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Deliverable D3.5

Definition of the target requirements for test facilities operating envelopes for snow

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Glossary

Abbreviation / Acronym	Description/meaning
A/C	Aircraft
F/T	Flight Tests
H/C	Helicopter
IGE	In Ground Effect
IWC	Ice Water Content (g/m^3)
LWC	Liquid Water Content (g/m^3)
LWE	Liquid Water Equivalent (g/m^3)
MMD	Median Mass Diameter (µm)
MSD	Mass Size Distribution
MVD	Median Volumetric Diameter (µm)
OGE	Out of Ground Effect
PIP	Precipitation Imaging Probe
PSD	Particle Size Distribution
SAT	Static Air Temperature (°C, °K)
SMART	Specific, Measurable, Achievable, Relevant, and Time-Bound
SPC	Snow Particle Counter
TAT	Total Air Temperature (°C, °K)
TWC	Total Water Content (g/m^3)

1. EXECUTIVE SUMMARY

Service history has shown that in-flight snow conditions have caused power interruptions on some engines with air intakes that incorporate plenum chambers, reverse flow, or particle separating design features. For instance, in the early 1980s, U.S. Coast Guard HH-65A Dolphin experienced a few unexpected cases of engine surge during demonstration tests and the problem took two years to correct.

To comply with certification requirements, manufacturers need to substantiate that each engine and its air inlet system can operate throughout the flight power range of the engine (including idling) in snow, both falling and blowing, without adverse effect on engine operation (power or thrust loss, surge, stall or flameout), within the established limitations (CS25/29, §1093(b)). The available regulatory, research and guidance documents define approximations of snow conditions to be tested when testing is required. However, there are no validated engineering tools (test facility and numerical tools) available to support design of power plant systems by assessing the risk of snow accretion or accumulation. Demonstration is thus performed at the end of the program development during certification flights. Any issue found at this stage of the development can lead to significant delay and cost to redesign the air inlet or integrate protection systems and can even impact the entry into service of new product. Therefore, to secure future program development and certification, there is a need to develop snow test capability to de-risk power plant system design before in-flight demonstration.

A few test facilities, such as RTA or CSTB, are already able to generate artificial snow using atomising nozzles and by controlling the ambient temperature, wind speed, and water and air supply. However, the generated artificial snow does not match natural snow properties (e.g. size, shape and density) and as such this capability cannot be used as a sole means of compliance or development tool during the design phase. To show compliance to CS 23/25/27/29, flight tests in natural snowstorms, beside their intrinsic risk, are difficult to schedule due to the rarity of events, fewer than 4% of all snowstorms conform to the requirements reported in the AMC, and cannot be used during the preliminary design phase.

Investigating a technology able to generate naturally equivalent snow is, as such, one of the main objectives of the ICE GENESIS project.

The current document provides the technical requirements for falling and blowing snow conditions to be reproduced in ground wind tunnel facilities. These requirements intend to cover all the different parts of the rotorcraft and aircraft affected by snow with a focus on power plant system.

This document will be also a guideline for test facilities development and will help the different partners within WP7 to define improvements and upgrades of the tests rigs as well as procedures and controls to achieve as much as possible a good reproduction of falling and blowing snow conditions.

2. INTRODUCTION

A few test facilities, such as RTA or CSTB, are already able to generate artificial snow using atomising nozzles and by controlling the ambient temperature, wind speed, and water and air supply. However, the generated artificial snow does not match natural snow properties (e.g. size, shape and density) and as such this capability cannot be used as a sole means of compliance or development tool during the design phase. To show compliance to CS 23/25/27/29, flight tests in natural snowstorms, beside their intrinsic risk, are difficult to schedule due to the rarity of events and cannot be used during the preliminary design phase.

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The current document provides the technical requirements for falling and blowing snow conditions to be reproduced in ground wind tunnel facilities. These requirements intend to cover all the different parts of the rotorcraft and aircraft affected by snow with a focus on power plant system.

In a first section, the issues related to the operation of rotorcraft and aircraft in falling and blowing snow conditions are recalled as well as certification requirements as defined in CS25/27/29/E. Then, some preliminary findings about snow conditions and snowflake characteristics are presented based on literature review and Airbus Helicopters in-flight measurements. Finally, the key parameters and requirements to be considered for simulation of falling and blowing snow conditions in ground facilities are defined along with priority level (from “*nice to have*” to “*essential*”).

This document will be a guideline for test facilities development and will help the different partners within WP7 to define improvements and upgrades of the tests rigs as well as procedures and controls to achieve as much as possible a good reproduction of falling and blowing snow conditions.

3. PROBLEM DEFINITION

3.1 ROTORCRAFT

Service history has shown that in-flight snow conditions have caused power interruptions on some engines with air intakes that incorporate plenum chambers, reverse flow, or particle separating design features. For instance, in the early 1980s, U.S. Coast Guard HH-65A Dolphin experienced a few unexpected cases of engine surge during demonstration tests and the problem took two years to correct.

To comply with certification requirements, manufacturers need to substantiate that each engine and its air inlet system can operate throughout the flight power range of the engine (including idling) in snow, both falling and blowing, without adverse effect on engine operation (power or thrust loss, surge, stall or flameout), within the established limitations (CS29, §1093(b)). The available regulatory, research and guidance documents define approximations of snow conditions to be tested when testing is required. However, there are no validated engineering tools (test facility and numerical tools) available to support design of power plant systems by assessing the risk of snow accretion or accumulation. Demonstration is thus performed at the end of the program development during certification flights. Any issue found at this stage of the development can lead to significant delay and cost to redesign the air inlet or integrate protection systems and can even impact the entry into service of new product. Therefore, to secure future program development and certification, there is a need to develop snow test capability to de-risk power plant system design before in-flight demonstration.

Figure 1 presents typical rotorcraft flight envelope.

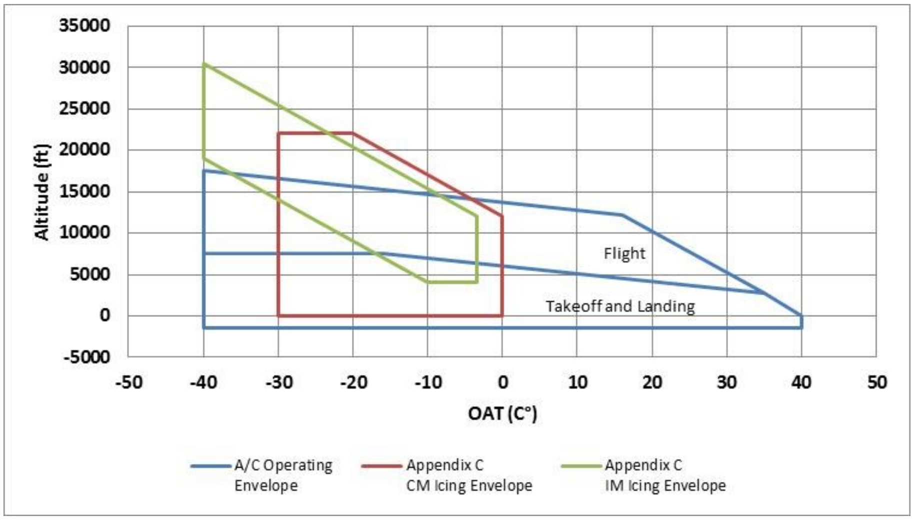

Figure 1: H/C typical flight envelope

Figure *3* illustrates rotorcraft flight tests in both falling and blowing snow conditions.

Figure 2: H/C flight tests in snow conditions

Figure 3: H/C flight tests in blowing snow conditions

3.2 ENGINE [42]

The FAA's Flight Standards Division regulates aircraft operators' ground based operations in icing conditions under 14 CFR 121.629. For the winter of 2014-2015, the FAA is considering incorporating guidance in the notice on allowing the use of LWE systems to provide holdover times in heavy snow operations.

In 2004 and 2005 the FAA sponsored an Aviation Rulemaking Advisory Committee (ARAC) that tasked the Engine Harmonization Working Group (EHWG) to review propulsion system icing service experience in order to recommend any potential changes to the airworthiness regulations. The EHWG concluded that the two estimates of precipitation rate (using visibility calculations of reference or using a 2.5 mm/hr accumulation rate along with a 0.8 m/s fall rate) are similar, and consequently, 0.9 g/m^3 became the recommended level for testing at ground idle in snow. The value of 0.9 g/m^3 atmospheric snow concentration was assumed to correspond to the limit for moderate snow conditions. Recent developments are challenging that assumption and ground operations in heavy snow conditions are recognized as more likely to occur. Indeed, 1.8g/m^3 is expected for Heavy Snow Operation.

3.3 REGULATION AND ADVISORY MATERIAL

3.3.1 Rotorcraft

H/C manufacturers need to demonstrate safe operations in falling and blowing snow conditions according to CS29.1093. Demonstration relies mainly on F/T.

For H/C Snow certification or Limited Icing certification, Applicant must demonstrate according to AC29-2C (§29.1093)

> *"For unrestricted flight capability into Full snow conditions, both falling and blowing, the applicant should show that each engine, and its inlet system, will operate satisfactorily throughout the flight power range of the engine and within the operating limitations of the rotorcraft. The applicant should show that any build-up or accumulation of snow will not reduce or block the flow of inlet air to the engine. Any accumulations that become dislodged should not affect engine operation."*

The available regulations (CS29) and guidance material (AC, AMC) provide recommendations for the types of snow conditions to be tested, if tests are required. However the conditions are less detailed than for other icing conditions especially with regards to Particle Size Distribution (PSD), density or wet/dry snowflake characteristics.

At most, Advisory Circular AC29-2C [5] defines minimum information on the temperature range to be considered [-4°C - +1°C] and a visibility criterion representative of snow water content (1/4-mile or less as limited by snow or about 0,9g/m^3):

> *"Engine induction system operation in falling and blowing snow can be approved without restriction if normal operations under the following conditions are demonstrated:*
>
> *FULL FALLING & BLOWING SNOW CONDITIONS*
>
> *Visibility: ¼-mile or less as limited by snow.*
>
> *Temperature: 25°F (-4°C) to 34°F (+1°C) [28°F (-2°C) to 34°F (+1°C) desired], unless other temperatures are deemed critical.*
>
> *Operations: Ground operations - 20 minutes. IGE hover - 5 minutes. Level flight - 1 hour. Descent and landing."*

The AC29-2C also states that "*Artificially produced snow is not sufficiently similar to natural snowflakes to justify the use of artificial snow as the sole basis of certification*"

3.3.2 Aircraft

A/C manufacturers need to demonstrate safe operations in falling and blowing snow conditions according to CS25.1093.

"Each Turbine engine, with all icing protection systems operating, must:

(1) Operate throughout its flight power range, including the minimum descent idling speeds, in the icing conditions defined in Appendices C, O and P, and in falling and blowing snow within the limitations established for the aeroplane for such operation, without the accumulation of ice on the engine, air intake system components or airframe components that would do any of the following:

> *(i) Adversely affect installed engine operation or cause a sustained loss of power or thrust; or an unacceptable increase in gas path operating temperature; or an airframe/engine incompatibility; or*
>
> *(ii) Result in unacceptable temporary power or thrust loss or engine damage; or*
>
> *(iii) Cause a stall, surge, or flameout or loss of engine controllability (for example, rollback).”*

AMC 25.1093 (b) precises:

“1.6.4 For turbojet and turbofan engines with traditional Pitot (straight duct) type air intakes, icing conditions are generally regarded as a more critical case than falling and blowing snow. For these types of air intake, compliance with the icing specifications (at least including the icing environment of Appendix C to CS-25) will be accepted in lieu of any specific snow testing or analysis

1.6.5 For non-Pitot type air intakes, demonstration of compliance with the falling and blowing snow specification on ground should be conducted by tests and/or analysis. If acceptable powerplant operation can be shown in the following conditions, no take-off restriction on the operation of the aeroplane in snow will be necessary.

> *a. Visibility: 0.4 Km or less as limited by snow, provided this low visibility is only due to falling snow (i.e. no fog). This condition corresponds approximately to 1 g/m3.*
>
> *b. Temperatures: − 3 °C to + 2 °C for wet (sticky) snow and – 9 °C to – 2 °C for dry snow, unless other temperatures are found to be critical (e.g. where dry snow at a lower temperature could cause runback ice where it contacts a heated surface).*
>
> *c. Blowing snow: Where tests are conducted, the effects of blowing snow may be simulated by taxiing the aircraft at 15 to 25 kts, or by using another aircraft to blow snow over the test powerplant. This condition corresponds approximately to 3 g/m3.*
>
> *d. Duration: It must be shown that there is no accumulation of snow or slush in the engine, air intake system or on airframe components, which would adversely affect engine operation during any intended ground operation. Compliance evidence should consider a duration which corresponds to the achievement of a steady state condition of accretion and (possible) shedding. Any snow shedding should be acceptable to the engine.”*

3.3.3 Engine

Engine manufacturers need to demonstrate, according to CS-E.780, that the Engine will function satisfactorily when operated throughout the conditions of atmospheric icing (including freezing fog on ground) and falling and blowing snow of the Certification Specifications applicable to the aircraft on which the Engine is to be installed.

“It must be established by tests, unless alternative appropriate evidence is available, that the Engine will function satisfactorily when operated throughout the conditions of atmospheric icing (including freezing fog on ground) and falling and blowing snow defined in the turbine Engines air intake system ice protection specifications (CS-23.1093(b), CS-25.1093(b), CS-27.1093(b) or CS-29.1093(b)) of the Certification Specifications applicable to the aircraft on which the Engine is to be installed, as specified in CS-E 20(b), without unacceptable:

(1) Immediate or ultimate reduction of Engine performance,

(2) Increase of Engine operating temperatures,

(3) Deterioration of Engine handling characteristics, and

(4) Mechanical damage.”

AMC E.780 precises:

“(1.6) Applicable Icing Environments

The applicable icing environments are those applicable to the aircraft on which the Engine is to be installed, defined in CS 23.1093(b), CS 25.1093(b), CS 27.1093(b) and CS 29.1093(b), as appropriate. This includes atmospheric icing conditions (including freezing fog on ground) and falling and blowing snow conditions. Falling and blowing snow conditions are defined in AMC 25.1093(b).

(2.3) Establishment of Test Points for Ground Operation

The Engine should demonstrate the ability to operate acceptably at minimum ground idle speed to be approved for use in icing conditions for a minimum of 30 minutes at each of the following icing conditions shown in Table 2, with the available air bleed for ice protection at its critical condition, without adverse effect.

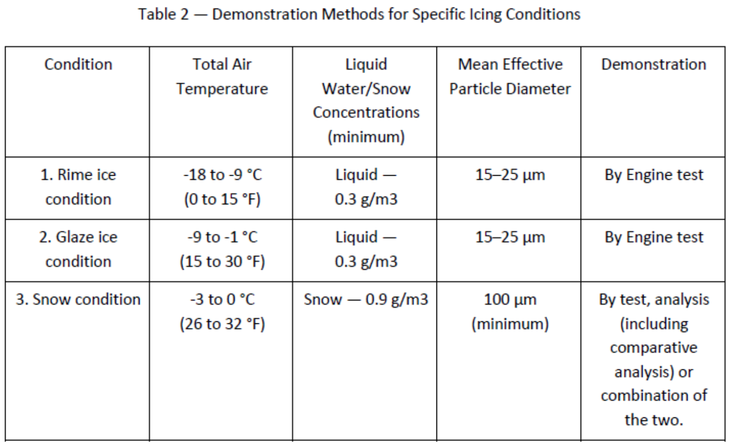

Table 2 — Demonstration Methods for Specific Icing Conditions

Condition	Total Air Temperature	Liquid Water/Snow Concentrations (minimum)	Mean Effective Particle Diameter	Demonstration
1. Rime ice condition	-18 to -9 °C (0 to 15 °F)	Liquid — 0.3 g/m3	15–25 µm	By Engine test
2. Glaze ice condition	-9 to -1 °C (15 to 30 °F)	Liquid — 0.3 g/m3	15–25 µm	By Engine test
3. Snow condition	-3 to 0 °C (26 to 32 °F)	Snow — 0.9 g/m3	100 µm (minimum)	By test, analysis (including comparative analysis) or combination of the two.

”

4. SNOW CONDITIONS

Snowflakes, also called snow crystals, are aggregates of many single ice crystals. In nature, ice crystals often form in mixed-phase clouds, where nucleated ice crystals grow via water vapour deposition at the expense of evaporating supercooled liquid water droplets once the environment becomes sub-saturated with respect to water. This so called Bergeron-Findeisen effect corresponds to a net transport of water vapour from the liquid to the ice phase; in this phase transition, water vapour transforms directly into solid [6] . The shape of the ice crystals depends on the temperature and humidity of the clouds, with a large variety of resulting crystal shapes. The “Snow Crystal Morphology Diagram” from Furukawa and Wettäufer (2007) [7] classifies the shapes into (1) plates and dendrites (from 0 to -3 °C), (2) needles, columns and prisms (from -3 to -10 °C), (3) solid, thin, and sectored plates and dendrites (from -10 to -22 °C), and finally solid plates and columns (below -22 °C), according to cloud temperature and water vapour content. In addition to crystal growth from pure water vapour deposition, aggregation and riming growth modes generate highly irregular shaped larger ice crystals.

Finally, snowflake aggregation mostly appears at air temperatures near 0°C[1] and is predominantly affected by the air temperature and the shape of the aggregating ice crystals. Columns and needles aggregate into rather small flakes, while aggregates of dendritic crystals tend to become large. Snowflake diameters [8] are mainly between 2 and 5 mm, ranging up to 15 mm. Snowflake density [9] varies, ranging from 0.005 to 0.2 g.cm^{-3}, being inversely proportional to snowflake diameter, i.e. the larger the flakes, the lower the density. This constant of proportionality between snowflake diameter and the density of the snowflake is almost four times larger for wet than for dry snowflakes.

The available regulations (CS25/29) and guidance material (AC, AMC) provide recommendations for the types of snow conditions to be tested, if tests are required. However the conditions are less detailed than for other icing conditions especially with regards to Particle Size Distribution (PSD), density or wet/dry snowflake characteristics.

Ground observations made during snow fall events show that the composition of snow particles varies from one observation site to another. In general, small particles account for more than one third of the total number of particles observed on ground. This is due to blowing snow and the proportion increases as the surface wind increases. If episodes of blowing snow are removed from the analysis, aggregates, graupels and small particles are the dominant types accounting for more than 85 % of the snow particles, regardless the location of the observation site.

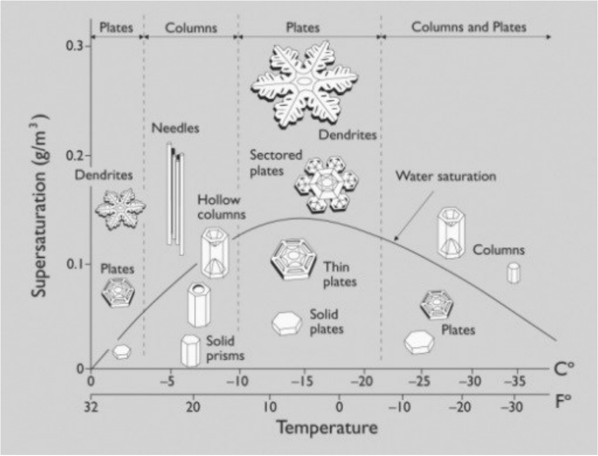

Figure 4: Snow Crystal Morphology Diagram

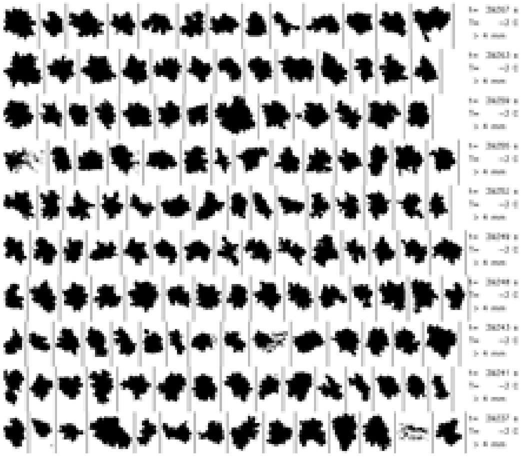

Figure 5: Representative snowflakes with sizes around 2 to 3 mm, obtained in flight test at -3°C (Source: Airbus Helicopters)

Additional information on snow microphysical properties are provided in the following deliverables:

- D5.7 / CNRS / Synthesis & Characterization of snow microphysical properties [44]

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[1] aggregation starts to be effective from -15°C to 0°C [36]

5. NEEDS AND REQUIREMENTS

5.1 REQUIREMENT LEVEL DEFINITION

The different expectations are classified according to the following definitions:

- **Essential** : any work cannot be performed without it and no alternatives exist;
- **Highly desirable** : The absence of this capability would have a significant impact on the potential of the tunnel to reproduce natural environment conditions although results can still be produced by other means;
- **Desirable** : this capability would improve the potential of the tunnel and the icing envelope of the test rig;
- **Nice to have** : this capability could be interesting but is not needed to achieve the main goals.

5.2 AIR FLOW

The following parameters are related to the onset flow or ambient conditions. Basically, the range of variation and the targeted values should be those of the H/C and A/C flight profiles.

5.2.1 Pressure or Altitude

Requirement	Classification	Comment
Pressure / Altitude capability	**Nice to have**	Low/mid altitude conditions. Altitude (ASL) ranges are [10]: Mid is between 5,000 and 20,000 ft (1.5-6 km), Low is below 5,000 ft (1.5 km).

Table 1: Air flow requirements – Altitude/Pressure

5.2.2 Velocity or Mach Number

Requirement	Classification	Comment
Velocity/Mach Range for H/C [20-150kts]	**Essential**	This requirement covers speed related to the following H/C flight phases and engines settings : • Ground Operations • IGE Hover • Level flight • Descent and Landing

Requirement	Classification	Comment
		Note: it is highly desirable to reach higher speed (up to 225-250kts) for future high speed helicopters Note: Fixed wing would require speeds up to 250knots

Table 2: Air flow requirements - Velocity

5.2.3 Temperature

Requirement	Classification	Comment
Static Temperature Range [-15°C ; +2°C]	**Essential**	As defined by regulation

Table 3: Air flow requirements - Temperature

5.2.4 Humidity

Requirement	Classification	Comment
Humidity monitoring	**Essential**	The icing facilities will insure by any acceptable means humidity monitoring and control. In wet conditions at negative temperature, classical values for relative humidity (around 100%) are expected. In case of engine environment, which means positive temperature and relative dry air, a few percent of relative humidity should be needed.
Humidity control	**Highly Desirable**	

Table 4: Air flow requirements - Humidity

5.3 SNOW CLOUD

Both mixed phase and solid phase conditions should be considered. So icing facilities should be capable to reproduce icing conditions representative of falling / blowing snow clouds and mixed phase with liquid and solid phases at the same time. Standard MVD definition will be used to define the requirement for the liquid phase. Taking into account the different means used to generate snowflakes as well as the different shapes observed in natural clouds, MMD_{eq} (2D area equivalent diameter) or MMD_{max} (maximum diameter) could be used for the requirement.

5.3.1 Falling/Blowing snow

Requirement	Classification	Comment
Falling snow	**Essential**	It is expected that particle morphology and PSD could be different between falling snow and blowing snow [33]. Indeed, falling snow particle population is dominated by Aggregates [44]
Blowing snow	**Highly Desirable**	
Mixed Phase (both liquid droplets and snowflakes)	**Desirable**	Even so regulatory material does not require investigation of mixed phase conditions, this capability could be useful

Table 5: Icing cloud requirements – Falling/Blowing snow

5.3.2 Dry/wet snow

Requirement	Classification	Comment
Dry snow	**Essential**	It is expected that particle morphology and particle density could be different between dry and wet snow [34]
Wet snow	**Essential**	

Table 6: Icing cloud requirements – Dry/Wet snow

5.3.3 Particle morphology

Requirement	Classification	Comment
Falling Snow / Particle morphology	**Highly Desirable**	Representative particle morphology and in any case particle morphology characterization from calibration The geometrical parameters to be considered are: D_{max}, D_{eq}, D_x, D_y, D_{mean}, Width, Area, Aspect Ratio, circularity [36], [44], [45], [46]. The snowflake population shall be classified. It is expected Aggregate (AG) and Graupel (GR) to dominate snowflake population. [33]
Blowing Snow / Particle morphology	**Desirable**	Representative particle morphology and in any case particle morphology characterization from calibration The geometrical parameters to be considered are: D_{max}, D_{eq}, D_x, D_y, D_{mean}, Width, Area, Aspect Ratio, fractal dimension [36].

Requirement	Classification	Comment
		The snowflake population shall be classified. It is expected blowing snow to have a larger number of small particles (SP) [33]

Table 7: Icing cloud requirements - Particle morphology

5.3.4 Particle sizes

Requirement	Classification	Comment
Falling Snow 1500µm $\leq MMD_{max} \leq$ 2500µm	**Highly Desirable**	Based on FAA report [10], Airbus Helicopters F/T measurement and ICE GENESIS ATR F/T measurements [43], [44], [45], [46]. MMD_{max} and MMD_{eq} show similar values.
Falling Snow 2000µm $\leq MVD_{eq} \leq$ 4000µm	**Highly Desirable**	Based on ICE GENESIS ATR F/T measurements [43], [44], [45], [46].
Blowing Snow 50µm $\leq MMD_{max} \leq$ 150µm	**Highly Desirable**	It is expected PSD for blowing snow to differ from falling snow: larger number of small particles (SP) with diameter ~ 100µm [33], [38], [39]
Mixed phase Snow: 1500µm $\leq MMD_{max} \leq$ 2500µm Water droplets: MVD= 15-50µm	**Desirable**	Falling snow is considered
Particle/Mass Size Distribution	**Highly Desirable**	Representative size distribution and in any case PSD/MSD from calibration

Table 8: Icing cloud requirements – Particle sizes (MMD, MVD)

5.3.5 Snow Density

5.3.5.1 Particle Effective Density

Requirement	Classification	Comment
Dry snow particle density	**Desirable**	Snowflake density has been shown to vary over two orders of magnitude, from 0.005 to 0.2 g cm^3, with the largest flakes having the lowest density (Magono and Nakamura 1965 [35]). For wet and/or rimed snowflakes, Rogers (1974) [34]

Requirement	Classification	Comment
Wet snow particle density	**Desirable**	showed that snowflake density was over four times larger than the dry snow. Rogers (1974) [34] as presented in Figure 6 or Baker & Lawson (2006) [16] are considered as an acceptable mass-diameter relationship where ICE GENESIS flight test data was in good agreement [44].

Table 9: Icing cloud requirements – Particle density

For wet and/or rimed snowflakes, Rogers (1974) [34] showed that snowflake density was over four times larger than the dry snow (Figure 6).

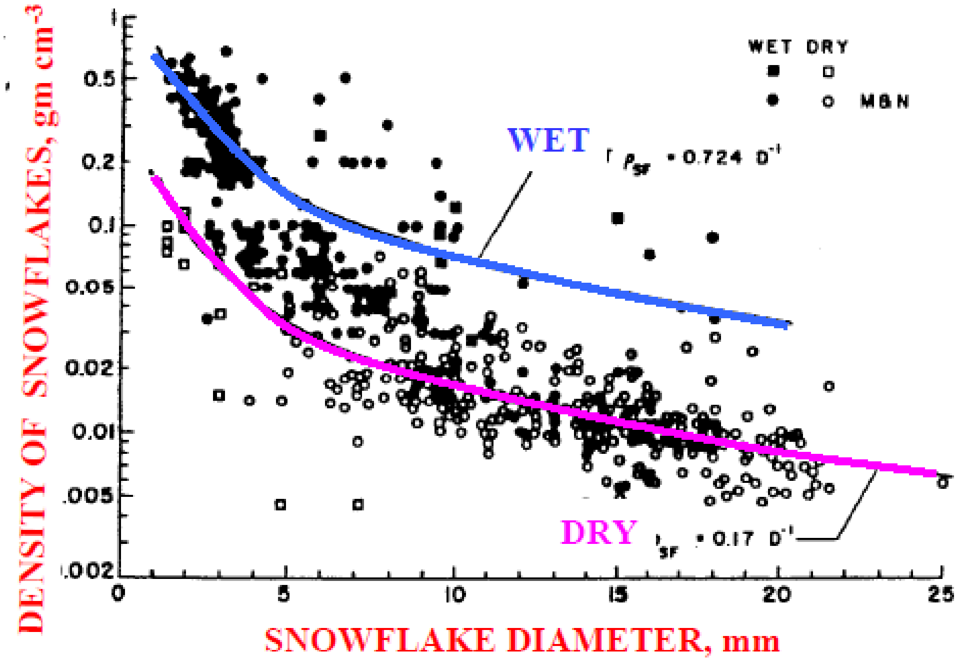

Figure 6: Average snowflake density [34]

5.3.5.2 Snow Bulk Density

Requirement		Classification	Comment
Falling Snow	Dry snow 40 kg.m^{-3} ≤$\rho_{snow,dry}$≤ 170 kg.m^{-3}	**Highly Desirable**	Based on [40], [41] and [9]. This requirement is consistent with §5.3.5.1 Particle Effective Density Values are adapted to fit with §5.3.4 Particle sizes : 1500µm ≤MMD$_{max}$≤ 2500µm
	Wet snow	**Highly Desirable**	

Requirement		Classification	Comment
	$180\ kg.m^{-3} \leq \rho_{snow,wet} \leq 720\ kg.m^{-3}$		Margin was taken into account by considering a size range of [1000 – 4000] µm
Blowing Snow	Dry / Wet snow $570\ kg.m^{-3} \leq \rho_{snow,dry} \leq 917\ kg.m^{-3}$	**Highly Desirable**	Upper value limited to 917 kg.m^{-3} Margin was taken into account by considering a size range of [50 – 300] µm

Table 10: Icing cloud requirements – Snow bulk density

5.3.6 Water Content

Water content should be addressed by considering liquid phase, solid phase and Total Water Content. Figures provided are in line with regulatory material presented in §3.2.

Requirement	Classification	Comment
Falling Snow (solid phase only) [0.5– 1g/m^3]	**Essential**	Ice water Content up to 0.9g/m^3 for H/C application (CS27/29, CS25 falling snow) 1.8g/m^3 expected for Heavy Snow Operation
Blowing Snow (solid phase only) [0.5– 3g/m^3]	**Highly Desirable**	Ice water Content up to 3g/m^3 for A/C application (CS25, blowing snow). Similar IWC is expected for rotorcraft in recirculating snow (rotor effect in hover)
Mixed phase conditions	**Desirable**	Ice water Content up to 0.9g/m^3 for H/C application (CS27/29, CS25 falling snow) and 3g/m^3 for A/C application (CS25, blowing snow) Liquid Water Content ≤ 1g/m^3.

Table 11: Icing cloud requirements – Water Content

5.3.7 Test Duration

Basically, test duration relies on guidance material presented in §3.2

Requirement	Classification	Comment
Test duration [5 – 60min]	**Essential**	For rotorcraft, up to 60 min according to AC29-2C: • Ground operations - 20 minutes, 0.91g/m^3, <20kts • IGE hover - 5 minutes, 0.91g/m^3, <20kts • Level flight - 1 hour, 0.91g/m^3, 80-150kts

Requirement	Classification	Comment
		- Descent and landing, 0.91g/m^3, < 40-80kts For fixed wing, up to 240 min - Ground operations - 240 minutes, 0.91g/m3, <20kts - Descent and landing – 10 minutes, 0.91g/m3, < 250kts

Table 12: Icing cloud requirements – Test duration

5.4 CONTINUITY CHECK

Characterization of microphysical properties of simulated falling and blowing snow conditions are not sufficient to validate snow test capability. Indeed, it is not possible to assess impact of any discrepancy vs natural falling and blowing snow characteristics on snow accretion phenomena. Alternative SMART criteria is needed:

Requirement	Classification	Comment
To demonstrate that test facility is able to reproduce snow accretion phenomena: - Snow / no snow accretion - Volume / mass - Growth rate - Shedding - etc…	**Essential**	The tunnel might have slightly different conditions to simulate the accretion. For instance, nature has more time to melt crystals compared to a tunnel. Therefore, to have the same wetness, higher temperatures may be required in a tunnel. Note: Only qualitative data was collected during ICE GENESIS ATR42 flight test campaign [43]. Additional data should be collected in the future to support validation of the capability.

Table 13: Continuity Check requirements

6. CONCLUSION

The current document provides the preliminary technical requirements for falling and blowing snow conditions to be reproduced in ground wind tunnel facilities. These requirements intend to cover all the different parts of the rotorcraft and aircraft affected by snow with a focus on power plant system.

This document will be also a guideline for test facilities development and will help the different partners within WP7 to define improvements and upgrades of the tests rigs as well as procedures and controls to achieve as much as possible a good reproduction of falling and blowing snow conditions.

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8. ANNEXE 1: TEST FACILITIES

8.1 RTA ICING WIND TUNNEL

The RTA IWT is a closed loop, climatic wind tunnel. A schematic of the wind tunnel is shown in Figure 16. Depending on the required cross section and wind speed range, two different configurations can be provided (see Figure 17). 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°. The RTA IWT is calibrated for CS25 / CS 29 Appendix C cloud conditions according to SAE ARP 5905 Calibration and Acceptance of Icing Wind Tunnels.

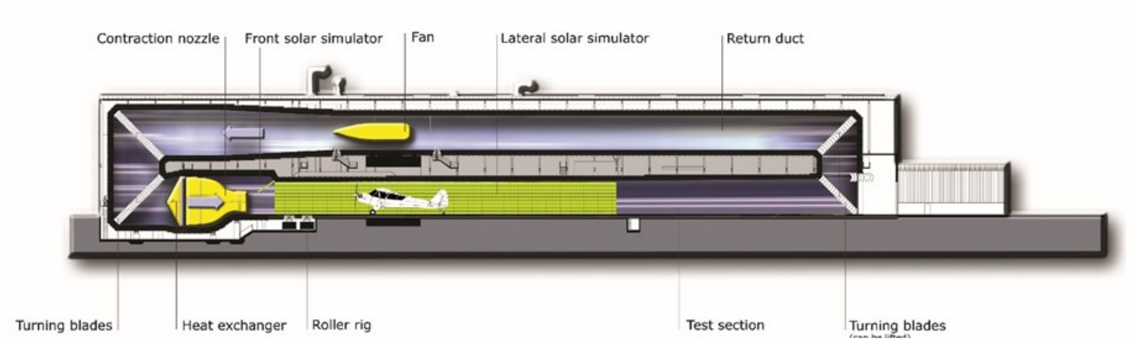

Figure 7: Aerodynamic layout of the RTA IWT

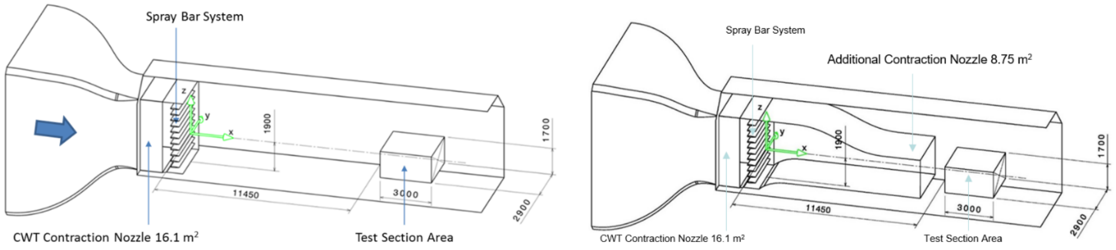

Figure 8: RTA-IWT full cross section configuration (left) and reduced cross section configuration (right)

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

8.1.1 SLD Icing Capability

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 14 shows the currently achievable 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 15: RTA-IWT achievable SLD conditions.

8.1.2 Current Snow Capability & Limitations

The snow conditions can be simulated at RTA with individual mobile atomising nozzles. The simulated snow density can be varied depending on the wind speed, snow quality and droplet size (MVD) as well as covered cross section in the Climatic Wind Tunnel (CWT)). The quality of snow (dry or wet) can be varied by changing the ambient conditions (temperature, wind speed, freezing time). Table 16 shows the currently achievable snow precipitation according to internal research.

Type (quality)	Temp. (°C)	MVD max (µm)	Max drop dia. (µm)	Density (kg/m^3)	LWC max at 2m^2 cross section (g/m^3)
Dry snow	-15 to -18	30	100	180 – 220	~0.7 – 3
Wet snow	-3 to -7	50	100	400 - 480	~1 – 3

Table 16: RTA- artificial snow capabilities

8.1.3 Instrumentation

This section reports detailed information on the instrumentation available in facility for cloud calibration.

8.1.3.1 Particle size distribution

The instrumentation available for MVD/MMD and PSD characterization are based on the maximum occurring droplet diameters. The table 15 reports the details for each instrument. 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 17: RTA-IWT particle spectrometers/ imagers used in the facility for cloud calibration

8.1.3.2 LWC/IWC

Listed in Table 5 below are the LWC / IWC 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 and snow 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.

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 18: RTA-IWT instruments available in the facility for LWC/IWC measurement

8.1.3.3 Cloud uniformity

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 18. 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 computerised sliding calliper. 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. New approach should be defined for snow cloud uniformity characterization.

Figure 9: Photograph of the ice accretion grid installed at the RTA IWT

8.2 THE NATIONAL RESEARCH COUNCIL CANADA, RESEARCH ALTITUDE TEST FACILITY (RATFAC)

8.2.1 Facility Overview

This section outlines the ice crystal icing (ICI) test environment that can be achieved at the National Research Council of Canada's Research Altitude Test Facility (RATFac). The purpose is to provide an overview of the capabilities but due to the interdependence of different variables, only general ranges are provided here. It is necessary to evaluate each test point individually to confirm what can be achieved.

RATFac consists of an altitude chamber that's approximately 32 ft long x 8.5 ft wide and high, Figure 10 and Figure 11. Upstream is a refrigeration cooling system to cool and dry the air down to approximately -45°C TAT but has the ability to cool down further to approximately -70°C using LN2 with a heat exchanger or direct injection system. Compressors downstream of this chamber are used to draw airflow through it and valves upstream of the chamber are closed off to reduce the pressure (and therefore increase the altitude) inside the chamber providing an approximate altitude range of 500 to 51,000 ft.

The ICI rig test system and the ice particle generating system are installed in separate parts of the RATFac chamber so that their temperatures can be independently controlled, Figure 11. This allows the generating system to produce ice particles consistently, independent of the environment seen by the rig. The rig side of the facility can therefore simulate both the ICI environment seen in an engine (warm, small particles, lower speeds, higher pressures) or the one seen in the atmosphere by an aircraft (cold, large particles, higher speeds, lower pressures).

To create ice crystals for the facility, ice is fed into a grinder, which produces particles of the desired sizes which are then injected into the rig inlet by the ice injection pipe. The ice flow rate, particle size reduction and injection speeds are independently controlled. Another key aspect is it is a flow-through facility, which means there is no recirculation of air or particles and the inlet humidity can be controlled down to very low dewpoints, typically dewpoint<-40°C. A full outline of the ICI test conditions currently achievable in the NRC cascade rig is provide in *Table 19*.

For mixed phase conditions, the ice particles will naturally melt by controlling the rig side TAT and humidity to set the wetbulb temperatures above zero. The ability to control humidity allows the wetbulb temperature (and therefore melt) to change independent of TAT. If additional water is desired for higher LWC or LWC where wetbulb is below 0°C (and therefore not allowing melting), there is also the ability to add supplemental water using the spray mast at the ice gun outlet.

Figure 11 is shown with the cascade rig as detailed in Section 8.2.2 but it is also possible to have any type of rig installed for exposure to altitude ICI test conditions.

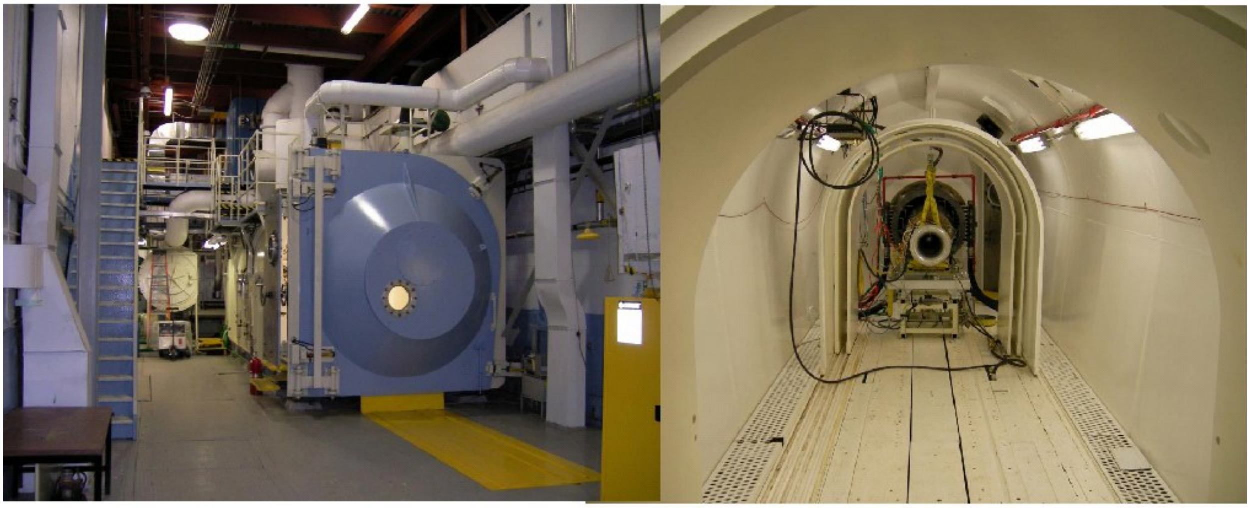

Figure 10 RATFac chamber, left: overall exterior view looking at large front door, right: inside view with large door open, looking towards chamber outlet

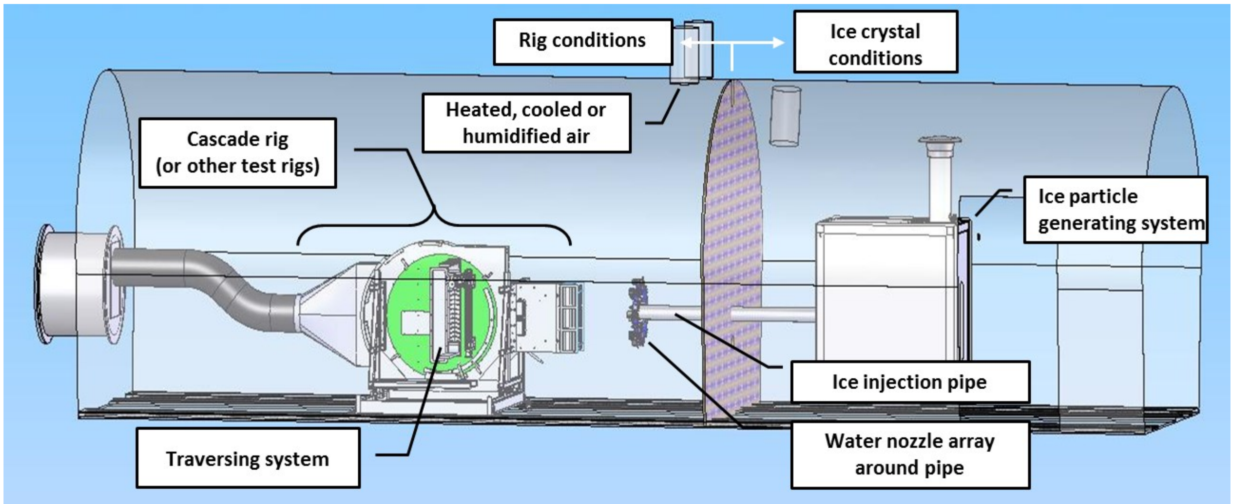

Figure 11 Ice crystal icing system installed in the Research Altitude Test Facility (RATFac), chamber outlet on left side

8.2.1.1 Maximum Airflow Versus Altitude

The maximum RATFac air flow rates versus total pressure are shown in Figure 12. The maximum flow through the refrigeration system, regardless of altitude, is 10 lb/s. However, the cascade rig has a maximum flow rate of 7.5 lb/s for ice crystal testing. If external/ambient air can be used, flow rates up to 24 lb/s can be achieved.

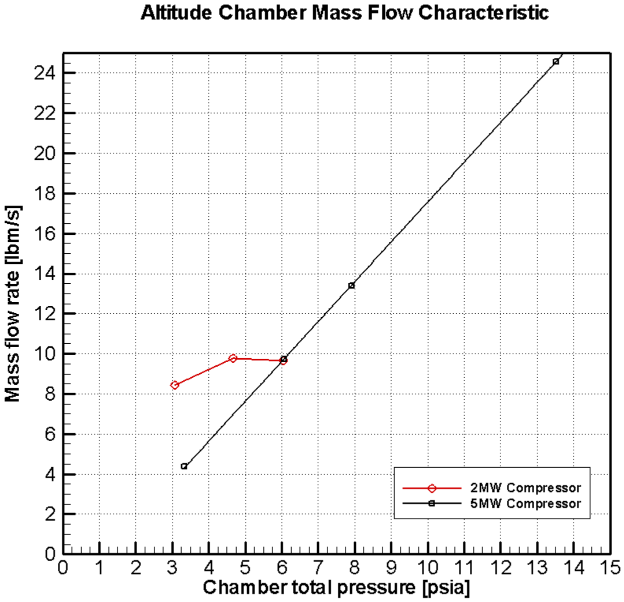

Figure 12 Maximum airflow

8.2.2 Cascade Rig

The rig consists of movable top and bottom walls and can be setup with tailboards that can vary the outlet airflow angles independently to simulate both the turning and diffusion achieved by a blade pack or vane segment. It also has many access windows/panels allowing for visualization and the installation of various test articles such as accretion geometries of interest or air data probes. The general operating range is outlined in *Table 19* and its geometry and instruments are outlined in Figure 13. The geometry shown in the figure has the tailboards in the straight-through configuration used for probe or accretion test articles.

Both sides of the rig have a turntable that can be rotated manually to achieve a desired angle of attack for the test article or instrumentation. However, the right side (fwd looking aft) turntable can be replaced with one that has a remotely controlled rotary table that can be used to set the AOA remotely from the control room. This allows for ±25 degrees for typical pitot probe geometries.

Param.	Min.	Max.	Unit
T_0	-50	+40	[^{MVD}]
P_0	1.9	14.3	[psia]
Mach #	0.15	0.8	
IWC	0.4	20	[g/m^3]
MVD_{ice**}	25	700	[µm]
LWC	0.25	5	[g/m^3]
$MVD_{water**}$	15	200	[µm]
RH	1	90	[%]
AOA	-25	+25	degrees

** at tunnel inlet

Table 19 General operating range of NRC cascade rig for ICI testing

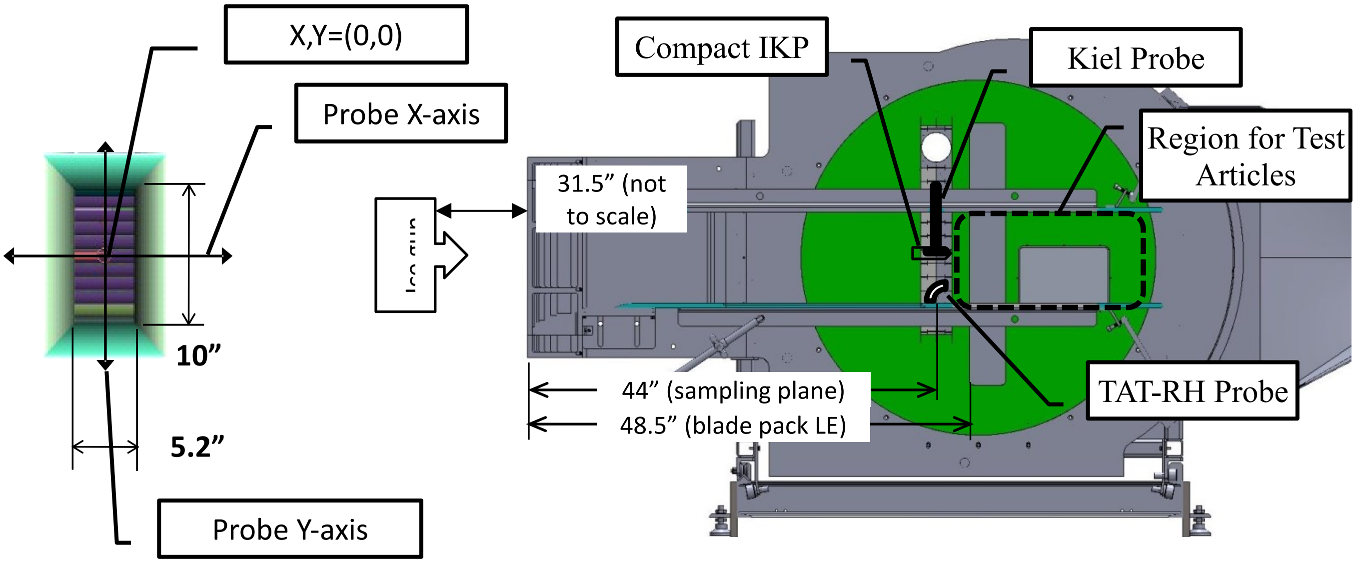

Figure 13 Inlet view and cross-section of cascade rig for ICI testing

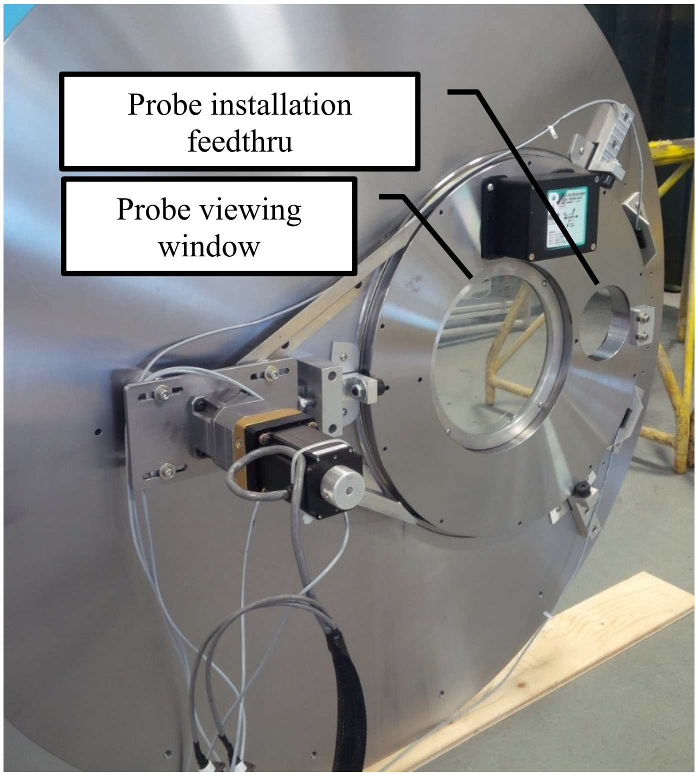

Figure 14 Rotary table for remote angle of attack setting

8.2.3 Instrumentation

The ICI environment is very different from typical SWD icing which means much of the instrumentation for SWD is not applicable. This test system uses standard instrumentation to setup the dry conditions but utilizes unique NRC developed instruments for the ICI environment. An outline of these measurements are provided in Table 20 along with a series of references detailing their operation (Currie T. a., 2015) (Davison, Landreville, Benner , & Fuleki, 2016) (Fuleki D. M., 2014).

Parameter	**Uncertainty**	**Typical Facility Control**	**Instrumentation**	**Traversable**	**Units**
Dv50	±10%	±15%	2D Shadowgraphy using particle imaging velocimetry (PIV) system (1)	FOV approx. Y=0, X=+1.5, 4” upstream of bellmouth inlet	µm
LWC, supplemental water addition	±5%	±0.5	NRC compact IKP	Full tunnel, X,Y	g/m^3
LWC, wire can estimate melt water on particles	NA	±0.5	SEA multi wire probe	Full tunnel, X,Y	g/m^3
Mach number	±0.003	±0.01	DSA3200 MKS Barometer	0”<Y<5.2”, X=0	
Mach number (wet): calculated from change in chamber total pressure and measured tunnel static. Used to estimate changes in M# in the tunnel, typically due to accretion. Its baseline (clean tunnel) value is set during a dry scan.	±0.003	NA	DSA3200 MKS Barometer	NA	
Power supply current output	±0.1	±0.2	Elgar Continuous Series AC power source CW 2501 P	NA	AC amps
Power supply voltage output	±0.3	±0.5	Elgar Continuous Series AC power source CW 2501 P	NA	AC volts
Specific Humidity, wet or dry	±1.5% reading	See wetbulb	NRC TAT-RH probe	See TAT-RH probe	g (H20)/ kg (dry air)

Parameter	**Uncertainty**	**Typical Facility Control**	**Instrumentation**	**Traversable**	**Units**
Static pressure	±0.03	±0.7	DSA3200 MKS Barometer	NA	kPa
Total air temperature	±1	±1	Kiel probe TC	0”<Y<5.2”, X=0	ºC
Total pressure	±0.03	±0.7	DSA3200 MKS Barometer	0”<Y<5.2”, X=0	kPa
Total pressure (wet)	±0.05	NA	DSA3200 MKS Barometer	NA	kPa
TWC, (based on wet tunnel conditions)	±5%	±0.5	NRC compact IKP	Full tunnel, X,Y	g/m³
Wetbulb (dry, total conditions). Calculation detailed in Appendix A of ref (Currie T. C., 2012)	±1.7	±0.5	Kiel and NRC TAT-RH probe	As per Kiel probe	ºC
Wetbulb as per Twbo_dry except using live humidity measurement from the TAT-RH probe and TAT_CAS_wet	±1.7	NA	NRC TAT-RH probe	NA	ºC

Table 20 Outline of test parameters, instrumentation and typical uncertainties

Below is a summary of the existing RATFac data system channels available for customer test articles and rigs. This however, can be upgraded to increase desired channel counts or change parameter ranges.

1) Data logging channel capabilities (1 to 40 Hz):
    a) 48 analog channels expandable up to 1000 channels
    b) 192 temperature channels (up to 72 T type, up to up to 120 K type)
2) 128 pressure channels, expandable to 256
    a) Accuracy:
        i) 1 and 2.5 psi ±0.12% of FS
        ii) 5 psi and higher is ±0.05% of FS
    b) Currently available:
        i) 1 psig x 16 channels
        ii) 2.5 psig x 32 channels
        iii) 5 psig x 32 channels
        iv) 15 psig x 32 channels
        v) 50 psig x 16 channels
        vi) 100 psig x 16 channels
        vii) 500 psig x 32 channels
3) 8 Channel 100 KHz Counter (Frequency inputs)
4) High Speed:
    a) 16 ch up to 2 MHz/ch
    b) 16 ch up to 500 kHz/ch

c) 8 ch up to 200 kHz

8.2.3.1 Particle Size Distribution

NRC has developed a technique to size fast moving airborne particles using components of a particle imaging velocimetry (PIV) system. The laser has the ability to produce a very short light pulse, duration ≈20 ns, allowing the ability to image particles traveling up to 200 m/s. This technique is described elsewhere (Fuleki D. J., 2015) but the basic principle is to backlight the airflow containing the particles with a light source of even intensity, which in this case, is laser light passed through a diffuser. This produces a backlit 2D image of particles allowing for size, morphology and 2D velocity and trajectory data to be characterized. The light source is in line with the camera which uses a telescopic lens to create a focal plane in the cloud of particles. This method is known as shadowgraphy. The PSD analysis is based on NRC-developed algorithms with their validation presented in reference (Fuleki D. J., 2015).Equipment Setup

Figure 15 and Figure 16 are examples of the PIV setup for the cascade rig. The camera and diffuser are installed in insulated enclosures to avoid exposure to altitude conditions and to be kept in a sea level, room temperature environment. Air knives were installed in front of the diffuser and camera enclosure windows to prevent particles or condensation from affecting the window clarity. The camera and optics for this setup had a field of view of approximately 6×4.5 mm (width x height) with the focal plane located as shown in Figure 16. The camera and diffuser along with all other components for the PIV system are controlled by a computer and an operator outside of the chamber.

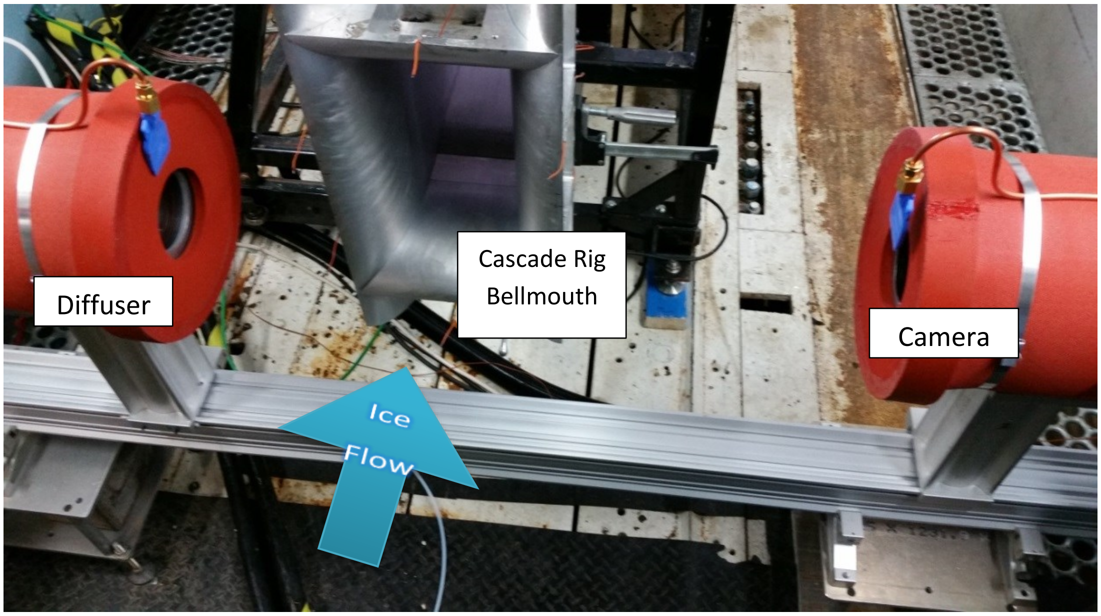

Figure 15 PIV system setup and its location relative to the rig

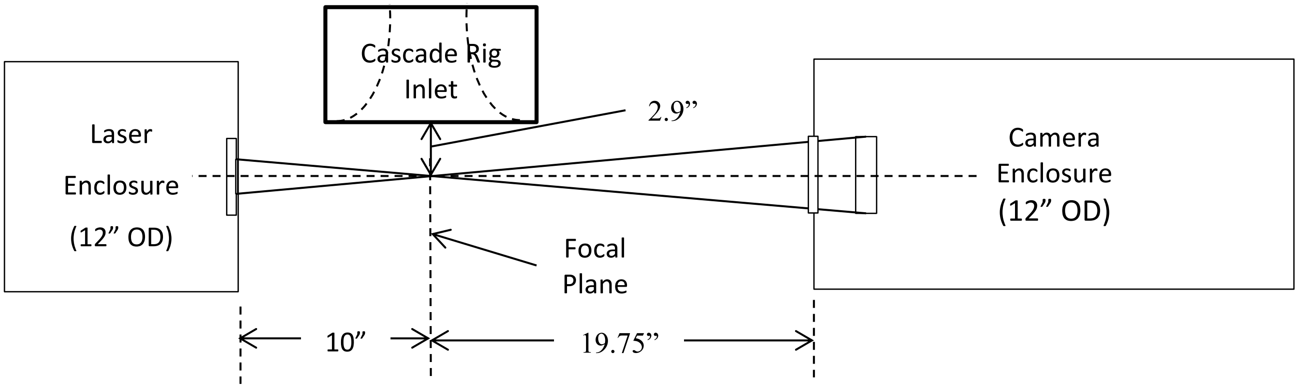

Figure 16 PIV setup for particle imaging upstream of cascade rig inlet bellmouth, top view, to scale

8.2.3.1.1 Particle size data for Ice Crystal Icing or blowing snow

Table 21 Range of particles sizes measured for the NRC altitude ice crystal test system

Grinder				
Config.	Operating Condition	Dv10	Dv50	Dv90
A2	X-Small	10	18	37
A2	Large	34	72	130
A	Small	31	57	126
D	Small	30	66	218
N	Small	41	123	665
N	Large	56	709	1,160

The ice particle generating system has the capability to provide a wide range of particles sizes with some examples shown in Table 21. There are a range of grinder configurations that can be used, allowing for subtle and significant changes to the particle size distribution. Changing the configuration requires physically modifying the system and about two hours of work. However, it is also possible to vary the particle size distribution for a given configuration in real time by changing grinding operating parameters. An example of this can be seen in Table 21, Figure 20 and Figure 21 where the Dv50 can be varied from approximately 125 to 700 microns and the Dv90 can be varied from 665 to 1,160 microns in a few seconds. This allows for easy variation of the PSD between test points or to run test points with PSD as a transient test parameter. A range of PDS's are shown in Figure 17 to Figure 21.

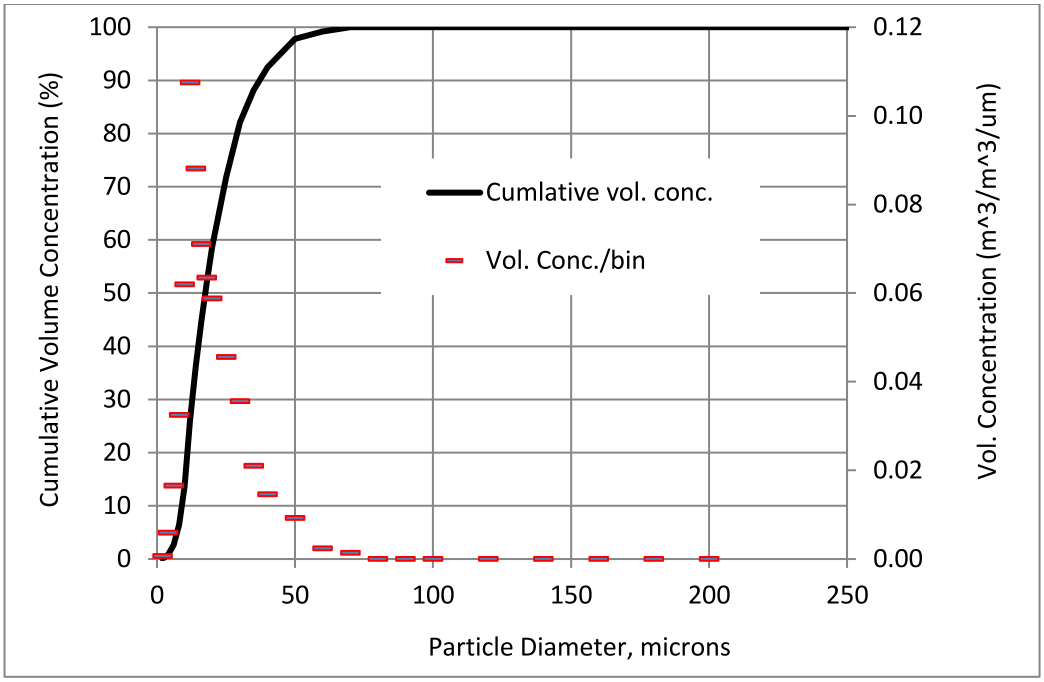

Figure 17 Particle size histogram and cumulative distributions for grinder configuration A2, operating condition: X-small

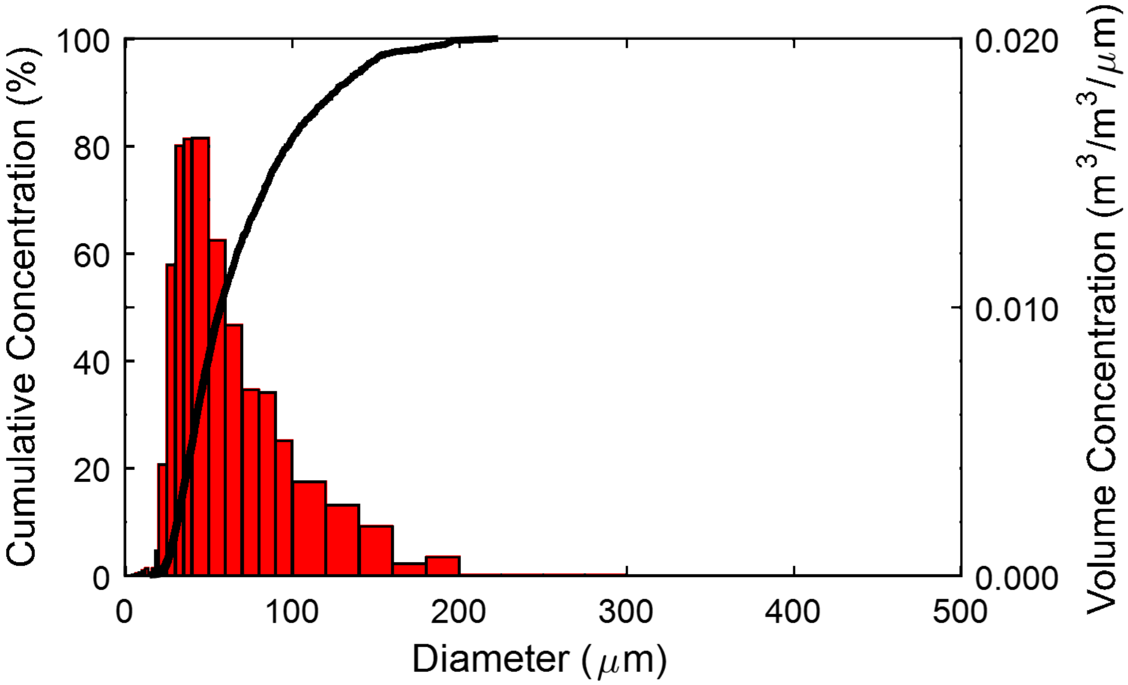

Figure 18 Particle size histogram and cumulative distributions for grinder configuration A, operating condition: small

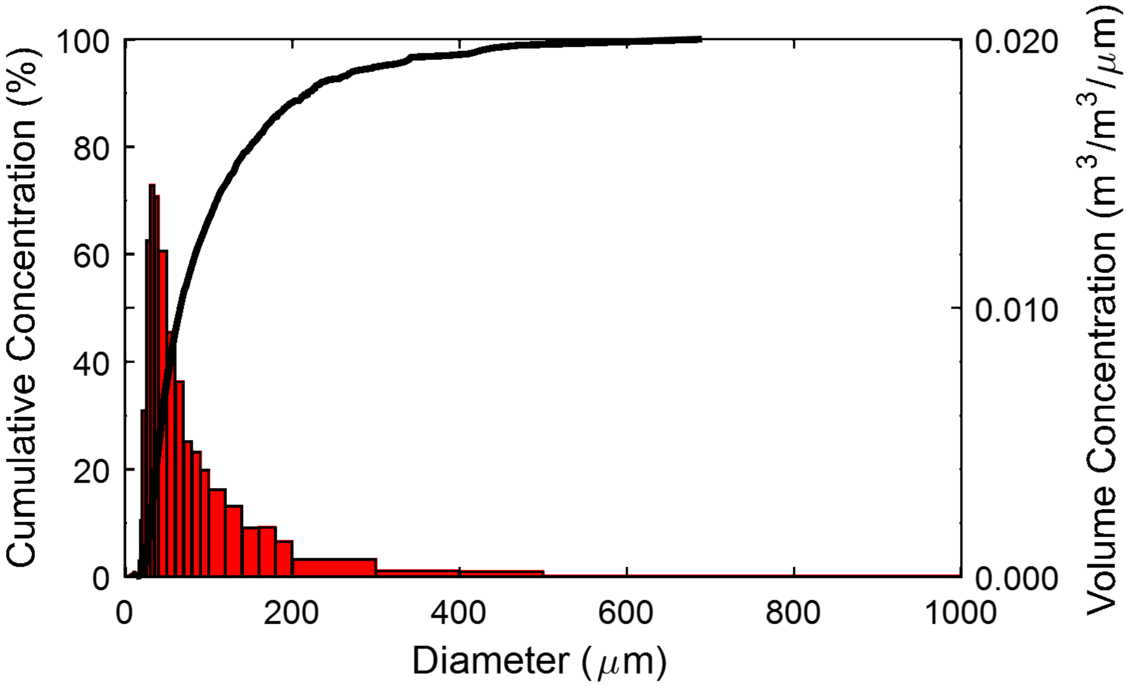

Figure 19 Particle size histogram and cumulative distributions for grinder configuration D, operating condition: small

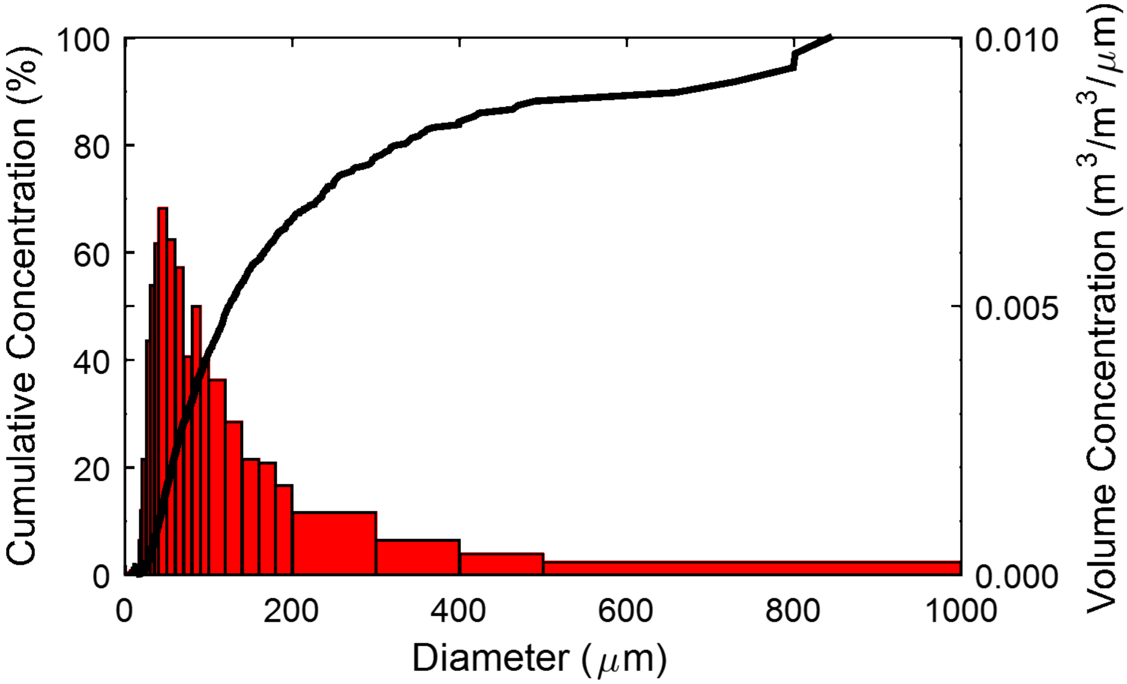

Figure 20 Particle size histogram and cumulative distributions for grinder configuration N, operating condition: small

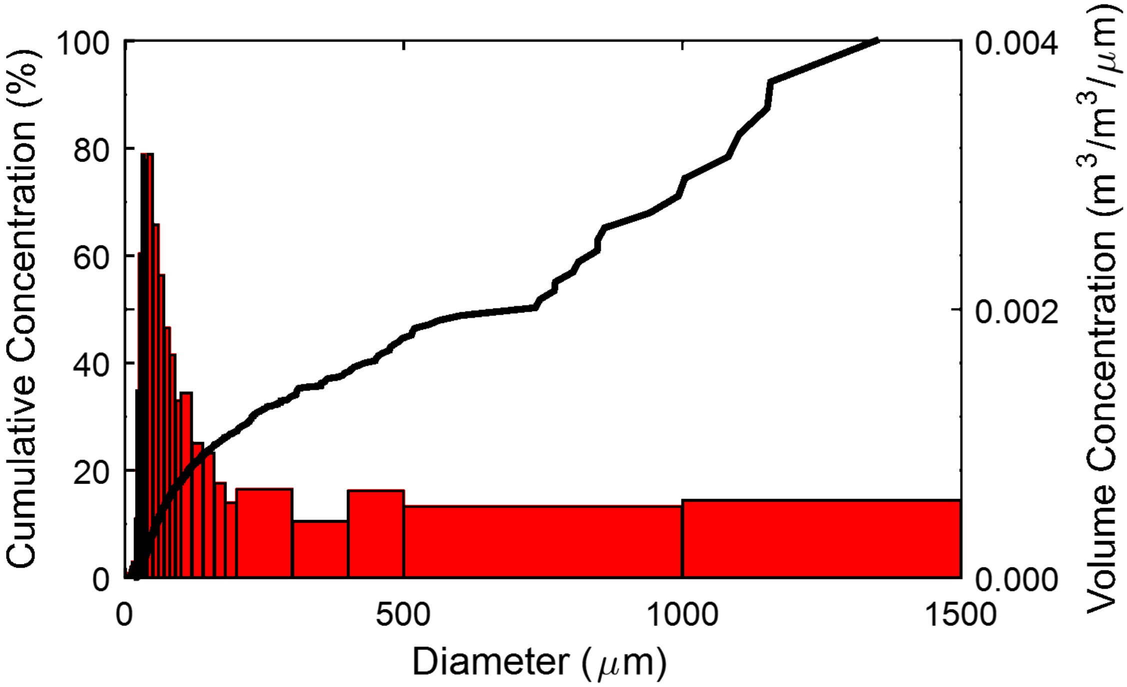

Figure 21 Particle size histogram and cumulative distributions for grinder configuration N, operating condition: large

8.2.3.1.2 Particle centricity

The particles are faceted with angular faces as shown in Figure 22 however, the morphology can be quantified using centricity which is defined as the ratio of the shortest edge-to-edge distance over that of the longest one, both passing through the centroid, i.e. Dmin/Dmax,

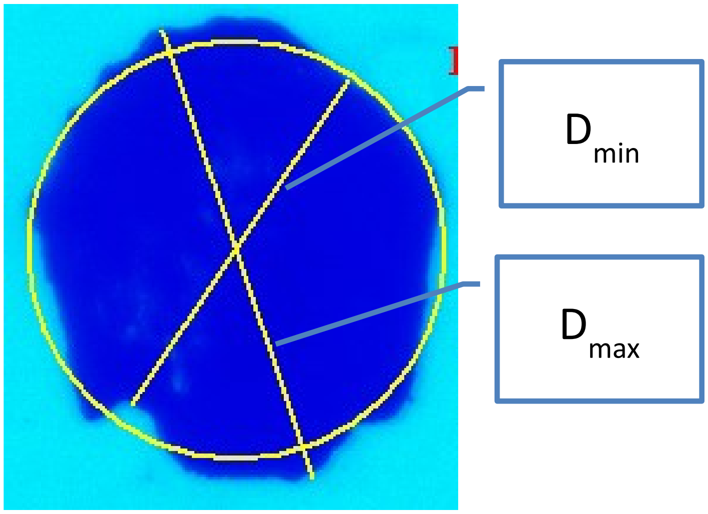

Figure 23. The average centricity based on the particle count is 0.63 whereas the volume weighted centricity is 0.66. These results are in good agreement being within 10% of previously published data (Fuleki D. J., 2015).

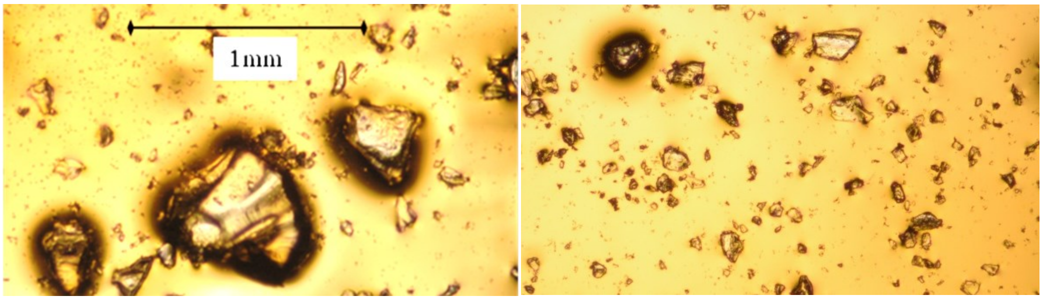

Figure 22 Example of particle morphology for a range of particle sizes

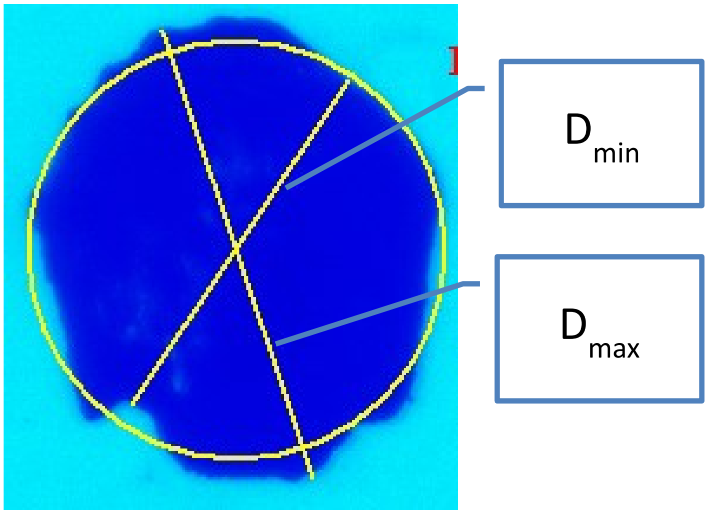

Figure 23 Description of centricity for a particle

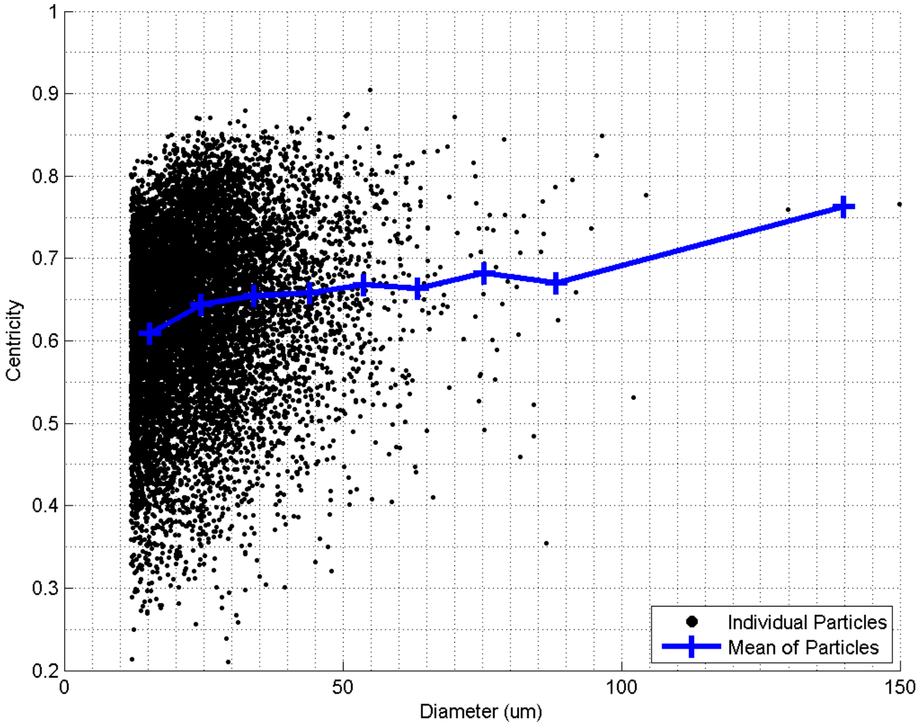

Figure 24 Centricity vs Diameter graph for the Dv50=35 µm

8.2.3.1.3 Particle velocity

The PIV shadowgraphy setup can also be configured with two lasers whose pulses can be timed to capture two images of the same particles having a known spacing in time and location. This permits the ability to measure particle velocity and 2D trajectory along the direction of the focal plane. As illustrated in Figure 25, the green particle is the one that was captured on the first image and the red particle is the same particle on the second image. The flow velocity of the particles at the focal plane is calculated based on the displacement and the known time interval between the two images.

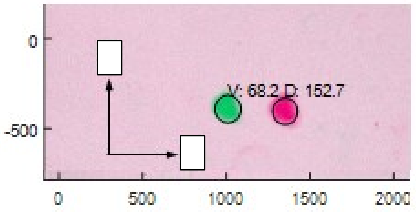

Figure 25 Velocity detection method using Shadowgraphy images and the PIV system

Figure 26 represents the particle velocity versus diameter for a small PSD. The average volume weighted velocity in the Z direction is 64 m/s, approximately 23% lower than the injection velocity of 84 m/s measured at the gun outlet. This drop in the velocity is expected as the jet slows down by the time it reaches the inlet of the rig as it is traveling through relatively still air. Given these are relatively small particles, they will have little momentum and tend to follow the airflow. This is supported by the Y velocity component data where only the larger particles, e.g. Φ>≈60 microns, have a relatively small Y component showing they do not follow the airflow turbulence as much as the smaller particles. The average volume weighted velocity in the Y direction is only +0.5 m/s showing the particle velocity is primarily in the Z direction, as expected.

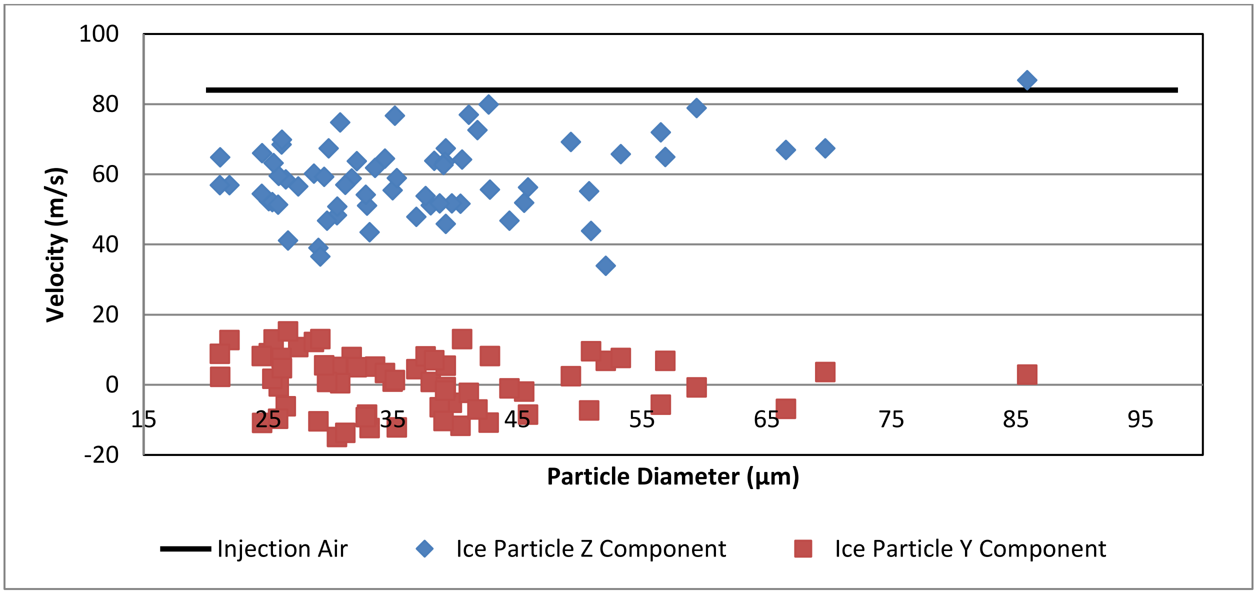

Figure 26 Particle velocity data

8.2.4 Transient testing

Test points are typically steady state where none of the icing or aero parameters are changing. However, it is possible to achieve transient conditions with nominal ranges of control outlined below for the RATFac ICI cascade rig. However, what is actually achievable depends on the specific test condition, e.g. where the test point is relative to facility limits. Other test parameters will likely vary outside normal limits but these excursions are minimized. It is necessary to know ahead of time if transient testing is required as it will affect how the test point is setup. Also, this is achieved through manual control so rate of change is typically not precise or highly repeatable but parameters are measured so rate of change is known.

Nominal ranges of control for the RATFac ICI cascade rig transient test points:

1. TAT: min/max rate: ~2-20 oC/minute, max. delta: ~25oC
2. alt: ~0.5-6 psia/min, ~3 psia
3. M#: ~0.2-0.5/min, ~0.25

8.2.5 Test Point Run Time

Typical ice crystal test points can be run up to 15 minutes in duration. However, it is possible to increase this to over an hour if necessary. Actual test parameters and times depend of the specifics of the test point.

8.2.6 Test Points per day

1) Typically 5 points/day ae easily achievable when varying any of the 3 main dry aero parameters: T, P or M.
2) Approximately 25-35 min/point when on aero condition to change supplemental LWC (i.e., nozzle spray, assuming an IKP cal measurement of that LWC is required)
3) Approximately 20-30 min/point when on aero condition to change RH (i.e. wetbulb), IWC, LWC_MVD and IWC_MVD (for a fixed grinder configuration, including an IWC calibration).
4) TWC traverses are typically 45 seconds per point. We typically run 25 point traverses therefore, approximately 25 minutes total time when including the dry aero measurement portion at the start of the point.
5) If accretion occurs and needs to be shed by heating up the facility, it can take anywhere from 20 to 90 minutes to shed and get back on point depending on how cold the point is (colder is longer).
6) Approximately 2 hrs to change grinder configuration
7) There is a maximum of 375 lb of ice available in a given test day. It is possible to use more if it’s known ahead of time but the chamber must be brought off point to reload.
8) Anytime the chamber is brought down to sea level for access, it takes about 45-90 minutes to return to test condition plus any time required in the chamber.

Note, downtime due to equipment failure will mean less points/day but the test time missed will be carried forward, not lost. That’s why contingency days are scheduled in to ensure required test time is achieved.

8.2.7 Blowing snow and upgraded icing test capabilities

The NRC blowing snow capabilities developed in this Ice Genesis project are summarized in Table 22 for both the research altitude test facility (RATFac) and the small sea level engine test facility, M7-TC5[1]. RATFac is currently undergoing an upgrade for higher flows and lower temperatures which are reflected in this table. For completeness, the blowing snow and liquid water conditions are also provided.

Table 22 Summary of NRC Icing test conditions for RATFac and M7-TC5

Parameter		RATFac[2]		M7-TC5[3]		Unit
		Min.	Max.	Min.	Max.	
Cross-sectional size		25 x 25		$\Phi = 75$[4]		cm
Aero-thermal	T_0	-50	+40	-20	+2	Deg C
	P_0	1.9	14.3	Sea Level		psia
	Mach #	0.13	0.8	0.07	0.5	
	RH	1	90	Ambient		%
Blowing Snow or Ice Crystals	IWC	0.4	20	0.1	5	g/m^3
	MVD_{ice}[5]	25	700	100	700	µm
Falling Snow	IWC (V=40 m/s)	0.2	2.5	0.1	1.2	g/m^3
	MVD[1]	1.0	2.5	1.0	2.5	mm
	Test Duration	1	60	1	60	min
	Snow bulk density (dry)	155 to 205				kg/m^3
	Type	Wet or dry				
Liquid Water[6]	LWC	0.25				5
	MVD_{water}[1]	15				200

---

[1] Estimated based on implementing the RATFac snow maker system

[2] Based on facility upgrade project currently underway

[3] Sea Level, outdoor air

[4] Tunnel can be customized to suit required test article geometry

[5] At tunnel inlet

[6] Independent of ice or snow and therefore can be used for mixed-phase

9. ANNEXE 2: SNOW MICROPHYSICAL PROPERTIES RETRIEVAL

9.1 DEFINITION OF SIZE PARAMETER

Various parameters are defined in order to characterize the size of a particle.

The first one is the 2D area equivalent diameter D_{eq} defined as the diameter of a circle of the same area as the 2D particle image:

$$D_{eq} = \sqrt{\frac{4\,S_{i\perp}}{\pi}}$$ where $S_{i\perp}$ is the total shaded area.

However, the equivalent diameter assumes that the particles are spherical and therefore provides no information about the particle shape that could be useful to distinguish different snowflake populations. A different way of retaining particle shape information is to use the maximum diameter D_{max}. The maximum diameter is derived from the analysis of the range of possible diameters passing through the barycenter of the image. Knowing D_{max}, the width W of the particle is defined as the diameter which is perpendicular to D_{max} and finally the aspect ratio (AR) is the ratio between the width and D_{max}:

$$AR = \frac{W}{D_{max}}$$

With such a definition, roundish particle will have an aspect ratio close to 1, whereas columnar- and needle-type snow crystals will be associated with lower aspect ratio values, as a function of the respective 2D-projection.

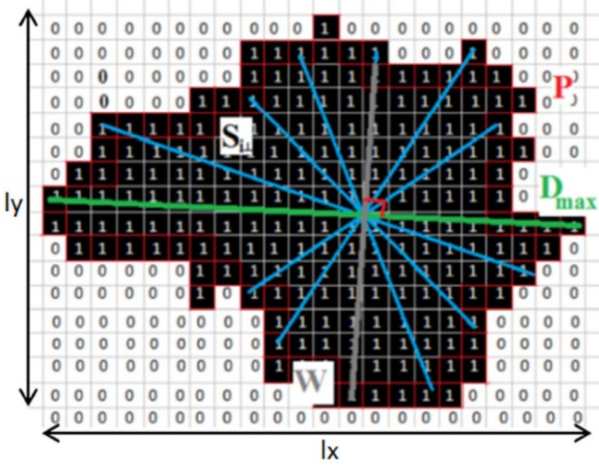

Figure 27: Binary matrix of a particle image recorded by an OAP probe. A value "0" corresponds to a non-shaded pixel whereas "1" corresponds to pixels shaded by the cloud particle when passing through the laser beam as a function of time. Red contoured pixels represent the pixels from which the perimeter P can be calculated. D_{max} is the maximum diameter of the particle and W the width of the particle perpendicular to D_{max}. $S_{i\perp}$ is the surface of the image (i.e. the area of the total number of shaded pixels). l_x is the size of the particle along the flow direction whereas l_y is the size along the photodiode array of the probe.

When the particle image is truncated on either one or both sides due to the limited width of the diode array, its size is determined following the work of Korolev and Sussman.

9.2 SNOW IWC RETRIEVAL METHODOLOGY

The approach to retrieve IWC from OAP measurements is complex. The described methodology relies on CNRS-LaMP expertize in the field [11] [12] [13] and the significant experience gained in the framework of the HAIC (FP7 High Altitude Ice Crystals) [14], EASA-HighIWC [28] and HIWC (US lead High Ice Water Content project) [15] projects to characterize ice crystals conditions and assess relevance of CS25 Appendix P (Glaciated and Mixed Phase Icing Conditions) envelope.

OAP cannot directly measure IWC, MMD or the distribution of mass versus size (mass size distribution, MSD) of a snowflake population. Such information must be derived from the PSDs (number concentrations), followed by an estimation of the MSDs using additional information and assumptions. The methodology used by CNRS-LaMP to retrieve IWC from OAP measurement is presented in Figure 28.

- First 2D images are processed to retrieve size of the particles. Not all images recorded by PIP are naturally-occurring cloud particles. Some are measurement artifacts (Splashing and Shattering, Out of focus particles) that need to be identified and either removed or carefully processed before further analysis,

- PSD is then calculated,

- In order to convert PSDs into MSDs, mass-size relationship is applied. It is represented as a power law relationship of the form $m = \alpha D^{\beta}$.

- Finally, the MMDs and IWC are deduced from the mass distributions.

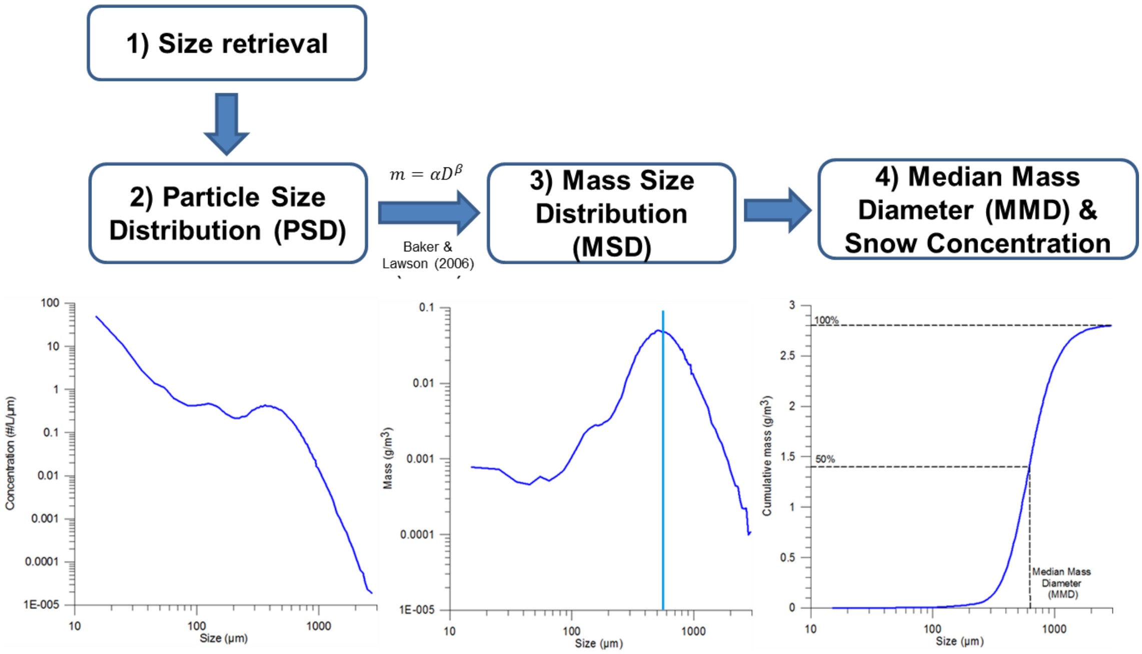

Figure 28: Snow IWC retrieval methodology

9.2.1 Splashing and Shattering

A fraction of cloud particles inevitably hits the housing of probes during sampling and may break up into multiple fragments that are recorded by the probe [26]. This break-up effect is called splashing for droplets and shattering for ice particles. From the fragmented image, there is no reliable way to infer the initial particle size. Thus, all images corresponding to a shattering or a splashing event must be removed; otherwise measurements of particle size distributions and subsequently derived microphysical properties would be incorrect.

When such a fragmentation event occurs, the probe usually records either a large number of different images with small inter-arrival times, a large image with multiple particles per image, or both. Most of the images related to a shattering/splashing event can be removed by a careful analysis of the ratio between the particle's surface and its sizes in the x and y directions and of the inter-arrival times [22] [23] [24] [25]).

9.2.2 Out of Focus Particles

The object plane for each channel of an OAP imaging system is at the midpoint between its respective sample arms. Particles are in focus when passing through the laser beam object plane, but are also detectable in different degrees of focus, depending on particle size, up to a certain distance away from the object plane. Out-of-focus diffraction patterns of particles passing through the laser beam are thus observed for OAP probes as a function of distance from the object plane. Using the Fresnel diffraction approximation, the response of spherical particles recorded on an OAP can be theoretically modelled [20]. These results show that out of focus spherical particles have a donut type appearance with a central Poisson spot void of shadowed pixels, and where the outside diameter of the donut exceeds the real particle size. For this study, the lookup tables presented in [20] are used to retrieve the predicted correct particle sizes for measured area ratios of the Poisson spot over the apparent out of focus particle size, assuming spherical particles.

9.2.3 Computation of Particle Size Distribution (PSD), Mass Size Distribution (MSD), Ice Water Content (IWC) and Median Mass Diameter (MMD)

Ice particle mass and size are usually related by a power law relationship: $m(D) = \alpha D^{\beta}$, where α and β coefficients depend on which size definition is used for the particle but also on the ice particle shape. Thus, a significant variation in values for (α, β) can be found in the literature.

Thanks to this relationship, MSD can be derived from PSD. The MMD (The MMD is the size at which 50% of the ice mass is contained in smaller particles, and 50% in larger particles) and IWC are then deduced from the mass distribution.