of -40 °C to 0 °C, a Liquid Water Content (LWC) range of 0.2—4.0 g/m³, and a Median Volume Diameter (MVD) range of 15—50 μm.

As shown in **Table 4** and **Figure 9**, the maximum particle size ranges from 71.536–116.940 μm, with a relatively large particle size distribution, exhibiting significant size discreteness resulting from the growth and fragmentation of pure ice crystals. The number median diameter (D_{50}) is concentrated in the range of 28.175–32.504 μm, with a fluctuation range of only 4.329 μm, an average value of approximately 30.9 μm, and a coefficient of variation (CV) of about 4.5%, demonstrating excellent centralization and indicating that the dominant particle size of ice crystals is stable under the wind tunnel operating conditions. The volume median diameter (D_{v50}) ranges from 35.455–39.536 μm, which is consistently significantly larger than the corresponding D_{50} in each group. However, the fluctuation range of D_{v50} (4.081 μm) is similar to that of D_{50} , with a CV of approximately 3.8%, also reflecting the consistency of the particle size distribution of pure ice crystals. The average mass concentration varies from 0.678–3.518 g/m³, covering the low to medium-high concentration range of pure ice crystal operating conditions. After excluding the data from No.1 (0-10s) and No.14 (130-140s), the CV of the concentration decreases to approximately 8.7%, demonstrating the excellent stability of the ice crystal field.

Table 4 CASE I -- Particle size and concentration under pure ice crystal conditions

Time (#/10s)	Dmax (μm)	D10 (μm)	D50 (μm)	D90 (μm)	Dv10 (μm)	Dv50 (μm)	Dv90 (μm)	IWC (g/m^3)
1	71.53 6	21.61 4	28.17 5	40.44 8	25.10 9	35.45 5	64.61 1	0.678
2	85.45 5	22.96 8	30.18 3	42.84 6	26.66 1	36.92 7	60.33 8	2.989
3	78.63 8	23.50 1	31.17 8	42.37 1	27.04 4	37.17 9	53.12 8	2.597
4	89.05 6	24.04	31.35 6	43.72 1	27.57 2	37.78 6	57.38 4	3.055
5	110.0 1	24.25 7	30.82 2	42.76 6	27.42 1	38.11 3	61.02 2	2.991
6	81.00 4	24.48	31.32 9	43.12 9	27.4 5	37.57 5	59.46 6	3.181
7	116.9 4	24.25 8	30.97 9	43.24 2	27.28 8	37.21 4	58.15 5	3.042
8	97.60 6	24.24 5	30.54 8	43.57 3	27.14 7	37.89 3	59.61 5	3.518
9	92.99	23.34 5	30.34 2	43.23 2	26.18 3	38.29 6	63.01 3	3.108
10	95.93 9	24.98 9	31.94 5	45.19 4	28.10 6	39.33 4	63.64 4	3.225
11	105.1 8	23.62 2	30.80 9	44.84 7	27.37	38.72 6	67.48 9	3.419
12	99.74 2	24.09 4	31.20 2	44.16 7	27.54 7	39.53 6	65.61 2	3.072
13	112.3 5	24.35 4	32.50 4	44.27 6	28.31 4	38.94 2	66.90 6	3.128
14	91.16 5	22.30 1	29.76 5	41.84 4	26.54 1	36.07 6	54.72 1	1.055

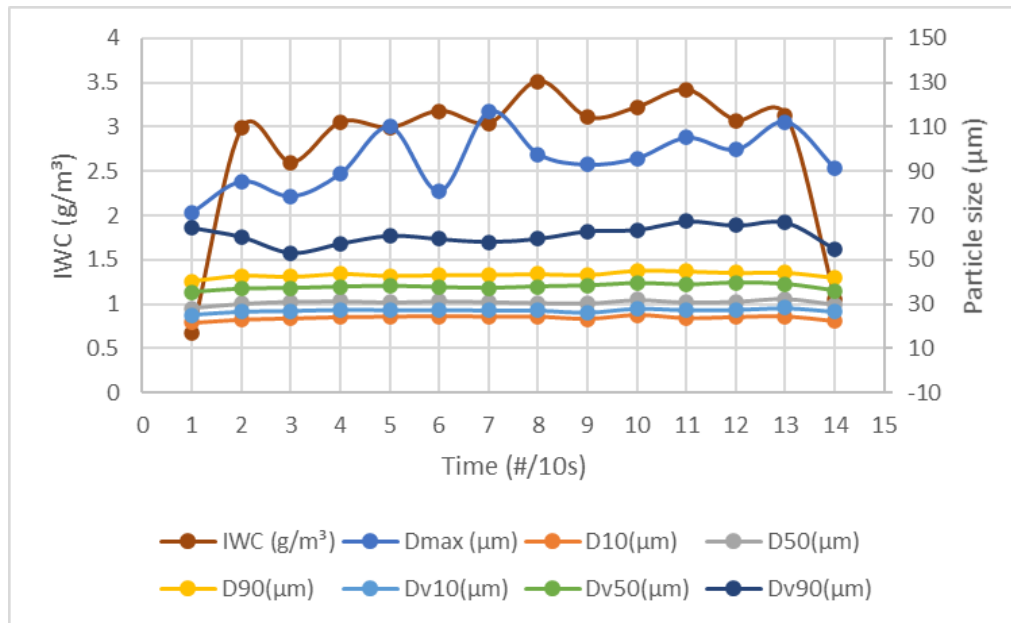


Figure 9 Particle size and concentration under pure ice crystal conditions

As shown in **Table 5** and **Figure 10**, the maximum particle size ranges from 38.554–144.566 μm , exhibiting significant discreteness. The number median diameter (D_{50}) is concentrated in the range of 21.208–23.577 μm , with a fluctuation range of only 2.369 μm , an average value of approximately 22.2 μm , and a coefficient of variation (CV) of about 2.7%, demonstrating excellent centralization. The volume median diameter (D_{v50}) ranges from 25.262–28.188 μm , which is consistently larger than the corresponding D_{50} in each group, consistent with the physical law that the volume distribution is weighted by large particles. The average mass concentration varies from 0.660–1.189 g/m^3 , covering the low to medium concentration range of pure SLD operating conditions. The CV of the average concentration is approximately 16.8%, which is higher than that of D_{50} . This may be related to local concentration variations caused by minor disturbances in the wind tunnel flow field and pressure fluctuations in the droplet generation system, and the fluctuation range is within the acceptable range for general icing wind tunnel tests ($\leq 20\%$).

Table5 CASE II -- Particle size and concentration under pure SLD conditions

Time (#/10s)	Dmax (μm)	D10 (μm)	D50 (μm)	D90 (μm)	Dv10 (μm)	Dv50 (μm)	Dv90 (μm)	LWC (g/m^3)
1	57.228	18.008	22.012	30.635	19.145	26.03	35.007	0.809
2	62.024	17.431	22.674	30.669	19.71	26.432	36.112	0.756
3	95.365	16.886	21.944	30.923	19.417	26.475	39.449	0.835
4	48.043	17.749	23.577	31.148	20.659	27.574	36.759	0.768
5	68.153	17.371	21.591	30.749	19.12	26.582	38.028	0.687
6	111.363	16.845	22.935	30.448	19.232	26.972	38.134	0.88
7	38.554	17.5	22.232	32.949	20.215	28.188	40.086	0.73
8	63.1	17.749	22.432	31.103	19.645	26.227	36.24	0.727

9	57.815	17.876	23.187	31.503	20.095	27.3	38.698	0.879
10	106.458	17.487	21.686	30.065	19.273	26.152	38.203	0.858
11	48.307	16.789	22.243	29.968	19.678	26.123	37.423	0.677
12	43.457	16.383	22.244	29.646	19.795	26.28	35.048	0.77
13	74.115	17.128	21.903	29.916	18.885	26.56	35.038	0.715
14	46.753	17.875	22.842	30.576	20.148	25.262	34.335	0.66
15	144.566	16.156	21.268	28.938	18.662	25.777	57.69	1.189
16	131.03	16.949	21.384	29.162	18.93	26.021	44.924	0.918
17	141.75	15.449	21.208	29.941	18.051	26.72	73.674	0.938

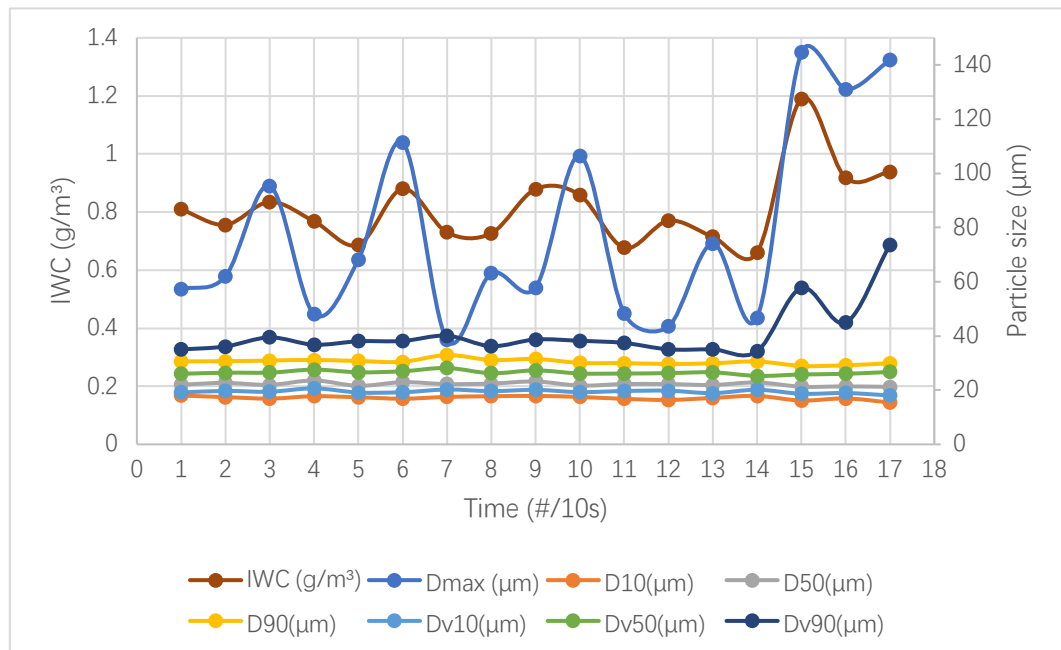


Figure 10 Particle size and concentration under pure SLD conditions

4. Conclusions

Icing wind tunnel experiments are critical for airworthiness certification, and quantitative measurement of cloud particle field parameters (e.g., size distribution, LWC, IWC, TWC) is essential for simulating in-flight cloud characteristics. To meet the measurement needs of high-speed ice crystals and supercooled droplets in icing wind tunnels, this study developed the DSPI, integrating core technologies (laser decoherence homogenization, piecewise fitting, etc.). It has achieved initial measurements of 10–1000 μm particle size, 0–130 m/s airspeed, and 0–10 g/m^3 TWC, satisfying basic test requirements. Currently, a traceable calibration device for particle size, shape, and concentration is under design and development to enable quantitative assessment of measurement precision, accuracy, and uncertainty. In the future, through the integration of compact light source design, integrated probe aerodynamic optimization, and high-speed signal

transmission with real-time image processing technologies, the instrument is expected to realize airborne measurements. This will not only support natural icing flight tests but also find applications in meteorological observation and icing mechanism research.

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