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1 Glossary

Abbreviation / Acronym	Description/meaning
ADA	Airborne Droplet Analyser
AMC	Acceptable Means of Compliance
CAS	Cloud, Aerosol, and Precipitation Spectrometer
ATF	Altitude Test Facility
CCD	Charge Coupled Device (Camera)
CIP	Cloud Imaging Probe
CS25	Certification Specification
FAR25/29/33	Federal Aviation Regulations
FCDP	Fast Cloud Droplet Probe
FSSP	Forward Scattering Spectrometer Probe
F/T	Flight Test
FZDZ	Freezing Drizzle
FZRA	Freezing Rain
GTF	Geared TurboFan
HVPS	High Volume Precipitation Spectrometer
IPHWG	Ice Protection Harmonization Working Group
ICD	Ice Crystals Detector
IWT	Icing Wind Tunnel
LWC	Liquid Water Content [g/m ³]
MOC	Means of Compliance
PDPA	Phase Doppler Particle Analyzer
PDI	Phase Doppler Interferometry
PIP	Precipitation Imaging Probe
PSD	Particle Size Distribution
SLD	Supercooled Large Droplets
TRL	Technology Readiness Level
TWC	Total Water Content [g/m ³]
WP	Work Package
W/T	Wind tunnel
CAS	Cloud, Aerosol, and Precipitation Spectrometer
ATF	Altitude Test Facility
CCD	Charge Coupled Device (Camera)
CIP	Cloud Imaging Probe

FCDP	Fast Cloud Droplet Probe
FSSP	Forward Scattering Spectrometer Probe
FZDZ	Freezing Drizzle
FZRA	Freezing Rain
HVPS	High Volume Precipitation Spectrometer

2 Executive Summary

This document D3.1 ‘Definition of the target requirements for test facilities operating envelopes for App O’ provides a definition of the requirements for W/Ts tests extracted from FAR/CS-25 Appendix O.

An overview of W/T capability to produce SLD conditions are also described together to the methodologies used for cloud measurements during their calibration process. With the contribution of Manufacturers have been defined the icing conditions and the A/C operating envelopes useful to support design validation and certification process under Appendix O conditions.

The operating envelope of W/T together with the available instrumentation characteristics to use for clouds measurements are shown with the aim to identify potential gaps fix within the WP4 activities.

3 Introduction

This document D3.1 “Definition of the target requirements for test facilities operating envelopes for App O” provides to the ICE GENESIS W/Ts partners, the requirements of operation envelope and relevant parameters to be investigated to support design validation and certification in App. O conditions.

To define the W/T operation envelopes following contributions are considered:

- Appendix O priorities coming from aircrafts’ Manufacturers where ice conditions for different aircrafts’ categories are defined to support their design validation and certification
- The improvements of W/T envelopes (WP6) arising from current gaps to generate cloud conditions in compliance with what is expected from A/C certification requirements defined by Appendix O criteria for the Freezing Drizzle conditions.
- From instrumentation expertise (WP4) to define a set of instruments more appropriate for the W/T calibration under Appendix O conditions

The Freezing Rain cloud envelope foresaw by Appendix O is out from the scope of this project where only the potentiality to generate such conditions will be analysed. This is due to the difficulties to achieve thermal-kinetic equilibrium with freestream conditions for the droplets with large diameters (> 500 µm) in the conventional horizontal icing wind tunnel. In this program, the feasibility to overcome such limitations will be verified, with the availability of a small vertical icing wind tunnels (e.g. TsAGI vertical icing wind tunnels).

Besides the needs and the requirements to achieve for test facilities operating envelopes, will be also defined as a target requirements to achieve, the minimum performance characteristics of main aero-clouds parameters.

In general, this deliverable D3.1 is part of the following WP3's achievements:

- Requirements for test capability needed for SLD and snow
- Specifications and plans for experimental tests in liquid conditions and snow
- Review of existing experimental data and icing models for liquid icing and snow conditions to support basic experimental activity and modelling activity in WP9 and WP10.

4 Icing environments defined in Appendix O of 14 CFR Part 25 to reproduce in W/Ts

The specific object of this section is to provide a brief summary of the requirements defined by Appendix O of EASA CS-25 (FAA 14 CFR Part 25 rules [1]) requiring to demonstrate that the airplane or its equipment will safely operate after encountering any of the defined environmental conditions. At this end, the Means of Compliances (MoC) must be updated to support the certification process which includes Supercooled Large Drop (SLD) with a higher droplet diameter sizes, bimodal mass distributions (mass 'peaks' for two different drop sizes), and a lower Liquid Water Content (LWC) than the values defined by Appendix C.

4.1 A brief definition of Appendix O features

The Appendix O defines SLD icing conditions in which the drop median volume diameter (MVD) is less than or greater than $40\ \mu\text{m}$ that corresponds to the maximum mean effective drop diameter (MED) of 14 CFR 25, Appendix C continuous maximum (Stratiform Clouds) icing conditions. For Appendix O, SLD icing conditions consist of Freezing Drizzle (FZDZ) and Freezing Rain (FZRA). Besides the parameters that characterize the Appendix C such as altitude, vertical and horizontal extent, ambient temperature, and liquid water content, the SLD conditions are also defined on the base of droplets mass distributions. Figures 1 show Appendix O envelopes in function of these parameters for FZDZ.

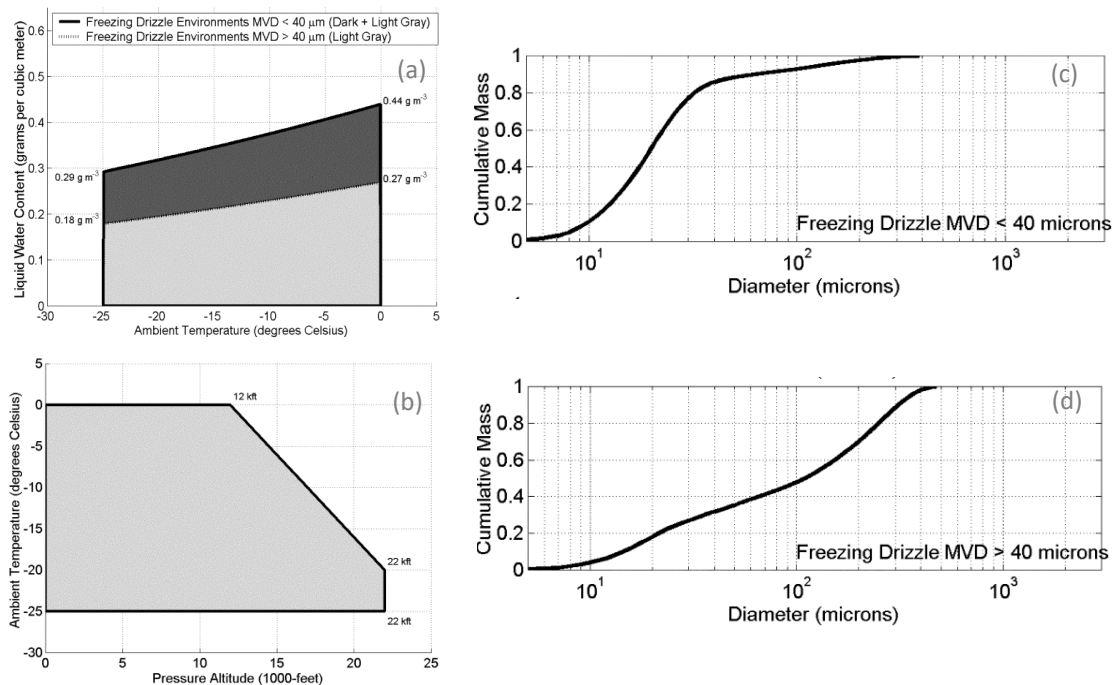


Figure 1: Appendix O: Freezing drizzle envelopes with MVD less than or greater than $40\ \mu\text{m}$.

Figure 1a shows the variation of LWC with respect to the ambient air temperature. The LWC behaviour indicate a steady decrease in maximum LWC with decreasing the temperature below $0\ ^\circ\text{C}$ for both FZDZ less than or greater than $40\ \mu\text{m}$. For each ambient temperature, the maximum LWC is well below the ones corresponding to the Appendix C. The pressure altitude ranges from 0 to 6,600 m (figure 1b). The Appendix O also provided an indication of the cumulative mass distributions, as fraction of the droplet diameter, for the two sub-cases with MVD < $40\ \mu\text{m}$ or MVD > $40\ \mu\text{m}$ (figures 1c and 1d).

Figure 2 shows the variation of the same parameters for FZRA. The maximum LWC (figure 2a) still keep the same steady decrease but in reduced range of ambient temperature. The temperature range

extends down to only -12 °C, over which there is no presence of maximum LWC. The temperature vs. altitude envelope for FZRA (figure 2b) faithfully reflects the behaviour for these conditions typically found at lower pressure altitude. These are conditions of precipitation within or below stratiform clouds [2]. Beyond to the warmest ambient temperature and lowest LWC, also for FZRA either the subsets shows cumulative mass distributions with bi-modal behaviour but with the maximum diameter larger than the FZDZ's cases (figures 2c and 2d).

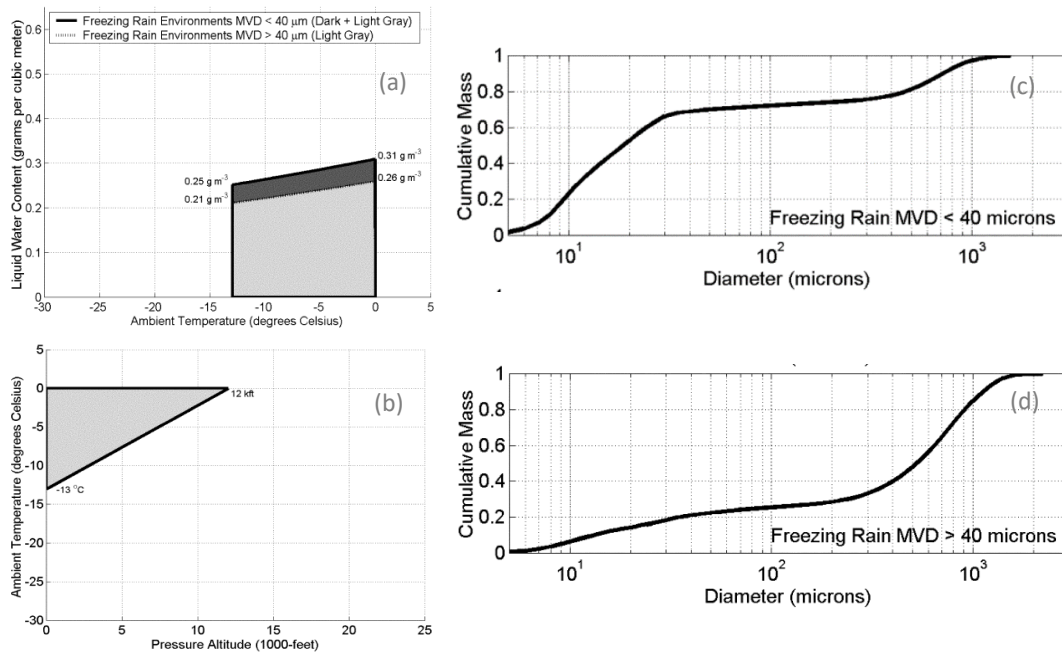


Figure 2: Appendix O: Freezing rain envelopes with MVD less than or greater than 40 μm.

The LWC represented in both the figure 1a and 2a, are valid only for reference distances of 32.2 km. Figure 3 shows the scale factor to derive the LWC in both FZDZ and FZRA conditions when exposure distance (W/T exposure time) exceed the reference distance of 32.2 km.

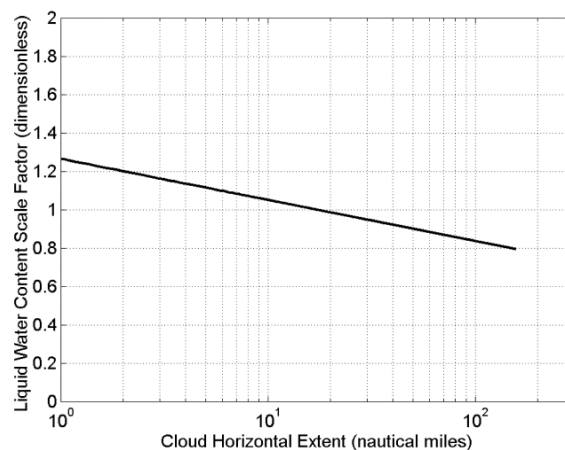


Figure 3: Appendix O, cloud horizontal extent, Freezing Drizzle and Freezing Rain

4.2 Targets of SLD conditions to reproduce in W/T

On the base of the Appendix O requirements, on below are described the most Critical Target (CT) to achieve for Freezing Drizzle conditions within the project at the end of the W/Ts improvements activities foreseen in the WP6 (SLD Capabilities).

The Freezing Rain represents a second priority of the project which target will be to study the feasibility in order to define the limits of the parameters showed in figure 2 for wind tunnel application with an acceptable level of confidence for an:

- thermal equilibrium between the large droplets and airstream temperature
- reduced effect of the mass inertia on droplets' trajectories in the test section

CT#1 – Liquid Water Content

Currently mostly of W/Ts are able to generate LWC close to the maximum values represented in figure 1a for Freezing Drizzle with MVD <math>< 40 \mu\text{m}</math> (FZDZ_In) . Maximum liquid water content reported for Freezing Drizzle with MVD >math>40 \mu\text{m}</math> (FZDZ_Out) represents the critical conditions to generate in W/T due to the range of values to achieve in test section for this environment (below the threshold range of 0.18 – 0.27 g m⁻³). The SAE AIR6341 on “SLD capabilities of icing wind tunnels” is still in the revision stage and as issued will provide an updated reference on the wind tunnels performance.

CT#2 – Ambient Temperature

Achieve the droplets' thermal equilibrium with airstream in the test section at warmest ambient temperature (0 °C) for both subset of conditions (FZDZ_In and FZDZ_out).

CT#3 – Drop Diameter Distribution

For each subset of Appendix O, all drop spectra concentrations were average together to derive a single droplet spectrum considered representative of the Appendix O subset [3]. Plots in figures 1c, 1d and figure 2c, 2d are derived from the average of several spectra measured for each subset defined for FZDZ and FZRZ. The plots in figure 4 and 5 shows the average cumulative mass spectrum (black curves) for each subset of Appendix O compared to each individual spectrum used in the average.

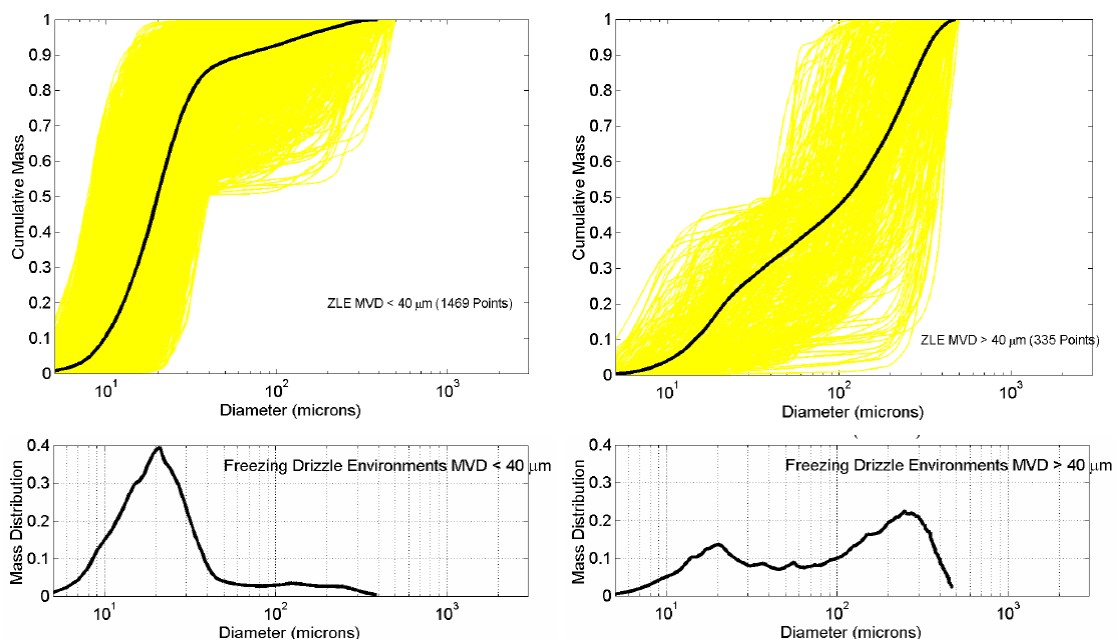


Figure 4: Average cumulative mass spectrum for FZDZ, compared to each individual cumulative Mass Spectrum, and normalized mass distribution for Freezing Drizzle Spectra [2]

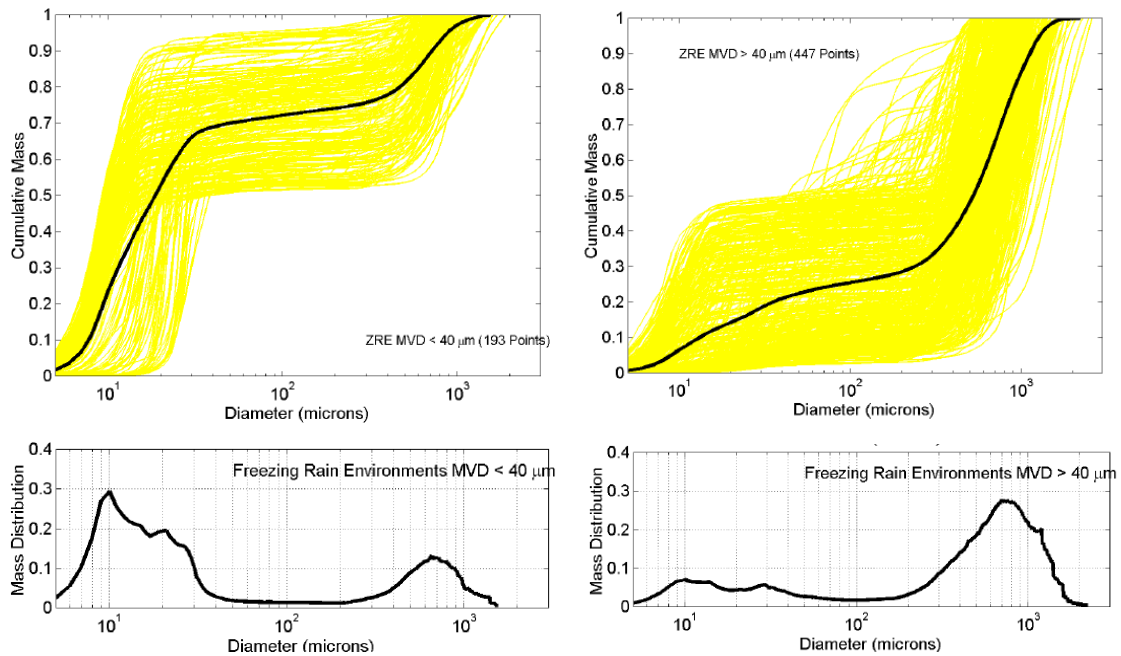


Figure 5: Average cumulative mass spectrum for FZRA, compared to each individual cumulative Mass Spectrum, and normalized mass distribution for Freezing Rain Spectra [2]

For practical and realistic indication on how to reproduce natural SLD cloud environments in compliance with Appendix O, it is common the application of Droplet Size Distributions (DSDs) in form of bin tabulation of the proportions mass (LWC) relative to droplet size [2] as shown below:

		ZLE (MVD < 40 μm)			ZLE (MVD > 40 μm)		
(a)		(b)		(b)			
	Proportion of Mass	Left Boundary Point (μm)	Mass-weighted Midpoint (μm)	Right Boundary Point (μm)	Left Boundary Point (μm)	Mass-weighted Midpoint (μm)	Right Boundary Point (μm)
Bin 1	0.100	1	9	10	1	11	15
2	0.200	10	13	16	15	22	36
3	0.200	16	18	20	36	66	110
4	0.200	20	23	27	110	155	202
5	0.100	27	29	33	202	227	252
6	0.050	33	35	39	252	266	280
7	0.050	39	46	64	280	296	313
8	0.050	64	96	138	313	333	357
9	0.025	138	166	205	357	373	392
10	0.025	205	254	389	392	419	474

Figure 6: Freezing drizzle distribution

	(a)	ZRE (MVD < 40 μm)			ZRE (MVD > 40 μm)		
		Left Boundary Point	Mass-weighted Midpoint	Right Boundary Point	Left Boundary Point	Mass-weighted Midpoint	Right Boundary Point
Bin	Proportion of Mass	(μm)	(μm)	(μm)	(μm)	(μm)	(μm)
1	0.100	1	7	8	1	9	14
2	0.200	8	10	12	14	36	239
3	0.200	12	15	19	239	400	526
4	0.200	19	25	51	526	645	766
5	0.100	51	263	470	766	834	912
6	0.050	470	535	595	912	957	1008
7	0.050	595	655	718	1008	1066	1130
8	0.050	718	792	883	1130	1198	1289
9	0.025	883	942	1035	1289	1346	1421
10	0.025	1045	1191	1553	1421	1546	2229

Figure 7: Freezing rain distribution

This type of representation (figures 6&7) are typically used as input to ice accretion computer codes. For the W/Ts application, the bin tabulation approach could be limited representing by only a single cumulative mass curve for each subset of Appendix O.

From a sensitivity study performed, it was found that the average spectra shapes are quite sensitive to MVD and D_{max} , and relatively insensitive to LWC [3]. In W/T the droplet number concentration for large droplets may range as function of air-water pressure ratio of the spray nozzles that may generate different spectra shapes for each subset. The critical target is to derive characteristic drop spectra for Freezing Drizzle showed in the first two rows of table 1 [3] representing the MVD and D_{max} range to achieve [1].

Definition	MVD range	D_{max} range	MVD (50% VD)	D_{max} (99.9% VD)
FZDZ_In	< 40 μm	100 – 500 μm	20 μm	389 μm
FZDZ_Out	> 40 μm	100 – 500 μm	110 μm	474 μm
FZRA_In	< 40 μm	> 500 μm	19 μm	1553 μm
FZRA_Out	> 40 μm	> 500 μm	526 μm	2229 μm

Table 1: The MVD for Appendix O conditions [3]

Data of this table have been extracted from droplet spectrum collected in natural clouds that have been truncated at the 99.9% of volume diameter (VD). The maximum diameter (D_{max}) showed corresponds to 99.9% of VD. The second and third columns represents the ranges of each defined subset while the last two columns are the values achieved for each average cumulative mass spectrum [2].

In consideration of the thresholds defined with the average cumulative mass spectrum for the two FZDZ subsets, the droplet spectra shape produced by W/T may change within the boundary indicated by these threshold curves (FZDZ_In and FZDZ_Out). The sketch in figure 8 shows the expected variations of cumulative mass spectrum produced in the W/T with respect to D_{max} (99.9% VD) ranging from 100 μm to 500 μm and the corresponding MVD (50% VD) which ranges from 20 μm to 110 μm of FZDZ environment.

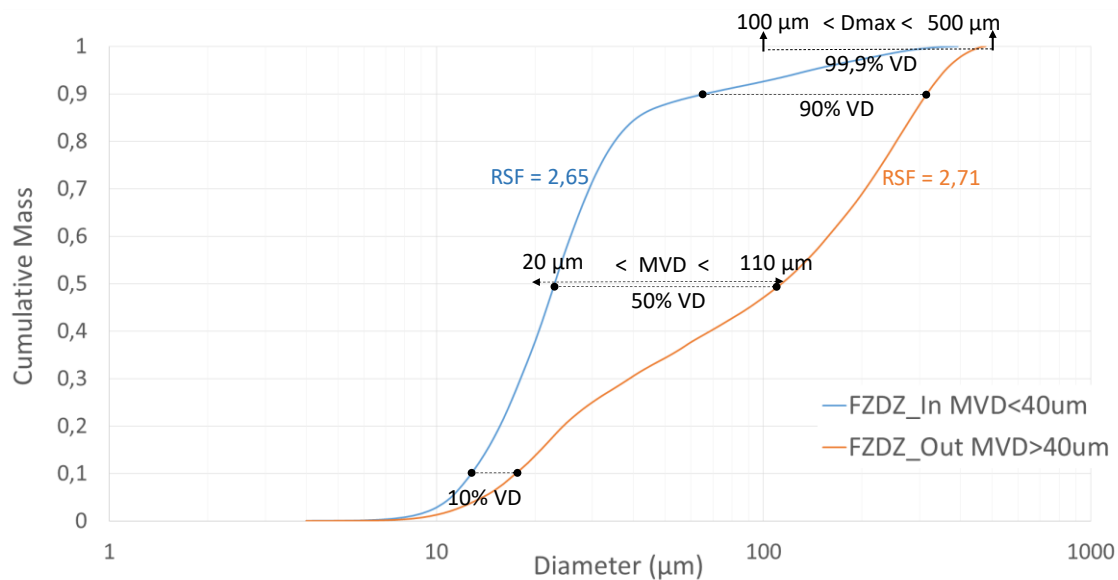


Figure 8: Average cumulative mass spectrum for both the Freezing Drizzle envelopes with the indication of expected D_{max} and MVD range to reproduce in W/Ts.

With the introduction of the dimensionless parameter [4] Relative Span Factor (RSF), it is possible to compare the uniformity between the artificial clouds produced in W/T with those represented by natural clouds size distribution. This parameter, defined by:

$$RSF = \frac{90\%VD - 10\%VD}{50\%VD}$$

provides a direct indication of the range for the droplet sizes relative to MVD (50% VD). Figure 8 indicates the RSF achieved for each average cumulative mass spectrum considered for FZDZ. It is evident that as the RSF increases, the normalized mass distributions show a more evident bi-modal characteristic as illustrated in figure 4 for the FZDZ_Out. A change of RSF is more marked for FZRA since the deviation relative to MVD is more amplified for the FZRA_In (RSF=37.4) with respect to the FZRA_Out (RSF=2.1) showing an attenuation on bimodality of normalized mass distribution (Figure 5).

The W/Ts targets to achieve for the SLD conditions are summarised in table 2 for both aero-thermal and cloud parameters in the same spirit of SAE ARP 5905 “Aerospace Recommended Practice – Calibration and Acceptance of Icing Wind Tunnels” [5] defined for Appendix C.

The criteria on which the W/Ts will be calibrated will be defined in WP6 (T6.1) through deliverable D6.1 “Proposal of calibration instruments and procedures for FZDZ”. In table 2 are defined the range of performance characteristics for airflow and cloud parameters to achieve over the area of uniform icing cloud. Compared to ref. [5], the uniform icing cloud is defined as the “*area of the test section over which the LWC does not vary by more than ± 20 percent from the test section centreline LWC value for a given airspeed and water droplet size*”.

Parameters	Instrumentation Accuracy/Uncertainty	W/T C _L Temporal stability	Spatial Uniformity	Limit
Aerodynamic				
Airspeed	± 1%	± 2%	± 2%	
Static Air Temperature SAT < -30 °C	± 2 °C	± 2 °C	± 2 °C	
Static Air Temperature -30 °C < SAT < +5 °C	± 0.5 °C	± 0.5 °C	± 1 °C	
Flow Angularity	± 0.25 deg	N/A	± 2 deg	± 3 deg
Flow Turbulence (Pair - Off)	± 0.25%	± 2%	< 2%	< 2%
Flow Turbulence (Pair - On)	± 0.25%	± 2%	< 2%	< 5%
Pressure Altitude	± 50 m	± 50 m	N/A	N/A
Cloud Uniformity				
Liquid Water Content	± 10%	± 20%	± 20%	N/A
Median Volumetric Diameter	± 10%	± 20%	± 20%	
Drop trajectory relative to the flow +/- %	± 10%	± 20%	± 20%	
Droplet's temp. deviation from free-stream SAT	± 3 °C	+10 °C	N/A	
Drop distribution Deviation from reference PSD: RSF	± 5%	±10%	±10%	
Drop sphericity	± 10%	± 20%	± 20%	
Relative Humidity	± 3%	± 10%		

Table 2: W/T performance target

5 ICING WIND TUNNELS

For each wind tunnel involved in ICE-GENESIS, the current capability to produce the SLD cloud conditions in order to compare with the target requirements defined in section 4 will be reviewed. Potential gaps that will appear shall be covered within the project with activities defined in WP6. To this end, the improvements foreseen during the project, for each facility, will be presented. Besides the current performance, the instruments used for cloud characterization will be reviewed to highlight their measurement range and their limitations in covering the SLD measurements' requirements. The aim of candidate instruments defined in WP4 for LWC, MVD, and PSD cloud measurements will be the mitigation of the facilities' instrumentation gaps during the SLD cloud calibration foreseen at the end of each facilities' improvements process. For instruments available in W/T based on the same technique of the reference instrumentation selected within the WP4, will be cross-compared in the laboratory to check their calibration status and assess if their performances are ready for the W/Ts' cloud calibrations.

5.1 CIRA-IWT

The CIRA-IWT facility is a closed loop circuit, refrigerated wind tunnel, with three closed interchangeable test sections and one Open Jet configuration (figure 9).

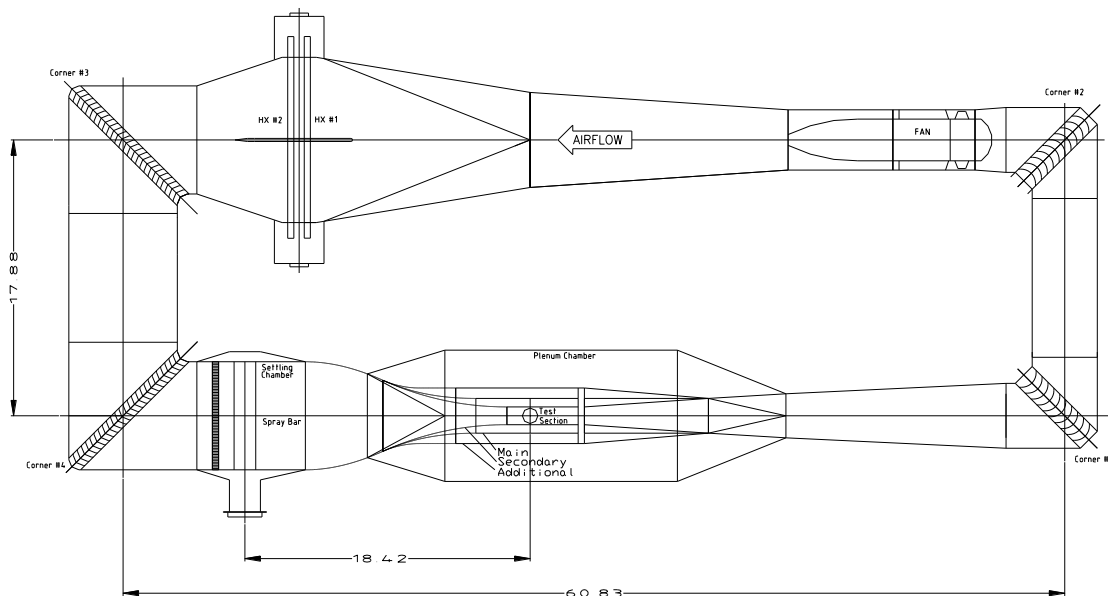


Figure 9: CIRA icing wind tunnel aerodynamic layout

The facility settling chamber is fitted with a honeycomb module to reduce large scale eddies thus ensuring flow straightening. Downstream the honeycomb, an interchangeable section provides the possibility to replace the spray bar module generating the cloud for icing tests, with screen module when lower turbulence airflow is requested for aerodynamic tests.

CIRA IWT can be configured with four different test sections. In all them, synchronized turntables are installed to be able to set the desired model orientation respect to the flow. Table 3 reports size and airflow conditions achievable for each test section configuration.

Test section	Size H (m) x W (m) x L (m)	Airspeed (m/s)	SAT (°C)	Altitude (m)
--------------	----------------------------	----------------	----------	--------------

Main (MTS)	2.35 x 2.25 x 7	30 to 135	to -32	to 7000
Secondary (STS)	2.35 x 1.15 x 5	40 to 225	to -40	to 7000
Additional (ATS)	2.35 x 3.6 x 8	20 to 90	to -32	to 7000
Open Jet (OJ)	2.35 x 2.25 x 8	30 to 135	to -32	to 7000

Table 3: CIRA-IWT test sections configurations and achievable airflow performance.

Main test section is the CIRA-IWT's configuration selected for the SLD calibration that will be followed by the icing test campaign foreseen in ICE-GENESIS.

5.1.1 Icing Cloud Performance

The Spay Bar System (SBS) has 20 bars having a low drag aerodynamic shaped section whose main feature is a low sensitivity to flow separation. Each bar is equipped with 50 spraying nozzle positions for a maximum total of 1000 possible spraying positions over 20 bars. To optimise the losses, the system is equipped with 500 active spraying nozzles only. The remaining 500 nozzle positions are plugged or can be used for different spray nozzles set-up. The number of operating nozzles may be changed during a run using the Facility Management System Software.

Table 4 shows the SLD cloud conditions achievable with current SBS for each test section configuration.

Test section	MVD max (μm)	Max drop dia. (μm)	Droplet size distribution				LWC max (g/m^3)
			FZDZ-In	FZDZ-Out	FZRA-In	FZRA-Out	
MTS	n.a.	n.a.					n.a.
STS	260	600	Yes	Yes	No	No	0.6
ATS	142	690	Yes	Yes	No	No	0.38
OJ	n.a.	n.a.					n.a.

Table 4: CIRA-IWT achievable SLD cloud conditions

The SLD calibration checks have been performed within an internal project, for the STS, and during the EXTICE program for the ATS configuration.

The SLD calibration for MTS for FZDZ conditions with the improvements defined in the WP6 is part of the scope of ICE-GENESIS program.

For cloud calibration following phases are followed in compliance with the SAE ARP recommendation [5]. The first phase is to assess the cloud uniformity assessment through the Icing Grid to optimise the active spray nozzles path on the SBS. In the second phase, the icing blade is the reference for LWC measurements at the centre of the test section. Rime ice temperature conditions for both cloud homogeneity and LWC measurements at specific airspeed are achieved.

To perform the PSD and MVD cloud measurements the phase Doppler method, under Appendix C conditions is used. For Appendix O besides the phase Doppler method also the 1D and 2D OAP are used. Droplet size measurements represents the third phase of calibration. In the sections reported on below, a summary of instrumentation used in each phase of calibration are included together with an example of result achieved.

5.1.2 Icing Instrumentation

This section reports detailed information on the instrumentation available in CIRA-IT for the cloud calibration. In particular, there are three categories of icing instrumentation used for MVD/PSD, LWC, and cloud uniformity assessment.

5.1.2.1 Particle size instrumentation

The instrumentation available for MVD and PSD characterization are based on different measurement methodologies and its selection is based on the cloud conditions generated with SBS. The table 5 reports the details for each instrument and its application in function of the cloud conditions (Appendix C or Appendix O with FZDZ or FZRA).

Instrument	Method	Size range	resolution	Sampling rate	Issues	Comment
ADA	Phase Doppler	#1) 0,5 - 138 μm #2) 2 - 748 μm	1 - 20 μm depending on size range	8-bit A/D converter operating at up to 800 MHz	Reflection signal from droplet scattering light; ice crystals rejection	Reliable for App C and for a portion of PSD in App. O_FZDZ
PDI-4D	Phase Doppler	#1) 1 - 143 μm #2) 5,2 - 776 μm	#1) 1 μm #2) 2 μm	up to 320 MHz	Limits the phase Doppler issues (see before)	Evaluating for App. C & O
2D-PDPA-LFL	Phase Doppler Particle Analyzer with Large Focal Length	LO1) 1,2/2,7 - 459/1044 μm LO2) 2,4/5,3 - 903/2053 μm	#1) 1 μm #2) 2 μm	up to 320 MHz	Same as ADA system	Modular system to use for non-intrusive measurements; two components of velocity are detectable for each droplet. (App. C & O)
OAP 260X	mono-cromatic Optical Array Probe (1DC)	15 - 900 μm	15 μm	up to 10 Hz	Electronic time response (to update as 2D mono-probe)	Same probe used in NASA-IRT for SLD cloud calibration (App. O)
OAP-2D-GA2	2D grey probe	#1) 15 - 930 μm #2) 25 - 1550 μm	#1) 15 μm #2) 25 μm	up to 10 Hz		Same probe used to collect SLD data base; useful to reject ice crystals (App. O)

Table 5: Particle spectrometers used at CIRA-IWT for cloud calibration

Figure 10 showing an example of measurements performed with phase Doppler technique and OAP 260X in the STS during the SLD calibration performed at 80 m/s.

Data were collected in two steps: first with PDPA-LFL (figure 11 a and b) installed externally to the test section with ADA in-situ probes simultaneously located with their measurement volume at the centreline of the test section (figure 11 c) and successively with OAP-260X (figure 11 d) to collect all the data for a full PSD composition. In figure 10 is showed the results where a wide diameter range of concentration overlap is shown for the two different measurement methods. The plots in figure 10

confirm the limitation of OAP to provide reliable concentration below 150 μm and show an overlap with PDPA-LFL up to 300 μm where the phase Doppler data beginning to scatter probably due to the presence of un-spherical particles in its measurement volume. The MVD corresponding to this specific case was found about 235 μm .

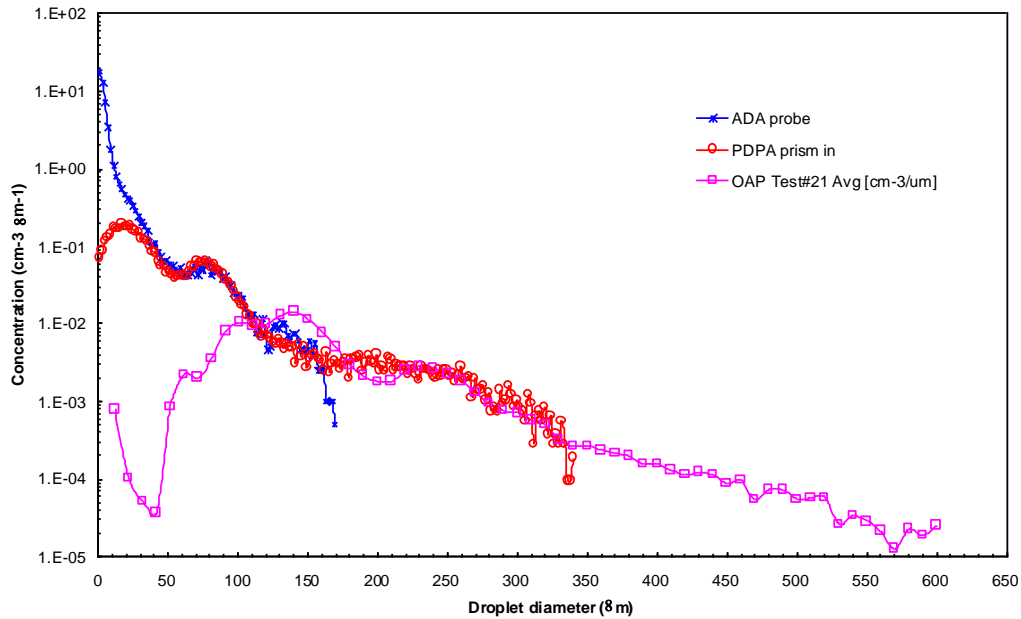


Figure 10: Example of comparison of different droplet spectra measured with PDPAs and OAP-260X

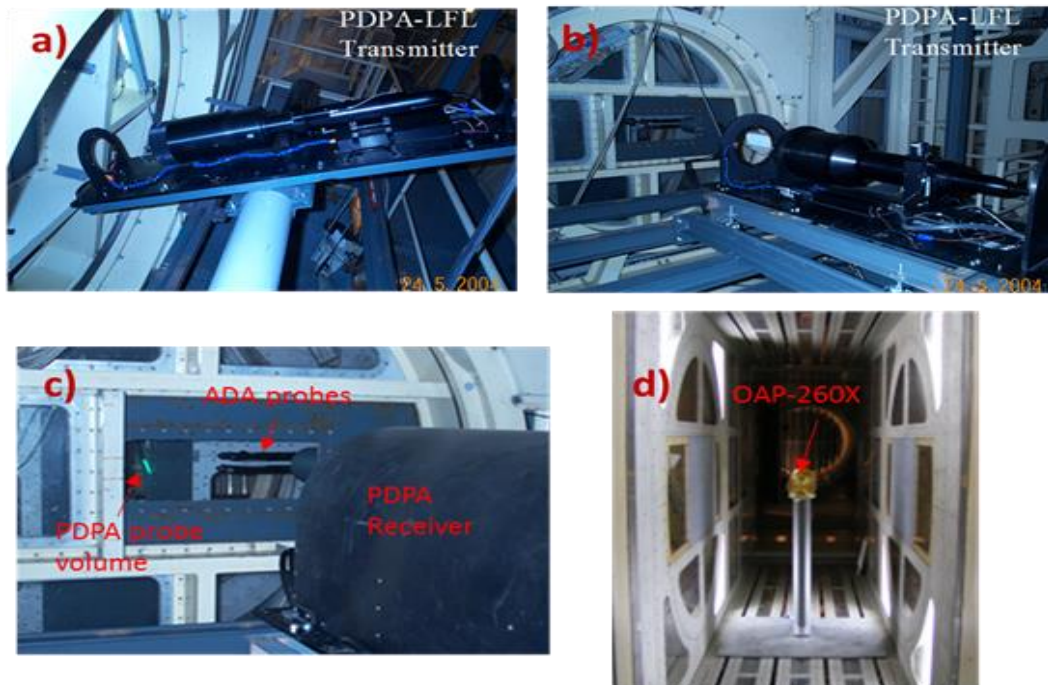


Figure 11: Instrumentation layout used for SLD measurements in STS configuration: PDPA-LFL transmitter (a) and receiver (b); ADA probes in the test section (c); OAP-260X mounted on the dedicated stand in the primary position of the test section (d).

5.1.2.2 LWC/TWC instruments

The instrumentation available for bulk LWC/TWC measurement are listed in below table 6.

Instrument	Method	LWC/TWC range	Airspeed range	Sensing head size	Control DAS	& Data update rate
IB	Icing Blade	0.05 – 4 (up to 50 μ m MVD with LWC below Ludlam limit)	Up to 200 m/s	n.a.	n.a.	App. C
2mm Hot-Wire (SEA)	Hot-wire technique	0 - 10 gm-3 (TAS <150 ms-1); 0 - 6 gm-3 (TAS <230 ms-1)	<230 m/s	2 mm + 0.5 mm	SEA M300	App C
RP	Robust Probe (heated concave element)	0 - 10 gms/m3 TAS < 150 m/s SL – 45,000 ft -40°C 0 - 6 gms/m3 TAS < 230 m/s SL - 45,000 ft - 40°C	< 230 m/s	$\Phi = 4$ mm	M300	App C & O
ICD	Ice Crystals Detector					Under evaluating for App. C & O
MW	Multi-wire					Under evaluating for App. C & O

Table 6: Instruments available at CIRA-IWT for LWC/TWC measurement

For Appendix C the liquid water content was determined using the standard Icing Blade (IB) method that is made in iron stainless steel. The blade is attached at the end of the support and mounted inside a deployable shield. The shield is connected to an actuator. The release of the actuator runs out the shield from the blade in 0,18 sec. The blade is run out from its shield for a time to expose the thin edge to the icing cloud in the centre of the test section to allow the ice to build up. The icing blade is 300 mm long, 600 mm deep, and 3 mm thick (figure 12 a). The blade was used to measure the LWC over a range of airspeed, water droplet sizes and all the tests were run at static air temperature that allow the rime ice accretion on the blade leading edge. The exposure time was adjusted to allow approximately 3 mm of ice thick to limit the maximum width of ice and reduce the variation of collection efficiency during the test. The thickness of ice on the icing blade was measured along three equidistant points, using chilled calliper.

The SEA 2 mm hot wire sensing head is also available to measure the LWC in Appendix C at different static air temperatures (figure 12 b). As for as the Appendix O the SEA Robust probe (figure 12 c) is available and its performance is evaluating in comparison with SEA Multi-Wire (MW) and SEA Ice Crystals Detector (ICD)

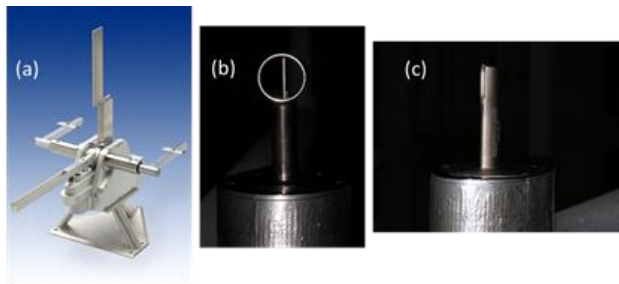


Figure 12: Available TWC/LWC measurement devices: icing blade (a); 2 mm SEA hot-wire sensor head (b); SEA Robust Probe (c)

5.1.2.3 Cloud uniformity methods

The Icing Grid is the standard calibration system used in CIRA IWT for cloud uniformity and coverage area assessment in the extended region of test section for all the cloud conditions foreseen in the Appendix C. The Icing Grid, see figure 13 (a) is made of vertical and horizontal stainless steel bars with 3 mm of thickness equally spaced (100 mm for MTS) in the cross section of the test chamber. The bars are connected to an external frame, fixed to the test section internal walls. In order to get a map of the LWC distribution in the cross-section, all the measurements are converted to relative LWC normalized to the center of the test section. The grid is exposed to the icing cloud to allow the ice to build up at -20°C air temperature. The number of measuring points changes in function of the tests section dimensions and ranges from 360 (MTS) to 220 (STS). Digital callipers are used for fast thickness measurements.

For the smaller area of the test section, three cylinders are used for a quick calibration check. See figure 13 (b).

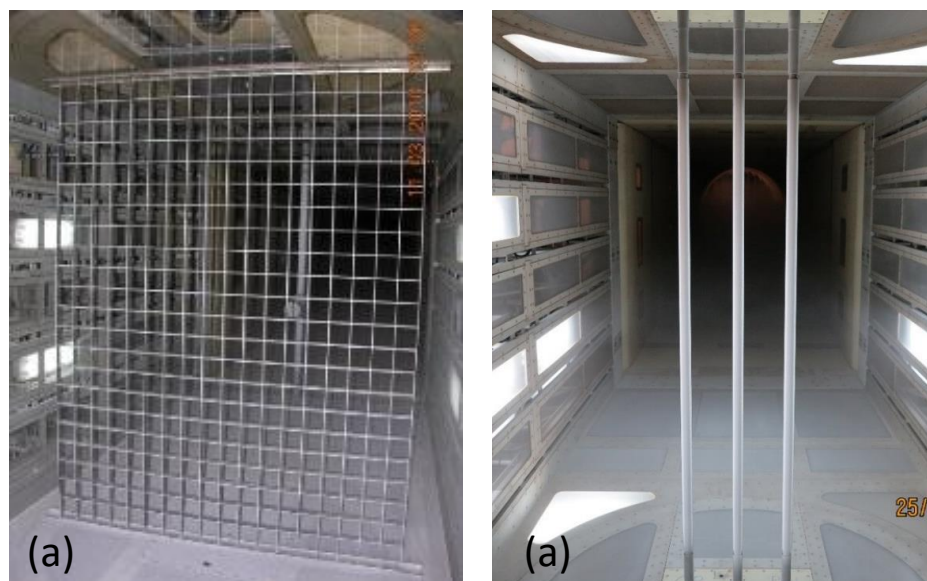


Figure 13: CIRA icing grid (a) and icing cylinders (b) for cloud homogeneity and coverage measurements in the CIRA-IWT test sections.

Figure 14 show an example of cloud uniformity achieved in the MTS for Appendix O conditions achieved during the SLD check and for ATS during the preparation of EXTICE project

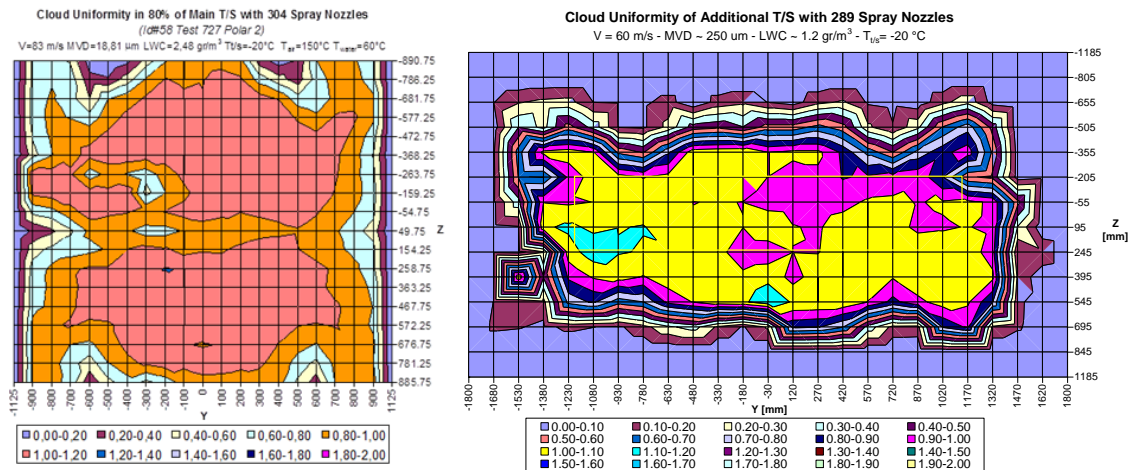


Figure 14: CIRA –SLD cloud uniformity measurements in MTS (on the left) and in ATS (on the right) with Icing Grid

5.1.3 Gaps with current facility

The CIRA IWT configuration to use in the project foresees the Main Test Section (MTS) that has never been calibrated for the SLD cloud conditions. During the EXTICE project, Additional Test Section (ATS) was shown the capability to reproduce the FZDZ-In and FZDZ_Out with LWC between 0.12 to 0.44 g m⁻³ at 60 m s⁻¹. For FZRA_Out with max MVD of 165 μm the lowest LWC achieved was 0.65 g m⁻³ at the same speed. With ATS configuration, the gaps were the reduced number of “good” conditions achievable with bi-modal PSD and with relevant LWC within the expected FZDZ range. Besides the lack of the SLD calibration, with the MTS configuration at high speed, even the expected LWC should be lower than the one achievable in the ATS for the same conditions, the PSD distribution should decrease the PSD bimodality. A novel approach to generate SLD will be developed and applied to mitigate this issue. As for the ATS configuration also in MTS will be limited the maximum droplet size with respect the airstream conditions in the test section in order to allow the supercooling regime to large droplets in the PSD.

5.1.4 Improvements of SLD cloud conditions

The improvements will start with the definition of a custom spray nozzle setup to install on CIRA SBS based on the selection and validation of candidate solutions, to improve the generation of SLD clouds with bi-modal PSDs and low LWC within a wide range of CIRA-IWT operation envelope. Droplets trajectory simulations in icing wind tunnel, as well as the simulation of atomizing nozzles, represents two methodologies that will be combined to achieve the target's objective.

In addition, will be updated and optimized the instruments and equipment for the activities covered within the CIRA IWT Freezing Drizzle (FZDZ) cloud conditions extension to support the calibration of spray bar system. The activities will include:

- Design and construct a 2D traversing system to sustain the installation of one optical spectrometer or up three bulk LWC/TWC probes for cloud uniformity assessment in the STS with potential application to MTS.
- PMS OAP-260X rebuild to get a dual mode probe to generate two outputs stream probe with 2D imaging and 1D spectra.

- Change the resolution from 15 - 930 μm to 25 - 1550 μm , and perform the calibration of the PMS OAP-2D-GA2 pro

5.1.5 Remaining gaps after improvements

Even with the improvements introduced in the spray bar system, at higher speed, the reduced droplet residence time will increase the delta between air and water droplet temperature, as droplet diameter increases. For that reason, it will be difficult to generate reliable FZDZ conditions close to 0 °C. Even if a prototype of spray bar will be developed in the project to allow better control of the generation process for the large droplets, still droplet residence time, as well as the size and concentration distribution (e.g. due to droplet's trajectory relative to the airflow direction), will be a remaining gap for FZRA that can hardly be removed with a current horizontally oriented aerodynamic wind tunnel circuit.

5.1.6 Parameters list

During the wind tunnel testing, tunnel parameters related to the airflow and to the Spray Bar System (SBS) will be acquired at 1 Hz of data recording rate. Cloud conditions, as defined by MVD and LWC, will not be directly measured during the tests. Cloud condition is related to the air and water feeding pressures through analytical equations developed as result of cloud calibration process that will be reported within D6.4 "Report on FZDZ calibration for each IWT involved in the project". Besides these parameters, also those for the test specimen configuration (e.g. AoA, flap deflection angle, etc...) and of its equipment (e.g. ice protection system parameters,..) will be provided. A list of such parameters available for database generation is reported on below:

Speed
Mach
Static Temperature
Total temperature
Liquid Water Content
MVD
PSD
Droplet temperature
Air density
Static Pressure
Dynamic Pressure
Total Pressure
Altitude
Relative Humidity
Water injection pressure
Water injection temperature
Cp distribution
Test specimen orientation (angles of yaw, pitch, roll)
Model balance (aerodynamic forces & coefficient)

BL transition (visualization nice to have)

Pressure and mass flow for hot air line (IPS)

Air temperature for hot line (IPS)

Power supply for electrical IPS heat regulation

video

Photos

5.2 MinDef Altitude Test Facility

The facility that will be used for ICE GENESIS wind tunnel 2D test campaign is the S1 facility. The S1 test bench is an open loop altitude test facility including an icing capability. The DGA EP air supply network, connected upstream and downstream the test cell, allows icing tests in simulated flight conditions:

- flight conditions adjustment (air speed, temperature, altitude, humidity)
- icing conditions adjustment by automaton (liquid water content, droplets diameter).

These capabilities comply with the icing specification of the FAR/CS 21, 23, 25, 27 and 29 standards appendix C. The FZDZ capability has been demonstrated during EXTICE. FZRA is the next purpose. A demonstration is planned in this project.

S1 Test capabilities are subsonic free jet testing in icing conditions for:

- airfoils (helicopter rotor blades, wing part),
- helicopter air intakes with or without the engine running,
- all types of probes (pressure, temperature, drop size distribution, liquid water content).

S1 Dimensions are:

- Inside diameter of the cell : 3.50 m
- Total length : 9.6 m
- Deck/vein axis : 0.882 m
- A universal deck to set-up specimens under testing :
- Designed with three tracks parallel to the axis vein
- Dimensions : 4 m x 1.8 m.

S1 Flight envelope (see figure 15) is:

- Inlet temperature : from -65°C to 110°C [-85°F to 212°F] ;
- Inlet pressure : from 5kPa to 150kPa [0.7psi to 22 psi] ;
- Air flow : 110 kg/s [241 lb/s];
- Minimum air speed : 10 m/s
- Maximum flight air speed : Mach 0.8 in icing conditions,
- LWC : above 0.1 g/m³ for Mach Number above 0.2.

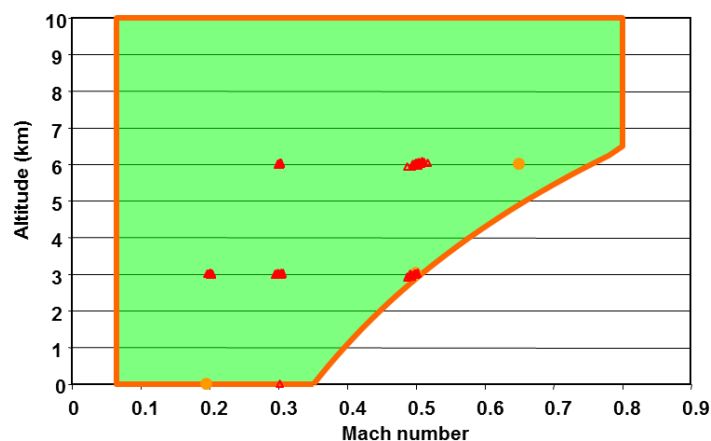


Figure 15: S1 flight envelope

Icing tests are carried out in free jet mode. To performed them, several nozzle diameters are available in order to comply with the specified air speed : diameters from 0.7 to 1.3 m. This diameter is chosen depending the specimen size (blade chord, engines sizes). For tests on airfoil or rotor blade, a specific nozzle with a 0.8 meter by 0.82 meter exit section has been designed.

Test section	Size H (m) x W (m) x L (m)	Airspeed (m/s)	SAT (°C)	Altitude (m)
Omega	0.82 x 0.7 x 3	10 - 250	-65 - 15	s.l. - 10000

Table 7: MINDEF - Test sections configurations and achievable airflow performance

The scheme (figure 16) shows the setting principle:

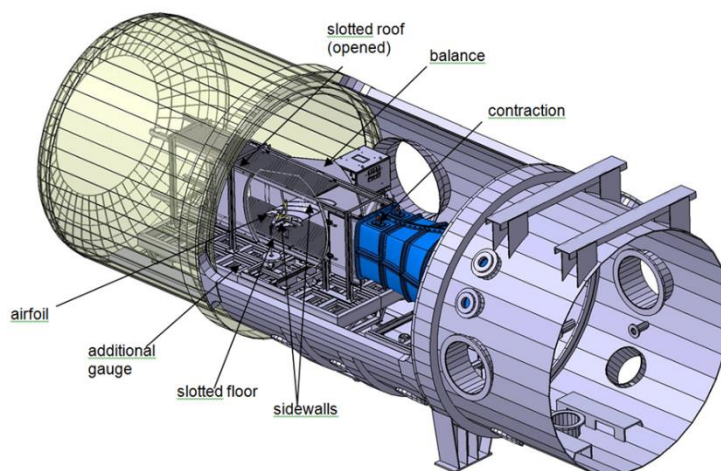


Figure 16: MINDEF - OMEGGA test rig overview

5.2.1 Icing Cloud Performance

The spray bars is composed of 61 nozzles in an uniform hexagonal distribution. To generate the Appendix O conditions, standard and SLD atomizers are mixed on the spray bars (table 8).

Test section	MVD max (μm)	Max drop dia. (μm)	Droplet size distribution				LWC max (g/m^3)
			FZDZ-In	FZDZ-Out	FZRA-In	FZRA-Out	
Omegg a	500 ($M < 0.4$)	800 ($M < 0.4$)	Yes	Yes	No	No	Above 0.1 g/m^3 for $M > 0.2$

Table 8: MINDEF - Achievable SLD cloud conditions.

5.2.2 Icing Instrumentation

This section reports detailed information on the instrumentation available in facility for cloud calibration. In particular, there are three categories of icing instrumentation used for MVD/PSD, LWC, and cloud uniformity assessment to consider.

5.2.2.1 Particle size instrumentation

The table 9 reports the details for each instrument and its application in function of the cloud conditions (Appendix C or Appendix O with FZDZ or FZRA).

Instrument	Method	Size range	resolution	Sampling rate	Issues	Comment
CAPS (CAS)	Forward Scattering Spectrometer Probe	0.5-50µm	~1µm	1Hz		New instrument
CAPS (CIP)	Optical array probe	12.5-1550 µm and 7.5-950	25µm and 15µm	1hz		New instrument

Table 9: MINDEF - Particle spectrometers used in the facility for cloud calibration

5.2.2.2 LWC/TWC instruments

The instrumentation available for bulk LWC/TWC measurement are listed in below table 10.

Instrument	Method	LWC/TWC range	Airspeed range	Sensing head size	Control & DAS	Data update rate
WCM-2000	Multi Element Water content System	0-10g/m3	0-230m/s			

Table 10: MINDEF - Instruments available in the facility for LWC/TWC measurement

5.2.2.3 Cloud uniformity methods

The MVD calibration is the first step of the whole procedure. The droplet size measurement are used to be measured using two kinds of Knollenberg probes simultaneously, a Forward Scattering Spectrometer Probe (FSSP ER 100, 2-47 and 5-95 microns) and an Optical Array Probe (OAP 1D, 30-450 microns). Recently, two CAPS have been acquired. Each CAPS is composed of a Cloud and Aerosol Spectrometer (CAP, 0.6-50µm) and a Cloud Imaging Probe (CIP, 7.5-950 µm for the first and 12.5-1550 µm for the second). Positive temperature is chosen to avoid ice accretion built-up on probes (figure 17).

The liquid water content uniformity is checked by accretion on an icing grid and measurement of ice accretion thicknesses on the bars of the grid at the midpoints of each vertical and horizontal components of the grid. A mesh of the icing grid measures 212.5mm length and 140mm height (figure 17).

Injection duration is defined to get 10 mm ice accretion. With such a value, ice accretion shape is not enough deformed and accuracy on ice thickness is not affected. Airflow temperature is also decreased to -25 °C in order to get rime ice and Mach number is corrected to get the same speed than in the test matrix.

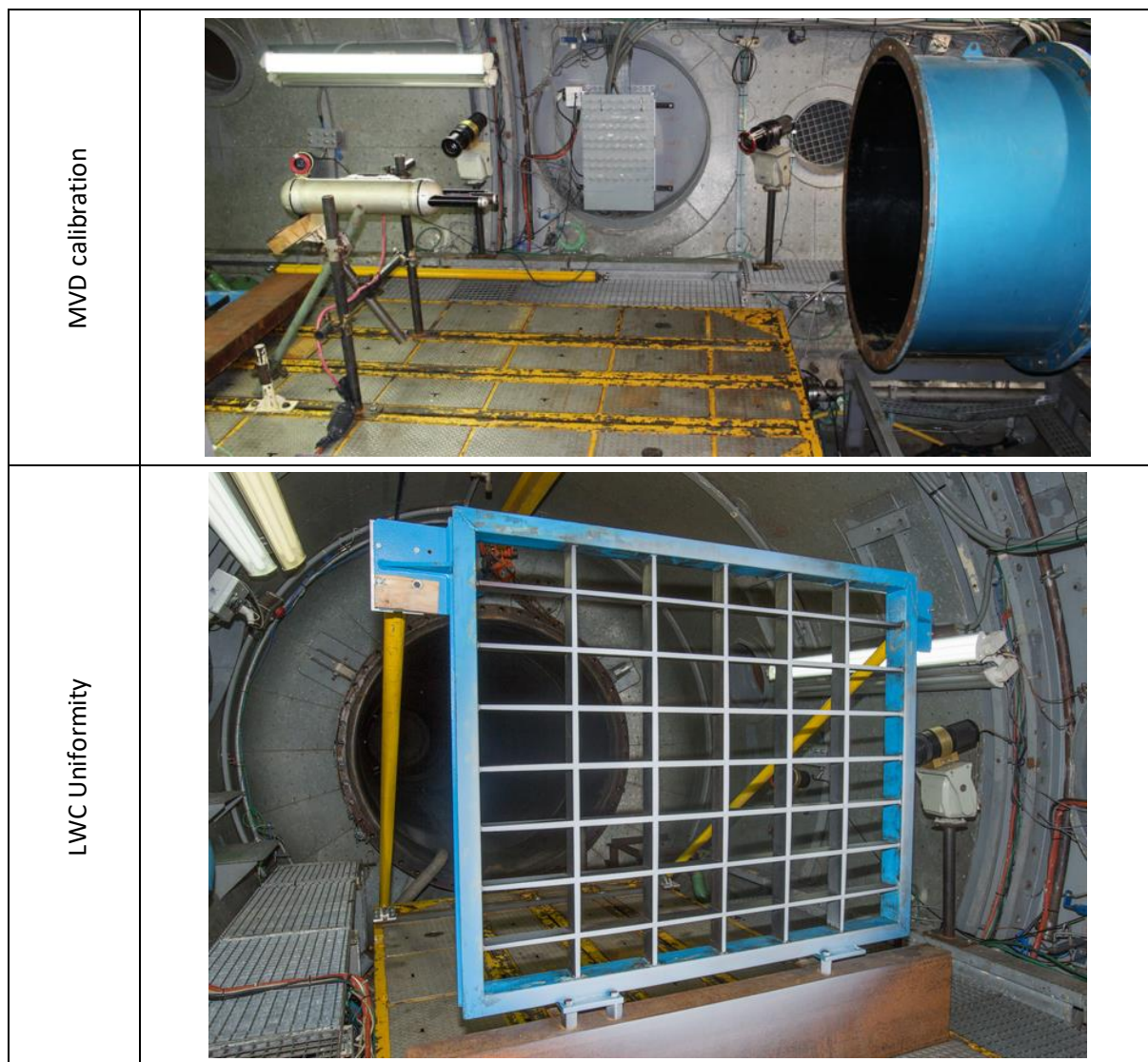


Figure 17: Instrumentation/device used for cloud parameters and homogeneity measurements at DGA-MINDEF

5.2.3 Gaps with current facility

Main gaps are related to the possibility of FZRA cloud generation with bi-modal PSD and with the larger droplets' temperature in supercooling regime especially in warmest airstream conditions (SAT close to -5 °C).

5.2.4 Improvements of SLD cloud conditions

No improvement of the facility will be done during the project.

The nozzles are already designed. Some tests on those nozzles have been done to verify their capability to also generate FZRA. Two CAPS have been bought to replace the FSSP and OAP. An internal goal is to use one of them to calibrate our facility. Also, the spray bars and the supply of water will not be modified. Therefore, the capability of LWC will not be improved.

5.2.5 Remaining gaps after improvements

In the project EXTICE, our capability to generate FZDZ conditions has been proved.

After it, some internal tests have shown our capability to generate the whole spectrum of size of drops. Here (figure 18) a particle size distribution at $M=0.3$ and $Z=1200m$:

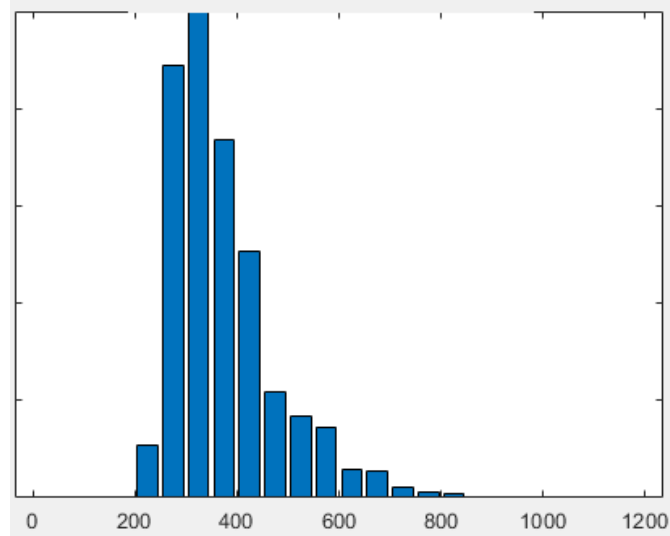


Figure 18: Example of a PSD at $M=0.3$, $Z=1200m$

But, the bimodal distribution in FZRA conditions has never been checked. Also, some difficulties to generate the FZRA conditions with DVM under $40\mu m$ are expected.

Another problematic is the drops' temperature. For FZDZ conditions, all the drops are supercooled when the SAT is under $-5^{\circ}C$, whatever the velocity. Concerning FZRA conditions, nowadays, MINDEF has no hint to answer to the problematic.

Another gap is to determinate the temperature distribution. In other words, the issue is, for a given condition, to know the temperature of each drops' size. For droplets (under $40\mu m$), the temperature of the drops is equivalent of the temperature of the flow. But for bigger drops, this is not true. As, the temperature of the drops is higher, more run-back could be noticed. So the ice shape can be completely different in facilities than in the reality.

5.2.6 Parameters list

The following list of parameters will be provided:

Speed
Mach
Static Temperature
Total temperature
Liquid Water Content
MVD
PSD
Droplet temperature

Air density
Static Pressure
Dynamic Pressure
Total Pressure
Altitude
Relative Humidity
Water injection pressure
Water injection temperature
Cp distribution
Test specimen orientation (angles of yaw, pitch, roll)
Model balance (aerodynamic forces & coefficient)
BL transition (visualization nice to have)
Pressure and mass flow for hot air line (IPS)
Air temperature for hot line (IPS)
Power supply for electrical IPS heat regulation
video
Photos

The maximum acquisition rate for the tunnel parameters is 25Hz.

5.3 RTA Icing Wind Tunnel

The RTA IWT is a closed loop, climatic wind tunnel. A schematic of the wind tunnel is shown in figure 19. Depending on the required cross section and wind speed range, two different configurations can be provided (see figure 20). The full cross section configuration is mainly used for icing tests with complete helicopters at wind speeds of up to 20 m/s, whereas the configuration with the reduced cross section is used for wing sections, engine inlets, etc., at wind speeds of up to 80 m/s. Wing sections with a wingspan of up to 3m and a chord of up to 2m can be mounted in the RTA ForceJig in order to be able to compare the aerodynamic characteristics of different ice shapes at an AoA range of -18° to + 18°. For the simulation of SLDs only the configuration with the reduced cross section can be used (table 11).

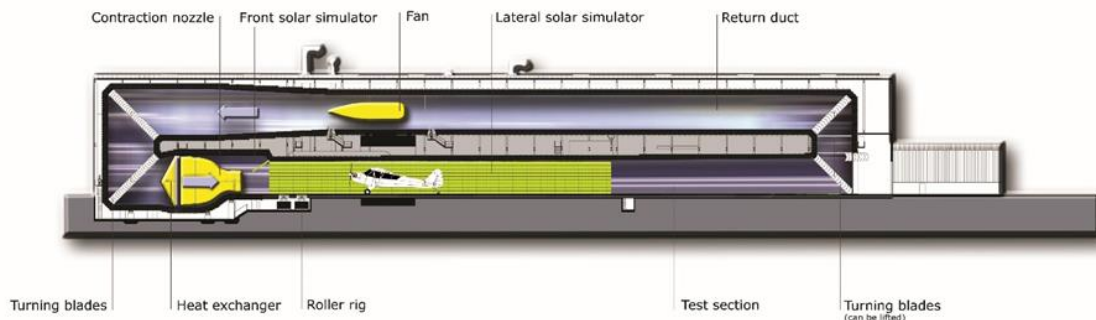


Figure 19: Aerodynamic layout of the RTA IWT

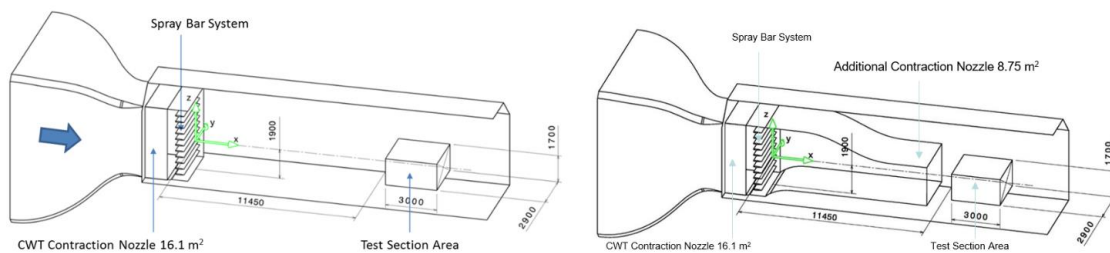


Figure 20: RTA-IWT full cross section configuration (left) and reduced cross section configuration (right)

Test section	Size H (m) x W (m) x L (m)	Airspeed (m/s)	SAT (°C)	Altitude (m)
IWT full cross section (Test Section)	3.5 x 4.6 x 100.0 (1.7 x 2.9 x 3.0)	10 to 20	-2°C to -30°C	sea level
IWT reduced cross section (Test Section)	3.5 x 2.5 x 90.0 (1.7 x 2.9 x 3.0)	20 to 80	-2°C to -30°C	sea level

Table 11: RTA-IWT Test sections configurations and achievable airflow performance.

5.3.1 Icing Cloud Performance

The spray bar system (SBS) of the RTA IWT consists of eleven airfoil shaped spray bars, each equipped with 24 spray nozzles which adds up to a total of 264 nozzles. There are two separate water and air supply lines for each spray bar so that every second nozzle can be supplied with a different air / water

pressure setting and a different water temperature. For the simulation of FZRA conditions each second nozzle on selected spray bars is equipped with a different nozzle type in order to be able to create the required PSD. Table 12 shows the currently achievable SLD cloud conditions for the configuration with the reduced cross section.

Test section	MVD max	Max drop dia.	Droplet size distribution				LWC max
	(μm)	(μm)	FZDZ-In	FZDZ-Out	FZRA-In	FZRA-Out	(g/m^3)
IWT full cross section	n.a.	n.a.					n.a.
IWT reduced cross section	550	1500	Yes	Yes	No	Yes	~0.38 - 0.60 (FZDZ) ~0.29 - 0.45 (FZRA)

Table 12: RTA-IWT achievable SLD cloud conditions.

5.3.2 Icing Instrumentation

This section reports detailed information on the instrumentation available in facility for cloud calibration. In particular, there are three categories of icing instrumentation used for MVD/PSD, LWC, and cloud uniformity assessment to consider.

5.3.2.1 Particle size instrumentation

The instrumentation available for MVD and PSD characterization are based on the maximum occurring droplet diameters. The table 13 reports the details for each instrument and its application in function of the cloud conditions (Appendix C or Appendix O with FZDZ or FZRA). It has to be noted that both devices are not owned by RTA but are rented for the calibration and research campaigns.

Instrument	Method	Size range	resolution	Sampling rate	Issues	Comment
Malvern Spraytec (300 mm lens)	laser diffraction	0.1 – 900 μm (MVD up to 600 μm)	dynamic ~0.02 – 140 μm	10 kHz	Stability at windspeeds of > 50 m/s	Entire bimodal distribution is provided in real time
Malvern Spraytec (750 mm lens)	laser diffraction	2.0 – 2000 μm (MVD up to 1600 μm)	dynamic ~0.16 – 300 μm	10 kHz	Stability at windspeeds of > 50 m/s	Entire bimodal distribution is provided in real time
Cloud Imaging Probe CIP	Photo - detectors	12.5 – 1550 μm	25 μm	Max. 25 Hz	Difficult to evaluate bimodal distribution (accuracy at < 150 μm)	Korolev anti-shatter tips were used

Table 13: RTA-IWT particle spectrometers used in the facility for cloud calibration

5.3.2.2 LWC/TWC instruments

Listed in table 14 below are the LWC / TWC measurement devices which have been used in the RTA IWT. The Calibration for Appendix C conditions is done with the icing blade exclusively. The WCM-2000 and the IKP from the Cranfield University were rented to be used for the research for SLD conditions and are not owned by RTA. First investigations have shown a good agreement of the IKP and the TWC sensor of the WCM-2000 in Appendix C conditions. However, with increasing droplet size (FZDZ, FZRA) the hot-wire instrument seemed to underestimate the water content compared to the IKP. The deviation was significant at the tested FZRA condition.

Instrument	Method	LWC/TWC range	Airspeed range	Sensing head size	Control & DAS	Data update rate
Icing Blade	Ice accretion	Ludlam limit	Ludlam limit	3.0 x 50.8 x 174 mm	/	/
WCM-2000	Hot wire	0 – 10 g/m ³ 0 – 6 g/m ³	< 150 m/s < 230 m/s	14.3 x 8.25 x 8.25 mm		1 – 10 Hz
CU IKP	Isokinetic sampling – laser absorption	0-5 g/m ³ 0-3 g/m ³	< 120 m/s < 200 m/s	Length: 0.7 m Inlet: 6 mm		1 Hz

Table 14: RTA-IWT instruments available in the facility for LWC/TWC measurement

5.3.2.3 Cloud uniformity methods

The RTA uses an ice accretion grid for the cloud uniformity calibration of Appendix C conditions, a photograph of the grid can be seen in figure 21. The grid is made of horizontal and vertical aluminium bars with a width of 5 mm and a spacing of 150 mm and can be installed at different positions of the test section. The grid is exposed to rime ice conditions for a certain amount of time in order to achieve a target ice thickness of about 6.4mm and then manually measured using a caliper. In order to get a map of the LWC distribution in the cross-section, all the measurements are converted to relative LWC normalized to the centre of the test section.

The ice accretion grid also was used to assess the cloud uniformity and coverage area of FZDZ and FZRA conditions. The applicability and accuracy of the icing grid for Appendix O conditions is questionable as it was not meant to be used for large droplet sizes due to splashing / bouncing and other effects that might change the results. However, it was used for first estimations and the observed patterns on the grid were similar to those observed when doing icing tests with wing sections. In Figure 22 and Figure 233 uniformity results are shown for FZDZ and FZRA respectively.



Figure 21: Photograph of the ice accretion grid installed at the RTA IWT

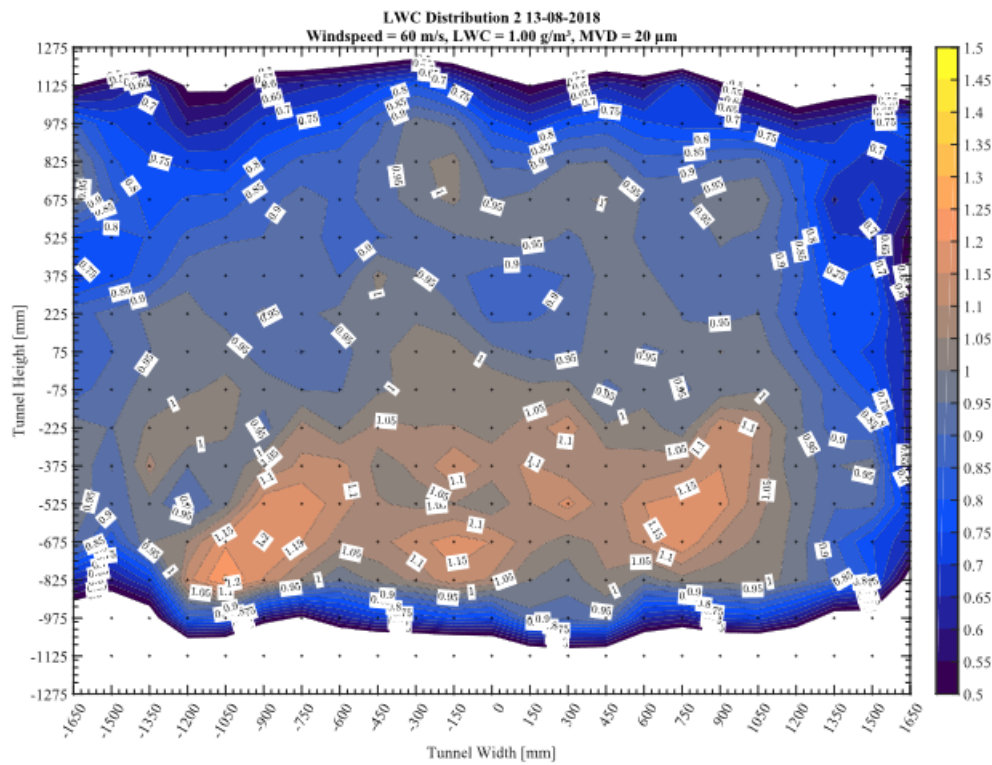


Figure 22 Freezing drizzle MVD > 40 µm cloud uniformity measurement using the ice accretion grid

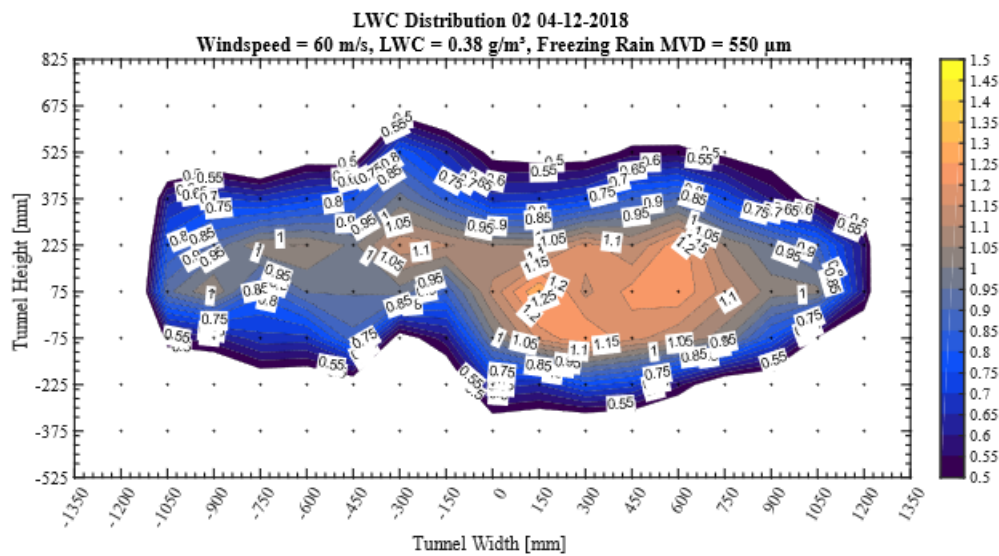


Figure 23 Freezing rain MVD > 40 µm cloud uniformity measurement using the ice accretion grid

5.3.3 Gaps with current facility

The RTA IWT already offers a limited capability to simulate SLD conditions, however some challenges and issues were detected during previous research. During the ICE GENESIS project those issues should be addressed, and the facility should be improved.

With the current spray bar system and spray nozzle configurations, PSDs close to the requirements for FZDZ-In, FZDZ-Out and FZRA-Out can be recreated. However, the produced LWCs for FZDZ-Out and FZRA-Out are higher as specified in the requirements. For FZDZ-out the lowest possible LWC is about 0.39 g/m³ at the maximum windspeed of 80 m/s, whereas at the minimum windspeed the lowest LWC is about 0.60 g/m³ according to measurements with the WCM-2000. Previous research has shown, that a PSD similar to the requirements for FZRA-In is only possible at very high LWCs.

With the current water precooling system, a supercooled state of the large droplets at the test section can only be reached at very low ambient temperatures ($< -10^{\circ}\text{C}$).

5.3.4 Improvements of SLD cloud conditions

One very challenging aspect of the simulation of SLD conditions is to ensure that the large droplets are supercooled when reaching the test section. In order to achieve that, the large droplets need to be injected at temperatures near freezing (while freezing at the or in the nozzle has to be prevented). RTA will upgrade its water precooling system to further reduce the possible water injection temperature from 5°C to about 1°C . The implemented upgrade then has to be validated with temperature measurements (at nozzle exit and at the test section) as well as further investigations on ice accretions (three-cylinder method, etc.).

Another very difficult aspect of Appendix O conditions is the low required LWC in combination with the bimodal PSD including very large droplets. PSD measurements of FZDZ and FZRA conditions have shown promising results but according to TWC / LWC measurements, a significant reduction of the LWC is necessary in order to comply with the requirements given in Appendix O. A detailed investigation of different methods to reduce the amount of injected water while still producing the correct droplet size distribution needs to be conducted.

Furthermore, an improvement of the cloud uniformity, by adjusting the pressure settings of the individual spray bars, is planned and measurements with a valid method are necessary. For that reason and in order to improve the flexibility of the system, different nozzle pressure settings need to be investigated concerning their PSD and LWC. Finally, the implemented improvements of the system have to be validated using an appropriate measurement technology.

5.3.5 Remaining gaps after improvements

After a successful implementation of the aforementioned improvements, there will still be some remaining gaps. For simulations of SLD conditions at static air temperatures of warmer than -5°C , a supercooled state of the very large droplets ($>500\ \mu\text{m}$) might not be reachable. Concerning the LWCs, RTA aims to achieve a reduction to the specified maxima at the corresponding ambient temperatures, lower water contents will be very difficult to achieve, especially at low airspeeds. Depending on the droplet sizes, slight deviations of the droplet trajectory angles as well as a deviation of the droplet velocities compared to the ambient flow can not be excluded.

For FZRA-In, it is not expected to reach a correct PSD while also producing a water content near the requirements.

5.3.6 List of parameters

During the wind tunnel tests, parameters related to the airflow and ambient conditions as well as parameters of the spray bar system will be recorded with a data acquisition rate of 1 Hz. The cloud conditions defined by MVD and LWC are not directly measured during the tests. The required conditions are created by adjusting the water and air supply pressures and temperatures according to calibration curves generated in WP6 (within D6.4 "Report on FZDZ calibration for each IWT involved in the project"). Furthermore parameters concerning the test specimen (e.g. AoA, aerodynamic forces, ...) and of its equipment (e.g. ice protection system parameters,..) can be recorded. The main parameters are listed below:

Speed
Mach
Static Temperature
Total temperature
Liquid Water Content
MVD
PSD
Droplet temperature
Air density
Static Pressure
Dynamic Pressure
Total Pressure
Altitude
Relative Humidity
Water injection pressure
Water injection temperature
Cp distribution
Test specimen orientation (angles of yaw, pitch, roll)
Model balance (aerodynamic forces & coefficient)
BL transition (visualization nice to have)
Pressure and mass flow for hot air line (IPS)
Air temperature for hot line (IPS)
Power supply for electrical IPS heat regulation
video
Photos

5.4 TsAGI AHT-SD Icing Wind Tunnel

Climatic-type icing wind tunnel AHT SD performed in the direct-flow scheme with the air intake from the atmosphere. AHT SD has no own cooling system and icing investigations are carried out in the cold season. Axial fan provides the air flow velocity range from 10 to 150 m/s with maximum motor power 1 MW. The closed working chamber has square cross-section 1m×1m in size and 3m in length (table 15). The experimental model is set in the working chamber vertically on a special supporting mechanism which provides AoA variation in the range -45° ... $+45^{\circ}$. The upper and side walls of the working chamber are equipped with 10 optical windows (4 with dimensions 300 mm × 300 mm on each side wall and 2 with the same sizes on the upper wall) and 3 infrared windows (one with a diameter of 80 mm on each wall). The upper wall of the working chamber is removable which provides access to the model before and after the experiment with maintaining of the air negative temperature. The general view of AHT SD is shown in figure 24.

Test section	Size H (m) x W (m) x L (m)	Airspeed (m/s)	SAT (°C)	Altitude (m)
Main	1x1x3	150	Up to -30	0

Table 15: TsAGI AHT SD test sections configurations and achievable airflow performance.



Figure 24: TsAGI - The general view of AHT-SD.

5.4.1 Icing Cloud Performance

The AHT-SD water spraying system consists of the following parts:

- water spraying manifold with controlled supply of water and air;
- water treatment and supply subsystem;
- air treatment and supply subsystem;
- control and monitoring subsystem.

The water-spraying collector consists of 11 pylons. Each pylon has a different number of injectors (a total of 85 injectors). The pylon is made in the shape of a well-streamlined wing, with insulation inside the material. Inside the pylon, water and air supply valves are laid, and nozzles are installed in the niches.

To improve the uniformity of the artificial cloud each injector can be rotated.

Manifold with injectors provides the working chamber LWC in the range 0-2. 5 g/m³ with the mean volume diameter of drops 15...50 μm in the range of flow rates 0...150 m/s (table 16). The non-

uniformity of the LWC distribution does not exceed 20 % of the average LWC in the working chamber cross section.

Test section	MVD max	Max drop dia.	Droplet size distribution				LWC max
	(μm)	(μm)	FZDZ-In	FZDZ-Out	FZRA-In	FZRA-Out	(g/m^3)
Main	50	90	No	No	No	No	2.5

Table 16: AHT-SD achievable SLD cloud conditions.

Up to this moment AHT SD can provide only App. C conditions but its water spraying manifold will be upgraded to provide FZDZ conditions up to M18 in accordance with ICE GENESIS working plan.

5.4.2 Icing Instrumentation

This section reports detailed information on the instrumentation available in facility for cloud calibration. In particular, there are three categories of icing instrumentation used for MVD/PSD, LWC, and cloud uniformity assessment to consider.

5.4.2.1 Particle size instrumentation

The instrumentation available for MVD and PSD characterization on AHT SD include Phase Doppler Interferometer PDI Artium 2D, Precipitation Imaging Probe PIP DMT (provided by Central Aerological Observatory), Cloud Imaging Probe CIP DMT DMT (provided by Central Aerological Observatory) and the impactor system for the droplets capture by the probes filled by silicon oil. The table 17 reports the details for each instrument and its application in function of the cloud conditions (Appendix C or Appendix O with FZDZ or FZRA).

Instrument	Method	Size range	resolution	Sampling rate	Issues	Comment
PDI Artium 2D	Phase Doppler Interferometer	0.5 μm -2.6 mm	0.5 μm	Up to 20000 kHz		
Precipitation Imaging Probe PIP DMT	Optical Array Probe with 64 elements: 62 sizing elements, end diode rejection	100 μm –6.2 mm		0.1-10 Hz		Will be provided by CAO
Cloud Imaging Probe CIP DMT	Optical Array Probe with 64 elements: 62 sizing elements, end diode rejection	12.5 μm – 1.55 mm		0.05-25 Hz		Will be provided by CAO
Impactor system	Droplets capture by the probes filled by silicon oil	4.9 μm – 1 mm		Up to 1 measurement per 1 minute		

Table 17: TsAGI particle spectrometers used in the facility for cloud calibration.

5.4.2.2 LWC/TWC instruments

The instrumentation available for bulk LWC/TWC measurement are listed in below table 18.

Instrument	Method	LWC/TWC range	Airspeed range	Sensing head size	Control & DAS	Data update rate
EIV-2K	Nevzorov probe	0.2 – 2.5 g/m ³	20...200 m/s	73 mm	Connected with common DAS of AHT SD	0.5-2 Hz
Cloud Imaging Probe CIP DMT	Temperature-Controlled Hotwire Sensor	0 – 3 g/m ³	10...200 m/s			

Table 18: TsAGI instruments available in the facility for LWC/TWC measurement.

5.4.2.3 Cloud uniformity methods

The artificial cloud homogeneity is checked by the measurement grid exposition in the water-air flow in the working chamber and by measuring the thickness of the ice grown on the grid bars (Figure 25). Grid is made of steel rod with a diameter of 5 mm with a spacing of 100 mm. When uneven distribution of ice on the rods and, consequently, the water content in the cross section of the IWT, exceeding 20 %, the adjustment of the water spraying manifold is done. Calibration for LWC uniformity is performed at an ambient temperature below -10 °C and flow velocities of 80-150 m/s.



Figure 25: The measurement grid in the AHT SD working chamber during cloud uniformity calibration

5.4.3 Gaps with current facility

Nowadays IWT AHT-SD provides only App C icing conditions. The calibration is now running to investigate the borders of AHT-SD icing envelope in the terms of PSD, LWC and cross-sections distributions of these values. After finishing this work, it would be clear what minimum and maximum drop sizes can be provided by existing manifold and what improvements would be made to reach the target sizes and LWC levels.

5.4.4 Improvements of SLD cloud conditions

In the frames of ICE GENESIS Project the AHT SD water spraying manifold will be upgraded and equipped by new injectors to provide FZDZ icing envelope with maximum drops diameter 500 µm at flow velocity 140 m/s. The main improvements will include new injector construction and changes in the air and water pressures supplying systems to achieve the necessary values of LWC and to obtain relevant bimodal particles diameters distribution function. The different injector types will be tested on TsAGI small IWT VSIO with PSD and LWC measurements to choose the best type of their construction.

5.4.5 Remaining gaps after improvements

Due to the AHT SD has the horizontally oriented aerodynamic channel it will be impossible avoid the particles sedimentation caused by the gravitation. Hence it will arise a vertical non-uniformity of PSD and LWC which will vary with flow velocity. The characterization of PSD and LWC distributions for IWT flow velocity range will be obtained during the calibration after water manifold improvement.

5.4.6 Parameters list

During the test, the flow data (velocity, temperature, humidity), water manifold parameters (air and water pressures and temperatures), test model parameters (thermocouples data, heater power etc) will be recorded by the data acquisition system. MVD and LWC will not be directly measured during the tests and will be provided as a functions of the manifold air and water feeding pressures. The corresponding dependencies will be obtained during the calibration and will be given in Deliverable D6.4 "Report on FZDZ calibration for each IWT involved in the project". A list of parameters available will include:

Speed
Mach
Static Temperature
Total temperature
Liquid Water Content
MVD
PSD
Droplet temperature
Air density
Static Pressure
Dynamic Pressure
Total Pressure
Altitude
Relative Humidity
Water injection pressure
Water injection temperature
Cp distribution
Test specimen orientation (angles of yaw, pitch, roll)
Model balance (aerodynamic forces & coefficient)
BL transition (visualization nice to have)
Pressure and mass flow for hot air line (IPS)
Air temperature for hot line (IPS)

Power supply for electrical IPS
heat regulation

video

Photos

5.5 TsAGI EU-1 Icing Wind Tunnel vertical working section

In the frames of the project a new working vertical working section for the climatic-type icing wind tunnel EU-1 will be designed and created to achieve FZDZ and partially FZRA conditions. Vertical orientation of the working channel allows to provide the maximum drop sizes and LWC level without gravitational sedimentation of the drops. Now the IWT project under consideration and only high-level information is available (table 19).

Test section	Size H (m) x W (m) x L (m)	Airspeed (m/s)	SAT (°C)	Altitude (m)
Main	0.5x0.25x0.25	110	Up to -30	0

Table 19: TsAGI EU-1 vertical test sections configurations and achievable airflow performance.

5.5.1 Icing Cloud Performance

The EU-1 water spraying system will include the following parts:

- water spraying manifold for FZDZ (one- and multy-nozzle options are under consideration);
- water spraying multy-nozzle manifold for FZRA;
- water treatment and supply subsystem;
- air treatment and supply subsystem

Water spraying multy-nozzle system will provide the working chamber LWC in the range 0.2-0.45 g/m³ with the maximum diameter of drops up to 500 µm (FZDZ) and up to 2300 mm (FZRA) in the range of flow rates 0...110 m/s (table 20).

Water manifold	MVD (µm)	Max drop dia. (µm)	Droplet size distribution				LWC max (g/m ³)
			FZDZ-In	FZDZ-Out	FZRA-In	FZRA-Out	
FZDZ	20-110	500	Yes	Yes	No	No	0.45
FZRA	19-530	2300	No	No	Yes	Yes	0.35

Table 20: Vertical EU-1 target SLD cloud conditions.

5.6 CIAM C-2 Icing Wind Tunnel

The scheme of the C-2 CIAM test cell is shown in figure 26. The test cell has a wind tunnel with an open working part. The wind tunnel is placed inside the thermo-chamber of the C-2 test cell. In order to obtain stream characteristics acceptable for research in wind tunnels, a honeycomb was installed in the receiver on the C-2 test cell, the leveling grids and tapering confuser air inlet, which can significantly reduce the level of flow heterogeneity.

The design of the C-2 CIAM test cell provides the possibility of replacing wind tunnel sections in order to fit the required test tasks. In the outlet section of the wind tunnel various test objects can be installed: elements of the wing or stabilizer of the aircraft, models of helicopter blades, models of the air intake, full-size engines, etc.

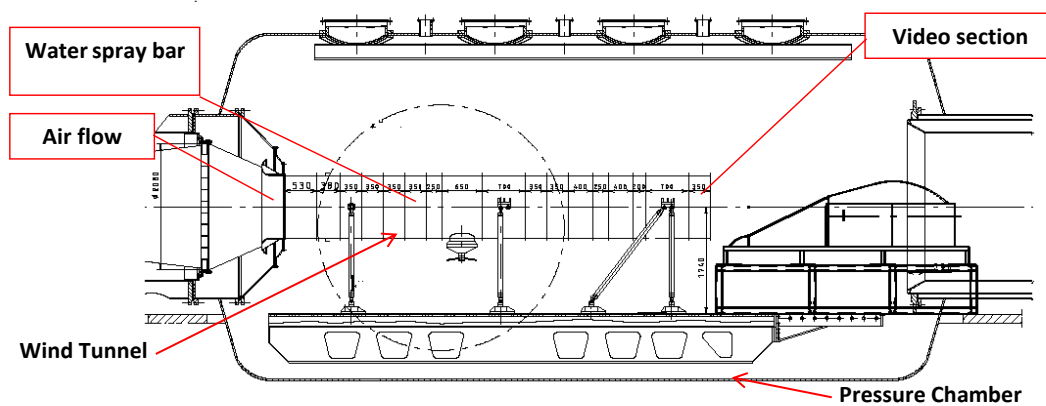


Figure 26: Scheme of the test cell C-2 CIAM with icing wind tunnel

Table 21 shows the dimensions and conditions of the air flow, achievable for the current configuration of the test cell.

Test section	Size H (m) x W (m) x L (m)	Airspeed (m/s)	SAT (°C)	Altitude (m)
Main	Φ 1,02 m	20÷200 m/s	From +20 down to -40 °C	Up to 15000 m

Table 21: Test sections configurations and achievable airflow performance

5.6.1 Icing Cloud Performance

The Spray Bar System (SBS) is shown in Fig. 27. The design of the collector includes 15 pylons with a spraying nozzle at the end of each one, there are 15 nozzles in total. To improve the uniformity of water spraying in the cross section of core stream, generators of local vortices are installed on the nozzles.

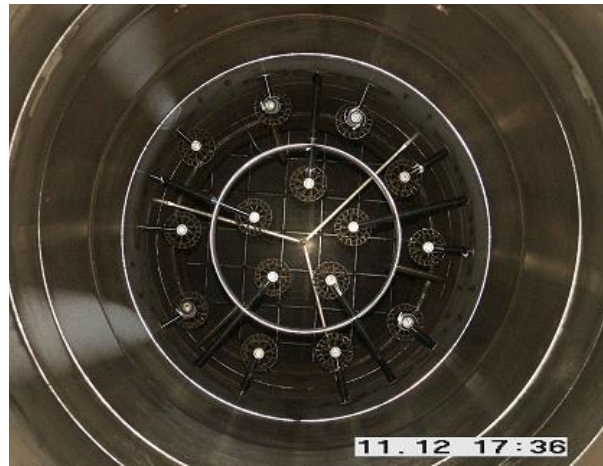


Figure 27: The Spray Bar System of the C-2 CIAM test cell

Table 22 shows the SLD cloud conditions achievable with the current SBS and current C-2 test cell configuration

Test section	MVD max (μm)	Max drop dia. (μm)	Droplet size distribution				LWC max (g/m^3)
			FZDZ-In	FZDZ-Out	FZRA-In	FZRA-Out	
Φ 1.2 m	50	300	Yes	No (for current configuration)	No	No	0.44

Table 22: Achievable SLD cloud conditions achievable in C-2 CIAM test cell.

5.6.2 Icing Instrumentation

This section reports detailed information on the instrumentation available in CIAM for cloud calibration. In particular, there are three categories of icing instrumentation used for MVD/PSD, LWC, and cloud uniformity assessment to consider.

5.6.2.1 Particle size instrumentation

The instrumentation available for MVD and PSD characterization are based on various measurement methodologies, and its selection is based on cloud conditions generated by SBS. The table 23 reports the details for each instrument and its application in function of the cloud conditions (Appendix C or Appendix O with FZDZ or FZRA).

Instrument	Method	Size range	Resolution	Sampling rate	Issues	Comment
Mastersizer-X	Laser scattering	0.5..180 μm 1.2..600 μm 4..2000 μm	Up to 100 numbers of size classes	From 0.1 Hz to 1 Hz	laboratory instrument, not applicable to large-scale IWT	
CCP	Optical Array Probe (CIP)	12.5..1550 μm	25 μm	From 0.05 Hz to 25 Hz (usually 1 Hz)	no standard software for data coupling from 2 probes	Includes CIP (Cloud imaging probe) and CDP (Cloud droplet probe)
	Light-scattering probe (CDP)	2..50 μm	2 μm			

Table 23: Particle spectrometers used in the CIAM facility for cloud calibration

Preliminary calibration of water spray nozzles is performed using the Mastersizer-X instrument (Figure 28).



Figure 28: Laser analyzer of droplets size MASTERSIZER-X

Calibration of the two-phase flow in the wind tunnel is performed using the CCP probe (figure 29).



Figure 29: CCP probe at CIAM

5.6.2.2 LWC/TWC instruments

The instruments used in the C-2 test cell for measuring LWC / TWC are presented in Figures 30, and are listed in table 24 below.



Figure 30: CIAM LWP probe KLWC-5

Instrument	Method	LWC/TWC range	Airspeed range	Sensing head size	Control & DAS	Data update rate
KLWC-5	Temperature -controlled hotwire sensor	0-6 g/m ³	Up to 100 m/s	Coil Diameter 1.8 mm	n/a	20 Hz
CCP	Temperature -controlled hotwire sensor	0-3 g/m ³	10-200 m/s	Coil Diameter 1.8 mm	Pulse width modulation control	> 25 Hz

Table 24: Instruments available in the facility for LWC/TWC measurement

5.6.2.3 Cloud uniformity methods

Tests to determine the uniformity of distribution of water content over the cross section of the wind tunnel are performed using a measuring grid placed in the working section of the IWT. The grid is made of 5.6 mm bar with size of the cell 105 mm (figure 31).

During the test, the grid is blown with cooled air flow with water droplets sprayed on it. After the process was completed, the thickness of the ice layer grown on the bars of the grid is being measured. The thickness of the ice layer is approximately proportional to the local value of the water content, since the tests were carried out at low temperatures. In order to prevent melting and changes in the thickness of the ice layer during measurements, they are carried out with a caliper pre-cooled to the flow temperature. During measurements, a small stream of cold air is being provided through the IWT.

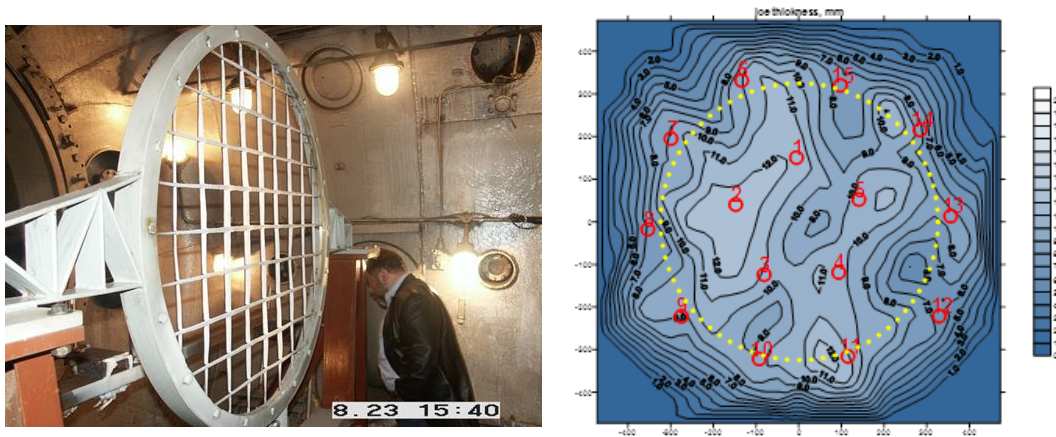


Figure 31: Measuring grid used for cloud homogeneity and coverage measurements in the C-2 test section.

5.6.3 Estimation of droplets supercooling extent

Estimation of droplets supercooling extent is performed by the method of three cylinders. The method is based on the phenomenon of the dependence of shape of the ice by the degree of supercooling of droplets. The method is combining calculating and experimental approach. Based on the calculations, the temperature values of a polydisperse stream of droplets moving in a stream of cooled air are measured (figure 32).

Then the calculated conditions are being modelled in the IWT and icing tests are performed using three cylinders located at different distances from the SBS. Differences between the ice shapes obtained on all three cylinders are being recorded using a Plexiglas plate (figure 33).

Then the comparison of the forms of ice build-up obtained on three cylinders (figure 34) is performed. In the event that ice accretions of similar shape and thickness were obtained on all three cylinders, it is concluded that the droplets are supercooling in the flow and that there is no significant out-freezing of the droplets.

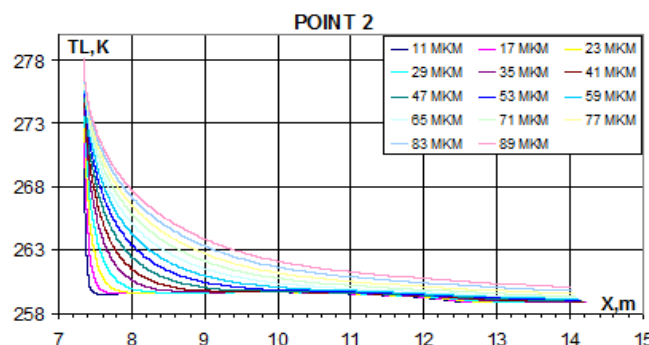


Figure 32: Calculation of the droplets supercooling degree



Figure 33: Change of ice buildup forms on three cylinders

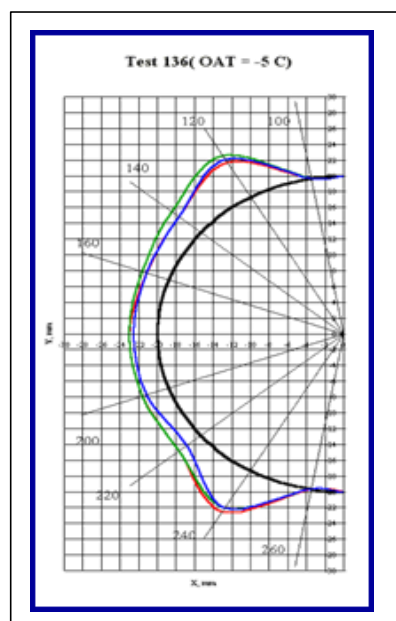


Figure 34: Comparison of ice accretions obtained on three cylinders

5.6.4 Gaps with current facility

The current configuration of the C-2 icing wind tunnel has the constant diameter of the whole channel from the Water Spray Bar System to the test section. Such configuration of the IWT does not allow to receive in the high velocity airflow large droplets as they break up due to high We number. In case of air flow with low velocity it is difficult to receive good quality of cloud uniformity as large droplets fall to the lower part of the wind channel due to the gravity forces.

The current configuration of the facility allows to receive FZDZ-In conditions for $MVD < 40 \mu m$ in the test section. In order to simulate FZDZ-Out conditions for $MVD > 40 \mu m$ the configuration of the IWT has to be changed.

The existing configuration of the Spray Bar System allows to receive minimum LWC in the test section 0.3 g/m^3 . The planning improvements to the Spray Bar System should lower the minimum achievable LWC to 0.18 g/m^3 .

5.6.5 Improvements of SLD cloud conditions

In this section, it will be described the improvements that will be performed in the process of improving the C-2 test cell with regard to the spraying conditions, subsystems and equipment of the facility in preparation for the test campaigns.

Based on preliminary experimental studies and calculations, the following improvements in the characteristics of C-2 IWT are proposed:

1. (droplets supercooling) Change of the wind tunnel configuration in order to prevent break-up of droplets in the air flow and to achieve their desired degree of supercooling,
2. (droplet preparation system) Use of an additional precooler for the preliminary deep cooling of water supplied to the nozzles (the necessity of the measure will be determined in the process of making calculations),
3. (MVD) Perform calibration tests of water spray nozzles available to obtain the required droplet diameter. Perhaps it will be necessary to manufacture water-spray nozzles of a new design and a new type Spray Bar System (SBS),

During IWT calibration the following instruments are planned for application:

1. For PSD measurements the CCP probe and Mastersizer-X are planned to use,
2. For droplets supercooling extent estimation the three-cylinder method is planned to apply,
3. For LWC uniformity assessment the measuring grid is applied,
4. For LWC measurements the CCP probe and KLWC-5 probe are planned to use.

5.6.6 Remaining gaps after improvements

After successful implementation of planned improvements to CIAM C-2 facility FZDZ conditions would be available for simulation. FZRA conditions could be still missing as the maximum size of the droplets in the spectra is very high.

The existing layout of the IWT allows to simulate FZDZ conditions with the required degree of droplets supercooling state for the SAT (Static Air Temperature) range from -10 to -25°C. After the process of improving the IWT configuration the SAT range to provide the required degree of droplets supercooling would be changed to -5...-25°C. With temperatures higher than -5°C supercooled state of large droplet (bigger than 300µm) could be not reachable.

Planned lowering of LWC available for simulation will be quite difficult to achieve, especially at low airspeeds.

Depending on droplet sizes, difference in droplet trajectories could lead to a large degree of irregularity in cloud uniformity referring to PSD and LWC. As a result, the final area of test section suitable for test object installation could be much smaller than the whole IWT section area.

The ability of facility to simulate FZRA conditions could be estimated only after all the improvements to the IWT configuration and SBS are implemented as PSD of spectra in Appendix O is quite difficult to model as well as providing supercooled state of large droplets.

5.6.7 Parameters list

During the wind tunnel testing, it will be acquired IWT parameters related to the airflow and to the Spray Bar System (SBS). Cloud conditions, as defined by MVD and LWC, will not be directly measured during the tests. Cloud condition is related to the airflow parameters and water feeding pressure through analytical equations developed as result of cloud calibration process that will be reported within D6.4 "Report on FZDZ calibration for each IWT involved in the project". A list of parameters available will include:

Speed
Mach
Static Temperature
Total temperature
Liquid Water Content
MVD
PSD
Droplet temperature
Air density
Static Pressure
Dynamic Pressure
Total Pressure
Altitude
Relative Humidity
Water injection pressure
Water injection temperature
Cp distribution
Test specimen orientation (angles of yaw, pitch, roll)
Model balance (aerodynamic forces & coefficient)
BL transition (visualization nice to have)
Pressure and mass flow for hot air line (IPS)
Air temperature for hot line (IPS)
Power supply for electrical IPS heat regulation
video
Photos

5.7 The National Research Council Canada, Altitude Icing wind tunnel

The AIWT is a refrigerated closed-loop low-speed wind tunnel oriented in a vertical plane as shown in figure 35. The wind tunnel has two test sections available, a 57 cm wide by 57 cm high test section with a demonstrated top simulated wind speed of over 100 m/s (195 kt) and a profiled insert, 52 cm wide by 33 cm high, that increases the top wind speed to 180 m/s (350 kts).

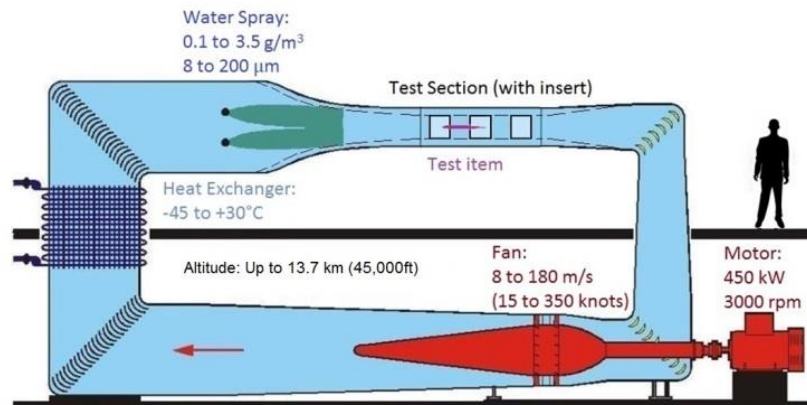


Figure 35: NRC-AIWT schematic diagram

The air temperature in the AIWT is controlled by varying the amount of chilled trichloroethylene¹ passing through a heat exchanger located in the tunnel circuit, resulting in achievable static air temperatures at Mach 0.3 ranging from -57°C to $+20^{\circ}\text{C}$ or warmer.

A vacuum pump can be used to evacuate a portion of the air in the tunnel. By controlling the amount of evacuated airflow, the pressure in the tunnel can be controlled between about 101 to 19 kPa. This permits simulations of flight at altitudes between ground level and 40,000 ft (table 25).

The tunnel airspeed is calculated through the use of total temperature and total pressure sensors located just upstream of the spray bars in the settling chamber as well as static pressure ports located at the entry of the AIWT test section. More detailed information on this facility is provided by Oleskiw et al [6].

Test section	Size H (m) x W (m) x L (m)	Airspeed (m/s)	SAT ($^{\circ}\text{C}$)	Altitude (m)
Full size	0.57 x 0.57 x 1.8	10 to 100	to -40	to 12,000
High speed	0.52 x 0.33 x 0.61	10 to 180	to -57	to 12,000

Table 25: NRC-AIWT test sections configurations and achievable airflow performance.

5.7.1 Icing Cloud Performance

Under normal operation of the AIWT, the spray distribution is provided by an array of up to 30 individual air atomising nozzles² installed on a spray bar assembly located in the settling chamber of the wind tunnel. These nozzles are fed via water flow controllers (one per spray bar) and a common

¹ Trichloroethylene has since been replaced as part of the AIWT cooling system

² Spraying Systems 2050 water nozzles with 120 air caps

air supply that can be adjusted to provide uniform spray distributions with LWC from less than 0.1g/m^3 to over 3g/m^3 and MVDs up to $150\ \mu\text{m}$.

In order to offer a spray profile that contains two distinct peaks of LWC over a range of droplet sizes (i.e., bi-modal distribution) two spray profiles with differing LWC and MVD are simultaneously injected into the flow of the AIWT.

5.7.1.1 Modification to the AIWT spray bars

4 of the 6 available spray bars are designated as belonging to either the “primary” or “secondary” water/air supply systems. In this configuration, all nozzles designated as “primary” are connected to the main air supply system of the AIWT while secondary nozzles are connected to an auxiliary air supply. Both air supplies are regulated by dedicated automated control valves and both have flow rate measured via mass flow rate meters installed in the air supply lines. With this set up, it was possible to provide a spray from 2 sets of nozzles that had different MVD and LWC settings.

Table 26 shows the SLD cloud conditions achievable with current SBS for each test section configuration.

Test section	MVD max (μm)	Max drop dia. (μm)	Droplet size distribution				LWC max (g/m^3)
			FZDZ-In	FZDZ-Out	FZRA-In	FZRA-Out	
Full test section	250	>500	yes	yes	yes	no	3

Table 26: NRC-AIWT achievable SLD cloud conditions.

5.7.2 Icing Instrumentation

This section reports detailed information on the instrumentation available in NRC-AIWT for the cloud calibration. In particular, there are three categories of icing instrumentation used for MVD/PSD, LWC, and cloud uniformity assessment.

5.7.2.1 Particle size instrumentation

A Malvern Spraytec particle size analyzer was used to measure and analyze the drop size spectrum. This is the AIWT main instrument for drop size measurements and facility calibration and has the ability to measure drop sizes from less than $10\ \mu\text{m}$ up to 2.5mm (table 27).

Instrument	Method	Size range	resolution	Sampling rate	Issues	Comment
Malvern Spraytec	Laser light scattering	10 – 2500 μm		1 – 10Hz		

Table 27: Particle spectrometers used at NRC-AIWT for cloud calibration

5.7.2.2 LWC/TWC instruments

The instrumentation available for bulk LWC/TWC measurement are listed in below table 28.

Instrument	Method	LWC/TWC range	Airspeed range	Sensing head size	Control DAS &	Data update rate
Rotating cylinders	Ice accretion	0.01 to 4 (depends on ludlam limit)	10 – 180m/s	2.81mm – 50mm diameter	N/A	N/A
Airfoil	Airfoil leading edge thickness	See above	See above	0.46m NACA 0012	N/A	N/A
King probe	Hot wire	0.01 - 1	10 - 100		SEA control system	1hz
Multi-wire	Hot wire	.1 – 1.5	10 - 180		See above	

Table 28: Instruments available at NRC-AIWT for LWC/TWC measurement

5.7.2.3 Cloud uniformity methods

The Icing Grid is the standard calibration system used in NRC-AIWT for cloud uniformity and coverage and has an array of 1.5mm thick “webs” that span across the test section to which the supercooled water cloud accretes. An example of an icing grid in the full test section of the AIWT is shown in the figure 36 below. After exposure to the cloud, ice thickness is measured across the grid and LWC calculated considering the heat balance between cooling and heating terms necessary for the formation rime ice.

In addition to the icing grid uniformity is also measured using a king probe attached to a traversing rig attached the outside of the tunnel. This enables the king probe to span the test section, the resulting measurements are then referenced to the LWC at the tunnel centre line.



Figure 36: Ice uniformity measurements using an icing grid in the full test section of the AIWT

5.7.3 Improvements of SLD cloud conditions

The AIWT has demonstrated the ability to provide a fully bi-modal spray for both freeze drizzle with $40\mu\text{m} < \text{MVD} > 40\mu\text{m}$ at low LWC's consistent with atmospheric SLD conditions e.g., $< 0.5\text{g}/\text{m}^3$. Recent

developments with new spray nozzles that provide large drop diameter, have indicated that both freezing rain SLD conditions (i.e., $40 \mu\text{m} < \text{MVD} < 40 \mu\text{m}$) can also be achieved. This is in the early stages of development and more calibration of the cloud is required.

The current bi-modal spray for freezing rain conditions compared to the Appendix O spray distribution is given in the figures 37 below.

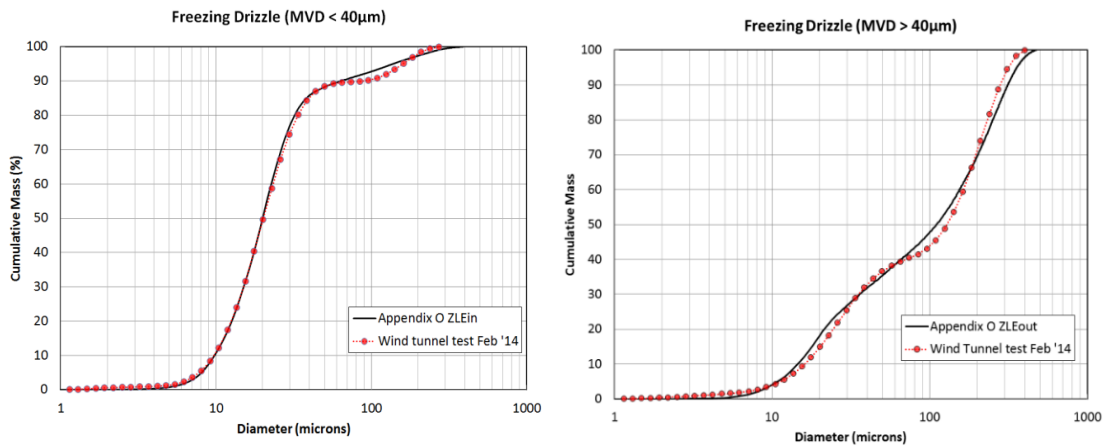


Figure 37: Freezing drizzle spray distribution compared to Appendix O.

5.8 Icing instrumentation from other partners

This section reports detailed information on the instrumentation available from partners beside the facility owners. These instruments will be used to mitigate gaps of the facilities' instrumentation. During WP4 the instrumentation will be characterized and assessed in detail. The definition of requirements for the installation of the instruments at each facility will be done within WP6.

5.8.1 Particle size instrumentation

The instrumentation available for MVD and PSD characterization are based on different measurement methodologies and its selection is based on the cloud conditions defined by Appendix C and Appendix O (table 29).

Instrument	Method	Size range	resolution	Sampling rate	Issues	Comment
CAPS: Cloud and Aerosol Spectrometer	forward and backward scattering technique (CAS-DPOL part); optical array probe (CIP part)	CAS: 0.5 - 50 μm , CIP: 7.5 - 950 μm	CAS: irregular according to Mie theory, CIP: 15 μm	0.05 - 25 Hz		provided by DLR
FCDP/2D-S combination: Fast Cloud Droplet Probe/2D Stereo Probe	forward scattering technique (FCDP part); optical array probe (2D-S part)	FCDP: 2 - 50 μm , 2D-S: 10 μm - 1.28 mm	FCDP: 3 μm , 2D-S: 10 μm	single particle		provided by DLR

Table 29: Particle spectrometers that can be used in a wind tunnel facility for cloud calibration

5.8.2 LWC/TWC instruments

The instrumentation available for bulk LWC/TWC measurement is listed below in 30.

Instrument	Method	LWC/TWC range	Airspeed range	Sensing head size	Control & DAS	Data update rate	Comment
IKP: Isokinetic Probe	forward facing inlet: isokinetic evaporation of particles and droplets; backward facing inlet: analysing gas phase water vapor	0-5 g/m ³ (TAS < 120m/s) 0-3 g/m ³ (TAS < 200m/s)	without correction up to 100-110 m/s	0.7 m length		1 Hz	provided by CU
Nevezorov Probe	hot wire sensor cone	0.003 - 3 g/m ³	10 - 180 m/s	23cm x 9cm x 5cm		10 Hz	provided by DLR/CNRS

<p>CR-2/WVSS-II combination: Cryogenic Hygrometer/ Water Vapor Sensing System</p>	<p>CR-2: dew/frost point hygrometer (backward facing inlet for gas phase water vapor); WVSS-II: Infrared absorption of laser radiation (forward facing inlet for evaporation of particles and droplets)</p>	<p>0.001 - 1 g/m³</p>	<p>10 - 180 m/s</p>			<p>0.3 Hz</p>	<p>provided by DLR</p>
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Table 30: Instruments available for LWC/TWC measurement in a wind tunnel facility.

6 Conclusions

This deliverable highlights the requirements that must be achieved from the upgrade of the Icing Wind Tunnels to be in compliance with the FAR / CS-25 Appendix O for the Freezing Drizzle environment. In addition, the target requirements defined by manufacturers provide the priorities to attend during the cloud calibration phase (WP6) in order to overlap with expected conditions defined in the test matrix (D3.2 and D3.3) finalized to the collection of the database.

The table 31 below shows the expected progress that will be achieved on the test facilities capabilities at the end of the project.

	IWT facility	CIRA-IWT MTS	MinDef ATF	RTA-IWT	TsAGI AHT-SD	TsAGI EU-1	CIAM C-2	NRC AIWT
Current performance	Altitude	Up to 7000 m	Up to 10000 m	Sea level			Up to 15000 m	
	Static Air Temperature Range	> -32 °C	> -65°C	> -30°C			> -40 °C	
	Airspeed (Mach number)	< 0.4	< 0.8	< 0.25			< 0.6	
	FZDZ_In	no available						
	bi-modal PSD (Y/N)		Y	N			N	
	LWC range (g m ⁻³)		Above 0.1 g m ⁻³ for M>0.2	0.1 - 0.6			0,1 - 0,44	
	MVD range (µm)		Max : 500 (M<0.4)	20 - 40			20 - 40	
	FZDZ_Out	no available					not available	
	bi-modal PSD (Y/N)		Y	Y			Y	
	LWC range (g m ⁻³)		Above 0.1 g m ⁻³ for M>0.2	0.4 - 0.6				
MVD range (µm)		Max : 500 (M<0.4)	100 - 120					
Expected performance after improvements	Altitude	Up to 7000 m	Up to 10000 m	Sea level			Up to 15000 m	
	Static Air Temperature Range	> -32 °C	> -65°C	> -30°C			> -40 °C	
	Airspeed (Mach number)	< 0.4	< 0.8	< 0.25			< 0.6	
	FZDZ_In							
	bi-modal PSD (Y/N)	Y	Y	Y			Y	
	LWC range (g m ⁻³)	0,1 - 0,4	Above 0.1 g m ⁻³ for M>0.2	0.1 - 0.4			0,1 - 0,44	
	MVD range (µm)	20 - 40	Max : 500 (M<0.4)	20 - 40			20 - 40	
	FZDZ_Out	no available						
	bi-modal PSD (Y/N)	Y	Y	Y			Y	
	LWC range (g m ⁻³)	0,1 - 0,4	Above 0.1 g m ⁻³ for M>0.2	0.1 - 0.4			0,1 - 0,44	
MVD range (µm)	45 - 100	Max : 500 (M<0.4)	80 - 120			40 - 110		

Table 31: ICE-GENESIS progress beyond the state of the art for icing wind tunnel

An important collaboration between the WP4 and WP6 teams will be on the base for the selection of candidate instruments based on laboratory activities aimed to characterize their sampling area and verify their measurable particle size range. The best instruments will be selected to support the wind tunnel calibrations.

7 Bibliography

1. 14 CFR Parts 25 and 33 “Airplane and Engine Certification Requirements in Supercooled Large Drop, Mixed Phase, and Ice Crystal Icing Conditions; Final Rule”, Vol 79, No. 273, November 4, 2014.
2. DOT/FAA/AR-09/10, Data and “Analysis for the Development of an Engineering Standard for Supercooled Large Drop Conditions”, Final Report, March 2009.
3. Cober, S.G. and Isaac, G.A., “Characterization of Aircraft Icing Environments with Supercooled Large Drops for Application to Commercial Aircraft Certification”, Journal of Applied Meteorology and Climatology, Volume 51, 265-284, 2012.
4. Di Arthur H. Lefebvre, Vincent G. McDonell, “Atomization and Sprays” CRC Press, 27 mar 2017
5. Aerospace Recommended Practice SAE ARP5905 “Calibration and Acceptance of Icing Wind Tunnels”, Sept. 2003.
6. Oleskiw et al “In-flight icing simulation capabilities of NRC’s Altitude Icing Wind Tunnel”, AIAA 2001-0094, 39th AIAA Aerospace Sciences and Meeting Exhibit, January 2001, Reno NV.