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1 Glossary

Abbreviation / Acronym	Description/meaning
2D-S	2D Stereo Probe
2D-G	2D-Grey probe
2D-P	2D Mono Probe for Precipitation
2D-C	2D Mono Probe for Clouds
ADA	Airborne Droplet Analyser
CAPS	Cloud, Aerosol, and Precipitation Spectrometer
CAS	Cloud and Aerosol Spectrometer
CAS-DPOL	Cloud and Aerosol Spectrometer with Depolarization
CCP	Cloud Combination Probe
CDP	Cloud Droplet Probe
CFD	Computational Fluid Dynamics
CIP	Cloud Imaging Probe
FCDP	Fast Cloud Droplet Probe
FSSP	Forward Scattering Spectrometer Probe
FZDZ	Freezing Drizzle
FZRA	Freezing Rain
HSI	multi-beam High Speed Imaging
IB	Icing Blade
IKP	Isokinetic Probe
LWC	Liquid Water Content
MVD	Median Volumetric Diameter
PDI	Phase Doppler Interferometry
PDI	Phase Doppler Interferometry
PDPA	Phase Doppler Particle Analyzer
PIP	Precipitation Imaging Probe
PMS	Particle Measuring Systems, Inc.
PSD	Particle Size Distribution
SBS	Spray Bar System
SLD	Supercooled Large Droplet
ZLE	Freezing Drizzle
ZRE	Freezing Rain

2 Executive Summary

Deliverable D6.1 / D6.2 provides information on the calibration method for Appendix O Freezing Drizzle and Freezing Rain cloud conditions in Icing Wind Tunnels. Recommended instrumentation for the different parameters as well as applicable procedures are described in order to assist the calibration. The document is structured in a similar way to the Aerospace Recommended Practice SAE ARP5905, "Calibration and Acceptance of Icing Wind Tunnels", which is used for calibration of Appendix C icing clouds [1]. This deliverable aims to act as additional input for the SAE AC-9C Aircraft Icing Technology Committee for IWTs working on the document SAE AIR6241 SLD capabilities of icing wind tunnels were commonly accepted procedures for the experimental simulation of Supercooled Large Drop (SLD) conditions in icing wind tunnels along with measurement techniques suitable to obtain calibration of the SLD icing cloud will be summarised.

3 Introduction

The ambition of the ICE GENESIS project is to improve the experimental test capabilities of icing facilities to generate or reproduce representative Supercooled Large Droplet (SLD) conditions and to propose a common calibration methodology.

This document aims to act as an extension of the ARP5905 for Appendix O conditions and should establish certain standards and acceptance criteria for IWTs to be used in testing of aircraft components and systems and for the development of simulated ice shapes under such conditions. The document provides recommended instrumentation and procedures for the calibration of EASA CS-25 [2] Appendix O SLD icing conditions generated in icing wind tunnels. Furthermore, proposed acceptance criteria and test facility performance targets defined at the beginning of ICE-GENESIS project (see WP3 deliverable D3.1 “Definition of the target requirements for test facilities operating envelopes for App O” [3]) were reviewed and evaluated by means of a numerical sensitivity analysis [4]. The methodology described in this document has been used as guideline for the calibrations performed within the ICE-GENESIS project.

The reference document for the calibration of icing wind tunnels is the SAE ARP 5905. However, the content is not adapted to include SLD conditions for which different instrumentation and procedures may be required. Basically, the calibration process of icing test facilities is divided into two steps: the “aero-thermal calibration” and the “icing cloud calibration”:

- **Aero-Thermal Calibration:** This is not directly related to specific icing conditions, so methods, procedures and instrumentation described in the ARP 5905 [1] are the same and will only be outlined briefly in this document. The difference with Appendix C might be the ability to generate bimodal clouds using different set of air pressures between the spray nozzles and/or air turbulence devices to improve cloud mixing, which could affect flow quality. For this reason, target requirements should be reviewed for the flow quality parameters when the spray bar is set to produce the SLD clouds (air-on / water-off). Nevertheless, a review or proposal for modification of aerothermal calibration requirements is not debated here.
- **Icing Cloud Calibration:** The basic logic remains unchanged including size distribution, water content and cloud uniformity measurements, but the icing cloud calibration instruments and procedures need to be adapted as the Appendix O conditions cover a much larger particle size range with specific required size distributions at low Liquid Water Contents (LWC). Due to the large particle sizes, additional parameters such as droplet trajectory, temperature and sphericity emerge which need to be assessed in addition. Therefore, the relevant parameters and acceptance criteria are updated. The characteristics of the recommended instrumentation are also further detailed in this document.

As an alternative to a tunnel calibration, the tunnel can operate with calibrated instrumentation that are used to measure the actual test conditions being obtained at each test point. This provides that the actual conditions for each test point including the effect of the test article can be characterized. In these circumstances, any aero-thermal or icing parameter that cannot be measured at a given test point, must be calibrated as outlined above.

4 Facility Description

There are a variety of icing wind tunnel types, ranging from refrigerated closed-circuit systems to open-air free-jet systems, which are typically used for engine testing. This report covers the recommended calibration methodologies for closed-circuit facilities based on tests / calibrations performed in the two largest icing wind tunnels (CIRA in Italy and RTA in Austria) in Europe. An overview of the general layout of closed-loop facilities is given in this section. Since no open-air free jet facility was involved in ICE-GENESIS, the information provided is focusing on closed-circuit IWTs only. Furthermore, an overview on additional spray bar system requirements for the generation of Appendix O SLD condition is provided.

4.1 Closed Circuit Facilities

An example of a typical closed-circuit refrigerated facility is shown in [Figure 1](#). The airflow is conducted from the exit of the test section back to the main fan by means of turning vanes. From the fan, the air is returned to the heat exchanger and the settling chamber, where it is reconditioned. The air is then accelerated through the contraction nozzle to reach the test section area at the required conditions.

The airspeed in the test section is controlled by a variable speed fan motor. The air temperature control / refrigeration is obtained via the heat exchanger upstream of the test section and the settling chamber. The settling chamber may be fitted with honeycomb flow straighteners and screens and a contraction section with sufficient area ratio to provide good airflow quality in the test section. In order to generate the icing cloud, a spray bar system is installed downstream of the heat exchanger, upstream of the contraction region. The water droplet spectrum and LWC is controlled by adjusting the spray nozzle supply pressures. The water used in the spray bar system is normally heated and treated, e.g., deionized, in order to avoid freeze-out.

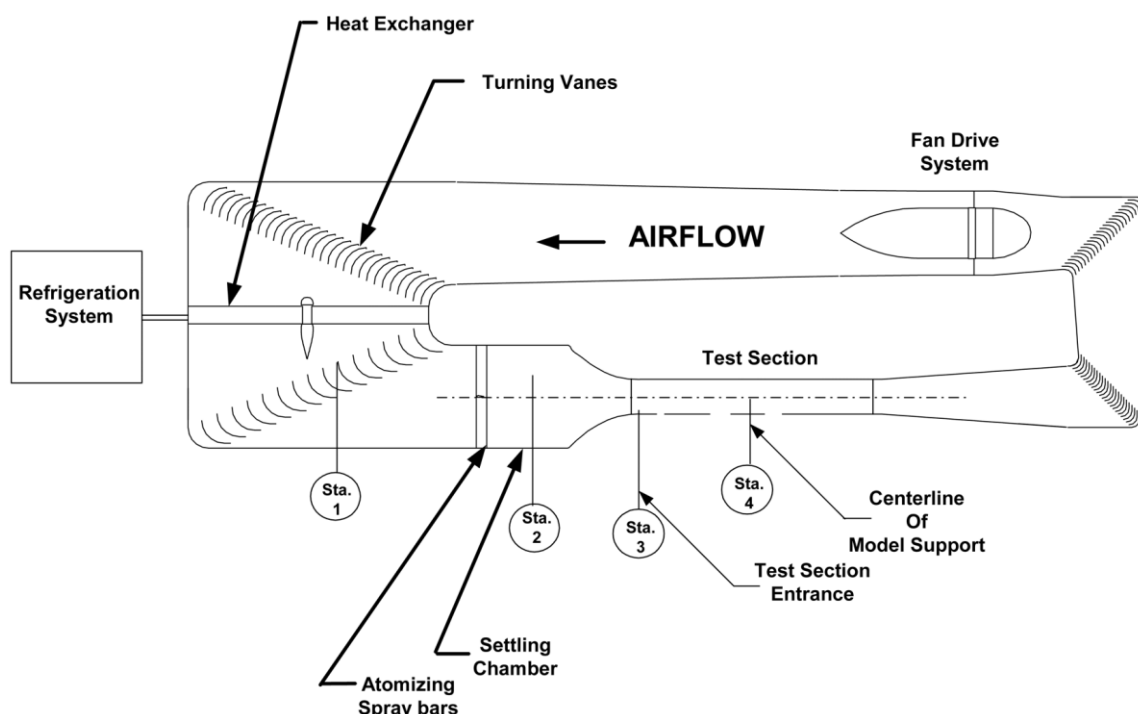


Figure 1: Example of a typical closed-circuit, refrigerated icing wind tunnel [1]

4.2 Spray Bar System Capabilities

In order to be able to generate the SLD conditions from Appendix O the spray bar systems needs to fulfil certain requirements. One of the main differences between Appendix C and Appendix O conditions besides the very low liquid water content range, is the fact that Appendix O clouds have bimodal droplet size distributions.

In order to match the required PSDs, it is necessary to inject two different modes simultaneously. This can be realized by setting different supply pressures to the same spray nozzle type or by using two different sets of spray nozzles. Furthermore, the spray nozzle arrangement (which and how many nozzles produce the small and which and how many nozzles produce the large mode) can have a significant effect on the overall generated LWC and PSD (and therefore the MVD) as well as the LWC and MVD uniformity in the test section. In addition to the different requirements for the spray nozzle supply pressures, the air and water temperatures supplied to the spray nozzles might also need to be very different for the small and the large mode. At colder ambient temperatures (e.g. -20°C) the small mode may require a preheated water and air supply in order to prevent freeze-out of the particles before they reach the test section whereas the large mode still needs a precooled water supply in order to guarantee sufficient cooling of the large droplets.

Spray bar systems developed for Appendix C clouds may lack some of these capabilities and need to be upgraded or modified to be suited for Appendix O conditions.

5 Target Requirements - Appendix O Icing Conditions

In this section, the SLD icing conditions defined in Appendix O of the EASA Certification Specification CS-25 Amendment 23 [2] are summarised. In general, the SLD conditions can be segregated into four subsets which include conditions with maximum drop sizes below 500 μm and higher than 500 μm in diameter, each with median volumetric diameters (MVDs) below 40 μm and larger than 40 μm .

Freezing drizzle (FZDZ) refers to icing environments with maximum diameters of less than 500 μm whereas environments with maximum diameters exceeding 500 μm are referred to as freezing rain (FZRA). Those two conditions are then further distinguished based on the MVD. “FZDZ In” and “FZRA In” refer to environments with MVDs of smaller than 40 μm (mainly occurring within clouds). “FZDZ Out” and “FZRA Out” refer to environments with MVDs of larger than 40 μm (mainly occurring below clouds).

For each SLD subset, envelopes of maximum LWC values as a function of the horizontal extent and temperature are available. The particle size distributions (PSDs) and LWC envelopes are based on in-situ measurements performed between 1995 and 2000, which include the first and third Canadian Freezing Drizzle Experiment [5], [6], the First International Satellite Cloud Climatology Project Regional Experiment Arctic Cloud Experiment [7], the First Alliance Icing Research Study [8], as well as the SLD Flight Research Study by NASA Glenn [9]. The main instrumentation used during the field projects were PMS FSSP probes for the small droplet spectra and PMS 2D-C, 2D-G and 2D-P probes for the large particles. PMS King LWC probes and Nevzorov LWC-TWC probes were used for the water content measurement except for very low LWC, of which the values have been integrated from PSDs collected by optical spectrometers. In [Table 1](#), an overview of the expected MVD range, maximum droplet diameter and maximum LWC for the different conditions is given [10].

Table 1 MVD, D_{max} and LWC values for each SLD subset [10]

Definition	MVD Range	D_{max} Range	MVD	D_{max}	LWC_{max}
FZDZ In	< 40 μm	100 – 500 μm	20 μm	389 μm	0.44 g/m^3
FZDZ Out	> 40 μm	100 – 500 μm	110 μm	474 μm	0.27 g/m^3
FZRA In	< 40 μm	> 500 μm	19 μm	1553 μm	0.31 g/m^3
FZRA Out	> 40 μm	> 500 μm	526 μm	2229 μm	0.26 g/m^3

5.1 Freezing Drizzle MVD < 40 μm

The PSD requirements for FZDZ with an MVD smaller than 40 μm are shown in [Figure 2](#). The average MVD is 20 μm and comes from the average of all of the cumulative mass spectrums (1469 points) with an average maximum diameter of 389 μm . [Figure 3](#) shows the individual measured PSDs and the average cumulative mass spectrum (black line). Characteristic for this condition is the very low contribution of large particles (> 100 μm) to the overall mass, which is only about 10%. The 99.0% LWC of all of the cloud measurements was 0.44 g/m^3 , which is used as the upper limit at 0°C ambient temperature in Appendix O. The lower temperature limit for “FZDZ In” is -25°C with a maximum LWC of 0.29 g/m^3 . The maximum observed LWC during the flight campaigns was 0.77 g/m^3 [10]. [Figure 4](#) shows the 99.0% LWC and altitude envelopes versus ambient temperature during the performed flight test campaigns. The numbers of data points observed for each subset of FZDZ data are shown in the caption. A different number of data points is available for PSD and LWC measurements. The term ZLE in the description refers to Freezing Drizzle.

5.2 Freezing Drizzle MVD > 40 μm

The PSD requirements for FZDZ with an MVD of larger than 40 μm are shown in Figure 4. The average MVD is 110 μm and comes from an average of all of the cumulative mass spectrums (335 points) with an average maximum diameter of 474 μm. Figure 5 shows the individual measured PSDs during the performed flight test campaigns and the average cumulative mass spectrum (black line). The 99.0% value of the LWC of all of the cloud measurements was 0.27 g/m³, which is used as the upper limit at 0°C ambient temperature in Appendix O. The lower temperature limit for “FZDZ Out” is also -25°C with a maximum LWC of 0.18 g/m³. The maximum LWC observed during the flight campaigns was 0.39 g/m³. [5]. Figure 6 shows the 99.0% LWC and altitude envelopes versus ambient temperature. The numbers of data points observed for each subset of FZDZ data are shown in the caption.

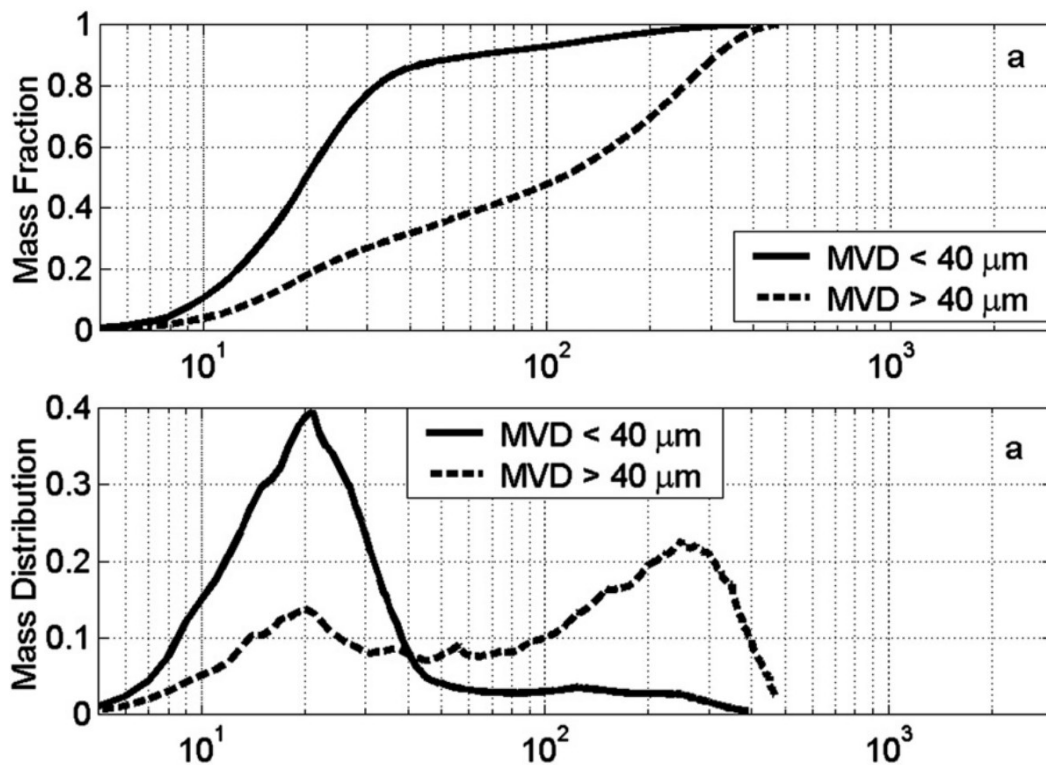


Figure 2 Cumulative mass fraction distributions (top) and normalised mass distributions (bottom) for FZDZ environments [10]

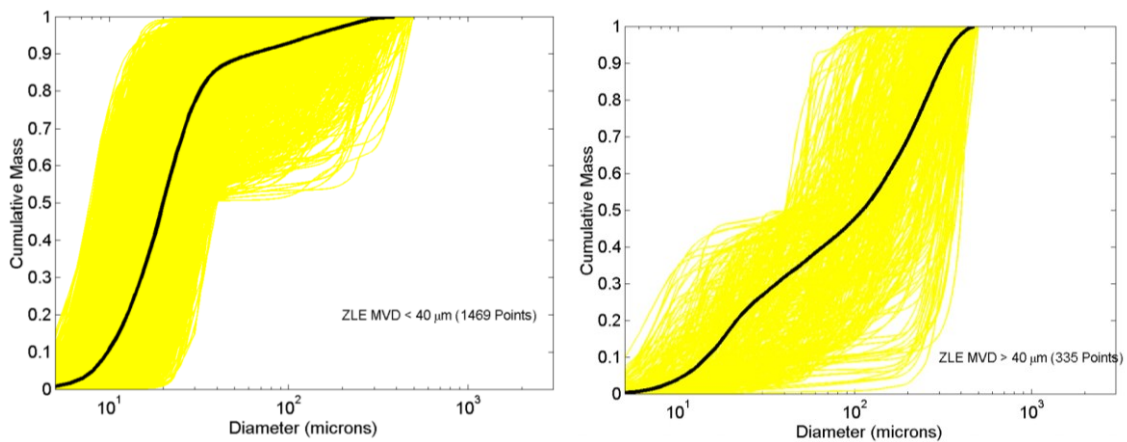


Figure 3 Average cumulative mass spectrum compared to each individual cumulative mass spectra for FZDZ MVD < 40 μm (left) and FZDZ MVD > 40 μm (right) [11]

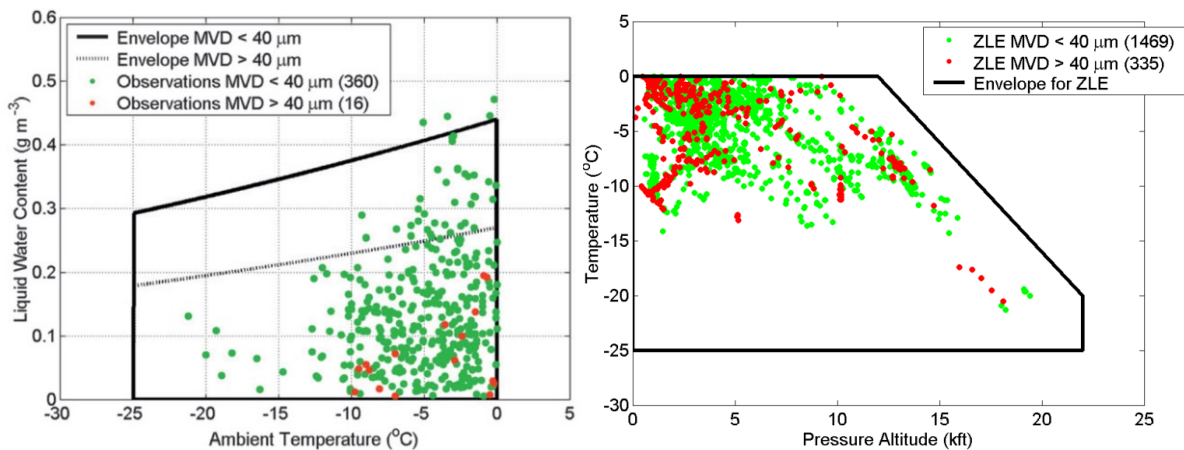


Figure 4 The 99% LWC envelopes vs temperature for FZDZ compared with 300-s data (left), altitude vs temperature envelopes for FZDZ compared to 30-s Data (right)

5.3 Freezing Rain MVD < 40 μm

The PSD requirements for FZRA with an MVD smaller than 40 μm are shown in [Figure 5](#). The average MVD is 19 μm and comes from the average of all of the cumulative mass spectrums (193 points) with an average maximum diameter of 1553 μm . [Figure 6](#) shows the individual measured PSDs and the average cumulative mass spectrum (black line). Characteristic for this condition is the low contribution of the large particles (> 100 μm) to the overall mass, which is about 25%. Due to the large particle sizes, this corresponds to only few individual “rain” droplets. The 99.0% LWC of all cloud measurements was 0.31 g/m^3 , which is used as the upper limit at 0°C ambient temperature in Appendix O. The lower temperature limit for “FZRA In” is -13°C with a maximum LWC of 0.26 g/m^3 . The maximum observed LWC during the flight campaigns was 0.49 g/m^3 . [10]. [Figure 7](#) shows the 99.0% LWC and altitude envelopes versus ambient temperature. The numbers of data points observed for each subset of FZRA data are shown in the caption. A different number of data points is available for PSD and LWC measurements. The term ZRE in the description refers to Freezing Rain.

5.4 Freezing Rain MVD > 40 μm

The PSD requirements for FZRA with an MVD larger than 40 μm are shown in [Figure 5](#). The average MVD is 526 μm and comes from the average of all of the cumulative mass spectrums (447 points) with an average maximum diameter of 2229 μm . [Figure 6](#) shows the individual measured PSDs and the average cumulative mass spectrum (black line). Characteristic for this condition is the low contribution of the small particles (< 100 μm) to the overall mass, which is about 25%. The 99.0% LWC of all cloud measurements was 0.26 g/m^3 , which is used as the upper limit at 0°C ambient temperature in Appendix O. The lower temperature limit for “FZRA Out” is -13°C with a maximum LWC of 0.21 g/m^3 . The maximum observed LWC during the flight campaigns was 0.41 g/m^3 . [10]. [Figure 7](#) shows the 99.0% LWC and altitude envelopes versus ambient temperature. The number of data points observed for each subset of FZRA data are shown in the caption.

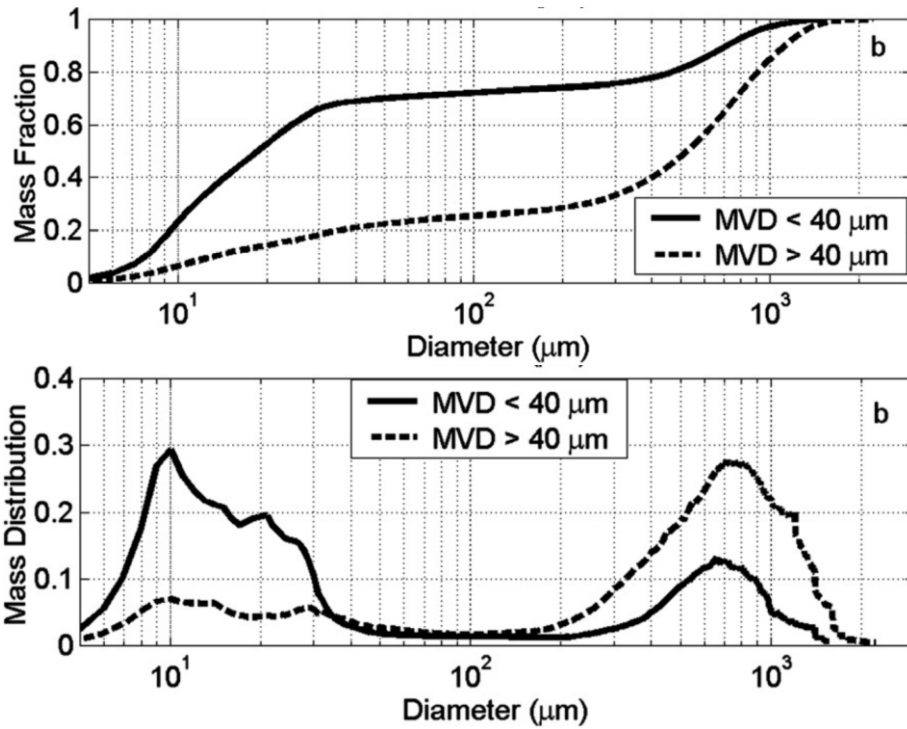


Figure 5 Cumulative mass fraction distributions (top) and normalised mass distributions (bottom) for FZRA environments [10]

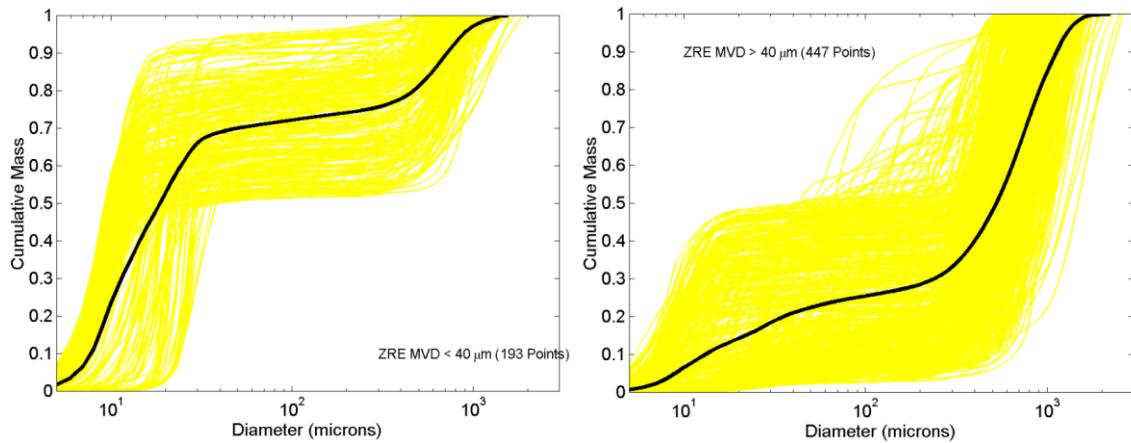


Figure 6 Average cumulative mass spectrum compared to each individual cumulative mass spectra for FZRA MVD < 40 µm (left) and FZRA MVD > 40 µm (right) [11]

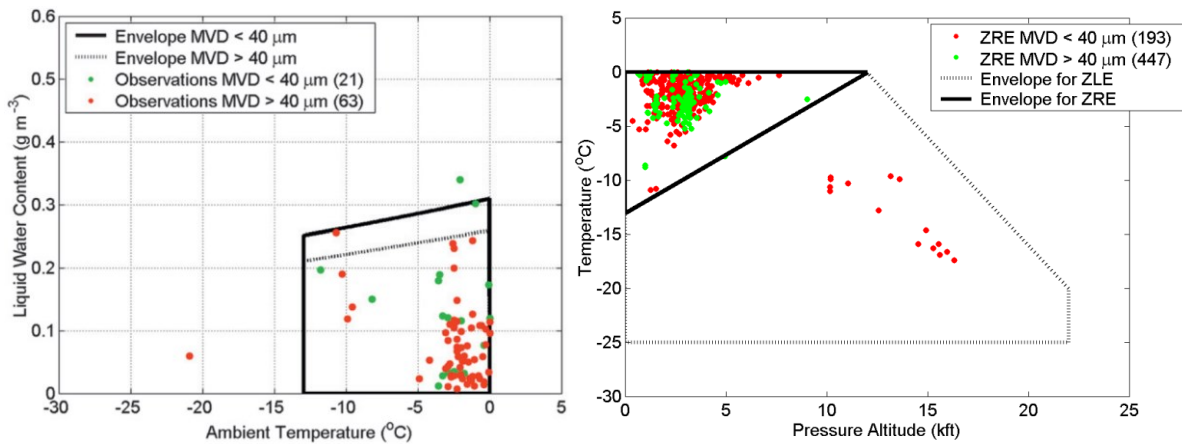


Figure 7 The 99% LWC envelopes vs temperature for FZRA compared with 300-s data (left), altitude vs temperature envelopes for FZRA compared to 30-s Data (right)

6 Facility Performance Target

Icing testing should be performed in facilities having measured, defined, and documented aerothermodynamic flow qualities, icing cloud qualities, and calibrated instrumentation. The facility should be calibrated in accordance with the recommended time frames in Section 8 and the procedures in Section 9. The test section airflow and icing cloud characteristics should be within the range of performance targets listed in [Table 2](#) and [Table 3](#), over the area of the uniform icing cloud. The uniform icing cloud is defined as the area of the test section over which the LWC and MVD does not vary by more than $\pm 20\%$ from the test section centreline values for a given airspeed and water droplet size.

A dedicated study was conducted to understand the impact of the additional cloud parameters required for SLD conditions, such as the particle size distribution, droplet temperature, droplet trajectory angle and velocity and droplet sphericity [4]. This sensitivity study [4], based on validated AeroTex proprietary numerical simulation tools (with identified constraints), allows for a better understanding of the effects of these cloud parameters on the accreted, unprotected ice shape on the aerofoil surface and provides a first-order indication of the requirements for facility acceptance under Appendix O conditions.

6.1 Aero-Thermal

The targets indicated in the following table are provided for an empty test section and dry airflow. If the targets cannot be achieved for any of the test points, the actual uncertainty should be stated. Values of the parameters herein reported are based on a table from the Aerospace Recommended Practice (ARP) 5905 [1], which provides recommended practices and target requirements for the calibration of Appendix C icing conditions in IWTs.

Table 2 Aero-thermal test section performance targets

Parameters	Instrumentation Uncertainty	Tunnel Centreline Temporal Stability	Spatial Uniformity	Limit value	Test Section Calibrations
Aerodynamic Parameters					
Airspeed	$\pm 1\%$	$\pm 2\%$	$\pm 2\%$	N/A	$\pm 1\%$
Static Air Temperature SAT $\leq -30^\circ\text{C}$	$\pm 2^\circ\text{C}$	$\pm 2^\circ\text{C}$	$\pm 2^\circ\text{C}$	N/A	$\pm 2^\circ\text{C}$
Static Air Temperature $-30^\circ\text{C} < \text{SAT} < 5^\circ\text{C}$	$\pm 0.5^\circ\text{C}$	$\pm 0.5^\circ\text{C}$	$\pm 1^\circ\text{C}$	N/A	$\pm 0.5^\circ\text{C}$
Flow Angularity	$\pm 0.25^\circ$	N/A	$\pm 2^\circ$	$\pm 3^\circ$	N/A
Flow Turbulence (Spray Nozzle Air Pressure – Off)	$\pm 0.25\%$	$\pm 2\%$	$< 2\%$	$< 2\%$	N/A
Flow Turbulence (Spray Nozzle Air Pressure – On)	$\pm 0.25\%$	$\pm 2\%$	$< 2\%$	$< 5\%$	N/A
Pressure altitude	$\pm 50\text{ m}$	$\pm 50\text{ m}$	N/A	N/A	$\pm 50\text{ m}$

It must be highlighted that some facilities are forced to modify the spray bar configuration in the transition from Appendix C to Appendix O (e.g., change the spray nozzle type, their position on the array, and add devices to improve the mixing between the different droplet sizes) to generate the SLD cloud conditions according to the requirements listed in Section 5. Moreover, for bi-modal PSDs, the spray nozzles can be set at different air pressures, typically higher for the small droplet generation than for the larger one's generation. In these cases, it is necessary to evaluate the flow quality parameters (Table 2) by simultaneously setting the automatization nozzle air at the typical value used for both small and large droplet injection. This procedure is proposed whether the spray bar system uses two air and water lines in each bar or operates with different air/water pressures set on each bar (e.g., all even bars to inject the small droplets and odd bars for large droplets).

6.2 Icing Cloud

For the icing wind tunnel performance target requirements, definitions of the main parameter uncertainties with expected instrumentation accuracies are reported in the [Table 3](#). The values are based on the main findings from the experiments and measurements conducted within WP4 and WP6 of the ICE-GENESIS project. Furthermore, inputs from research conducted outside of ICE GENESIS and from the AC-9C working group as well as numerical investigation results were taken into account.

The icing cloud characteristics should be within the range of the performance targets listed in Table 3, over the area of the uniform icing cloud. The uniform icing cloud is defined as the area of the test section over which the LWC and MVD does not vary by more than $\pm 20\%$ from the test section centreline LWC value for a given airspeed and water droplet size.

Due to the bimodal nature of the SLD conditions in Appendix O, the larger range of particle sizes and the relatively low LWCs, the instrumentation accuracies for LWC, MVD and the PSD are expected to be in the range of at least $\pm 15\%$. Intercomparison results of different instrumentation in the same facility for the same nominal conditions have shown differences of up to $\pm 25\%$. Based on the accuracy of current state of the art instrumentation, the achievable uncertainty of the test section calibration for LWC, MVD and PSD is expected to be in the range of $\pm 15\%$ to $\pm 20\%$ (compared to $\pm 10\%$ for Appendix C). In terms of the temporal stability and spatial uniformity $\pm 20\%$ should be achievable. The numerical sensitivity study shows that a LWC variation of larger than 10 % may provide the biggest impact on the ice shape for a specimen exposed to the Appendix O cloud conditions. This result must be carefully addressed with the measurement process, considering the uncertainty of $\pm 20\%$ for current hot-wire technology, which represents the expected facility error in the range of Appendix O, [12]. Which means, that the achievable uncertainty of the calibrated LWC is currently limited by the measurement accuracy. According to the numerical study, uncertainties in the PSD have a bigger impact on the ice shape than uncertainties in the MVD. MVD deviations of up to $\pm 20\%$ might still be acceptable, which is also roughly in line with the instrumentation accuracy of particle size measurement devices. In terms of PSD remaining within $\pm 10\%$ to $\pm 15\%$ of cumulative volume and maximum particle size should be targeted.

The instrumentation accuracy for the droplet temperature is based on the Rainbow Vision technology [13]. The effect of warmer droplet temperatures compared to the ambient airflow was only evaluated in the numerical sensitivity study. The mass averaged temperature (using at least a 10-bin resolution of the investigated PSD) should remain within 10°C compared to the static ambient temperature, whereas ideally it remains within 5°C. Since there is a physical limit to how cold the particles can be injected ($> 0^\circ\text{C}$) it is not possible to cool the larger particles down to the ambient temperature given the distance and time which is available from the spray bar system to the test section. This is especially challenging for FZRA. Therefore, the achievable conditions in each facility and the effect of the droplet temperature for unprotected and protected cases need to be well understood.

The effect of differences in the droplet velocity and trajectory angles compared to the ambient airflow were also investigated in the numerical sensitivity study. It was concluded that even a 25% slower droplet velocity (based on the largest droplet size bin in the PSD) did not have a significant effect on the ice shape. It was also found that in large test facility (such as RTA and CIRA), once a large particle

can be transported to the test section without secondary breakup, it will be within less than 25% of the test section velocity and therefore also the trajectory angle will be within less than 1-2° compared to a droplet falling with terminal velocity at the given test section airspeed. For smaller facilities this might be more significant, but no detailed investigations were made. No performance targets for droplet velocity and trajectory angle are provided. The characteristics of these parameters in each facility need to be investigated by means of numerical simulations as shown in Section 0.

The droplet sphericity itself can not be measured in IWTs, since the optical probes only take 2D images. But droplet circularities can be extracted from imaging probes such as the CIP or PIP. The effect of droplet deformations on the collection efficiency and ice shape have not been investigated in detail. The $\pm 20\%$ value is based on what can realistically be achieved in an IWT, the circularity is directly linked to the relative velocity of the droplet compared to the ambient airflow.

Table 3 Icing cloud test section performance targets

Parameters	Instrumentation	Test Section Calibration Uncertainty	Tunnel Centreline Temporal Stability	Spatial Uniformity	Limit value
Cloud & Cloud Uniformity Parameters					
Liquid Water Content	$\pm 15\%$	$\pm 15\%$	$\pm 20\%$	$\pm 20\%$	N/A
Median Volumetric Diameter	$\pm 15\%$	$\pm 20\%$	$\pm 20\%$	$\pm 20\%$	N/A
Particle size distribution cumulative volume fraction	$\pm 15\%$	$\pm 15\%$	$\pm 20\%$	$\pm 20\%$	N/A
Droplet temperature deviation from free stream SAT	$\pm 3^\circ\text{C}$	+10°C (mass averaged)*	N/A	N/A	+20°C (for largest droplet size bin)**
Droplet circularity	$\pm 10\%$	$\pm 20\%$	N/A	N/A	N/A
Relative humidity	$\pm 3\%$	$\pm 10\%$	$\pm 10\%$	N/A	N/A

* Mass average of particle size distribution consisting of at least 10 bins; if it can't be measured, numerical validation must be shown

** Droplet size bin which contains the upper 2,5% of the total mass in the particle size distribution

7 Instrumentation

The instrumentation to characterize the generated SLD conditions in the icing facilities was reviewed and assessed within WP4 “Instrumentation for liquid icing conditions” (see [14] and [15]).

The following objectives to define the most appropriate instrumentation should be ensured for each W/T facility:

- 1) Guarantee a wide measurement range for particle sizes between 1 μm and several millimetres to cover Appendix C and Appendix O (freezing drizzle and freezing rain) conditions by using state of the art scattering probes or optical array probes.
- 2) Ensure measurement capabilities for a large range of droplet number concentrations from a few tens per cubic centimetre (cm^{-3}) over Appendix O to a several thousand cm^{-3} in Appendix C conditions [16]
- 3) Guarantee a wide measurement range for the LWC (nearly three orders of magnitudes starting from 0.01 g m^{-3}).
- 4) Ensure spatial cloud homogeneity in the test section.
- 5) Enable the determination of the droplet temperature for small and large droplets within the test section to characterize the flow conditions.
- 6) Allow for the droplet sphericity characterization.

The icing cloud calibration instrumentation is specific to each W/T test facility. Therefore, data analysis and uncertainty assessment should be harmonised between the facilities. The possible use of the same instruments (e.g. for PSD, LWC, droplet temperature) in different facilities enables to reduce the risk of facility calibration biases and is thus recommended.

During the calibration, the measurements shall be performed by setting the total air temperature (TAT) to a value that avoids the droplets’ re-circulation around the tunnel, which may influence the collected data for both LWC and PSD/MVD instruments.

Standard icing tunnel instrumentation probes should be used to measure aerothermal parameters as velocity distribution, total temperature distribution, total pressure, static pressure, and flow angularity. For more information see the ARP 5905 [1].

7.1 Particle size distribution (PSD)

For the selection of the most appropriate instrumentation for measurement of the particle size distribution (PSD) under Appendix O conditions in various wind tunnel (W/T) facilities see WP4 deliverable D4.1 “Report on the review, assessment and selection of instrumentation for PSD” [14]. In particular, this deliverable deals with:

- a) Selection of the best instrumentation required to measure PSD under appendix O conditions with focus on supercooled large droplets (SLD), using optical array and scattering probes. The respective W/T installation requirements should be considered.
- b) Calibration of selected instruments regarding sample area (e.g., depth of field vs. droplet size) with mono-disperse droplet generators in the laboratory.
- c) Evaluation of PSD under Appendix O conditions with respect to appropriate correction methods for image processing and uncertainty assessment.

7.2 Particle Size Distribution Uniformity

The MVD / PSD uniformity can be measured by mounting one of the probes mentioned in Section 7.1 on a traversing system. The traversing system should be able to cover the intended test section area. A matrix with a minimum number of positions is shown in [Figure 22](#). The holding time depends on the acquisition rate of the used instrument and the stability of the icing cloud. Sufficient time to get a good average needs to be foreseen. [Figure 8](#) (left) shows an example of such a setup with a CAPS probe.

7.3 Liquid Water Content (LWC)

For the selection of the most appropriate instrumentation for measurement of the liquid water content (LWC) under Appendix O conditions in various wind tunnel (W/T) facilities see the deliverable D4.2 "Report on the review, assessment and selection of instrumentation for LWC" [15]. In particular, this deliverable deals with:

- a) Selection of the best instrumentation required to measure LWC under Appendix C/O conditions in W/T facilities. The W/T installation requirements have to be taken into account.
- b) Evaluation of the LWC measurements with respect to appropriate correction methods and uncertainty assessment.

7.4 Liquid Water Content Uniformity

A Preliminary assessment of cloud uniformity and coverage area in the reference plane at the center of rotation of the model support system (center-line position, as for the section 4 in Figure 1) can be performed either with the Icing Calibration Grid (IG) or the Icing Cylinders (IC). The IG, which is commonly used to evaluate the uniformity of Appendix C icing clouds can be used as a qualitative mean of assessing the LWC uniformity of FZDZ conditions. [Figure 9](#) shows an iced ice accretion grid. The IC generally allows for a longer exposure time to better verify spray stabilization time. As a starting point, the target MVD must be set to a minimum value depending on the SBS configuration (e.g., for FZDZ with $MVD < 40 \mu m$). The cloud uniformity check must be performed at different airspeeds (e.g., 60% and 90% of V_{max}).

For FZRA conditions the IG or IC can be used as well for qualitative assessment and functionality of the SBS. For the accurate measurements of LWC uniformity in Appendix O conditions, the same procedure can be used as for mapping with PSD instruments. An example of a setup with a Nevzorov probe on a traverse system is shown in [Figure 8](#) (right).



Figure 8: PSD (left) and LWC instrumentation (right) mounted on a traversing system in the RTA IWT

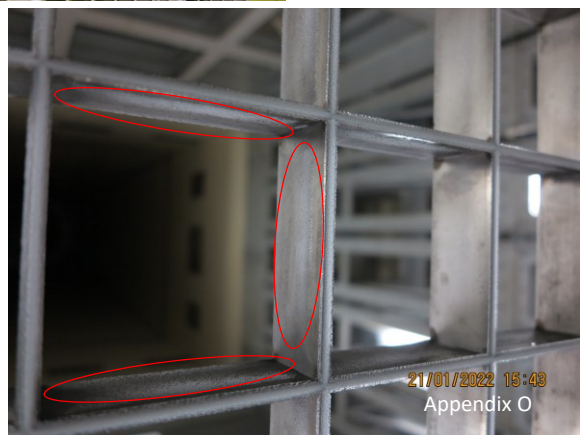
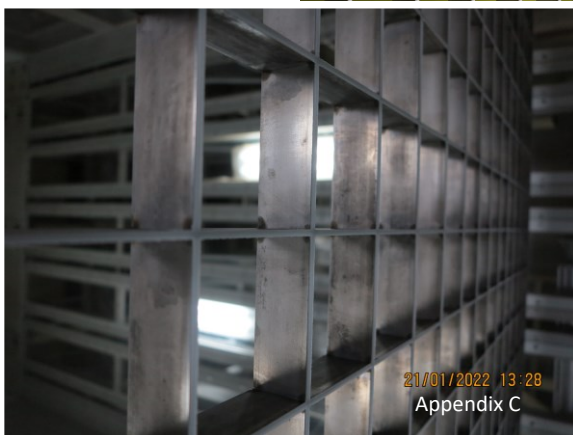


Figure 9: Example ice accretion grid in the RTA and CIRA IWT

7.5 Droplet Temperature

The precise knowledge of supercooled droplet temperature is of utmost importance for wind tunnel testing and numerical simulations as it determines the type, extent, height, roughness and other characteristics of the ice accreted on surfaces. In the natural environment, the droplet temperature of liquid droplets formed in the troposphere can be assumed to be equal to the surrounding air temperature due to their long-time existence. On the contrary, in an IWT, the droplets are injected at a positive temperature and the residence time is limited. For several icing conditions, not all the droplets may come in thermal equilibrium with air. Therefore, the measurement of the droplet temperature in an IWT is a challenge to simultaneously cover a wide spectra of droplet distribution size and high velocities.

Within WP4 on the Ice GENESIS project it was decided to measure the average droplet temperature in icing W/T with the Global Rainbow Technique (GRT) realised with measurement devices from *RainbowVision SAS* [13] and [17].

Incident light on a spherical droplet is scattered in space, according to the Lorenz-Mie theory. The scattering phase function is a complex function depending on the droplet size, the droplet refractive index and the incident wavelength. Among the different possible elastic scattering measurement strategies, a particularly interesting configuration is based on the analysis of the light scattered around the rainbow angle. The rainbow angular location at a certain wavelength is a function of the refractive index and, therefore, also a function of the droplet temperature. Accordingly, the evaluation of light scattered around the rainbow angle ($\sim 138^\circ$, for water) enables a measurement of the droplet temperature. Moreover, the shape of the light scattered around the rainbow angle depends on the droplet size. Therefore, by analysing the light scattered around the rainbow angle, both the temperature and size of the droplets are simultaneously measured. Using this principle, different configurations have been developed. The Single Rainbow technique is very accurate but very sensitive to any departure from perfect sphericity. The measurement of individual droplets is performed with a pulsed laser light, the measurement of a monodispersed droplet chain is performed with continuous laser light. The Global rainbow technique is based on the recording and analysis of the synthetic rainbow created by a large number of droplets with different sizes, orientations and locations for a sufficient long exposure time. It has been demonstrated that GRT is less sensitive to the droplet shape (sphericity) than the single rainbow technique. The measurement operates in the water spray with continuous laser light.

RainbowVision SAS provided two mobile GRT instruments to measure water droplet temperature. A first model, called GRT-XL in [Figure 10 \(a\)](#), has been designed to measure the droplets from outside of a wind tunnel, through an optical window. A second model, called GRT-mini [Figure 10 \(b\)](#), has been designed to measure the droplets directly inside a wind tunnel.

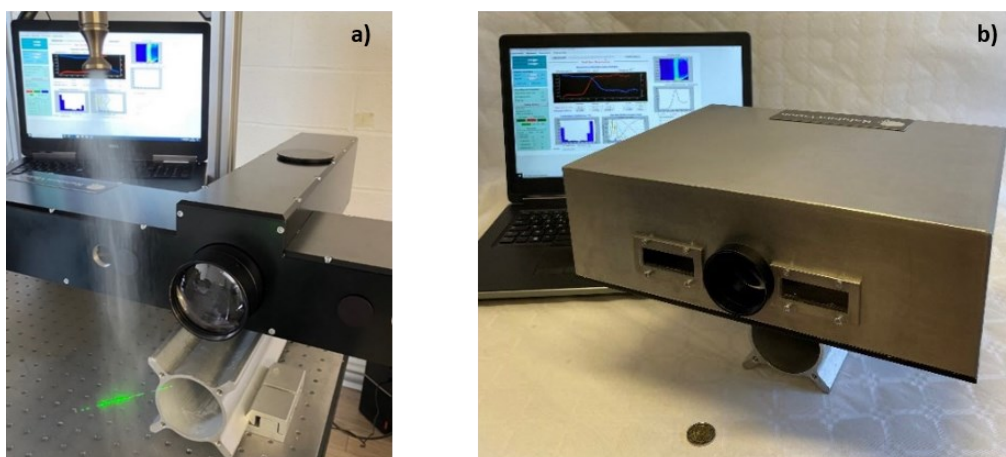


Figure 10: GRT_XL Model (a) and GRT-Mini Model (b)

The accuracy of GRT average temperature measurement has been defined at a laboratory scale to be about 1°C (for water), but the difficult environment in a real IWT provides a first estimation of the GRT temperature uncertainty of about 2-3 °C.

For an operational use in icing environments of the GRT instruments, the following issues have to be considered:

- Reduce the presence of droplets on the emission window by blowing air along the glass window,
- Prevent the deposition of water or ice on the inner side of the optical window,
- Possibility to record images with a very long exposure times to permit statistical smoothing of the effect of non-sphericity on refractive index measurement.

A review on droplet temperature measurement methods as well as a detailed description on the Global Rainbow Technique and its first tests in icing wind tunnels is provided by the deliverable D4.3 “Report on the review, assessment and selection of instrumentation/model for droplet temperature measurement” [18]. For the large icing wind tunnels, the GRT_XL instrument has shown some drawbacks in its application at high speed (< 60 m/s) and in collecting enough droplet sampling to provide an acceptable uncertainty on droplet temperature measurements (see Table 3). The ice accretion on the strut and sensor box itself further affects the GRT_XL capability to operate in icing environmental conditions.

7.6 Droplet Circularity

An estimation on the droplet circularity can be derived from PSD measurements using imaging probes. The particle images then can be post processed with an image processing software or built in functionality in the software of the probe. An example of such an evaluation is shown below. A set of about 50 randomly selected droplets with equivalent diameters (diameter of circle with same area as the deformed droplet) ranging from about 100 to 450 μm were analyzed using an algorithm implemented in the Matlab Image Processing Toolbox. Equation 1 shows how the circularity was calculated. In [Figure 11](#) the resulting circularity values are listed. Circularities from 0.8 to ~1 were obtained, where 1 describes a perfect circle. Some values exceeded a circularity of 1, this is due to the uncertainty in the area and perimeter estimation. A slight trend towards more non perfect circles with increasing droplet sizes was identified.

$$Circularity = \frac{4 * \pi * Area}{Perimeter^2} \quad (1)$$

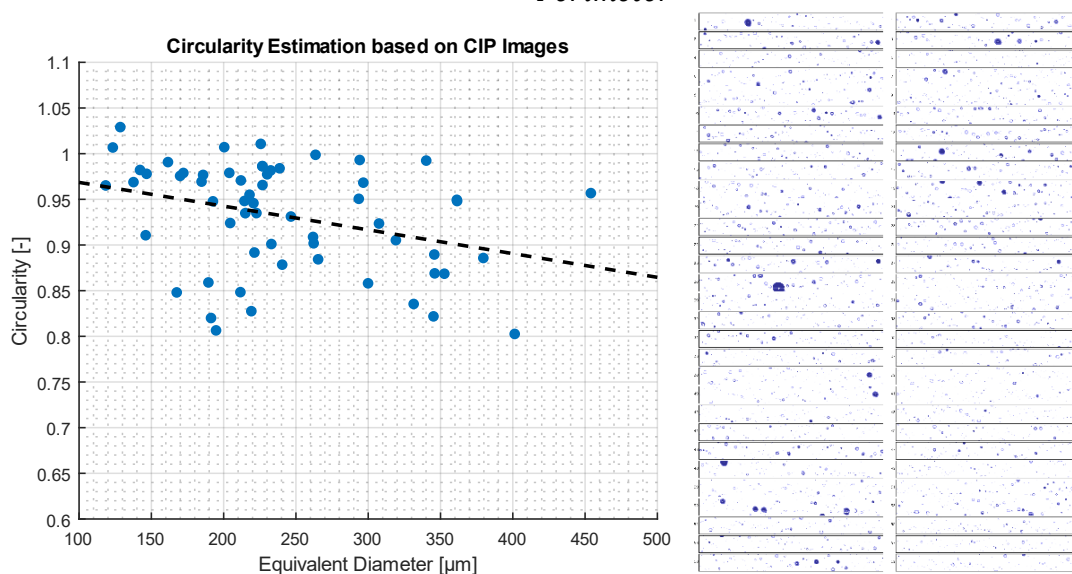


Figure 11: Circularity estimation based on CIP measurement results of FZDZ MVD > 40 μm in the RTA IWT

8 Facility Calibration

Following the ARP5905 [1] recommendation a facility should be in calibration when performing certification tests. The intent of the calibration is to establish a history on the repeatability of the facility with respect to relevant aero and icing related parameters over long periods, beginning from the date of commissioning. At first, a baseline calibration needs to be performed, assessing the capabilities of the facility and deriving the required correlations between the spray bar settings and the cloud parameters. The validity of this calibration then shall be checked periodically by means of check calibrations.

8.1 Baseline Calibration

The baseline calibration should be a full calibration of the facility and include aerothermal and icing cloud calibrations as defined in Section 9. Full calibrations are required on initial commissioning or following any major facility modifications that change the characteristics of the airflow or the icing cloud, such as replacement of the heat exchanger, test section, spray bar systems or other.

8.2 Interim Calibration

The interim calibration should be performed on an annual basis for the first two years following the baseline calibration resulting from initial commissioning or a major change to the facility in order to establish a history on repeatability.

The interim calibration should include, as a minimum:

- Confirmation that icing cloud uniformity has not changed from that established during the baseline calibration (use a representative number of uniformity plots at the airspeeds for which uniformity has been established)
- Confirmation of tunnel axial centreline LWC measurements.

The interim calibration should include a model-relative spanwise measurement of the total and static pressure and total temperature at the calibrated test section area over the range of airspeeds and temperatures at which the tunnel is operated. The interim calibration should also include confirmation of the MVD calibration, using a representative sampling from the baseline calibration. If the interim calibration indicates a shift in tunnel performance from the established baseline calibration by values greater than the values in Table 2 and Table 3, the facility operator should correct the problem(s) and repeat the interim calibration. If the out-of-tolerance condition still exists, then the full calibration is required to re-establish a baseline, after the operator has ensured system stability.

8.3 Check Calibration

Check calibrations should be performed periodically. When performing certification tests, the last check calibration should not be older than six months. The check calibration consists of measurements of icing cloud uniformity and centreline LWC measurements, over a representative sampling of uniformity and LWC measurements from the baseline calibration. If the check calibration indicates a shift in tunnel performance from the established baseline calibration with values greater than the values given in Table 3, the problem should be corrected, and the check calibration repeated. If the out-of-tolerance condition still exists, then the full calibration is required to re-establish a baseline, after the operator has ensured system stability.

8.4 Continuity Check

A model should be tested during, or before and after, the above calibration tests to assess changes or stability of the tunnel's ice/snow accretion characteristics. When commissioning a new facility, the test is used to establish reference ice shapes on an operator owned model. The selection and design of the model is left to the discretion of the tunnel operator. As well as Facility calibration procedure.

9 Calibration Procedures

The calibration procedures for any facility should be numbered, released, and maintained under company configuration (change) control procedures commonly accepted by the aerospace industry and the regulatory authorities.

The facility should perform an aero-thermal and icing cloud calibration per the time intervals defined in Section 8 to demonstrate that the facility, instrumentation, and procedures continue to produce acceptable data. The calibration should cover the area of the test section where tests are performed in the facility. The area for which the spatial aero-thermal and icing cloud requirements according to Table 2 and Table 3 are achieved, is considered to be the calibrated test section area.

9.1 Aero-Thermal

A dry air aero-thermal calibration should be conducted to determine the basic airflow qualities of the facility. The flow properties to be documented should be:

- Airspeed distribution
- Temperature distribution
- Turbulence intensity distribution
- Centreline Airspeed Correction
- Clean tunnel flow angularity distribution
- Altitude time history (for altitude test facility)

Each facility should develop a test matrix applicable for their intended operation range. The calibration matrix should, as a minimum, include:

- An aerodynamic calibration consisting of: centreline static and total pressure correction measurements, and velocity, flow angularity and turbulence measurements at ambient temperature as in [Table 4](#).
- A thermodynamic calibration consisting of temperature surveys at four temperatures spanning the range: 0°C to -30 °C (or the minimum operating temperature to be used for tests) as found in [Table 5](#).

Table 4: Minimum Test Matrix for Aerodynamic Calibration

Vertical Position (% of distance between centreline and WT wall)	Horizontal Position (% of distance between centreline and WT wall)	Spray Bar Air Pressure	Tunnel Static Air Temperature [°C]	Test Section Velocity (% of operating range)
0%, ±25%, ±50%, ±75%	0%, ±25%, ±50%, ±75%	Maximum	Ambient	0%, 33%, 67%, 100%

Table 5: Minimum Test Matrix for Thermodynamic Calibration

Vertical Position (% of distance between centreline and WT wall)	Horizontal Position (% of distance between centreline and WT wall)	Spray Bar Air Pressure	Tunnel Static Air Temperature [°C]	Test Section Velocity (% of operating range)
0%, ±25%, ±50%, ±75%	0%, ±25%, ±50%, ±75%	Zero, Maximum	4, -6, -18, -30	0%, 33%, 67%, 100%

9.2 Feasibility Study creating and transporting large droplets

Prior to performing extensive test campaigns in the wind tunnel, it is recommended to perform some preliminary investigations to check the feasibility of creating and transporting large droplets from the spray bar system to the test section for all of the available configurations. There are mainly four factors that could hinder a facility to create Appendix O clouds:

- Secondary droplet breakup
- Ballistic trajectories of large droplets that may concentrate on the lower portion of the reference area of the test section
- Droplet temperature (insufficient time for droplet cool down)
- Spray bar system capabilities

9.2.1 Secondary Droplet Breakup

The deformation and breakup of liquid particles in gas streams have been evaluated experimentally by multiple institutes [5]. The non-dimensional parameter characterizing the different breakup types is the so-called Weber number. It describes the ratio of the drag force to the cohesion force (see equation 2) and is mainly dependent on the initial droplet diameter and the relative airflow velocity between the gas and the droplets.

$$We = \frac{\text{Drag Force}}{\text{Cohesion Force}} = \left(\frac{8}{C_D} \right) \frac{\left(\frac{\rho v^2}{2} C_D \pi \frac{d^2}{4} \right)}{(\pi d \sigma)} = \frac{\rho v^2 d}{\sigma} \quad (2)$$

C_D ... drag coefficient

ρ ... density of the airflow

v ... relative flow velocity ($v_{air} - v_{droplet}$) slip velocity between the airstream and water droplet

d ... initial droplet diameter

σ ... surface tension

According to the Appendix O requirements, the maximum diameter for FZDZ droplets is 474 μm and 2229 μm for FZRA droplets. There are two regions with high relative airflow velocities, the first is right after the injection and the second one is in the contraction zone. In order to get the relative velocities after the injection, the exit velocity of the particles needs to be assessed, which could be done by means of high-speed video recording. The relative airspeed in the contraction zone mainly depends on the contraction ratio of the contraction nozzle, where high contraction ratios may trigger secondary breakup of the largest particles. The critical Weber number for when breakup starts to occur varies between 11-14 [19] and [20]. The Weber number can among be derived by means of Computational Fluid Dynamics (CFD) simulations, some codes have droplet breakup and deformation simulation capabilities included. An example of a Weber number investigation is shown in [Figure 12](#). The top left image shows the trajectory of a rain droplet from the spray bar system to the test section. On the Top right figure the speed of the airflow along the particle trajectory and the actual speed of the droplet is shown. In the bottom left image of [Figure 12](#) the relative velocities (between the airflow and the particle) are shown for the X and Y direction. In the bottom right the Weber Number along the trajectory is shown. The maximum Weber numbers occur right after the injection and in the contraction zone.

If the results show Weber numbers slightly exceeding the critical numbers of 11-14, the duration of how long the droplet is exposed to the high relative airspeeds also can determine whether breakup occurs or not. Very short durations might only lead to droplet deformation rather than breakup.

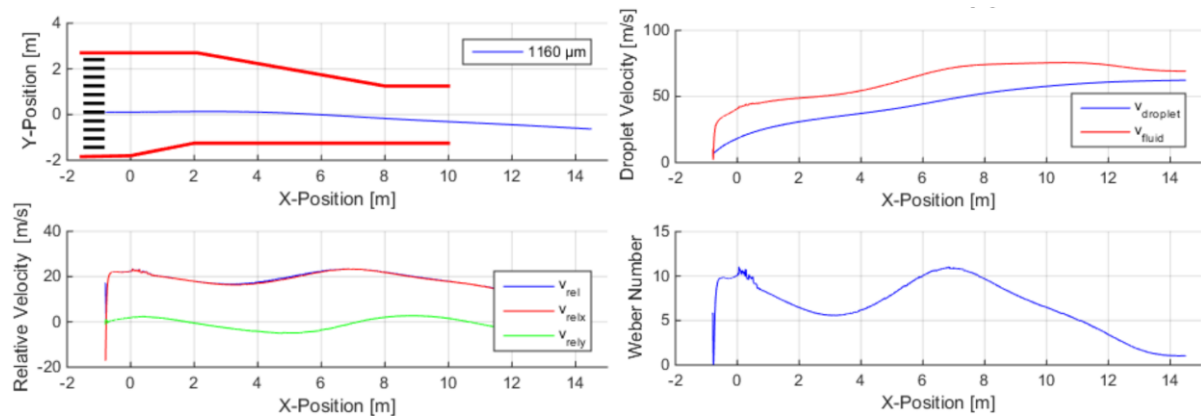


Figure 12: Example of secondary droplet breakup analysis at 80 m/s in the RTA IWT [6]

This method can be used to get an indication about the maximum possible droplet diameter and maximum achievable airspeed at which no secondary breakup is expected. The results of the simulations provide valuable information on whether it is worth to investigate a given configuration experimentally in the tunnel. Uncertainties in the simulation (flow solution, particle drag, Weber number, ...) need to be considered when evaluating the results. For this reason, an experimental investigation using an imaging probe located at different locations (e.g., at three stations) from the contraction nozzles exit to the center of the test section would be appropriate to find out how the shape and number of counts of the largest droplet diameter detected in the PSD, for certain spray bar set, may decrease at the expense of increasing concentrations in the smaller size bins due to the evolution of droplet breakup phenomena that may also be verified with raw imaging.

9.2.2 Particle Trajectories

Another important factor to consider, are the particle trajectories at given airspeeds. Depending on the spray bar system and the contraction nozzle design, the trajectories of large drizzle or rain particles might deviate substantially from Appendix C droplets. This can lead to a separation of differently sized droplets with larger particles only impinging in the lower region of the test section and therefore adversely affecting the MVD and LWC uniformity. A preliminary investigation of this effect, which is also dependent on the airspeed, can be performed by means of numerical simulations. The simulations should give an indication of favourable spray bar configurations (e.g. large particles are injected at higher spray bars) and the required minimum airspeed to transport the large particles to the test section.

The simulations might also reveal information about the relative droplet trajectory angle to the airflow and differences in droplet velocity and airspeed in the test section. Large deviations might limit the capability of simulating Appendix O clouds. Especially for rain droplets, the gravitational influence can be quite significant, but is also present in actual clouds to some extent, due to the terminal velocity of falling rain droplets. [Figure 12](#) (left) shows an example of the trajectories of large rain droplets. In [Figure 13](#), the potential effect of the airspeed on the particle trajectories is shown. Experimental results at the RTA IWT have shown a good agreement between the predicted and the actual impingement locations of SLD droplets [19].

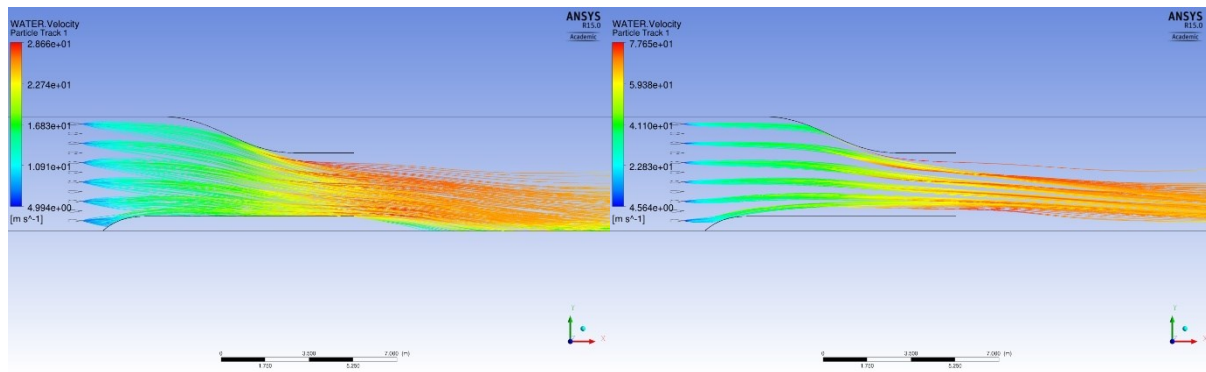


Figure 13: Example particle tracks at a test section airspeed of 30 m/s (left) and 80 m/s (right) at the RTA IWT

Example of Ansys-Fluent analysis applied on the CIRA-IWT test leg [21] with the spray bar configuration setting with two types of spray nozzles to generate bi-modal cloud condition at 110 m/s. A computational mesh with more than 12×10^6 of polyhedral cells has been developed to study the effect of modified spray bar parameters and spray nozzles layout on the main cloud properties in the test section (e.g., droplets' trajectories, droplets' temperature, droplet diameters distributions). This model is based on experimental measurements performed on the single spray nozzle at different conditions on the test rig. Figure 14 shows the study of the LWC homogeneity in the test section with two different spray bar configurations to improve the generation of the bi-modal PSD and other critical cloud parameters. Two steps cover the boundary conditions for this simulation: 1) simulation of airspeed and mass flow rate internally and at the nozzle exit for each type of the spray nozzle; 2) experimental measurements on the spray rig which provide information on the spray plume angle; droplet velocity component, droplet concentration. These information were used to modelling the water spray at the exit of the spray bar. Therefore it was reconstructed the spray condition at the exit of the spray bar considering the settling chamber conditions with the average airspeed and using the k-ε turbulence model during cloud transportation in the facility test leg.

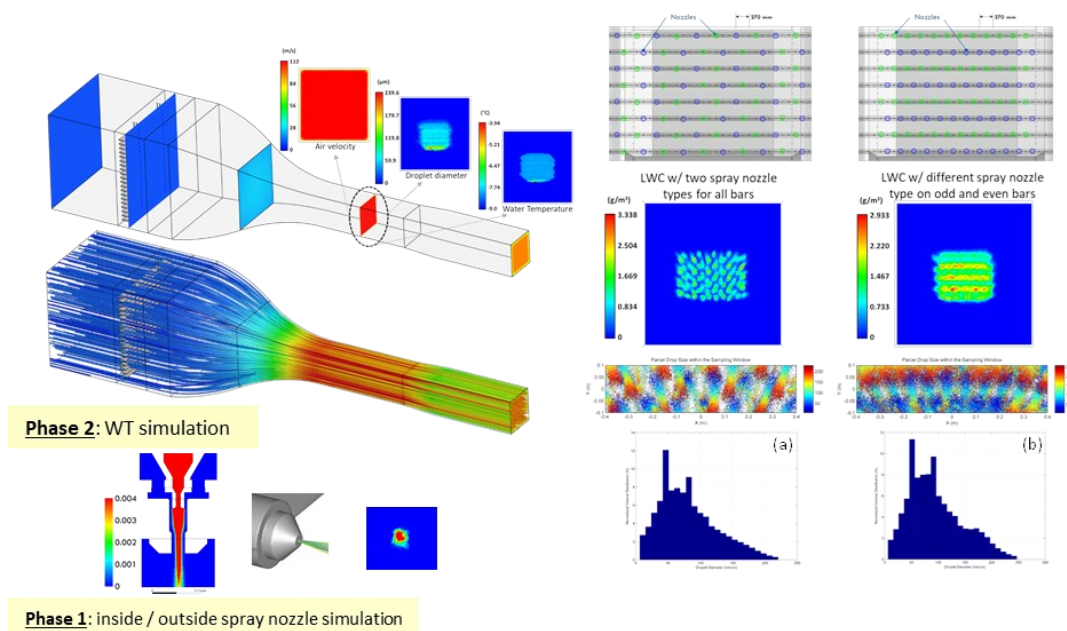


Figure 14: Study of the spray bar performance when equipped with two spray nozzle types. Simulation of the LWC homogeneity with indication of potential PSD (normalized volume distribution) modifications due to different spray nozzles pattern on the spray bar module: (a) The two spray nozzles alternate on each bar; (b) each bar has a different spray nozzle (the even bars are those that produce large drops, and the odd bars are those that produce small drops).

Experimental data have confirmed the behaviour of the simulated results, providing some indication for PSD shape (mono-modal or bi-modal) and cloud uniformity in function of the spray bar configuration in use. Thus, it highlighted the usefulness of the 3D model for the icing wind tunnel that may be useful to simulate any potential optimization solution for the spray bar system to improve the performance for SLD cloud conditions, limiting the facility cost only to the specific validation tests.

9.2.3 Droplet Temperature

Another aspect to consider in the experimental simulation of Appendix O condition is the temperature of the droplets when they reach the test section. Depending on the droplet diameter, the injection temperature and the flow conditions, a very long distance might be required to cool down the particles to ambient temperatures. For large drizzle and rain particles, an equilibrium might not be obtainable. Acceptable deviations currently are based solely on numerical predictions using ice accretion codes. In order to correctly represent the natural conditions, the droplets need to as close to the ambient conditions as possible when impinging on the test object. Increasing temperature differences between the droplet and the airflow are expected with increasing droplet diameters. The mass averaged temperature should be considered for the uncertainty requirements.

In order to estimate the required injection temperature to achieve sufficiently cold droplet temperatures (ideally $< 0^{\circ}\text{C}$), numerical simulation tools can again be exploited. While the complexity of the thermodynamic models varies significantly, a recommended model is described in [22]. [Figure 15](#) shows an example of the droplet temperature evolution for particles of different sizes along their trajectory.

From this investigation, further limits on possible droplet size and ambient temperature ranges can be estimated. Furthermore, the results can give valuable input for the spray bar system requirements in terms of the lowest required injection temperature.

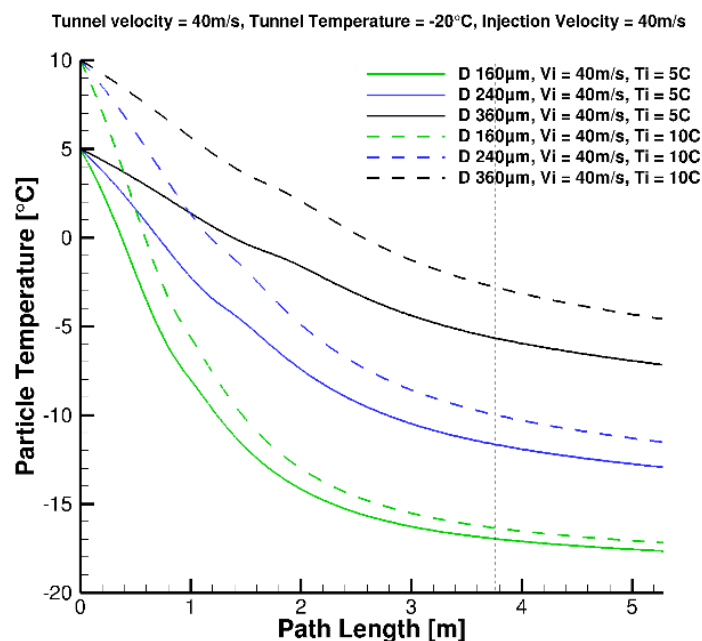


Figure 15: Droplet temperature for tunnel conditions 40m/s at -20°C

9.3 Spray Bar System Requirements

The preliminary investigations mentioned above should give a good indication about the suitability of a given wind tunnel configuration to simulate Appendix O icing clouds. However, the spray bar system itself needs also to fulfil certain requirements. One of the main differences between Appendix C and Appendix O conditions besides the different particle size ranges, is the fact that Appendix O clouds have bimodal droplet size distributions.

In order to match the required PSDs, it is necessary to inject two different modes simultaneously. This can be realized by setting different supply pressure to the same spray nozzle type or by using two different sets of spray nozzles. The selection of the most suitable spray nozzle depends on the condition (FZDZ in/out or FZRA in/out), and the required waterflow rate. The required waterflow rates depend on the number of nozzles used and the airspeed range and the cross section of the test section. For FZDZ with an MVD of larger than 40 μm for example, about 35% of the water is contained in the small mode and the remaining 65% in the large mode. The ratio is important in order to closely match the required PSD. The selection might be further complicated as the required waterflow rates can be very low. It is recommended to investigate the spray characteristics (spray plume, exit velocity, waterflow, PSD and MVD) of the candidate nozzles in a nozzle test rig before performing large scale tests in the IWT.

Furthermore, the spray nozzle arrangement (which and how many nozzles produce the small and which and how many nozzles produce the large mode) can have a significant effect on the overall generated LWC and PSD (and therefore the MVD) as well as the LWC and MVD uniformity in the test section. Setting up simulations to accurately predict the cloud uniformity is much more difficult, than estimating the trajectories of individual particles. This is mainly due to the difficulty of accurately capturing the stochastic dispersion of (mainly smaller) particles caused by flow turbulence. Besides, the required computational power is much higher as a complete 3D wind tunnel flow solution is needed.

In addition to the different requirements in spray nozzle pressures, the air and water temperatures supplied to the spray nozzles might also need to be very different for the small and the large mode. At colder ambient temperatures (e.g. -20°C) the small mode may require a preheated water and air supply in order to prevent freeze-out of the particles before they reach the test section whereas the large mode still needs a precooled water supply in order to guarantee supercooling of the large droplets. Spray bar systems developed for Appendix C clouds may lack some of these capabilities and need to be upgraded or modified to be suited for Appendix O conditions.

9.4 Icing Cloud Calibration Procedure

An icing cloud calibration should be conducted to determine the basic Appendix O icing cloud characteristics of the facility. For Appendix O conditions, more parameters need to be considered compared to the standard Appendix C clouds. A description of the recommended instrumentation required for defining the water droplet MVD, PSD, LWC, cloud uniformity, droplet temperature and droplet Circularity are in Section 7.

For altitude icing wind tunnels, one representative pressure altitudes (e.g., 6000 m) should be added in the test matrixes.

The first baseline calibration most likely is an iterative process going through PSD / MVD, LWC measurements and uniformity assessments, making adjustments to the settings and repeating this process.

The steps for the SLD cloud calibration follow the same recommendations according to the guidelines of ARP 5905 [1]. The instrumentations for cloud characterization will be the reference ones available in each facility, where the team's familiarity with their strengths and weaknesses will be updated with information on the uncertainty of each technique in use for PSD/MVD and LWC measurements. The lists of state of art instruments currently in use for cloud characterization are included in the reference [14] and [15].

9.4.1 Spray Nozzle Calibration

When a new set of spray nozzles is being installed, the original set of nozzles should be calibrated and selected based on a maximum deviation of 3 to 5% (discharge coefficient / waterflow rate). This nozzle configuration then shall be used to determine the cloud uniformity. Once the cloud uniformity has been established, replacement nozzles should have flow coefficients matching the original nozzles as close as possible (generally 1% or less). Section 8.2.1 of the ARP5905 [1] gives more detailed information of how the discharge coefficients for internal and external mixing spray nozzles can be determined.

9.4.2 PSD / MVD Calibration

Due to the bimodality of the droplet size distributions of for Appendix O conditions, solely measuring the MVD is not sufficient and the PSD for each setting needs also to be assessed. In terms of MVD, the aim should be to get as close as possible (within the stated uncertainty in [Table 3](#)) to the MVD values indicated in [Table 1](#). Droplet size measurements should be performed in the tunnel centreline over the full airspeed envelope to detect potential secondary droplet breakup or trajectory deviations.

Examples of FZDZ and FZRA measurements are shown in [Figure 16](#) and [Figure 17](#) respectively. For a qualitative assessment, the measured distributions can be directly compared with the Appendix O requirements by plotting the PSDs in a single figure. The PSD can also be evaluated by means of a “Q-Q plot”, where the measured cumulative distributions are compared to the cumulative distribution from the requirements. In [Figure 16](#) (right) and [Figure 17](#) (right) deviations within $\pm 10\%$ to the cumulative volume of the Appendix O distribution are indicated with a grey band. For the quantitative assessment, the coefficient of determination (R^2) can be determined by performing a linear regression of the measured cumulative distribution compared to the requirements. In regression, R^2 is a statistical measure of how well the regression predictions (the measured distributions) approximate the Appendix O distributions points. R^2 values between 0.95 and 1.00 indicate a good fit.

The MVD / PSD can either be calibrated for a fixed spray nozzle setting combinations or for a water- and air-pressure range of both small and large modes. Calibrating only fixed settings might be more accurate (as for each setting, PSDs measurement data is available), but limits the achievable range of conditions and offers less controllability. The LWC of the individual fixed settings might be dependent on the airspeed and cannot be directly controlled. This approach could be used, if the lowest possible spray nozzle pressure settings (lowest possible waterflow rates) which can produce the correct PSDs, still exceed the maximum LWC according to Appendix O requirements.

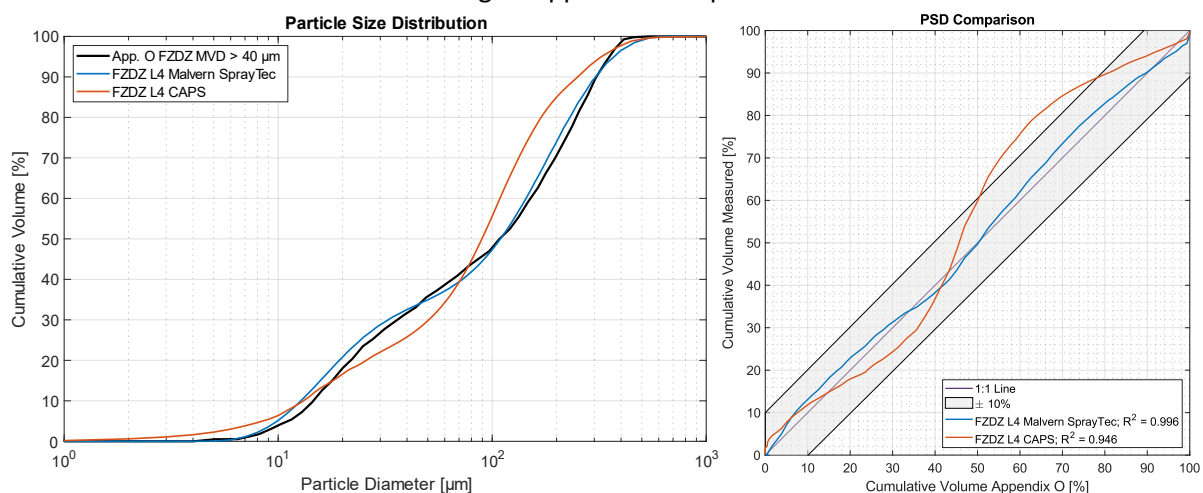


Figure 16: Example of measured FZDZ PSDs at the RTA IWT compared to Appendix O requirements, cumulative volume (left), q - q plot (right)

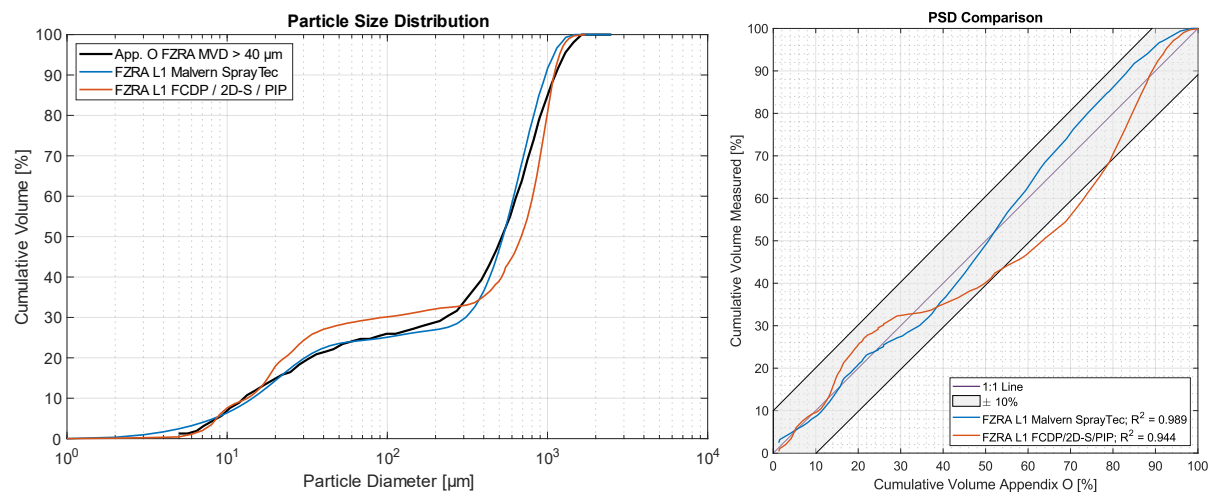


Figure 17: Example of measured FZRA PSDs at the RTA IWT compared to Appendix O requirements, cumulative volume (left), $q - q$ plot (right)

Calibrating for a range of spray nozzle settings requires more testing time, as small and large modes need to be investigated separately. A sufficient number of test points to derive viable MVD calibration curves for the two modes is required. Furthermore, a number of spray nozzle setting combinations need to be investigated to generate validation data.

One method to derive the combined MVD and PSD from MVD calibration curves of the small and large modes, is to assume appropriate Langmuir distributions and weight them with their respective LWCs as shown in Equation 3 (subscript “s” denotes the small mode, subscript “l” the large mode). In [Figure 18](#), a comparison of the calibrated and the measured MVD of FZDZ MVD > 40 μm using this method is shown.

$$MVD = MVD_s * \frac{LWC_s}{LWC_s + LWC_l} + MVD_l * \left(1 - \frac{LWC_s}{LWC_s + LWC_l}\right) \quad (3)$$

A similar approach is used to combine the two Langmuir distributions of the small and large mode into a bimodal distribution. [Figure 19](#) shows the resulting calibrated PSD compared to the measurement data. A quantitative analysis of how good the calibrated PSD matches the measurements can again be performed via a linear regression using the R^2 value. Agreements within ±10% and R^2 values of higher than 0.95 indicate a reasonable calibration model. In [Figure 20](#), the final calibrated PSD is compared to the Appendix O requirement again.

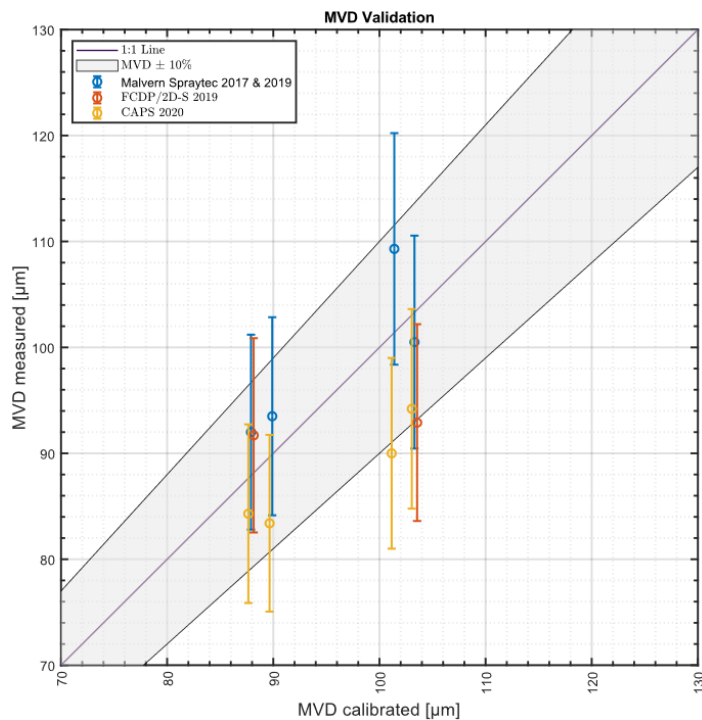


Figure 18: Comparison of calibrated and measured MVDs for all investigated FZDZ MVD > 40 μm settings at the RTA IWT

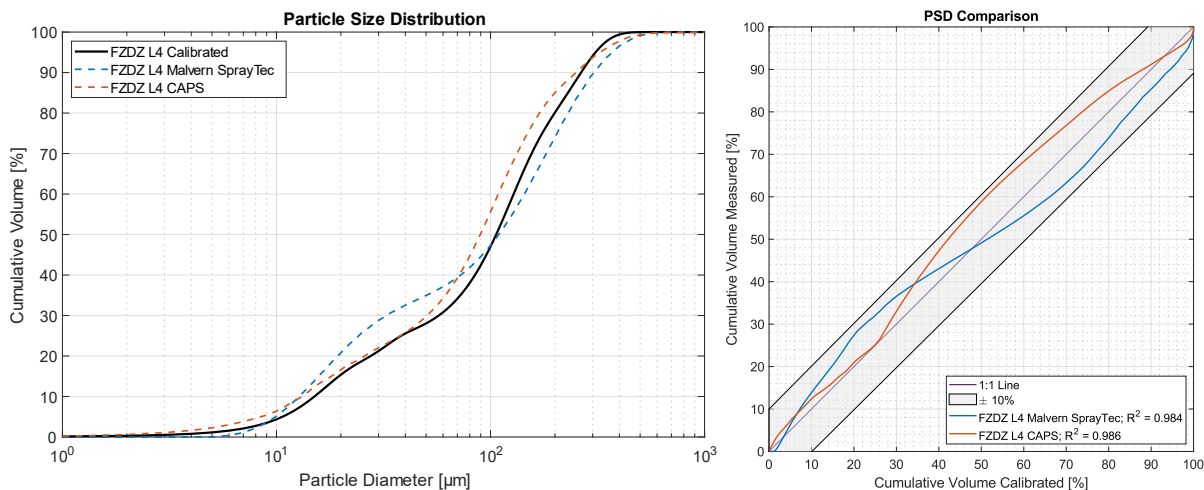


Figure 19: Example of measured and calibrated cumulative volume (left) at the RTA IWT, q - q plot of calibrated versus measured distribution (right)

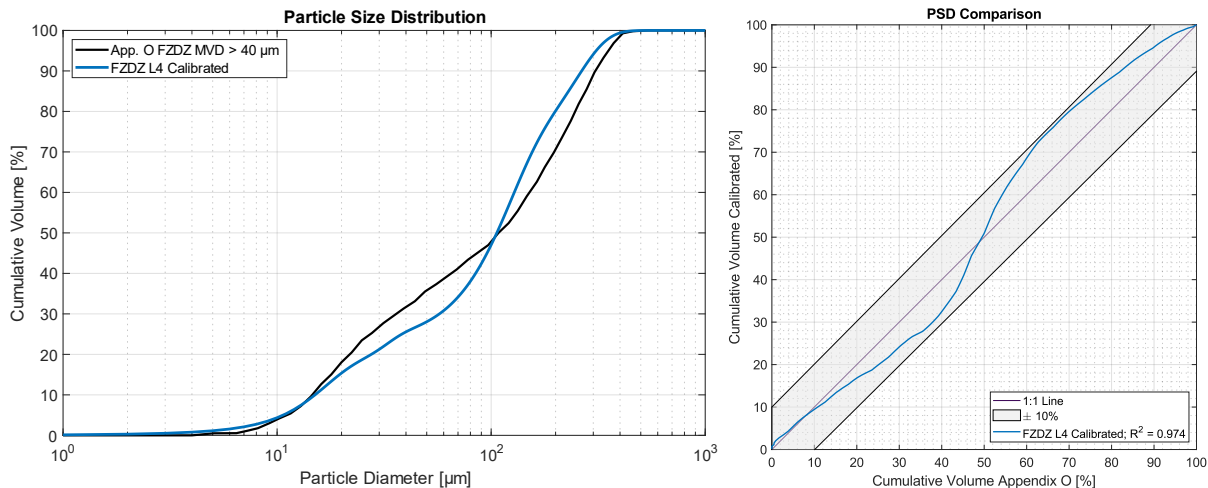


Figure 20: Example of calibrated PSD compared to Appendix O requirements (left), q - q plot(right)

9.4.3 LWC Calibration

The LWC calibration is closely linked to the MVD / PSD calibration and can also be performed either for fixed spray nozzle setting combinations or for a range of pressure settings. Calibrating for fixed nozzle settings makes sense when there are only a few settings available which produce the right PSD. The LWC is mainly dependent on the test section airspeed. Measurements over the full airspeed envelope for each spray bar setting should be performed. This approach offers higher accuracy but less controllability.

If the MVD / PSD calibration has shown that reasonable PSDs can be achieved over a range of spray nozzle pressures, the LWC also needs to be calibrated for this range. Individual measurements of the LWC at the tunnel centreline for the small and large modes are required to derive their respective calibration curves. Furthermore, LWC measurements of bimodal distributions should be performed to gather validation data. The effect of different test section airspeeds on the LWC also needs to be investigated as shifts in the particle trajectories or changes in the overall cloud uniformity could significantly influence the tunnel centreline LWC.

The total LWC of a certain spray nozzle pressure setting can then be derived by combining the calibrated LWC of the small and large modes, as shown in Equation 4. This approach offers higher controllability but might be less accurate and requires much more measurement data. In [Figure 21](#), a comparison between the measured LWCs of FZDZ MVD > 40 μm conditions using different instrumentation is shown.

$$LWC \left[\frac{g}{m^3} \right] = LWC_s \left[\frac{g}{m^3} \right] + LWC_l \left[\frac{g}{m^3} \right] \quad (4)$$

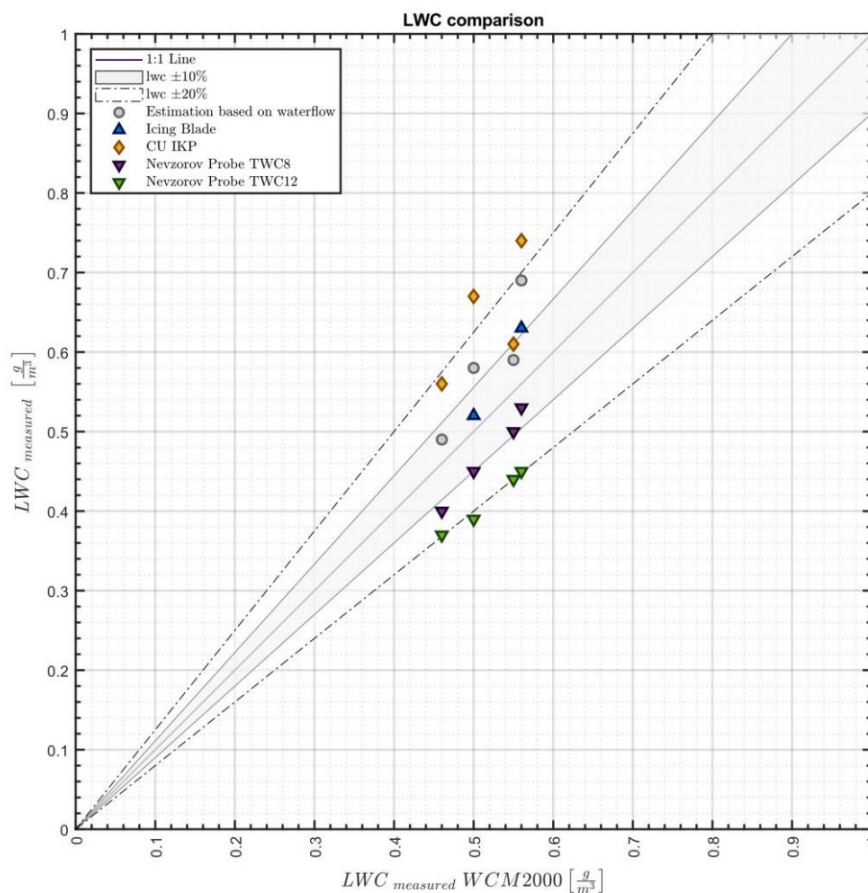


Figure 21: Comparison of measured liquid water contents for FZDZ MVD > 40 μm at the RTA IWT

9.4.4 Icing Cloud Size and Uniformity

The large droplets from Appendix O conditions are less affected by flow turbulence and, therefore, it is more difficult to achieve a homogeneous distribution. Furthermore, the gravitational influence on the large particles is much more effective, leading possibly to higher concentrations of the largest particles in the lower test section regions. Moreover, the effect of the wind tunnel contraction nozzle tends to increase the concentration of large droplets in the center of the test section when the wind tunnel contraction ratio becomes high (e.g., > 10). For that reason, not only the LWC but also the MVD uniformity needs to be investigated over the test section area. The measurements shall be performed setting the total air temperature (TAT) to a value that avoids the droplets' re-circulation around the tunnel that may influence the collected data for both LWC and PSD/MVD.

Once the MVD / PSD and the LWC of promising candidate settings have been measured, it is recommended to investigate the icing cloud size and uniformity before performing further extensive MVD and LWC calibration measurements. An ice accretion grid (at test section air temperatures of -18°C or colder) might be used for a first qualitative assessment of FZDZ clouds. The uniformity can also be investigated by exposing a simple test object, for example a NACA0012 wing section, to the Appendix O cloud. This method can also be used for FZRA conditions. It is recommended to investigate both rime and glaze ice conditions, as the leading edge and horn thicknesses, as well as the impingement limits, can provide valuable information about the overall LWC and MVD uniformities.

The final uniformity assessments should be performed by means of test section mappings (using a traversing system) with suitable instrumentation from Section 7. The resolution of the mapping should be as fine as possible and cover the main area of interest. It is recommended to maintain at least 2 minutes at each position, to get enough data for a sensible average. [Figure 22](#) shows the minimum resolution to be used for the uniformity assessments. Due to the long time durations of a full test section mapping, ice accretion forming on the traversing system could become an issue. The measurements therefore might be performed at test section temperatures just above 0°C , if it can be shown that this does not significantly affect the spray characteristics.

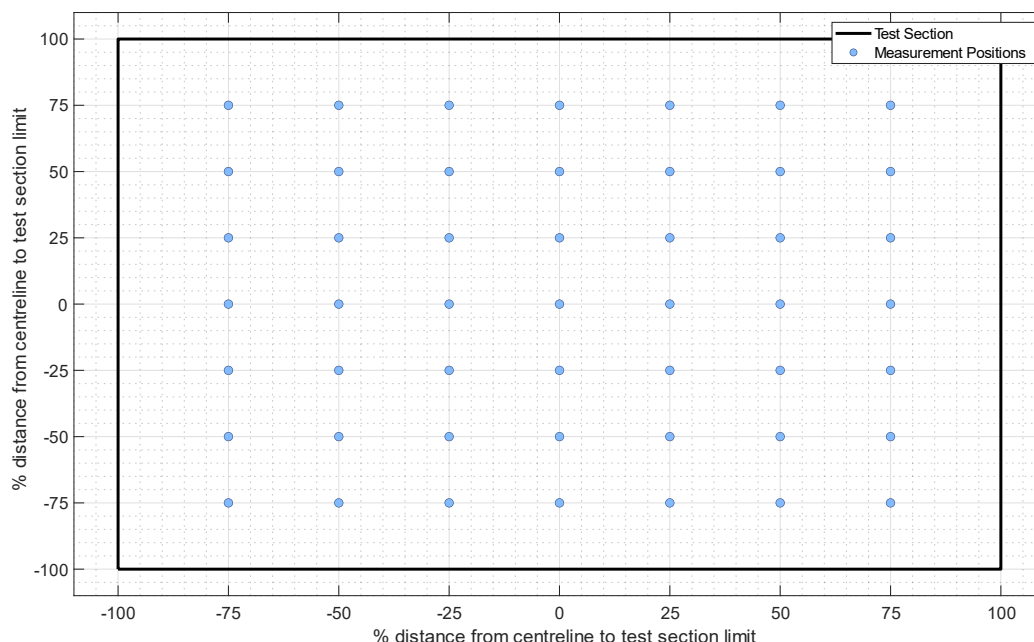


Figure 22: Example measurement positions for LWC / MVD uniformity investigations

LWC and MVD mappings should be performed at different airspeeds, including the minimum and maximum aimed to achieve calibration for. Furthermore, it is recommended to perform measurements with only the small or large mode active as well as measurements for full bimodal distributions to better understand the distribution of the large droplets. For the final cloud uniformity assessment only the full droplet spectra is relevant. [Figure 23](#) shows an example of the LWC uniformity

for a bimodal FZDZ MVD > 40 μm condition, where the relative LWC compared to the measurement in the test section centre is indicated. In [Figure 24](#), the MVD uniformity in the same condition is shown, indicating the relative deviations compared to the measurement in the test section centre.

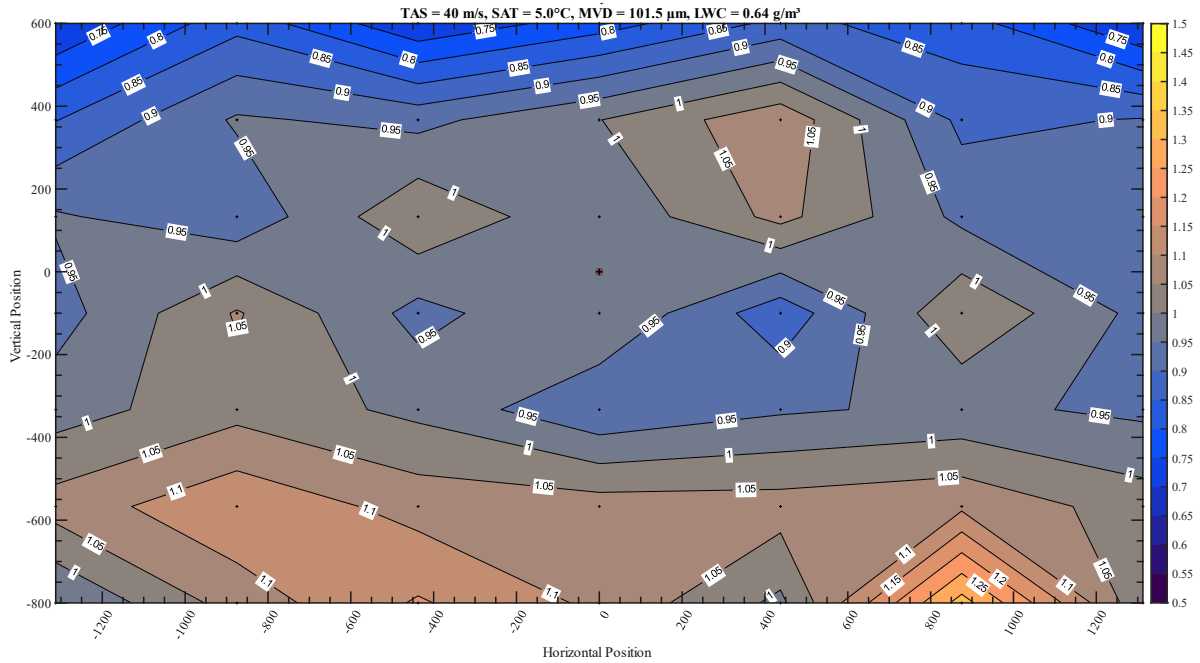


Figure 23: Example of LWC uniformity for bimodal FZDZ MVD > 40 μm conditions at RTA IWT

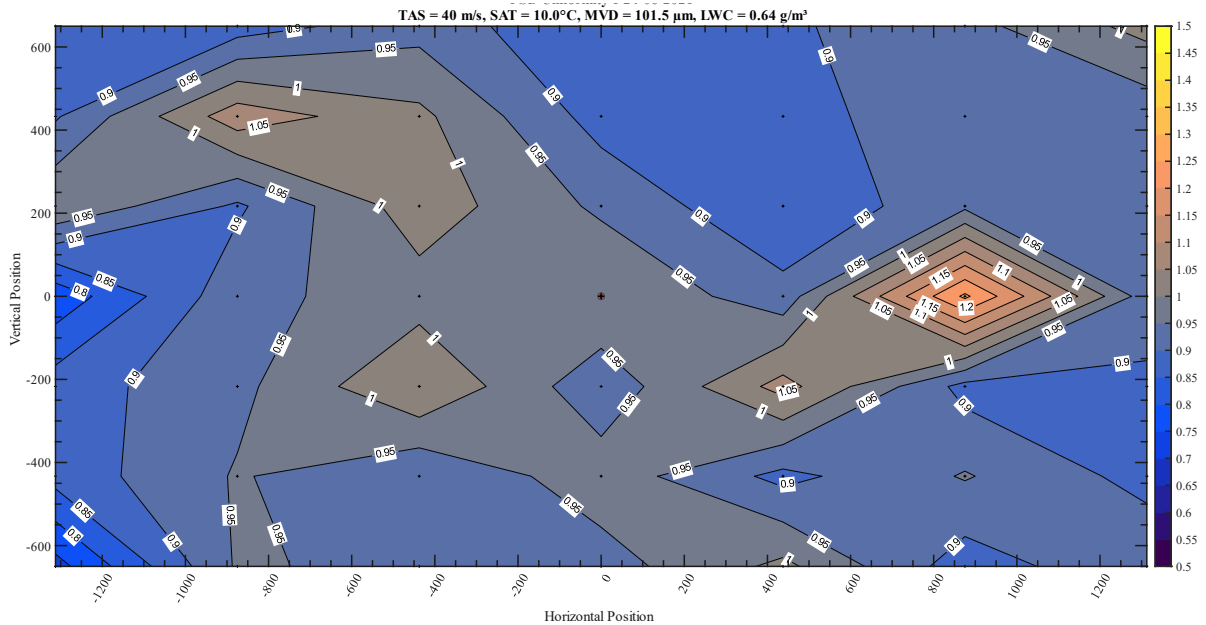


Figure 24: Example of MVD uniformity for bimodal FZDZ MVD > 40 μm conditions at RTA IWT

9.4.5 Droplet Temperature Validation

Droplet temperature measurements should be foreseen at least for the worst-case conditions (warmest test section air temperature, at which supercooled droplets can still be achieved) in the test section centre. The spray bar supply temperatures should be set to the same temperatures used for actual testing and, ideally, also measured as close as possible to the spray nozzle outlet. If possible, only the large mode should be active, to reduce any noise from the small particles in the measurement. The measurements for the selected conditions should be repeated for a minimum of three SATs (e.g., -5°C, -10°C, and -20°C) to assess water droplet temperature deviation from the test section air temperature (STS). These measurements should help to check if the SBS water temperature has appropriately been set to reduce the gap between the air and droplet temperatures in the test section, in compliance with the requirements from [Table 3](#).

The measurement results should then be used to validate numerical droplet temperature simulations. If a good agreement can be achieved, simulations can be used to further assess the temperature at different conditions.

9.4.6 Ice-shape to collect on representative test model

To assess the overall results of facility cloud calibration a reduced amount of ice accretion tests on the facility's calibration model (e.g., 2D wing with NACA0012 aerofoil or 3D wing model) should be performed at the end of the cloud calibration process. For the same test cases, there will be a way to check the deviation between the LWCs measured for e.g. with hot-wire during the calibration with those derived from ice accretion on the test model in rime ice conditions. Moreover, additional information (e.g., cloud uniformity checks with icing shapes tracing in different sections, collection efficiency, freezing fraction, ...) may be collected to contribute to the building up of the facility database, which can be used for comparison purposes with future calibration data, as well as for CFD codes validation.

10 Acceptance Criteria

The acceptance criteria are basically identical to the criteria for Appendix C clouds from the ARP5905 [1] but with the variables and quantities defined in Section 6, [Table 2](#) and [Table 3](#) of this document.

10.1 Aerodynamic

The aerodynamic performance characteristics should be applied only within the selected test volume. If the tunnel calibration shows that the aerodynamic performance meets the spatial uniformity requirements shown for the Aerodynamic Parameters in [Table 2](#), then the tunnel should be deemed acceptable for icing tests.

10.2 Icing Cloud

The calibration should cover the area of the test section where the LWC spatial uniformity defined in [Table 3](#) is met. This area may vary from condition to condition. Temporal stability of the LWC and droplet MVD values may be inferred from the controlled spray bar parameters or measured in situ during testing. The acceptable area for icing testing should be restricted to the area of the icing uniform cloud as defined in Section 0. If the icing calibration demonstrates that the conditions of spatial uniformity and temporal stability in the icing cloud parameters from [Table 3](#) are met, then the tunnel should be deemed acceptable for icing performance.

11 Calibration Report

A final report should be prepared and be available after each calibration (full, interim, and check) consistent with the requirements of Section 8 that defines the techniques used and should contain as a minimum the data required in Section 10. The report should contain photographs of test setup, a list of instrumentation, and test results. The intent of the final test report is to provide guidance to the user with regard to the calibration process and results.

11.1 Aerodynamic Calibration:

The aerodynamic calibration is the same as for Appendix C conditions provided in the ARP5905 [1] and is not further explained here.

Graphical presentation of the measurements taken for:

- a) Static and total pressure correction
- b) Velocity distributions and flow angularity
- c) Turbulence intensity
- d) Temperature distribution

11.2 Icing Cloud Calibration:

Graphical presentations of the measurements taken for:

- a) PSD and MVD calibration for each nozzle configuration defined in Section 9.4.2.
- b) LWC calibration defined in Section 9.4.3
- c) Icing cloud size and uniformity defined in Section 9.4.4
- d) Droplet temperature validation defined in Section 0

The facility operator should maintain a record that indicates the quality of the engineering data used to generate plots described above.

11.3 Test Facility Qualification Statement

If results from testing are to be used for acceptance of the facility, the data generated in the facility will be submitted to a regulatory/certifying agency for certification credit, the facility operator should include a statement that all testing and calibration have been performed in accordance with these recommended practices and found to be in accordance with the acceptance criteria defined in Section 10.

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