

# ICE GENESIS

## Creating the next generation of 3D simulation means for icing

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OTHER	Software, technical diagram, etc.	
ETHICS	Ethics requirement	
ORDP	Open Research Data Pilot	
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# 1 Glossary

Abbreviation / Acronym	Description/meaning
SAE	Society of Automotive Engineers
ARP	Aerospace Recommended Practice
ATF	Altitude Test Facility
BCP	Backscatter Cloud Probe
BCPD	Backscatter Cloud Probe with Polarization Detection
BWV	Background Water Vapour
Circularity	Particle roundness parameter computed as $(4 \cdot \text{Area} \cdot \pi) / (\text{Perimeter}^2)$ . For a perfect circle, the circularity value is 1. Given as a dimensionless ratio.
CAPS	Cloud, Aerosol and Precipitation Spectrometer
CAS	Cloud and Aerosol Spectrometer
CAS-DPOL	Cloud and Aerosol Spectrometer with Depolarization
CAPS	Cloud Aerosol Particle Spectrometer
CDP	Cloud Droplet Probe
CIKP	Compact Iso-Kinetic Probe [37]
CIP	Cloud Imaging Probe
CNRS	Centre National de Recherche Scientifique
CPI	Cloud Probe Imager
CPSPD	Cloud Particle Spectrometer with Depolarization
CWC	Cloud Water Content [ $\text{g} \cdot \text{m}^{-3}$ ]
DMT	Droplet Measurement Technology
FCDP	Fast Cloud Droplet Probe
FSSP	Forward Scattering Spectrometer Probe
HSI	High Speed Imager
ICC	Ice Capture Cylinder
ICD	Ice Crystal Detector (SEA)
IKP	Iso-Kinetic Probe
IPP	Ice Property Probe (NRC)
IWC	Ice Water Content [ $\text{g} \cdot \text{m}^{-3}$ ]
IWT	Icing Wind Tunnel
LWC	Liquid Water Content [ $\text{g} \cdot \text{m}^{-3}$ ]
MASC	Multi Angle Snowflake Camera
MMD	Median Mass Dimension [ $\mu\text{m}$ ]
MSD	Mass Size Distribution
MVD	Median Volumic Diameter [ $\mu\text{m}$ ]

OAP	Optical Array Probe
PDI	Phase Doppler Interferometer
PMS	Particle Measuring System
PSD	Particle Size Distribution
RP	Robust Probe
SAT	Static Air Temperature [K] [°C]
TAT	Total Air Temperature [K] [°C]
TWC	Total Water Content [g.m <sup>-3</sup> ]
2D-S	2D Stereo spectrometer

## 2 Executive Summary

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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.

Deliverable *D3.5 Definition of the target requirements for test facilities operating envelopes for snow* 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.

The current document describes calibration methodology for snow test facilities. It has been derived from the SAE ARP 5905. In particular, relevant parameters and acceptance criteria for snow cloud calibration have been updated. The basic procedure remains unchanged including particle size distribution, particle characteristics, water content and cloud uniformity measurements but the instrumentation and techniques to be used for the calibration of snow conditions change. The characteristics of this new instrumentation are further detailed in this document. Finally, a continuity check test is introduced as main acceptance criteria by testing a model (simple configuration e.g. NACA airfoil) to demonstrate the ability of the test facilities to reproduce snow accretion phenomena, to allow an inter-comparison of the test facilities or/and to assess the impact of any change in the test facility configuration.

This document could be the baseline for a future update of the SAE ARP5905 “Calibration and Acceptance of Icing Wind Tunnels”.

### 3 Introduction

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The ambition of the ICE GENESIS is to further upscale and mature natural like snow generation systems and to provide European aeronautic industry with large scale test facilities able to generate snowflakes in variety, size distribution and quantity suitable to support both design and certification of power plant systems.

Requirements regarding snow conditions to be simulated in test facilities are detailed in the deliverable *D3.5 Definition of the target requirements for test facilities operating envelopes for snow*. The current document complements this later deliverable by providing calibration methodology for snow test facilities.

The reference document for the calibration of icing wind tunnel is the SAE ARP 5905. However, the content is not adapted to snow conditions because these conditions were not considered when it had been issued.

Basically, the calibration process is divided into two steps: the aero-thermal calibration and the icing cloud calibration.

- The first step is not directly related to icing conditions, so methods, procedures and instrumentation described in the ARP 5905 are the same and will not be further detailed in this document. However, the impact of the snow generation devices on the flow field characteristics has to be taken into account.
- The second step, relative to the icing cloud calibration process, has to be revised compared to the ARP 5905 because the features of snow clouds are different from small supercooled droplets in terms of size, shapes and density. Then, relevant parameters and acceptance criteria needs to be updated. The basic procedure remains unchanged including size distribution, water content and cloud uniformity measurements but the instrumentation and techniques to be used for the calibration of snow conditions change. The characteristics of this new instrumentation are further detailed in this document.

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

Finally, a continuity check test is introduced as main acceptance criteria by testing a model (simple configuration e.g. NACA airfoil) to demonstrate the ability of the test facilities to reproduce snow accretion phenomena, to allow an inter-comparison of the test facilities or/and to assess the impact of any change in the test facility configuration.

## 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 [2]. 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 Wettäuffer (2007) [3] 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 sectorial 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<sup>2</sup> 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 [4] are mainly between 2 and 5 mm, ranging up to 15 mm. Snowflake density [5] varies, ranging from 0.005 to 0.2 g cm<sup>-3</sup>, 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.

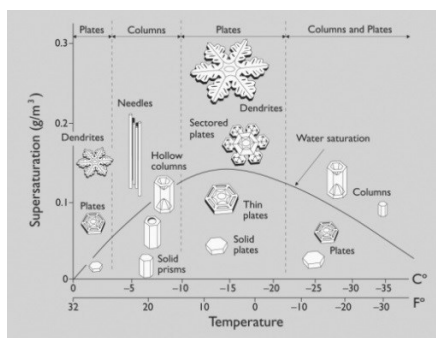


Figure 1: Snow Crystal Morphology Diagram



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

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.

Airborne observations made in snow conditions or in the lower portion of mesoscale convective systems anvils where ice crystal aggregates are abundant show that number and mass concentrations vary with the atmospheric context. In snow conditions, mass concentrations of hydrometeors range

<sup>2</sup> aggregation starts to be effective from -15°C to 0°C

from about 0.2 to 1 g/m<sup>3</sup> of air with median mass diameters ranging from 1 to 4 mm roughly. The reported spatiotemporal variability of particle size distributions indicates that the proportion of particles in a given size class is not constant relatively to the others. The size distribution of millimetric particles is well described by exponential laws ( $N(D)=N_0 e^{(-\lambda D)}$ ) with  $\lambda$  varying from 6.4 to 20 cm<sup>-1</sup>. Finally, the particles' bulk density is strongly influenced by the dominant shape of particles but it generally decreases with size, with typical values of 0.1 g/cm<sup>3</sup> for 1-mm particles to less than 0.01 g/cm<sup>3</sup> for 10mm particles, in average.

The variability in the shape of snowflakes and in their physical properties is such that it seems unlikely that a limited number of snow particles models with typical size and shape could be defined to represent "what is snow". Instead, snow particles would be better described by a combination of statistical quantities such as size distribution, bulk density law, and habit composition law.

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

- ID3.3 / ON / Snow Literature Review
- D5.7 / CNRS / Synthesis & Characterization of snow microphysical properties

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

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

Requirements regarding snow conditions to be simulated in test facilities are detailed in the deliverable *D3.5 Definition of the target requirements for test facilities operating envelopes for snow*.

## 6 Facility performance target

Snow testing should be performed in facilities having measured, defined, and documented aerothermodynamic flow qualities, snow cloud qualities, and calibrated instrumentation.

The facility should be calibrated in accordance with the time frames in Section 7 and the procedures in Section 8.

The test section airflow and snow cloud characteristics should be within the range of performance targets listed in Table 1 over the area of the uniform snow cloud. The uniform snow cloud is defined as the area of the test section over which the IWC does not vary by more than  $\pm 20\%$  relative to the average IWC value or the test section centerline IWC value for a given airspeed and snow particle size.

### 6.1 Aero-thermal parameters

Aero-thermal parameters to be measured are described in Table 1.

The influence of the snow generator and/or the blowing device must be taken into account and combined with the atomization air pressure effect if any.

### 6.2 Icing/snow cloud parameters

Compared to ARP 5905, parameters and acceptance criteria must be revised.

- Total water content (TWC) or Ice Water Content (IWC) are more relevant than Liquid Water Content (LWC) for solid phase (snow).
- Median Mass Diameter (MMD) is preferred instead of Median Volume Diameter (MVD) for snow because of the variability of the density of the snowflakes.
- Absolute humidity is chosen instead of relative humidity to avoid ambiguity when liquid and solid phases are simultaneously present.
- Snow particle bulk density and snow bulk density are added since they constitute a key parameter to assess the quality and the type of simulated snow and representativity with regard to “real” snowflakes.
- Liquid Water Ratio since it is expected to be one of the most important parameters on snow accretion
- Continuity check test as main acceptance criteria by testing a model (simple configuration e.g. NACA airfoil) to demonstrate the ability of the test facilities to reproduce snow accretion phenomena, to allow an inter-comparison of the test facilities or/and to assess the impact of any change in the test facility configuration.

### 6.3 Acceptance criteria and performance target

The targets indicated in the following table are provided for an empty test section and dry airflow. If the targets cannot be achieved for any of the test points, then the actual uncertainty should be stated.

Parameters	Measurement Instrument Maximum Uncertainty	Tunnel Centerline Temporal Stability	Spatial Uniformity	Limit value
<b>Aerodynamic Parameters</b>				
Airspeed <sup>1</sup>	$\pm 1 \%$	$\pm 2 \%$	$\pm 2 \%$	N/A
Static Air Temperature < -15 °C	$\pm 2 \text{ °C}$	$\pm 2 \text{ °C}$	$\pm 2 \text{ °C}$	N/A
Static Air Temperature between -10 and +2 °C	$\pm 0.5 \text{ °C}$	$\pm 0.5 \text{ °C}$	$\pm 1 \text{ °C}$	N/A
Flow Angularity	$\pm 1.0 \text{ °}$	N/A	$\pm 2 \text{ °}$	$\pm 3 \text{ °}$

Parameters	Measurement Instrument Maximum Uncertainty	Tunnel Centerline Temporal Stability	Spatial Uniformity	Limit value
<b>Flow Turbulence<sup>2</sup></b>				
Atomization pressure/Snow generation system off	± 0.25 %	± 2 %	< 2 %	N/A
Atomization pressure/Snow generation system on (maximum)	± 0.25 %	± 2 %	< 2 %	N/A
Pressure altitude	± 50 m	± 50 m	N/A	N/A
<b>Cloud &amp; Cloud Uniformity Parameters</b>				
Total Water Content / Ice Water Content / Liquid Water Content <sup>3</sup>	± 15 %	± 20 %	± 20 %	N/A
Liquid Water Ratio / Wetness of the snow	± 20 %	N/A	N/A	N/A
Median Mass Diameter / Median Volumetric Diameter <sup>3</sup>	± 20 %	± 20 %	± 20 %	N/A
Absolute Humidity	± 3 %	N/A	N/A	N/A
Snow bulk density	± 20 %	N/A	N/A	N/A
Snow particle bulk density <sup>4</sup>	± 20 %	N/A	N/A	N/A
Parameters	Measurement Instrument Maximum Uncertainty	Accuracy		
<b>Real atmospheric conditions representativeness &amp; Continuity check<sup>5</sup></b>				
Snow / No Snow Accretion	TBD	TBD		
Growth rate [mm.min <sup>-1</sup> ]	TBD	TBD		

Table 1 : Performance target and acceptance criteria

Accuracy and uncertainty are determined by a statistical process whereby measured data is analyzed by acceptable means.

Temporal stability is defined as the variation of the parameter over the run.

Uniformity is the spatial variation of the parameter over the cross-sectional area of the uniform icing/snow cloud. The limits in the last column of Table 1 are applicable for parameters that are characteristics of a facility design and generally are not controlled.

In addition to the non-controlled performance parameters found in Table 1, the facility operator should also document the time to achieve icing/snow cloud generation system stability. This performance feature of an icing wind tunnel does not lend itself to definition in Table 1. However, it

is an important performance characteristic to document, as the operator has the responsibility to ensure that time to achieve a stable icing/snow cloud is consistent with (generally much less than) the icing/snow duration for a given test point. The operator should know the time required to stabilize the icing/snow cloud generation system to within  $\pm 2$  s.

#### Notes

1. For airspeed less than 40 m/s, instead of  $\pm 1\%$  use  $\pm 0.4$  m/s maximum accuracy to single point measurements at the geometric center (x, y, z) of the tunnel
2. Characterization of flow turbulence is desirable. If criteria can't be achieved, the associated parameters shall be characterized and documented
3. For assessment of Water Content and Particle Size temporal stability, a 60-120s average should be considered
4. Evaluation of Snow particle bulk density is very challenging and there is no agreed methodology yet to comply with this criterion. Coutris [41] proposed a new approach to derive mass-size relationships (m - D) from size distributions and ice water contents. The retrieval is formulated as an inverse problem.
5. Unfortunately, no accurate in-flight snow accretion measurement database exists to date.

## 7 Instrumentation

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The main measurement objectives to be met to ensure calibration with the selected instrumental payload for IWT are listed below:

1. Guarantee measurement reliability of large ice particle properties (size dependent crystal number and mass) up to 10 mm (and beyond if possible): Use of imaging instruments like PIP, HVPS
2. Ensure the snow IWC measurement capabilities of bulk snow water content containing large snow crystals: Use of bulk CWC instruments like IKP, NEVZOROV and/or ROBUST probes (to be characterized), CVI evaporator probe
3. Allow a reasonably good morphological analysis and in best case retrieve an indicator for dry and wet snow of the snow particles (snow crystals, snowflakes): Use of high resolution grey scale imager as CPI or HSI, others...
4. Ensure cloud homogeneity in test section

Main recommendations to define the most adequate instrumental payload are:

1. **Need of precipitation particle imaging probes for largest crystal sizes beyond 1-2 mm** up to even several tens of mm. In order to fulfil this size specification, the two precipitation imaging probes PIP and HVPS are capable of sizing crystals up to 6.4 mm (PIP 64 photodiodes at 100  $\mu\text{m}$  pixel resolution, twice the resolution of the legacy 2D-P probe) and 19.2 (HVPS 128 photodiodes at 150  $\mu\text{m}$  pixel resolution), respectively. The more the ice particle is at the upper size limit of a corresponding probe, the higher is the probability of truncated images, that need to be reconstructed, however with some uncertainties (in general the retrieved reconstructed image underestimates real size and mass, when image truncation occurs).
2. **Need of cloud particle imaging probes for intermediate crystal sizes between 50  $\mu\text{m}$  and 1-2 mm**, in order not to miss information in that size range, even though not much mass contribution to snow water content is expected in the range below 1 mm. This is why the use of best quantitative array probes such as the 2D-Stereo probe is recommended in order to complement PIP or HVPS OAP probes. Also, there is a potential that snow crystal fragmentation in a wind tunnel may produce non-negligible submillimetric crystal mass that needs to be documented. The 2D-S has a pixel resolution of 10  $\mu\text{m}$  (and 128 photodiodes) as compared to a standard cloud imaging probe CIP (64 photodiodes) of a pixel resolution of 25  $\mu\text{m}$ . Another instrument candidate in that field should be the 15  $\mu\text{m}$  resolution greyscale CIP (also 64 photodiodes). All those probes are considered to be quantitative probes with a large sampling volume (thousands and ten thousands of particle images measured per second), allowing good PSD statistics within short time intervals (1s, 5s).
3. **Need of high resolution imaging probes.** In addition to OAP imaging probes, spanning the entire snow particle size range and disposing of extremely large sampling volumes for good statistics of snow microphysical properties and also concentration (PSD), high resolution imaging probes have been designed, mainly based on CCD cameras, that considerably improve the knowledge of cloud particle morphological information with potential to create a proxy or an indicator of the presence of liquid water in the snow particle, thus distinguishing at least dry and wet snow, however with extremely limited sample volume that does not allow quantifying particle statistics with high frequency. Amongst those probes two very sophisticated imagers are the Cloud Particle Imager (CPI) and the High Speed Imager (HSI). Both probes are excellent instruments for morphological analysis of individual snow particles, but should be considered semi quantitative or even qualitative in terms of cloud particle statistics (PSD, IWC,..., etc)! Whereas common OAP greyscale probes have maximum 3 greyscale levels, the CPI and HSI have 256 greyscales, which then give much more morphological insights. The most important feature of the 256 levels of greyscale, however, should be the idea of possibly

distinguishing dry and wet snow, as has been presented by Praz et al (2017) for the MASC ground-based instrument composed of three separate camera systems. Comparing both high resolution imagers CPI and HSI, an advantage of the HSI over the CPI constitutes the fact that the HSI is an open path probe, whereas the CPI represents a closed path instrument, subject to considerable shattering artefacts as large (snow) particles impinge on the circular inlet of the CPI.

4. **Need of bulk IWC measurement devices.** The need for implementation of reliable snow water content measurements in test facilities is extremely challenging. During HAIC project the two probes ROBUST and NEVZOROV (Korolev 1998) have been compared/evaluated with respect to the IKP-2 reference measurement of IWC. Results from these comparisons could be used for snow water content retrievals. The Cranfield University IKP or NRC CIKP seem to be the first choice for snow measurements in test facility. The Snow CVI could be a backup probe. Major drawbacks of the NEVZOROV and ROBUST hot wire technology probes are sampling efficiencies, which have been estimated for smaller ice particles from the HAIC dataset, and are less well known for larger snow particles.
5. In case that liquid cloud droplet are injected into the test section in addition to the snow type particles there is a clear **need for phase discrimination of particles (solid/liquid)**. It is suggested to use data from high resolution imaging probes (HSI or CPI), NEVZOROV probe and/or cloud droplet spectrometer.
6. **Need for artefact minimization during snow particle sampling.** The possible small ice crystals contamination (and loss of large snow particles) due to ice particle shattering should be avoided. Anti-shattering tips for open path instrument allow reducing the possible artefacts created by particle breakups (Korolev 1998, 2005) and bouncing off surfaces ahead of the instrumentation sample volume.
7. Unfortunately, no single instrument covers the range from  $1\mu\text{m}$  to several tens of mm. A selection of adequate instrumentation shall be deployed to cover the range for snow crystal populations.

Additional information on recommended instrumentations for snow test facility calibration are provided in the deliverable *D5.3 - Selection of most suitable instrumentation for IWT/T calibration*.

All instrumentation (sensors, transducers, and data acquisition systems) used in the facility for monitoring facility operation and for determining the aerodynamic and icing/snow cloud properties should be traceable to the applicable national standards setting agency and should be calibrated at least annually or in accordance with each facility-operator organization's processes and procedures.

## 7.1 Aerothermal parameters

Standard icing tunnel instrumentation probes should be used to measure the velocity distribution, total temperature distribution, total pressure, static pressure, and flow angularity.

For more information see ARP 5905 [1].

## 7.2 Humidity

Humidity is an important parameter for icing that can be characterized using different values like relative humidity, absolute humidity or dew-point temperature. It depends on the fraction of water vapour in air but also on air temperature and pressure.

It is not possible to measure correctly the humidity in the working section of the facilities in icing conditions because the measurement of the sensor is biased by the presence of supercooled droplets or/and snow. Then, humidity measurement is generally done upstream the cloud generation system in the still chamber.

Absolute humidity  $c_v$  is calculated from the vapour pressure and the local pressure  $P$ . Vapour pressure is the saturated vapour pressure at dew point temperature  $T_d$  or the product of the relative humidity  $RH$  and the saturated vapour pressure  $e_{v,sat}$  at the local temperature  $T$ .

$$c_v = \frac{e_{v,sat}(T_d)}{P} = RH \times \frac{e_{v,sat}(T)}{P}$$

If relative humidity can be easily defined in snow conditions, this is not the case in mixed phase conditions because saturated vapour is not the same for liquid and solid phases at given temperature. Then, it is suggested to use absolute humidity as the reference parameter instead of the relative humidity.

The assumption for the calculation of the humidity in the test section is that the absolute humidity is constant. The effects of the atomization air if any and the evaporation of the droplets/particles are generally neglected because the atomization air mass flow rate is about 1-2 % of the facility flow rate and the transit time between the spray bars and the test section is small compared to the characteristic time for evaporation, even for small droplets.

Following table provides a synthetic presentation of acceptable instrumentation for humidity measurement:

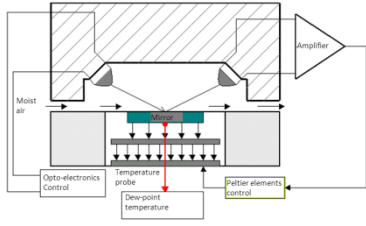

Instrumentation	Principle	Illustration
Chilled Mirror Hygrometer	<p>This device measures the dew-point temperature by controlling the temperature of the mirror in order to condensate the water vapour of sampling flow</p> <p>This technology is able to measure very low dew-point temperature (-70 °C) but response time and stability could be affected by the sampling flow rate. Sometimes, an error on dew-point temperature is possible due to an uncertainty on the state of water, supercooled water or ice, over the mirror for negative temperature.</p>	
Capacity Hygrometer	<p>This device measures the relative humidity and the local temperature. The principle of measurement is based on the change of the permittivity of material with relative humidity. The local vapour pressure.</p> <p>This technology cannot operate accurately in very dry or wet conditions</p>	
Optical sensors	<p>Water vapour has an interesting absorption spectrum with some peaks in the IR and UV wavelengths. Based on this property, some devices measure the extinction of a laser beam crossing a sample of air and calculate the vapour concentration from the Beer-Lambert's law.</p> <p>The absorption coefficient of the medium depends also on its pressure and temperature and must be corrected to ensure a good accuracy.</p>	N/A

Table 2 : Instrumentation for humidity measurement

### 7.3 Particle Morphology and Particle Size Distribution

The current state of the art instruments (Figure 3) for particle size and shape determination as well as bulk measurements are mainly based on three principles:

1. **Optical spectrometers:** Diffusion of light of single particles (in principal to determine the size of assumed spherical particles of known refractive index)
2. **Particle imagers:** Non-intrusive imaging (2D cross section of a 3D particle passing through the imaging laser beam) to derive concentrations in number and surface size distributions and to estimate volume and mass size distributions.

### 3. Bulk TWC & IWC devices: Phase change of particles (in order to measure the bulk mass of condensed water).

It is generally necessary to combine several instruments to cover complete size range from  $1\mu\text{m}$  to several mm.

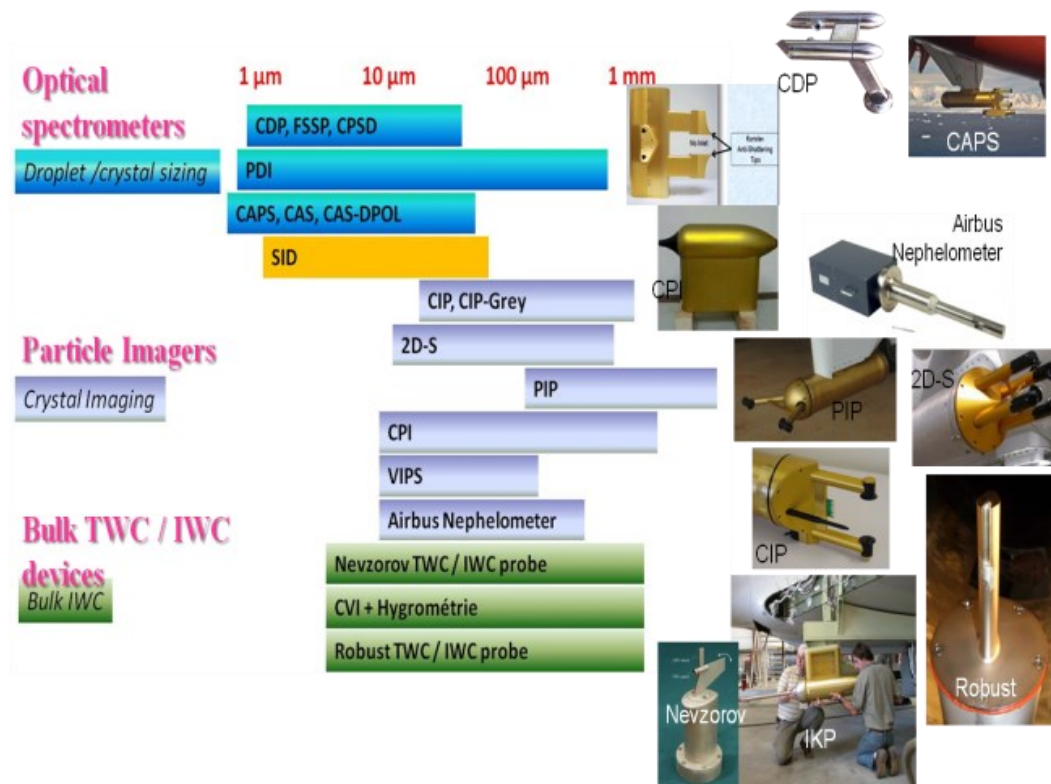


Figure 3: Multiple instruments to cover complete range from  $1\mu\text{m}$  to several mm.

As for the wind tunnel calibration within the FAR/CS 25/29 App. C (liquid water cloud), the reference document describing the instrumentation is the SAE ARP 5905 [1].

#### 7.3.1 Particle Size Distribution (PSD)

Snowflake size is mainly between 2 and 5 mm, ranging up to 15 mm. As such, **PSD measurement typically requires at least the use of two (2) probes<sup>3</sup> typically used for flight testing, to cover the whole size range.** 2D-S (10-1280  $\mu\text{m}$  range), CIP (25 – 1600  $\mu\text{m}$  range) and PIP (100 - 6400  $\mu\text{m}$  range) or HVPS (150 - 19200 $\mu\text{m}$  range) are appropriate choice. Use of alternative instrumentation would be possible but choice shall be substantiated.

The test facility shall provide detailed description of processing methods to account for shattering or out of focus particles. If the instrument is also used for evaluating Water Content, mass-size relationship should be substantiated. In that case, it has to be noted that such instrumentation can't be used as sole basis for Water Content calibration.

Suggested post-processing method is provided in Appendix.

<sup>3</sup> true for current flight probes but other instrumentation such shadowgraph system can cover the full PSD





Instrumentation	Principle	Illustration
Two-Dimensional Stereo probe (2D-S)	<p>Optical array probe developed by SPEC. Cloud particle enters field of view passing through a laser beam. Particle shadow falls on a collecting optical array (normally a photodiode array). This is sampled at a rate such that the pixel resolution in time is the same as that in the across-array dimension. This forms a digitized shadow image of the particle.</p> <p>The 2D-S measures cloud particles in the 10-1280 <math>\mu\text{m}</math> range with a resolution of 10<math>\mu\text{m}</math> (64 photodiodes).</p> <p>Detailed information and references:  <a href="http://www.specinc.com/2d-s-stereo-probe-operation">http://www.specinc.com/2d-s-stereo-probe-operation</a></p>	
Cloud Imaging Probe (CIP)	<p>Cloud Imaging Probe developed by DMT. Shadow images of particles passing through a collimated laser beam are projected onto a linear array of 64 photodetectors. The presence of a particle is registered by a change in the light level on each diode. The registered changes in the photodetectors are stored at a rate consistent with probe velocity and the instrument's size resolution. Particle images are reconstructed from individual "slices," where a slice is the state of the 64-element linear array at a given moment in time. A slice must be stored at each time interval that the particle advances through the beam a distance equal to the resolution of the probe. Optional grayscale imaging gives three levels of shadow recording on each photodetector, allowing more detailed information on the particles.</p> <p>The CIP also contains a Hotwire LWC sensor. This sensor estimates liquid water content using a heated sensing coil. The system maintains the coil at a constant temperature, usually 125 <math>^{\circ}\text{C}</math>, and measures the power necessary to maintain this temperature. More power is needed to maintain the temperature as droplets evaporate on the coil surface and cool the surface and surrounding air. Hence, this power reading can be used to estimate LWC.</p> <p>The CIP measures cloud particles in the 25-1600 <math>\mu\text{m}</math> range with a resolution of 25<math>\mu\text{m}</math> (64 photodiodes).</p> <p>Detailed information and references:  <a href="http://www.dropletmeasurement.com/cloud-imaging-probe-cip">http://www.dropletmeasurement.com/cloud-imaging-probe-cip</a></p>	
Precipitation Imaging Probe (PIP)	<p>Optical array probe developed by DMT. Cloud particle enters field of view passing through a laser beam. Particle shadow falls on a collecting optical array (normally a photodiode array). This is sampled at a rate such that the pixel resolution in time is the same as that in the across-array dimension. This forms a digitized shadow image of the particle.</p> <p>The Precipitation Imaging Probe (PIP) is a state-of-the-art probe that measures particles in the 100 to 6200 <math>\mu\text{m}</math> range. It is an ideal choice for measuring rain, snow, graupel, and hail. The PIP provides precipitation size distributions and particle images.</p> <p>Detailed information and references:  <a href="http://www.dropletmeasurement.com/products/airborne/PIP#Overview">http://www.dropletmeasurement.com/products/airborne/PIP#Overview</a></p>	
High Volume Precipitation Spectrometer (HVPS)	<p>The HVPS-3 (Version 3), developed by SPEC, combines 2D-S opto-electronics with HVPS optics and probe tips designed to minimize shattering.</p> <p>Probe images precipitation sized particles using the 2D-S 128-photodiode array with 150 micron pixel resolution</p> <p>The HVPS probe measures particles in the 150 to 19200<math>\mu\text{m}</math> range. It is an ideal choice for measuring rain, snow, graupel, and hail. The PIP provides precipitation size distributions and particle images.</p> <p>Detailed information and references: <a href="http://www.specinc.com/high-volume-precipitation-spectrometer">http://www.specinc.com/high-volume-precipitation-spectrometer</a></p>	

Table 3 : Instrumentation for PSD measurement

### 7.3.2 Particle morphology

In addition to OAP imaging probes, spanning the entire snow particle size range and disposing of extremely large sampling volumes for good statistics of snow microphysical properties and also concentration (PSD), high resolution imaging probes have been designed, mainly based on CCD cameras, that considerably improve the knowledge of cloud particle morphological information. They have the potential to create a proxy or an indicator of the presence of liquid water in the snow particle, thus distinguishing at least dry and wet snow, however with extremely limited sample volume that does not allow quantifying particle statistics with high frequency.

Following table provides a synthetic presentation of acceptable instrumentation for ice particle morphology measurement. Use of alternative instrumentation would be possible but choice shall be substantiated.



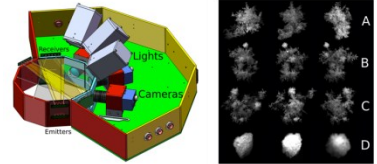
Instrumentation	Principle	Illustration
High Speed Imager (HSI)	<p>Developed by ARTIUM, the HSI records high resolution (5 <math>\mu\text{m}</math>) digital images of cloud particles as they pass through the measurement volume of the instrument. It collects the images of the particles on a 2000 by 900 CMOS array with sufficient resolution for obtaining the drop size and shape over the size range 3 <math>\mu\text{m}</math> - 4000 <math>\mu\text{m}</math>, with the images having a resolution of 3<math>\mu\text{m}</math>. The method of data processing leads to the particle size distribution and calculates the usual microphysical parameters: ice particle concentration, mean particle size, and ice water content. The classification of the shape of the ice particles can also be derived.</p> <p>Detailed information and references: <a href="https://www.artium.com/hsi">https://www.artium.com/hsi</a></p>	
Cloud Particle Imager (CPI)	<p>Developed by SPEC INC. in 1997, the CPI is a major improvement on existing imaging/shadowing probes such as the PMS classical OAPS. The CPI can image and count particles in the size range of 2.3-2300<math>\mu\text{m}</math>, with the images having a nominal 2.3<math>\mu\text{m}</math> resolution. Image analysis and data processing software provided with the probe takes particle size information (including area and volume) and ice crystal habit classification from the images to produce histograms etc.</p> <p>Detailed information and references: <a href="http://www.specinc.com/cloud-particle-imager">http://www.specinc.com/cloud-particle-imager</a></p>	
Multi Angle Snow Camera (MASC)	<p>The Multi-Angle Snowflake Camera, or MASC, was developed to address the need for high-resolution multi-angle imaging of hydrometeors in free fall, while simultaneously measuring their fall speed. The instrument was developed out of the University of Utah and is now available through Fallgatter Technologies.</p> <p>The MASC consists of three cameras, separated by 36 and each pointing at an identical focal point approximately 10 cm away. The focal point itself lies within a ring through which hydrometeors fall. The ring houses a system of near-infrared emitter-detector pairs, arranged in two arrays that are separated vertically by 32 mm. Hydrometeors passing through the lower array simultaneously trigger each of the three cameras as well as a bank of lights aimed at the center of the camera depth of field. Fall speed is calculated from the time it takes to traverse the distance between the upper and lower triggering array.</p> <p><u>Comment:</u> the probe is particularly well suited for characterization of generated snow at zero speed. It can't be used with air flow.</p>	

Table 4 : Instrumentation for Particle Morphology measurement

### 7.3.3 Mixed Phase

Determining the phase of cloud particles smaller than about 100  $\mu\text{m}$ , however, is challenging. Within HAIC solely a non-depolarizing CDP probe has been used which was a good compromise between robustness of the probe performance and clear supercooled water detection with subsequent estimation of LWC.

Following table provides a summary of some acceptable instrumentation for small supercooled water droplet measurement and small particle phase discrimination. Use of alternative instrumentation would be possible but choice shall be substantiated.

Instrumentation	Principle	Illustration
Cloud and Aerosol Spectrometer with Depolarization (CAS-DPOL)	<p>The CAS-DPOL (Cloud and Aerosol Spectrometer, with detector for polarization) instrument provides measurements of the concentration and size of aerosol particles, cloud droplets and ice crystals in the size range between 0.5 and 50.0 <math>\mu\text{m}</math>. Intensity distributions from the forward and backward scattered light by individual particles that pass through a focused laser beam are measured to derive the size distribution of the particles and the phase (liquid or ice). Additionally the intensity of the S and P polarized light is measured.</p>	
Cloud Droplet Probe (CDP)	<p>Developed by DMT, the CDP is a forward-scattering optical spectrometer. For accurate sizing, the CDP accepts and sizes only particles that pass through a region of the laser beam with uniform power. This region of the laser is called the depth of field.</p> <p>As particles pass through the laser beam, light scatters in all directions. The CDP collects forward-scattered photons within an annular cone that is 4° to 12° from the laser beam. The collected light is then directed onto a 50/50 optical beam splitter and finally to a pair of photodetectors, referred to as the sizer and the qualifier. There is a mask in front of the qualifier detector to define the depth of field. The edge of the depth of field is defined by the points where half of the light scattered from a particle is blocked by the mask.</p> <p>The photodetectors then convert the photon pulses into electrical pulses. The pulse from the qualifier is multiplied by two, and if the resulting signal exceeds the pulse from the sizer, the particle is deemed within the depth of field. The particle is then sized based on the amplitude of the sizer pulse.</p> <p>Measurement range: 2-50<math>\mu\text{m}</math></p> <p>Detailed information and references:  <a href="http://www.dropletmeasurement.com/products/cloud-physics/CDP-2">http://www.dropletmeasurement.com/products/cloud-physics/CDP-2</a></p>	
Fast Cloud Droplet Probe (FCDP)	<p>SPEC has developed a Fast Cloud Droplet Probe (FCDP) with state-of-the-art electro-optics and electronics that utilizes forward scattering to determine cloud droplet distributions and concentrations in the range of 1.5 to 50 microns. The new electronics include a temperature controlled fiber-coupled laser, FSSP-300 optics with pinhole limiting depth of field (Lance et al. 2010), a field programmable gate array (FPGA), 40 MHz analog-to-digital-converter (ADC) sampling, custom amplifiers, a very small and low power Linux based 400 MHz processor and a 16-Gigabyte flash drive that stores data at the probe.</p> <p>Detailed information and references: <a href="http://www.specinc.com/node/123">http://www.specinc.com/node/123</a></p>	

Table 5 : Instrumentation for Mixed Phase measurement

## 7.4 Total / Ice Water Content (TWC / IWC)

Beside the instruments to measure particle size spectra distribution in the cloud, there are other techniques able to measure integral properties of the cloud such as liquid, ice and total (liquid + ice) water content.

The measurement principle is to keep constant the temperature of the sampling wire element [11]. This device represents the most common way to measure LWC in the wind tunnel providing the evolution of the cloud time stability during the spray. A variety of hot-wire devices have been developed that incorporate the constant-wire-temperature technique [16][17][18]. The output voltage is proportional to the amount of power delivered to the wire to keep it at a constant temperature in cloud. This power is composed by the sum of the convective cooling of the tunnel airflow, the “dry” term, and by a “wet” term representing the evaporation of water droplets / ice particles:

$$P_t = P_{\text{dry}} + P_{\text{TWC}} \quad (1)$$

Where  $P_t$  is the total power measured across the wire,  $P_{\text{dry}}$  is the dry-air convective heat loss across the wire, and  $P_{\text{TWC}}$  is the power expected to evaporate water droplets / ice particles.

Typically the sensor head is a cylinder of 2 mm diameter that is not only mechanically robust, but is also relatively more sensitive to the heat loss associated with the droplet / ice particle evaporating than it is to the convective heat losses. From energy balance equation it is possible to derive the calculation for cloud liquid water content:

$$P_t = L_w * D_w * V_{\text{TS}} * \varepsilon * [L_v + c * (T_w - T_s)] + \pi * L_w * k * (T_w - T_s) * \text{Nu} \quad (2)$$

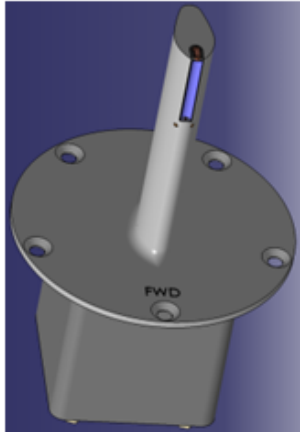
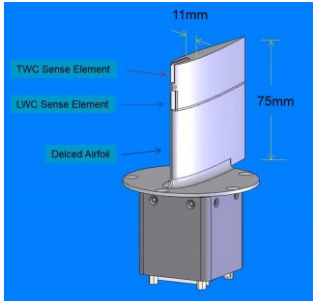
Where  $L_w$  and  $D_w$  are the length and diameter of the cylinder,  $V_{\text{TS}}$  is the true airspeed in the test section,  $\varepsilon$  is the collection efficiency of the sensor for droplets / ice particles,  $L_v$  and  $c$  the latent and specific heats of water,  $T_w$  is the temperature at which water droplet / ice particle evaporates,  $T_s$  is the static air temperature,  $k$  the thermal conductivity of air, and  $\text{Nu}$  Nusselt number for heat transferred from the wire. From eq. 2, it is possible to determine the total water content (TWC) that is given by:


$$\text{TWC} = \frac{P_t - P_{\text{dry}}}{L_w * D_w * V_{\text{TS}} * \varepsilon * [L_v + c * (T_w - T_s)]} \quad (3)$$

To estimate the dry air convective heat losses, some hot-wire systems have a reference hot-wire not directly exposed to the impact of water droplets to better determine the dry term. In other hot-wire the dry term is determined empirically. From King et al. 1978 [13], it is estimated that the overall uncertainty due to the dry term is of the order of  $0.03 \text{ gm}^{-3}$ . The sensor sensitivity can be improved by re-zero manually the LWC readings in dry air conditions just before the cloud exposure. For cylinder sensing element, the  $\text{Nu}$  number varies as its diameter  $d^{0.62}$  for dry term whereas for wet term varies as  $d$ . That means increasing the diameter  $d$  increases the magnitude of the wet term relative to the dry. For that reason and also to reduce the spread out of droplets after the impact on the sensing element, the wire diameters have been chosen between 0.5 mm and 2 mm. The collection efficiency  $\varepsilon$ , is included in the calculation of LWC (3) and tend to exceed 0.8 for droplets larger than about 10  $\mu\text{m}$  at typical aircraft speed, except for the largest wire diameter [21]. The uncertainty of hot wire system is estimated in wind tunnel by means inter-comparison with wind tunnel reference measurements performed with standard icing blade or icing cylinder [22], [23]. Typically for MVD of 20  $\mu\text{m}$  the uncertainty is within  $\pm 15\%$  of reference wind tunnel LWC [24], [25] and drops to as low as 50% (200  $\mu\text{m}$  MVD, 100  $\text{ms}^{-1}$ , 1.85 mm cylindrical wire) at high MVD [21] due to droplet splashing and re-entrainment of water after impact with the wire. From wind tunnel studies it is possible to define a formulation for LWC corrections based on empirical measurements correlating the response of the instrument to the increased value of droplets size. At constant cloud conditions, with higher MVD, has been found a reduced effect of LWC rolloff as the hot-wire diameter increase and vice versa, an increasing of the rolloff as the hot-wire diameter decreases. Different geometry of sensing element, like the concave cylinder element are found to have highest efficiencies at high MVD but tend to have larger inertial collision efficiency corrections at small MVD due to their typically larger wire diameter. The amount of particles mass lost after their impact on the sensing element is function of how high is the MVD respect to the wire dimension and this property can be used as a method to estimate the droplet MVD [26] through an empirical wind tunnel calibration. To measure the TWC and LWC in mixed-phase conditions, wire with concave cylinder elements have been used together with other two

different diameter wire elements in the same sensor unit [27]. With independent measurement of LWC and TWC, a qualitative estimation of ice water content (IWC) can be also obtained.

The wind tunnel simulation of supercooled large droplets (SLD) pose significant problems for the hot-wire devices with large diameter of sensing element and for the reference instruments as icing blade and rotating cylinder commonly used to measure the LWC in icing wind tunnel due to their accuracies that tends to degrade with increasing the MVD [31], [32], [32]. To address this inlet-based evaporating systems have been developed to measure LWC in an SLD icing cloud and also ice crystals. The concept is based on the iso-kinetic sampling of hydrometeors in order to be less sensitive to droplet splashing and cope with large droplets or mixed-phase conditions (Cohen et al. 1989 [30]). Unlike an icing blade and hot-wire probes, droplets can be drawn iso-kinetically into the probe and caught by a barrier filter or evaporated. The water mass collected can be weighed to provide a direct LWC measurement or humidity measured and background humidity subtracted to give TWC. The iso-kinetic condition defines a cylindrical stream tube in a wind tunnel spray cloud with a cross-sectional area equal to the probe's inlet area, hence, each measurement represents a discrete point in a spray cloud distribution. This iso-kinetic condition is achieved by nulling (or simply equalizing) the wall static pressures between the flows and outside of the probe, hence, equal velocities prevailed (inside and outside the probe).

Instrumentation	Principle	Illustration
Robust Probe	<p>The SEA Model WC-3000 Robust Water content System was designed to provide aircraft and wind tunnel users with a single, rugged sensor to measure Total Water Content (TWC). The instrument consists of one heated stainless steel element. The element is directly heated by low voltage dc current flowing through the element. The element is maintained at a constant temperature, typically 140 °C, by a digital, closed loop, control system.</p> <p>Given the dimensions of the element and the true airspeed of the airflow the power level set by the control system to maintain temperature can be converted directly into the water content of the air stream.</p> <p>The instrument uses a scoop shaped sensor to collect both liquid water (LWC) and ice crystals ( IWC). The combined total of LWC and IWC is referred to as Total Water Content (TWC).</p> <p>Measurement range: 0-10g.m<sup>-3</sup></p> <p><u>Comment:</u> the probe shall be calibrated (collection efficiency with respect to snow) before use for test facility calibration. The probe does not distinguish LWC from IWC.</p> <p><u>Detailed information and references:</u>  <a href="http://www.scieng.com/products/robust.htm">http://www.scieng.com/products/robust.htm</a></p>	
ICD (Ice Crystals Detector) [42]	<p>The major design elements of the SEA Ice Crystals Detector (ICD) are two heated sensing elements which are embedded in the leading edge of a larger, deiced airfoil. One of the elements is referred to as the Total Water Content (TWC) element. The other element is referred to as the Liquid Water Content (LWC) Element. The TWC element consists of a half cylinder with the concave surface facing into the oncoming airstream. The LWC element is identical to the TWC element except that its convex surface is oriented into the oncoming airstream.</p> <p>An electronic control system maintains the elements at a constant temperature. The signal from each element is the amount of power needed to maintain the element at its set, constant temperature. From this information the TWC and LWC can be retrieved.</p> <p><u>Comment:</u> the probe shall be calibrated (collection efficiency with respect to snow) before use for test facility calibration</p>	


<p>Nevezorov Probe, deep cone version</p>	<p>The Nevezorov liquid water content (LWC) and total water content (TWC) probe is a constant-temperature, hot-wire probe designed for aircraft measurements of the ice and liquid water content of clouds. The probe consists of two separate sensors for measurements of cloud liquid and total (ice plus liquid) water content. Each sensor consists of a collector and a reference winding. The reference sensors are shielded from impact with cloud particles, specifically to provide an automatic compensation for convective heat losses. This results in a potentially improved sensitivity over uncompensated probes such as the King LWC probe.</p> <p>Measurement range: 0.003-3.0g.m<sup>-3</sup></p> <p><u>Comment:</u> the probe shall be calibrated (collection efficiency with respect to snow) before use for test facility calibration</p>	
<p>Ice Capture Cylinder (ICC)</p>	<p>The measurement principle is to trap ice into a volume exposed to the airflow; weigh and deduce IWC from time interval and sample area of device</p> <p>Used in Europe for many years</p> <p><u>Comment:</u> the probe shall be calibrated (collection efficiency with respect to snow) before use for test facility calibration. In particular, tube geometry should be adapted to snow conditions. Indeed, NRC assessment [35] in icing wind tunnel under ice crystals conditions showed that:</p> <ul style="list-style-type: none"> <li>• Ice Capture Cylinder method with 10 cm cylinders correlated well with mass-closure results at 80 m.s<sup>-1</sup>, but chaotic results were observed at 150 m.s<sup>-1</sup> (turbulence and captured mass ejection?)</li> <li>• Agreement much better with 20 cm cylinders (straight and bent), and best with straight 20-cm cylinders (within 4% of tunnel map at 150 m.s<sup>-1</sup>)</li> </ul> <p><u>Note:</u> RTA [44] showed good correlation with IKP measurements in the framework of ICE GENESIS</p>	
<p>Counterflow Virtual Impactor (CVI)</p>	<p>Counterflow Virtual Impactor (CVI) including High tech humidity sensors (TDL, Licor 580A, Buck dew point sensor, Vaisala sensor). The CVI is designed by CNRS/LaMP and manufacture by Enviscope GmbH.</p> <p>Measurement range: 1-2g.m<sup>-3</sup></p> <p><u>Comment:</u> most recommended probe. The probe does not distinguish LWC from IWC.</p>	
<p>Iso-Kinetic Probe (IKP)</p>	<p>The IKP is an instrument that will quasi-iso-kinetically sample a 6-7 mm diameter stream tube with liquid and ice particles without significant mass loss. The IKP evaporates all water, then measures the total water vapor before the air exits out the vent at the aft end of the probe. The total water content is then found by subtracting the background water vapor in the air from this measurement.</p> <p>Measurement range: 0-10g.m<sup>-3</sup></p> <p><u>Comment:</u> most recommended probe. The probe does not distinguish LWC from IWC.</p>	 <p style="text-align: center;">Cranfield IKP</p>

		 <p style="text-align: center;">NRC CIKP [37]</p>
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*Table 6 : Instrumentation for TWC / IWC measurement*

## 7.5 Snow Bulk Density


Following table provides a synthetic presentation of acceptable instrumentation for snow bulk density measurement

Instrumentation	Principle	Illustration
Weight of collected Snow	The snow bulk density is measured by collecting snow in a container of know volume and weighing it. In order to not compress the snow and affect the result, the snow ideally needs to be collected from free falling particles at minimum airspeed.	

*Table 7 : Instrumentation for Snow Bulk Density measurement*

## 7.6 Snow LWR

Following table provides a synthetic presentation of acceptable instrumentation for snow LWR measurement.

Instrumentation	Principle	Illustration
Calorimetry	The calorimetry method works as follows: the snow collected (within a defined volume) is weighed and put into a container with a predefined amount of preheated water. The temperature of the water is measured before the snow is added. After the snow has completely melted, the water temperature is measured again. From the temperature difference and the initial snow mass, the liquid water ratio can be calculated.	

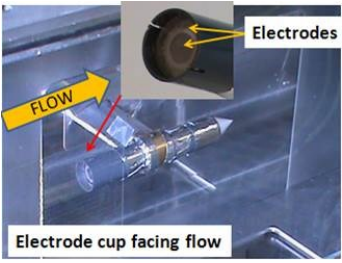
<p>IPP [43] or equivalent</p>	<p>The Ice Properties Probe (IPP) developed by NRC allows to measure the liquid water content <math>v_{liq}</math> of an ice accretion.</p>	
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Table 8 : Instrumentation for Snow LWR measurement

Calorimetry: Snow is collected (within a defined volume) and weighed to get the initial snow mass. The snow is then put into a container with a predefined amount of water. The temperature of the preheated water (normally to 35°C) needs to be measured just before the snow is added. After the snow has completely melted, the water temperature is measured again. From the temperature difference and the initial snow mass, the liquid water ratio can be calculated using the equations below.

**Measured Parameters:**

- Water Mass  $m_{Water}$  [kg]
- Starting temperature:  $T_{Water\_Start}$  [°C]
- Snow Mass  $m_{Snow}$  [kg] + water mass  $m_{Water}$  [kg]
- Temperature after melting:  $T_{Water\_End}$  [°C]

**Constants:**

- Specific heat capacity water  $c_W = 4.19 \frac{kJ}{kg \cdot K}$
- Melting enthalpy water  $c_{Melt} = 332 \frac{kJ}{kg}$

**Results:**

- Frozen Mass of snow  $m_{Snow\ frozen}$  [kg]
- Liquid Water Ratio LWR [%]

$$Q [KJ] = m_{Water} \cdot c_W \cdot (T_{Water\ End} - T_{Water\ Start})$$

$$m_{Snow\ frozen} = \frac{Q}{c_{Melt}}$$

$$LWR [\%] = \left(1 - \frac{m_{Snow\ Frozen}}{m_{Snow}}\right) \cdot 100$$

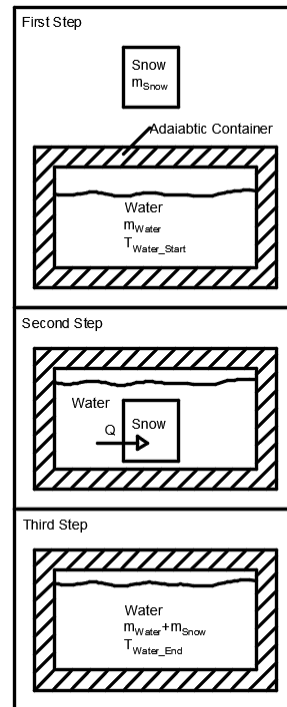
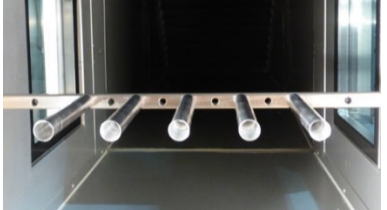


Figure 4: Schematic of calorimetry method

**7.7 The snow cloud uniformity assessment**

The cloud coverage area and concentration uniformity in the tests section is another important wind tunnel measurement to support the calibration activity. For liquid clouds the icing calibration grid is the recommended method reported in the SAE ARP 5905 which is based on the rime ice accreted.

For the snow cloud, the following methods are considered:

Instrumentation	Principle	Illustration
<p>2D mapping using a TWC probe</p>	<p>Cloud uniformity is measured through measurement of TWC at a matrix of points across the test section using one of the instruments mentioned in section §7.4</p> <p>The spacing of the grid or matrix should be related to the size of the tunnel test section</p> <p><u>Comment:</u> The ICC can be used for a qualitative relative evaluation of IWC within the test section. For quantitative evaluation the ICC needs to be calibrated</p>	 <p>ICC set-up at TUBS</p>

2D mapping using a PSD probe	Cloud uniformity is measured through measurement of PSD at a matrix of points across the test section using one of the instruments mentioned in section §7.3	N/A
Ice accretion based method	TWC uniformity can also be determined using growth rates on an accretion surface covering the area of interest, analogous to an icing grid used for supercooled liquid water uniformity measurements. This also has the advantage of being affected by other parameters and therefore requires uniformity of all relevant accretion parameters. However, the growth rate (or size after a specific exposure time) should only be measured physically (e.g. using vernier calipers) when the accretion is hard so as to ensure the measurement device measures from the surface of the accretion. Snow accretion can be soft and in these circumstances, a non-contact method should be employed or it frozen to allow physical contact	N/A

*Table 9 : Approaches for snow clouds uniformity assessment*

## 8 Facility calibration

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A facility should be in calibration when performing certification tests. The intent of the calibration is to establish a history on the repeatability of the facility with respect to relevant aero and icing/snow related parameters over long periods, beginning from the date of commissioning.

Three types of calibration should be performed for each facility. They include: baseline calibration, interim calibration, and check calibration.

### 8.1 Baseline Calibration

The baseline calibration should be a full calibration of the facility, and will include an aerothermal calibration and icing/snow cloud calibration. Full calibrations are required on initial commissioning or following any major facility modifications that change the aerolines or icing/snow cloud, such as replacement of the heat exchanger, test section, spray bar systems, etc. As a minimum, baseline calibrations should be performed on a five-year interval.

### 8.2 Interim Calibration

The interim calibration should be performed on an annual basis for the first two years following the baseline calibration resulting from initial commissioning or a major change to the facility. The interim calibration should include, as a minimum:

- a) confirmation that icing/snow cloud uniformity has not changed from that established during the baseline calibration (use a representative number of uniformity plots at the airspeeds for which uniformity has been established) and
- b) confirmation of tunnel axial centerline LWC/IWC measurements.

The interim calibration should include a model-relative spanwise measurement of the total and static pressure and total temperature at the model test station over the range of airspeeds and temperatures at which the tunnel is operated. The interim calibration should also include confirmation of the MVD/MMD calibration, using a representative sampling from the baseline calibration.

If the interim calibration indicates a shift in tunnel performance from the established baseline calibration by values greater than the values in Table 1, the facility operator should correct the problem(s) and repeat the interim calibration. If the out-of-tolerance condition still exists, then the full calibration is required to re-establish a baseline, after the operator has ensured system stability.

### 8.3 Check Calibration

The check calibration should be performed every six months, except when it is superseded by a baseline or interim calibration. The check calibration consists of measurements of icing/snow cloud uniformity and centerline LWC/IWC measurements, over a representative sampling of uniformity and LWC/IWC measurements from the baseline calibration. If the check calibration indicates a shift in tunnel performance from the established baseline calibration values greater than the values in Table 1, the problem should be corrected and the check calibration repeated. If the out-of-tolerance condition still exists, then the full calibration is required to re-establish a baseline, after the operator has ensured system stability.

### 8.4 Continuity Check

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

## 8.5 Direct measurement

In some cases, a tunnel can directly measure parameters for each test point. This must be done using a calibrated instrument designed for that type of measurement in the conditions being used for a given test point. Therefore, that parameter is known for each test point and does not require a prior tunnel calibration for that parameter.

## 9 Facility calibration procedures

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

The facility should perform an aero-thermal and icing/snow cloud calibration per the time frames defined in Section 8 to demonstrate that the facility, instrumentation, and procedures continue to produce acceptable data. The calibration should cover the area of the test section where tests are performed in the facility. The calibration should cover the area of the test section where the LWC and IWC spatial uniformity defined in Table 1 is met.

### 9.1 Aero-thermal calibration

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

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

Each facility should develop a test matrix applicable for their intended operation range.

The calibration matrix should, as a minimum, include:

1. An aerodynamic calibration consisting of: centerline static and total pressure correction measurements, and velocity, flow angularity and turbulence measurements at ambient temperature as in Table 10.
2. A thermodynamic calibration consisting of temperature surveys at four temperatures spanning the range: +2 °C to -10 °C (or the minimum operating temperature to be used for tests) as found in Table 11.

#### Notes:

1. Aero-thermal calibration may be performed with snow generation system non operative. Calibration with system operative is however desirable especially to assess impact on temperature (potential cooling effect due to humidity).
2. in the table below, the minimum operating velocity is 20kts

#### 9.1.1 Aerodynamic calibration matrix

Aerodynamic calibration should be performed in dry air at ambient temperature or controlled positive temperature.

Vertical position (% of test section half height)	Horizontal position (% of test section half width)	Tunnel Static Air Temperature	Test section Velocity (% of operating range)
0, ±25, ±50, ±75	0, ±25, ±50, ±75	Ambient	0, 33, 67, 100

Table 10: Aerodynamic minimum calibration matrix

### 9.1.2 Thermodynamic calibration matrix

Vertical position (% of test section half height)	Horizontal position (% of test section half width)	Snow generation system (% of operating range)	Tunnel Static Air Temperature	Test section Velocity (% of operating range)	Test section Humidity (% of operating range)
0, ±25, ±50, ±75	0, ±25, ±50, ±75	0, 33, 67, 100	-10, -4, +1	0, 33, 67, 100	0, 33, 67, 100

Table 11: Thermodynamic minimum calibration matrix

Note: Thermodynamic calibration should be performed at least with snow generation system OFF.

## 9.2 Icing/snow cloud calibration

An icing/snow cloud calibration should be conducted to determine the basic icing/snow cloud characteristics of the facility. All instrumentation required for defining the MVD, MMD, LWC, IWC, TWC, particle morphology, particle density and cloud uniformity are defined in section 7. Calibration should be performed for the different types of snow: 1) dry and wet snow 2) falling and blowing snow.

### 9.2.1 Particle size distribution or MMD calibration

Particle size distribution should be measured on the centerline. The minimum acquisition duration is 30 seconds.

A functional relationship should be determined between the MMD and these snow generator settings. PSD and MMD should be measured using one or more of the instruments described in 7, as required. These instruments should be in current calibration.

In order to adequately determine the relationship between MMD and the independent variables, the facility should make measurements of MMD at an array of points defined by the independent variables. The values chosen to define the array should not exceed 15% of the range of each independent variable necessary to cover the desired MMD range for the facility.

In order to evaluate the validity of the MMD relationship generated by this procedure, a sufficient number of widely spaced additional values should be taken to determine the repeatability of the MMD measurements.

Snow generation system (% of operating range) <sup>1</sup>	MMD (% of operating range)	Tunnel Static Air Temperature <sup>4</sup>	Test section Velocity (% of operating range)	Test section Humidity (% of operating range) <sup>2,3</sup>
0, 50, 100	MMD <sub>target</sub>	-10, -4, +1	33, 67, 100	33, 67, 100

Table 12: Particle size distribution minimum calibration matrix

Notes :

- Control of the melting of the particles from dry snow to wet snow is important
- Humidity is expected to have an impact on the test (evaporative cooling effect with lower humidity) especially for engine application
- As a minimum, Humidity shall be characterized and documented as it may affect snow accretion
- For snow generation system able to control snow particle melting, static temperature is not expected to have major impact on PSD and MMD. Given static temperature in the range [-4 ; +1]°C may be chosen.

### 9.2.2 Total/Ice water content calibration

Total/Ice water content shall be measured on the centerline. The minimum acquisition duration is 30 seconds.

Each facility should first determine the functional relationship between the Water Content (TWC, IWC, LWC), snow generation settings, and test section airspeed. This may be performed experimentally, provided that the curve defining the functional relationship has been determined with a sufficient number of points to be statistically valid. Alternatively, an analytical relationship may be postulated, in which case it will be necessary to verify this relationship experimentally. In either case, it is necessary to perform a set of experiments to determine or substantiate the relationships using one or more of the instruments described in Section 7 to measure Water Content.

Snow Generation System (% of operating range) <sup>1</sup>	MMD (% of operating range)	Tunnel Static Air Temperature <sup>4</sup>	Test section Velocity (% of operating range)	Test section Humidity (% of operating range) <sup>2,3</sup>
0, 25, 50, 75, 100	MMD <sub>target</sub>	-10, -4, +1	0, 33, 67, 100	0, 33, 67, 100

Table 13: Total water content minimum calibration matrix

Notes :

1. Control of the melting of the particles from dry snow to wet snow
2. Humidity is expected to have an impact on the test (cooling effect) especially for engine application
3. As a minimum, Humidity shall be characterized and documented as it may affect snow accretion
4. For snow generation system able to control snow particle melting, static temperature is not expected to have any impact. Given static temperature in the range [-4 ; +1]°C may be chosen.

### 9.2.3 Particle Morphology

The snowflake morphology shall be characterized for comparison with “real” snowflake characteristics<sup>1</sup>. The calibration matrix will be the same than for water content calibration presented in Table 13.

Notes:

1. Further processing of ICE GENESIS ATR dataset shall be performed.

### 9.2.4 Particle bulk density

The snowflake bulk density<sup>1</sup> should be characterized for comparison with “real” snowfakes characteristics. The calibration matrix will be the same than for water content calibration presented in Table 13.

Notes:

1. Evaluation of Snow particle bulk density is very challenging and there is no agreed methodology yet to comply with this criterion. Coutris [41] proposed a new approach to derive mass-size relationships (m - D) from size distributions and ice water contents. The retrieval is formulated as an inverse problem.

### 9.2.5 Snow bulk density

The Snow bulk density shall be estimated by either

- Comparing the snow cumulated volume derived from the PSD measurement with the snow cumulated mass derived from the IWC measurement at the same location.
- Simple method (volume, mass – cf§7.5)

The calibration matrix will be the same than for water content calibration presented in Table 13.

### 9.2.6 Snow melting

The Snow melting shall be estimated by either

- Calorimetry (Cf §7.6)
- IPP or equivalent

The calibration matrix will be the same than for water content calibration presented in Table 13.

### 9.2.7 Cloud size and uniformity

The calibration matrix will be the same like that used for water content calibration presented in Table 13.

The matrix of measured points should be taken at a reference plane positioned at the center of rotation of the model support system. The spacing between points in the matrix should be no greater than 12.5%, not to exceed 15 cm (6 in) of the span in either direction.

Four possible characterization methods for TWC have been identified in Section 7.4:

- Mapping with TWC, IWC instrumentation. The Water Content value at any given point should be an average of the measurements over an interval sufficient to provide a statistically stable value of the Water Content at that point
- Rakes of ice captured cylinder (ICC)
- Ice accretion based method
- Laser sheet technique.

One possible characterization methods for PSD have been identified:

- Mapping with PSD instrumentation

For mixed phase, a separated calibration is possible assuming no interaction between ice and liquid phase.

## 9.3 Continuity check

The aim of this continuity check is to have some reference tests to ensure that the reproducibility of the icing conditions is not affected by any modification of the test facility.

A simple model may be tested during or after calibration or commissioning tests to have some reference data. Test matrix should at least consider:

- Speed variation
- TWC variation
- Particle melting variation from dry to wet snow

## 10 Acceptance criteria

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### 10.1 Aerodynamic

The aerodynamic performance characteristics should be applied only within the selected test volume. If the tunnel calibration shows that the aerodynamic performance meets the spatial uniformity requirements shown for the Aerodynamic Parameters in Table 1, then the tunnel should be deemed acceptable for snow tests.

### 10.2 Snow Cloud

The calibration should cover the area of the test section where the Water Content and particle size spatial uniformity defined in Table 1 is met. This area may vary from condition to condition. Temporal stability of the Water Content and snow MMD values may be inferred from the controlled snow generation parameters, or measured in situ during testing. The acceptable area for snow testing should be restricted to the area of the snow uniform cloud. If the snow calibration demonstrates that the conditions of spatial uniformity and temporal stability in the snow cloud parameters from Table 1 are met, then the tunnel should be deemed acceptable for snow performance.

## 11 Calibration report

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A final report should be prepared and be available after each calibration (full, interim, and check). The report should contain photographs of test setup, a list of instrumentation, and test results. The intent of the final test report is to provide guidance to the user with regard to the calibration process and results.

The calibration report shall include:

- A description of the facility
- Aero-thermal calibration
  - Velocity distribution and static and total pressure
  - Turbulence intensity
  - Flow angularity
  - Temperature distribution
- Icing cloud calibration
  - Humidity
  - PSD and aspect ratio/circularity distribution
  - TWC, IWC, LWC
  - Snow bulk density estimate
  - Snow particle density estimate
  - Cloud uniformity
- Continuity check data
- Test Facility Qualification Statement: If results from testing are to be used for acceptance of the facility, such that data generated in the facility will be submitted to a regulatory/certifying agency for certification credit, the facility operator should include a statement that all testing and calibration have been performed in accordance with these recommended practices and found to be in accordance with the acceptance criteria defined in Section 6.

## 12 Conclusion

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The calibration methodology proposed in this document has been developed for snow and mixed phase conditions, starting from SAE ARP 5905. The scope of this document includes sea level and altitude test facilities.

The relevant parameters for calibration with their acceptance criteria for measurement accuracy, temporal stability, spatial uniformity and target values have been defined.

The possible instrumentation for particle size distribution, particle characteristics and water content measurements is described. Measurement of humidity is also considered.

This methodology focuses mainly on the characterization of the cloud like the particle size distribution and characteristics, the water content and the spatial uniformity.

Minimum calibration test matrices are proposed. A specific “continuity check” test has been included in the procedure as a reference test on a model sensitive to snow. This test would allow assessing the continuity of the facility’s performance after upgrading.

This document could be the baseline for a future update of the SAE ARP5905 “Calibration and Acceptance of Icing Wind Tunnels”.

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## 14 Appendices

### 14.1 Appendix 1 : Definition of Size Parameters [38][39][40]

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:

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

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 (cf. Figure 5). 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.

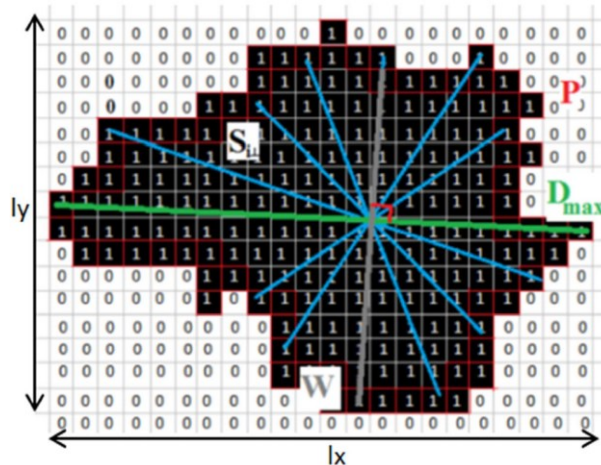


Figure 5: Binary matrix of a particle image recorded by an OAP probe. A value “0” corresponds to a non-shaded pixel whereas “1” corresponds to pixels shaded by the cloud particle when passing through the laser beam as a function of time. Red contoured pixels represent the pixels from which the perimeter  $P$  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.

### 14.2 Appendix 2 : Snow particle density retrieval methodology

Evaluation of Snow particle bulk density is very challenging and there is no agreed methodology yet to comply with this criterion. Coutris [41] proposed a new approach to derive mass-size relationships

( $m - D$ ) from size distributions and ice water contents. The retrieval is formulated as an inverse problem.

### 14.3 Appendix 3 : Snow MMD and IWC retrieval methodology

The approach to retrieve IWC from OAP measurements is complex. The described methodology relies on CNRS-LaMP expertise in the field [38] [39] [40] and the significant experience gained in the framework of the HAIC (FP7 High Altitude Ice Crystals), EASA-HighIWC and HIWC (US lead High Ice Water Content project) 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 6.

- 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.

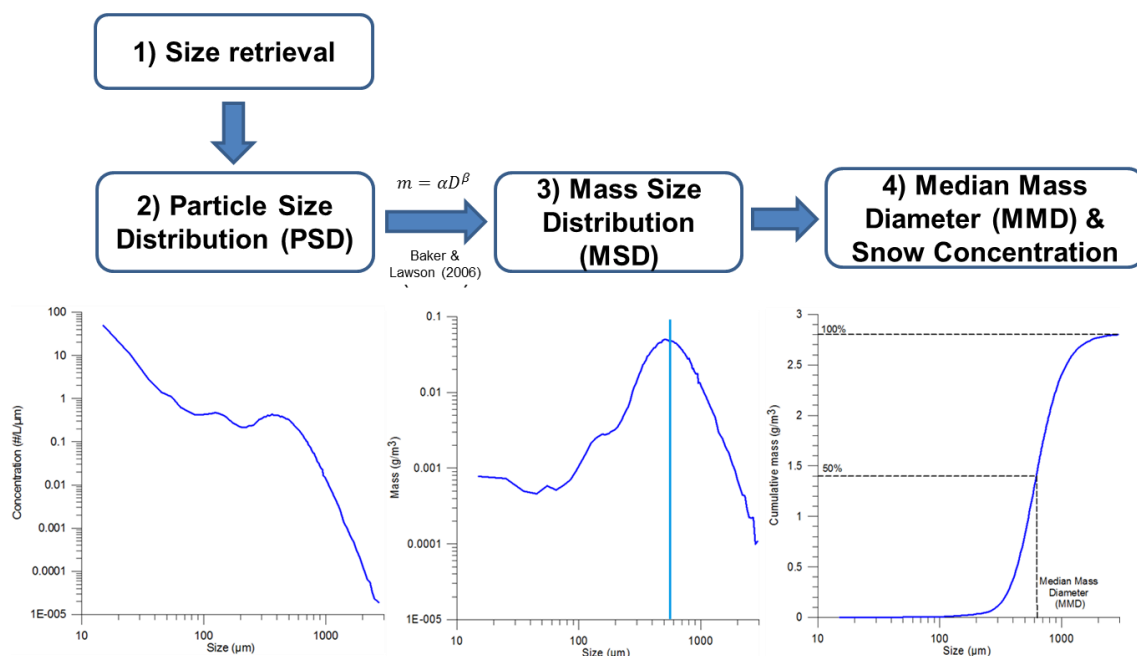


Figure 6: Snow IWC retrieval methodology

#### 14.3.1 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. 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).

### 14.3.2 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. 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 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.

### 14.3.3 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  $\alpha$  and  $\beta$  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 ( $\alpha$ ,  $\beta$ ) 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.