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# ICE GENESIS

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

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# Deliverable D4.2

# Report on the review, assessment and selection of instrumentation for LWC

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# 1 Glossary

| Abbreviation / Acronym | Description/meaning |
|---|---|
| ATF | Altitude Test Facility |
| CLH | Closed Path TDL Hygrometer |
| CS25 | Certification Specification |
| CVF | Cumulative Volume Fraction |
| CVI | Counterflow Virtual Impactor |
| CWC | Condensed Water Content [g $m^{-3}$] |
| DMT | Droplet Measurement Technologies, Inc. |
| FAR25 | Federal Aviation Regulation |
| FZDZ | Freezing Drizzle |
| FZRA | Freezing Rain |
| IB | Icing Blade |
| ICD | Ice Crystals Detector |
| IKP | Isokinetic Probe |
| IWT | Icing Wind Tunnel |
| LWC | Liquid Water Content [g $m^{-3}$] |
| MOC | Means of Compliance |
| MVD | Median Volume Diameter |
| PSD | Particle Size Distribution |
| RB | Robust Probe |
| SEA | Science Engineering Associates, Inc |
| SLD | Supercooled Large Droplets |
| SPEC | Stratton Park Engineering Company |
| TAS | True Air Speed [m $s^{-1}$] |
| TDL | Tunable Diode Laser |
| TWC | Total Water Content [g $m^{-3}$] |
| W/T | Wind tunnel |
| WCM | Multi Element Water Content System |
| WP | Work Package |
| | |
| | |
| | |

# 2 Executive Summary

The Deliverable D4.2 of the European ICE GENESIS project deals with the "review, assessment and selection of instrumentation for LWC". It is closely related to Task 4.2 of the work package 4. This task is dedicated to the review and selection of the most appropriate instrumentation for measurements of the liquid water content (LWC) under Appendix C and O conditions in wind tunnel (W/T) facilities. In particular, task 4.2 deals with the

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

Within this document, state-of-the-art instrumentation to characterize the LWC of small droplets and supercooled large droplets (SLD) is reviewed. The measurement requirements are extracted from FAR/CS-25 Appendix C & O conditions (FAA, 2014). The instruments should cover the LWC range from 0.01 g m$^{-3}$ to 3 g m$^{-3}$ for Appendix C. For Appendix O and SLD conditions, the icing envelope for LWC includes LWC lower than 0.5 g m$^{-3}$ for all FZDZ and FZRA cases. Further the instruments should be able to detect small droplets with sizes larger than 1 µm as well as SLD with a maximum diameter range of 100 to 500 µm for freezing drizzle (FZDZ) environments and droplet diameters larger than 500 µm for freezing rain (FZRA) conditions.

The recommended instrumentation is either provided by the participating test facilities (CIRA, MinDef and RTA) or by independent institutes (CU, DLR) as reference in several test facilities. The work of task 4.2 is to select best available instrumentation for the calibration of SLD conditions in W/T facilities and is therefore essential for work package 6. The calibration of selected instruments as well as the evaluation of correction methods and uncertainty assessment during data analysis provides a reference setup for W/T facilities and helps to reduce the risk of facility calibration bias for aircraft icing certification programs in Appendix C and O.

Liquid water content instruments are bulk measurement devices and often used in wind tunnel as well as aircraft experiments. The LWC is derived as an integral over the whole droplet size spectrum. Direct information on the droplet size or the distribution of the LWC on different sizes is not possible. Therefore, it has to be known if an instrument can measure all droplet sizes with the same efficiency. Otherwise, correction methods have to be implemented with respect to simultaneously measured particle size distribution (PSD) or information about the median volume diameter (MVD) of a distribution. The document will discuss data analysis methods of each selected instrument in the context of Appendix C/O conditions.

The instrumentation will be used for the calibration of SLD conditions in W/T facilities (WP6), which means the facilities have to consider installation possibilities and constraints of homogeneous sampling test sections.

The main objectives to meet with the selected LWC instrumentation for icing wind tunnels are summarized below. The objectives consider discussions related to W/T SLD test capabilities (WP6), W/T tests for liquid and snow conditions (WP8) and numerical capabilities (WP9).

Objectives:

a) Guarantee a wide measurement range for the LWC (nearly three orders of magnitudes starting from 0.01 g m$^{-3}$). Expected droplet sizes range between 1 µm and several millimetres to cover Appendix C and SLD conditions under Appendix O.
b) Provide correction methods for bulk measurements with respect to varying collection efficiencies of different droplet size spectra.
c) Give a reasonable uncertainty assessment for the used measurement techniques.

While instrument uncertainties are given for the complete set of instruments, three instruments were selected and have proven good performance for icing W/T measurements in Appendix C conditions. Results show that the Isokinetic Probe IKP, the WCM-2000 and the Nevzorov probe agree within better than 10% for LWC measurements in Appendix C conditions for LWC between 0.4 and 2.4 g/m³.

Tests with bimodal particle size distributions in Appendix O FZDZ conditions with MVD > 40µm at RTA at LWC between 0.4 and 0.6 g/m³ generally show a sufficient agreement with < 25% deviation of the results of the individual instruments from the multi instrument mean. The WCM2000 was closest to the multi instrument mean with deviations <1%. Compared to the multi instrument mean up to 10% deviation was detected for the Nevzorov 8 mm cone. The IKP trend tends to overestimate by ~20% the measurement conditions between 0.4 and 0.6 g/m³ of LWC. However, in addition to challenges in subtracting high levels of water vapour for background correction from a small LWC content, inhomogeneities in IWT particle distributions of up to 20% may significantly contribute to this bias. Additional measurements are required to derive respective uncertainties and to better constrain the homogeneity and humidity measurements at low LWC conditions.

***The document has been adapted for export control. Therefore, DLR contribution of technical data has been removed due to export control unsolved issues.***

# 3 Introduction

This document provides information on the instrumentation for LWC measurements under Appendix C and O conditions in W/T facilities. The instruments selected within Task 4.2 and documented in this Deliverable will be used for W/T calibration in Appendix C and Appendix O Freezing Drizzle conditions in the frame of WP6. An LWC range between 0.01 g $m^{-3}$ and 3 g $m^{-3}$ has to be covered. Therefore, the best possibility to minimize measurement biases between different wind tunnels is to use a single reference instrument in each facility. Otherwise, all WP partners may provide their own most appropriate instrumentation.

The specifications for W/T calibration of Appendix C and O conditions with a focus on LWC are described in Section 3.1. Sections 3.2 and 3.3 present a review of common used (bulk) LWC measurement techniques and an overview of available state-of-the-Art LWC instrument devices within the ICE GENESSIS community.

The selection (Section 4) of the recommended LWC instrumentation within this project is based on the measurement objectives under SLD conditions as well as installation requirements of each test facility. Besides the final selection, a description of calibration of selected instruments is given. The evaluation of the collection efficiency for different droplet sizes enables a detailed data analysis and reduces the risk of a facility calibration bias for the aircraft icing certification programs in Appendix C and O.

Furthermore, a description of suitable data analysis algorithms and correction methods is added. A similar data analysis for different devices improves the comparability between different facilities.

The work documented in this Deliverable serves as preparation for W/T calibration in WP6, W/T tests in liquid and snow conditions in WP8 and numerical test scenarios in WP9.

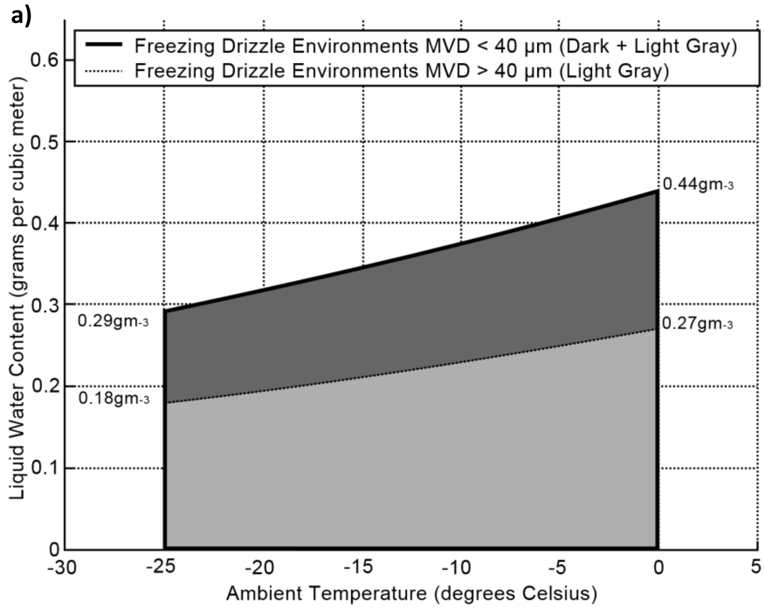
## 3.1 Specifications for W/T calibration of SLD conditions

The icing envelopes characteristic for Appendix C & O conditions are defined in the Code of Federal Regulations Title 14 Section Part 25 Appendix C and Appendix O of the EASA CS-25 (FAA, 2014). A description of the requirements can be found in Deliverable D3.1 (Section 4.1) as well as in Deliverable D4.1 (Section 3.1, table 1) with a focus on droplet sizes.

The maximum LWC for Appendix C conditions shows characteristic values of 0.05-0.8 g $m^{-3}$ for stratiform clouds and values up to 3.0 g $m^{-3}$ for convective clouds.

For Appendix O SLD conditions, the icing envelope for LWC depends on the ambient temperature but results in values lower than 0.5 g $m^{-3}$ for all FZDZ and FZRA cases (Figure 1).

a)



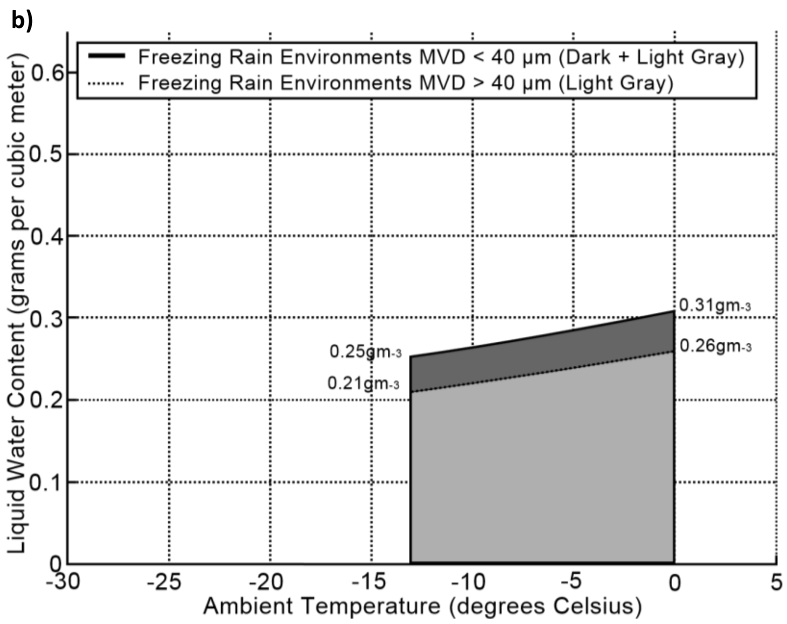



*Figure 1: Liquid water content for Appendix O FZDZ (a) and FZRA (b) conditions over ambient temperature. The LWC is based on the horizontal extent standard distance of 17.4 nautical miles (FAA, 2014).*

Besides the requirements regarding LWC range, expected high number concentrations of droplets, the cloud homogeneity in the W/T test facilities, and the installation requirements of each facility due to different dimensions in space are limiting factors for selecting the most appropriate LWC instrumentation. The range of performance characteristics in the W/Ts for airflow and cloud parameters to achieve over the area of uniform cloud was given in Deliverable D3.1, table 2. The instrument uncertainty for LWC is there defined with ± 10 %. The definition of this uncertainty range might need further revision with input from Deliverable 4.2.

## 3.2 Review of available LWC instrumentation

Clouds in icing conditions including supercooled large droplets are characterized by a wide variety of parameters. Besides the size and distribution of particles over the entire size range, their temperature and ambient conditions (e.g. temperature, altitude, and horizontal/vertical extent), also the liquid water content of the cloud is an important indicator.

Techniques to measure LWC in clouds were developed and are used for measurements in wind tunnels, cloud chambers and on aircraft. Most of the techniques are bulk measurement devices that characterize the total LWC of the cloud independent from the droplet sizes.

One commonly used technique is the **hot-wire technique**. Several instruments as Nevzorov probe, WCM-2000, King Probe, and Robust Probe were developed. The devices operate on the principle that the LWC can be determined from the amount of power delivered to a wire to evaporate cloud droplets (Baumgardner et al., 2011). Thereby, the surface of the heated element (wire/cone) is kept at a constant temperature. The difference in the power results from the convective heat loss in the airstream (dry term) and the evaporation of water droplets in clouds (wet term).

$$P_{total} = P_{dry} + P_{wet} \qquad 1$$

With the total power measured across the heated surface $P_{total}$, the dry-air convective heat loss from the surface $P_{dry}$ and the power expended to evaporate droplets $P_{wet}$.

The dry term can be derived from measurements in cloud-free conditions. The LWC is then:

$$LWC = P_{wet}/(L_w U S \varepsilon) \qquad 2$$

Where $L_w$ is the expanded heat of water, $U$ is the true air speed, $S$ is the sample area of the sensor and $\varepsilon$ is the collection efficiency of the sensor for droplets.

Several devices have additional reference sensors that measure the dry term in cloud conditions. These sensors are in contact with the air stream but not exposed to a direct impact with cloud particles.

The geometry of the sensors highly affects the collection efficiency of various droplet sizes. Cylindrical wires with typical cross-Sectional diameters of 0.5 mm to 3 mm are known to approach a good accuracy for droplets with a median volume diameter (MVD) between 5 µm and 50 µm. Larger droplets are splashing on the surface or re-entrain after impact and therefore are detected with a lower efficiency. Newer developments designed wire-wound, cup-like sensors to capture not just droplets but also ice particles. These cones also have higher collection efficiencies for larger droplets since they are captured and melted inside the conical volume (Korolev et al., 1998; Baumgardner et al., 2011). Other sensors, like multi-wire (MW) and robust probe (RP) have the concave sensing element (2 mm half cylinders for MW and 3.6 mm for RP) which design has been studied to reduce the mass losses of large droplets after their impact (splashing phenomena). Except to the MW, RP cannot discriminate water droplets from the ice crystals so only indication of TWC (LWC+IWC) can be providing during the measurements.

Another technique to measure the LWC or TWC (total condensed water content) is the **inlet-based evaporation and detection**. The inlet is exposed directly to the air stream and operates as a deep capture volume for droplets and ice particles. The particles are evaporated and the enhanced humidity is measured with a separate hygrometer. Often used are absorption hygrometers such as tunable diode laser (TDL) or Lyman-α. Examples for such devices are the Isokinetic Probe (IKP), the Counterflow Virtual Impactor (CVI) or the Closed Path TDL Hygrometer (CLH) (Baumgardner et al., 2011; Strapp et al., 2016).

By just having a forward-facing inlet the Total Water Content (sum of gas phase water content and LWC/IWC) is determined. Therefore, a separate gas phase background water vapour measurement is necessary to derive LWC or IWC. This can be realised with another device exposed to the air stream but without the impact of cloud particles such as a backward-facing inlet. For example, the IKP combines a forward- and a backward-facing inlet and measures the water vapour mixing ratio in two separate cells.

The advantage of inlet-based evaporating systems compared to the hot-wire technique is their higher collection efficiency for larger droplets. Bouncing and re-entrainment is minimized. Nevertheless, the inlet geometry is of great importance for a good performance. The size of the inlet diameter influences the size of hydrometeors than can be collected. Also, the inlet has to be positioned undisturbed from other devices or surfaces (more important for aircraft measurements). True air speed and the flow velocity inside the inlet need to know. For each device a correction method called aspiration coefficient or enhancement factor for individual conditions has to be implemented since large particles are sampled with enhanced efficiency compared to the gas molecules (Schiller et al., 2008). A major uncertainty for an IKP arises for small liquid water contents in App. O conditions, as the gas phase background signal is significantly larger than the LWC in droplets, thus the uncertainty in gas phase water determination increases uncertainties in the LWC determination.

In wind tunnel experiments **ice accretion** is a commonly used method to measure the LWC. This technique is not based on the continuous measurement during an experiment but on the accretion of ice on a blade or a rotating cylinder for a certain time period (Stallabrass, 1978; Orchard et al., 2019). The LWC is determined from the accreted ice mass and depends on the wind tunnel temperature, air speed, ice density, blade/cylinder geometry and collection efficiency for a known MVD. An essential requirement is that all tests are performed at temperatures of -18°C or below to create rime ice (Ludlam, 1951). The droplets instantaneously freeze after impact at a cold surface. The collection efficiency for a droplet size spectrum of a rotating cylinder depends on length and diameter of the cylinder (ranging from 1 mm to tens of millimetres).

Besides the integral measurement of the LWC, **particle size measurements** (e.g. scattering probes, optical array probes) can be used to derive the LWC on a particle by particle basis (compare Deliverable

D4.1, Section 3.2.1). This method leads to larger uncertainties (Baumgardner et al., 2011; Baumgardner et al., 2017) and cannot match the proposed instrument uncertainty of ± 10 %. Therefore, this method will not be part of this Deliverable.

## 3.3 Overview of the state-of-the-art LWC instrumentation

In this Section the entire available instrumentation from all WP4 partners is listed. Table 1 shows which instruments commonly used in the test facilities and which may be used as comparison or reference instruments by their possibility to measure in different facilities. The candidate instruments are described with their measurement features (LWC range, airspeed range, sampling frequency) as well as parameters that can be provided, performance and dimensions.

| Instrument (Manufacturer) | Instrument name | LWC range | airspeed range | Sampling frequency | provided by |
|---|---|---|---|---|---|
| **KLWC-5** | | 0-6 g/$m^3$ | <100 m s-1 | 20 Hz | **CIAM** |
| **IB (NLR)** | Icing Blade | 0.05 – 4 g/m3 (up to 50 µm MVD with LWC below Ludlam limit) | < 200 m s-1 | | **CIRA** |
| **2mm Hot-Wire (SEA)** | | 0 - 10 g/m3<br>0 - 6 g/m3 | <150 m s-1<br><230 m s-1 | 1 - 100 Hz | **CIRA** |
| **RB (SEA)** | Robust Probe | 0 - 10 gms/m3<br>SL – 45,000 ft<br>-40°C<br><br>0 - 6 gms/m3<br>SL - 45,000 ft<br>-40°C | <150 m s-1<br><230 m s-1 | 1 - 100 Hz | **CIRA** |
| **WCM-2000 (SEA)** | Multi-Element Water Content System | 0 - 10 g/m3<br>0 - 6 g/m3 | <150 m s-1<br><230 m s-1 | 1 - 100 Hz | **CIRA** |
| **ICD (SEA)** | Ice Crystal Detector | | | 1 - 100 Hz | **SEA (Sponsored by CIRA)** |
| **WCM-2000 (SEA)** | Multi-Element Water Content System | 0 - 10 g/m3<br>0 - 6 g/m3 | <150 m s-1<br><230 m s-1 | 1 - 20 Hz | **MinDef** |
| **IB** | Icing Blade | Ludlam limit | Ludlam limit | | **RTA** |
| **WCM-2000 (SEA)** | Multi-Element Water | 0 - 10 g/m3<br>0 - 6 g/m3 | <150 m s-1<br><230 m s-1 | 1 - 20 Hz | **RTA** |

| | | | | | |
|---|---|---|---|---|---|
| | Content System | | | | |
| **EIV-2K (Nevzorov probe system)** | | 0.2 – 2.5 g/m$^3$ | 20 - 200 m s-1 | 0.5 – 2 Hz | **TsAGI** |
| **Instrumentation from partners beside the facilities** | | | | | |
| **IKP-CU** | Isokinetic Probe | 0-5 g/m3<br>0-3 g/m3 | < 120m s-1<br>< 200m s-1 | 1 Hz | **CU** |
| **Nevzorov probe (SkyPhysTech)** | | 0.003 - 3 g/m3 | 10 - 180 m s-1 | 10 Hz | **DLR** |

| Instrument | Parameters provided | Performance | Dimensions | provided by |
|---|---|---|---|---|
| **KLWC-5** | LWC; LWP | | hot-wire: 1.8 mm | **CIAM** |
| **WCM-2000** | direct: LWC + TWC, derived: IWC + MVD | low contamination (<1 %) of LWC measurement by ice crystals | 0.7 kg; 14 cm x 8 cm x 8 cm<br>hot-wire: 2 mm; 0.5 mm | **MinDef, CIRA, RTA (rented for campaign)** |
| **IB Icing Blade** | derive LWC from ice thickness | Icing Blade vs. 1" Cylinder: ±5.6% @ 125 m s-1 for App. C | 300 mm height, 3 mm thick, 60 mm wide | **CIRA** |
| **2mm Hot-Wire** | direct: LWC | ± 10% vs. NASA_IB @ App. C cond. | 0.7 kg; 14 cm x 8 cm x 8 cm<br>hot-wire: 2 mm; 0.5 mm | **CIRA** |
| **RB Robust Probe** | direct: LWC, TWC | ± 10% vs. IKP-2… | Sensor Head Weight 0.7 kg<br>8.25 x 3.1 x 5.7 cm external<br>14.3 x 8.3 x 8.3 cm overall | **CIRA** |
| **ICD Icing Detector** | direct: LWC, TWC; derive: IWC | Low thermal mass response (< 1 sec) - Able to discriminate between ice crystals and ordinary super-cooled liquid icing conditions including SLD conditions<br>Evaluating phase | | **SEA (CIRA)** |
| **IB Icing Blade** | derives LWC from ice thickness | | 3.0 x 54.8 x 174 mm | **RTA** |

| Instrumentation from other partners | | | | |
|---|---|---|---|---|
| **Isokintic Probe CU-IKP** | TWC | Estimated ±10% | 0.7m Length, 1 kg (X2) | **CU** |
| **Nevzorov probe** | direct: LWC, TWC | Accuracy ±10 % | 1.5 kg; 23 cm x 9 cm x 5 cm<br>hot-wire: 2 mm; TWC cones: 8 mm; 12 mm | **DLR** |

*Table 1: LWC instrumentation available for measurements in WT facilities.*

# 4 Final selection of LWC instrumentation

## 4.1 LWC instrumentation for W/T calibration

Each W/T test facility that is part of WP6 decided on the LWC instrumentation for the calibration of SLD FZDZ conditions during task 6.4 taking into account the collective work of Task 4.2. The finally selected LWC instrumentation is here described in more detail. If available, previous measurements in Appendix C/O conditions with the instruments will be shortly explained. The availability of the instrumentation for SLD conditions with consideration of installation requirements have to be shown. In this Section, measurement results in Appendix C and Appendix O FZDZ conditions will be shown. Since, FZRA measurements are not part of WP6, first results of FZRA will be shown in the Appendix.

The SLD calibration in the different W/T facilities should be as comparable as possible. To enhance the comparability of LWC measurement in the test facilities and to minimize measurement biases a single reference instrument is chosen. The Isokinetic Probe from Cranfield University (CU-IKP) can be installed in different wind tunnel test sections and was chosen to measure LWC/TWC in the MinDef IWT and the RTA IWT during WP6. The instrument is capable to derive LWC in Appendix C and O conditions, assuming no ice crystals are present in the cloud, due to a large inlet tube that can collect small droplets as well as large droplets.

Another instrument, capable to be installed in different test facilities can be the DLR Nevzorov probe. It is foreseen to use the Nevzorov probe in the RTA IWT simultaneously to the CU-IKP to perform an instrument comparison and to reduce the uncertainty of the wind tunnel LWC.

In the CIRA IWT, an extended multi-wire sensor (SEA WCM2000) will be used for cloud calibration. An assessment of this technique with the RP is still ongoing and will be introduced in the Section 4.1.3.

### 4.1.1 The isokinetic probe CU-IKP

The probe designed and operated by Cranfield University (herein called CU-IKP) is essentially composed of 3 parts; a forward facing iso-kinetic inlet or iso-kinetic probe, a backward facing inlet and a double-cell hygrometer for water concentration measurement. It works on the principle of sampling air from the stream and analysing the water content.
The forward facing inlet isokinetically collects a representative sample of hydrometeors (droplets, ice crystals) including background water vapour so as to permit the making of a measurement of the total water content of the flow. The hydrometeors collected with the isokinetic inlet are melted/evaporated in their humid environment. The backward-facing inlet takes a second sample of solely background water vapour, without any particles or droplets in it. Subtraction of both hygrometric signals, allows to eliminate background water vapour and thus, retrieving TWC solely (related to droplets and/or ice).

The IKP probe stays free of ice build-up which would alter the isokinetic sampling. The flow conditions at the entrance to the probe can be carefully matched to oncoming flow in order to achieve the correct sampling, not too rich or depleted with respect to the condensed water. The heating inside the inlet drives all sampled water droplets and ice crystals into the vapour phase. After the initial heating from the IKP probe, the humid air is conveyed via a long insulated and temperature controlled pipe before reaching the measurement system. This pipe allows the main measurement system to not be located within the test section, even for large icing wind tunnel. It also ensures that the air reaching the measurement system is between a temperature of 20° and 35°C. This essentially prevents water re-condensation within the pipe for large condensed water concentrations and ensures the measurement system is not overheated by the hot air. The commercially available LICOR7000 is the instrument used to obtain the water concentration from both probes. The principle of this instrument is infrared absorption of water to derive the concentration in 2 independent cells. This is a real time measurement, which allows the CU-IKP to obtain real time CWC measurements.

Figure 2 shows the CU-IKP installed next to the WCM2000 in the RTA icing wind tunnel test section during a preliminary inter-comparison of both instruments.


*Figure 2: CU-IKP along with the WCM2000 at the RTA facility*

A test campaign has been conducted at RTA in October 2018, to obtain inter-comparison data between the CU-IKP and the SEA WCM2000 probe. The two probes were mounted as shown in Figure 2. The tunnel speed ranged from 30 to 60 m $s^{-1}$ and the total temperature was -5°C. Tests were conducted in Appendix C conditions with 20 and 40 µm MVD. The TWC ranged from 0.4 to 2.3 g $m^{-3}$. The results can be seen in Figure 3. There is a good agreement between the 2 probes with less than 20 % discrepancy.

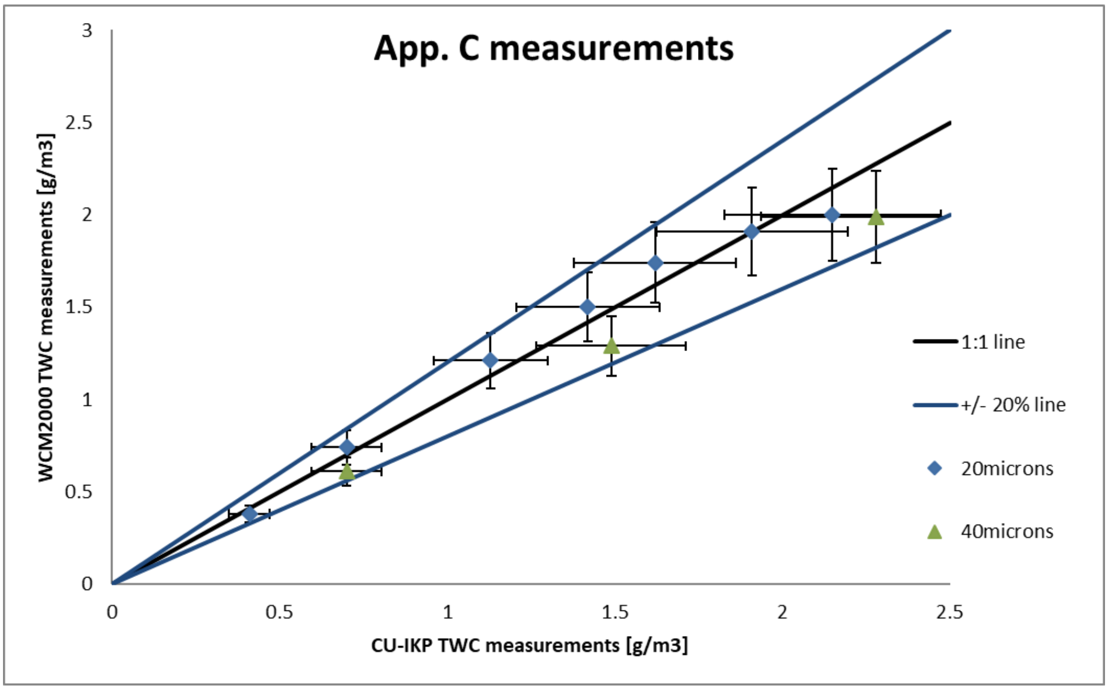



*Figure 3: App C test series for 20 and 40 µm MVD and error bars.*

Then, also tests were conducted for Appendix O conditions. In this case, the spray was generated from two different types of nozzles. One nozzle type was still spraying with the 20 µm MVD, the second type of nozzle was spraying with larger droplets of up to 1000 µm. The combination of both nozzle types provided the Appendix O conditions with MVD of 100, 550 and 650 µm.

The results for FZDZ conditions with an MVD > 40 µm are shown in Figure 4. Since results on Appendix O FZRA conditions are not relevant for the W/T calibration in WP6, all measurements in FZRA conditions will be shown and shortly described in the Appendix. It can be seen that in FZDZ conditions, there is a systematic difference between IKP and WCM2000. Overall, the IKP is reporting higher TWC with a discrepancy to the WCM-2000 of +20 % and more. The difference in both devices can be explained with the different positions (x- and z-direction) in the test section (Figure 2). The expected cloud uniformity in the RTA test section is within ±20 % and may therefore influence results at different probe positions. In addition, the high humidity levels of the background add to the uncertainties of the LWC data. Further measurements should include tests of both instruments at the exact same position to evaluate the expected effect of differing cloud uniformity within the test section.

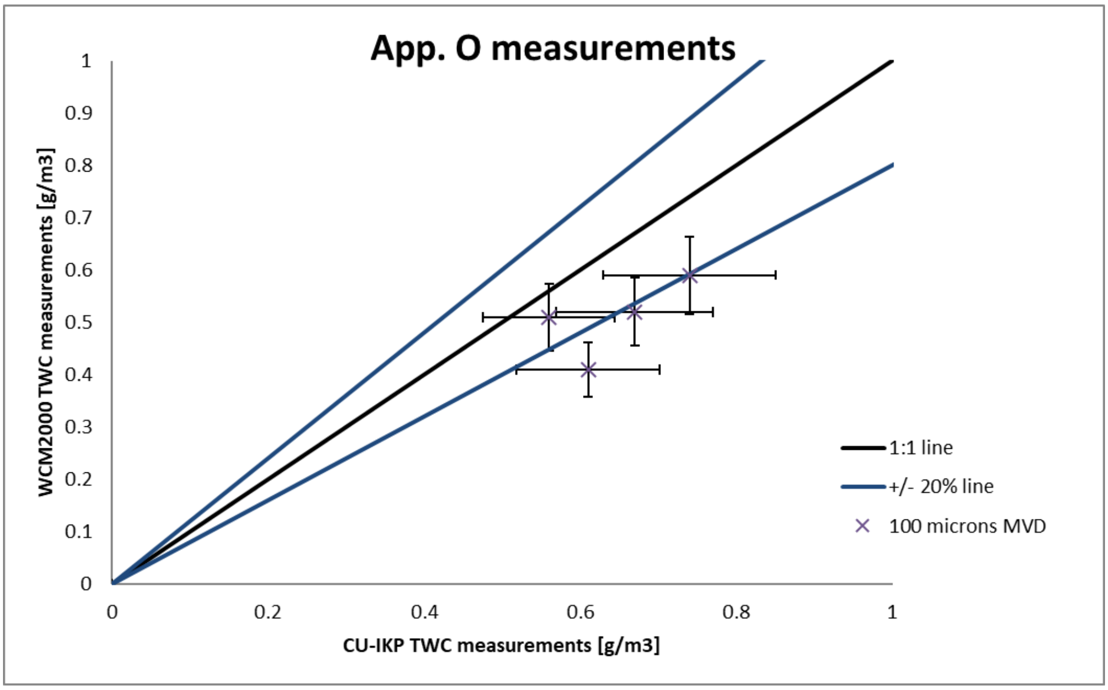



*Figure 4: Result obtained for App. O FZDZ conditions with 100 µm MVD.*

**Instrument calibration procedure**

Before any measurement, a calibration of the instrument is required. The main part that needs regular calibration is the LICOR $H_2O$ detector. The procedure is done every morning and afternoon. To proceed with the calibration, it is necessary to warm the instrument to an equilibrium temperature inside the LICOR of about 30°C. This is to ensure that the calibration is done close to the temperature at which the LICOR will be operating during the actual measurement. Also, the calibration is performed with the LICOR disconnected from the rest of the IKP instrument at ambient pressure. The first step is to use the nitrogen (which act as a zero water concentration gas) to feed both cells of the LICOR and to do a zeroing of the reference cell once the reading is stable. The second step is to continue feeding nitrogen and to set the sampling cell to read the same value as the reference cell. Once done, the nitrogen feed is stopped and ambient air is sent through both cells instead. When both cells reading become stable the sampling cell is again set to read the reference cell. This is the span calibration to ensure that when water is present; both cells read the same concentration. This can be done at any water concentration which is why ambient air is fine for doing so.

Additionally, before all the test campaigns, it is required re-calibrate both the air mass flow meter that is used to determine the isokinetic behaviour of the probe during measurement and the LICOR7000. Both, have been completed and are back to factory accuracy.

The CU-IKP is planned to be used to calibrate the following facilities for Appendix O LWC conditions: MinDef, RTA, TsAGI.

### 4.1.2 The Nevzorov probe

Within WP4 DLR can provide a Nevzorov probe to measure LWC and TWC in W/T facilities. This Probe can be installed in each facility under consideration of the individual installation requirements for the test section.

The Nevzorov probe is based on the hot-wire technique. Several sensor head configurations are compatible with the whole sensor systems to account for different atmospheric measurement conditions. For the ICE GENESIS project, a sensor head with three individual collector sensors and one reference sensor is used. It consists of one LWC wire und two cones to measure TWC with different cross sections. The collection efficiency of each sensor varies with the particle diameter. The LWC wire is most efficient for small droplets up to 50-60 µm with a maximum collection efficiency of 1.0 around 20-30 µm droplet size (Korolev et al., 1998; Schwarzenboeck et al., 2009). The TWC collectors have a conical larger sample area and capture both, droplets and ice particles. Small particles <30 µm tend to pass around the cone without being captured, whereas, larger droplets are captured and evaporated with high efficiency. The large cone with a diameter of the sample area of 12 mm is suitable for droplets larger than 2 mm. With this combination of different sensors, the Nevzorov probe should be able to measure in Appendix C as well as Appendix O conditions.

<u>Performance, requirements, limitations:</u>

Test measurements show the ability of the instrument to perform measurements in both, Appendix C and O conditions. Low and high LWC (0.4-1.2 g $m^{-3}$) can be covered. The device can be easily installed in small and large W/T facilities. The control box and data recording are then positioned outside the wind tunnel test section. With heating of the sensor vane and the sensor head, no icing is expected. One limitation that should be considered during the test procedure is the need to have reference measurements for each new TAS, wind tunnel temperature and position of the device in cloud-free conditions.

For Appendix C conditions it is recommended to use the LWC wire. For FZDZ conditions the TWC8 cone seems more appropriate in consideration of the collection efficiency.

It is planned to use the Nevzorov probe for the LWC measurements of the W/T SLD calibration of the RTA IWT in WP6 (Task 6.4) simultaneously with the CU-IKP and the WCM-2000.

### 4.1.3 Multi-Element Water Content system WCM-2000

In order to guarantee reference LWC measurements for different ICE GENESIS wind tunnels, the LWC will be measured during WP6 tunnel campaigns with the Isokinetic Probe from Cranfield University (CU-IKP) in MinDef ATF and in RTA IWT.

Beyond the common use of the CU-IKP, MinDef is currently carrying out an evaluation phase of the Multi-Element Water Content system WCM-2000 outside the framework of ICE GENESIS (Figure 5). Although not yet calibrated at the time of the WP6 tests, a WCM-2000 probe will be used for comparison with the CU-IKP probe during the ICE GENESIS tests.

*Figure 5: WCM-2000 Multi Wire probes in evaluation at MinDef*

The WCM-2000 multi wire (MW) probe evaluation phase is currently carried out in the MinDef small IWT (PAG). The expected LWC is measured with the MW probe, while the theoretical LWC is obtained from the calibrated water flow in the spay nozzles. Cloud homogeneity in the test section is measured on an icing grid. The purpose of this evaluation phase is to be able to use the MW probe to perform a direct reading of the LWC and, if possible, evaluate the distribution of LWC over an App. C and App. O droplet size spectrum. Magnitudes of water content will also be analysed, as this parameter can constitute a limitation for hot wire technology. As specified in paragraph 3.2, the measurement depends on the collection efficiency ε (therefore on the MVD and on the flow speed), but also on the droplets' temperature. As this parameter is not always easy to control along particle trajectories from spray nozzle to test section, especially for App O conditions, it also contributes to system limitations. Finally, by identifying and quantifying potential error sources on the whole measurement chain, the final goal of the current MW evaluation phase is to assess uncertainty when using it in MinDef ATF. The next paragraphs describe the first steps of the evaluation phase already carried out at MinDef.

Using an accretion grid like shown in Figure 6, the homogeneity matrices are obtained for different conditions. Thus, since the injection of water in the icing tunnel is repeatable, it is possible to know the value of the LWC locally in the test section where the MW probe is positioned. This local LWC measurement is performed for several values of MVD and flow speeds in order to analyse the influence on each of these parameters on the LWC directly read from the probe.

*Figure 6: Accretion grid used for MW probe evaluation at MinDef*

The graph in Figure 7 represents a reading of LWC values during 2 minutes of water injection. An average over 1.5 minutes out of these 2 minutes is then used to reduce the measurement uncertainty.

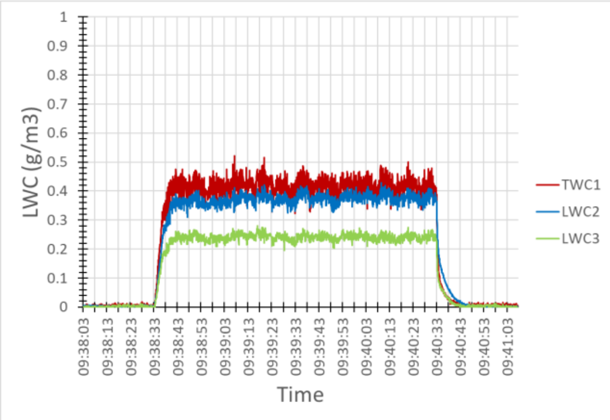



*Figure 7: Typical LWC direct measurement on the MW probe.*

The MW probe contains three sensing elements of various geometries, as well as a compensation wire. The sensing elements are a 2.1 mm diameter forward-facing half-pipe (Total Water Content, or TWC1 element on Figure 7), a 2.1 mm diameter hollow cylinder (LWC2 element), and a 0.5 mm diameter wire (LWC3 element). It can clearly be observed on Figure 7 a difference of directly read LWC values, as because of their different shape and size each of these three elements have different efficiencies in collecting droplets. The half pipe element is most efficient, closely followed by the relatively broad hollow cylinder, and finally the very slim wire (of 0.5 mm width compared to 1.8 mm or 2.0 mm wire of the comparable Nevzorov LWC wire).

Figure 8 shows three graphs of directly read LWC values for different MVD, all other parameters being equal for these three conditions. These test points illustrate the influence of droplets size on collection efficiency, and hence on LWC value directly read from the probe.

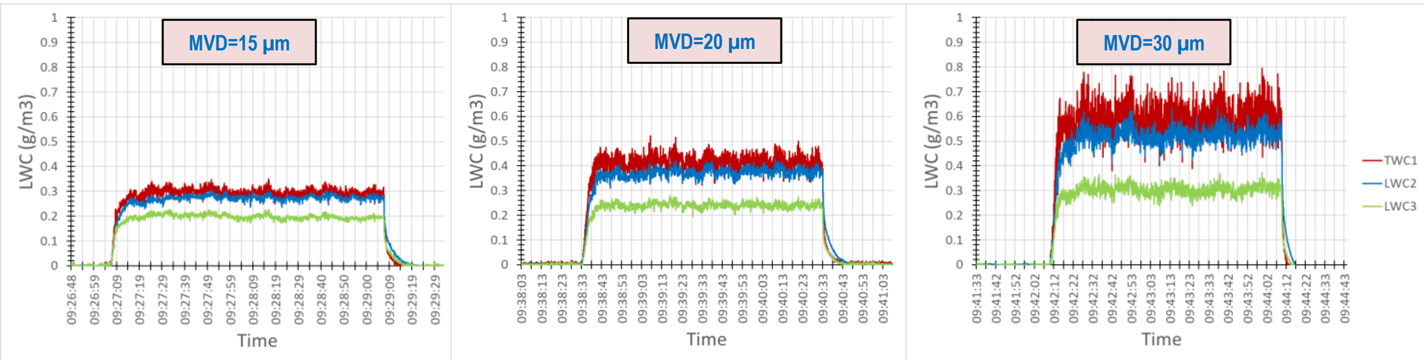



*Figure 8: Influence of droplets size on LWC.*

As already explained in Section 3.2, direct information of the LWC on different droplet sizes is not possible, and a correction method has to be implemented with respect to the particle size distribution (PSD) or the median volume diameter (MVD) of a distribution. The study of these correction methods is the subject of the present phase of evaluation of the MW probe. This study is based in particular on CFD simulation results undertaken at MinDef. Also, the uncertainty of each sensor element will be assessed during this study. In particular the frequency distribution of the sensor signal is evaluated. Currently, further information might be added at a later status of the work or in the WP6 W/T calibration reports.

### 4.1.4 LWC measurement devices at CIRA IWT

The response of hotwire techniques must be analysed at CIRA-IWT for both App. C and App. O to improve the methodologies in use for CIRA-IWT calibration in different configuration (low and high-speed test section facility layouts). Table 1 in Section 3.3 shows bulk LWC devices available at CIRA. In order to selecting the most appropriate device able to cover both Appendix C and Appendix O cloud conditions with capability to traverse the cross Section for cloud homogeneity assessment, an experiment test campaign has been organized at AIWT (Altitude Ice Wind Tunnel) of NRCC. The activities were performed in the framework of NRC-CIRA agreement involving both the AIWT and the FRL (Flight Research Lab) teams from NRCC. DLR provided a Nevzorov 2-cup instrument for the intercomparison. Besides of these teams, for the success of this campaign an important support was also provided by SEA teams to resolve some issues encountered during the tests.

Four hot-wire LWC probes were tested within 15-24 Sept. 2020 facility slot to characterize the LWC response as a function of cloud MVD: SEA Multi-Wire (MW); SEA Robust Probe (RP), SEA Ice Crystal Detector (ICD), standard Nevzorov, and Nevzorov two-cup provided by DLR. Besides these devices, rotating cylinder and AIWT Malvern have been used for checking the facility's calibration conditions before the experiment. Moreover, the AIWT Malvern has been installed at the first window of the test section to check the PSD/MVD for each test point.

Each hotwire has been installed with its sampling volume located in the centreline in order to sample each test point in the same location. Figure 9 shows the SEA MW, the Nevzorov two-cup, and SEA Robust Probe aligned with the test section centreline. One of the AIWT experiment focus was to study the efficiency of TWC sensing element with different shape and size as showed for the probes reported in Figure 9. Each solution has been designed from manufacturer to reduce the effect of droplet splashing that may cause the droplet's mass losses before their full evaporation after the impact on the sensing element. This loss of information is typically reported on the response of hotwire techniques as roll-off in LWC/TWC values as the MVD increases. As showed in the picture each probe has a specific shape and size for TWC element. Considering the results Nevzorov two-cup collection efficiency from the RTA testing, the smaller cup with 8 mm diameter has been aligned with the test section centreline. This chose comes from the TWC gradient measured with Robust probe that increases of 20% from the centreline to 1 inch below, for MVD of 250 µm. No significant TWC gradient variation has been recorded up to 60 µm MVD. Differences are within typical ± 5% of wind tunnel repeatability.

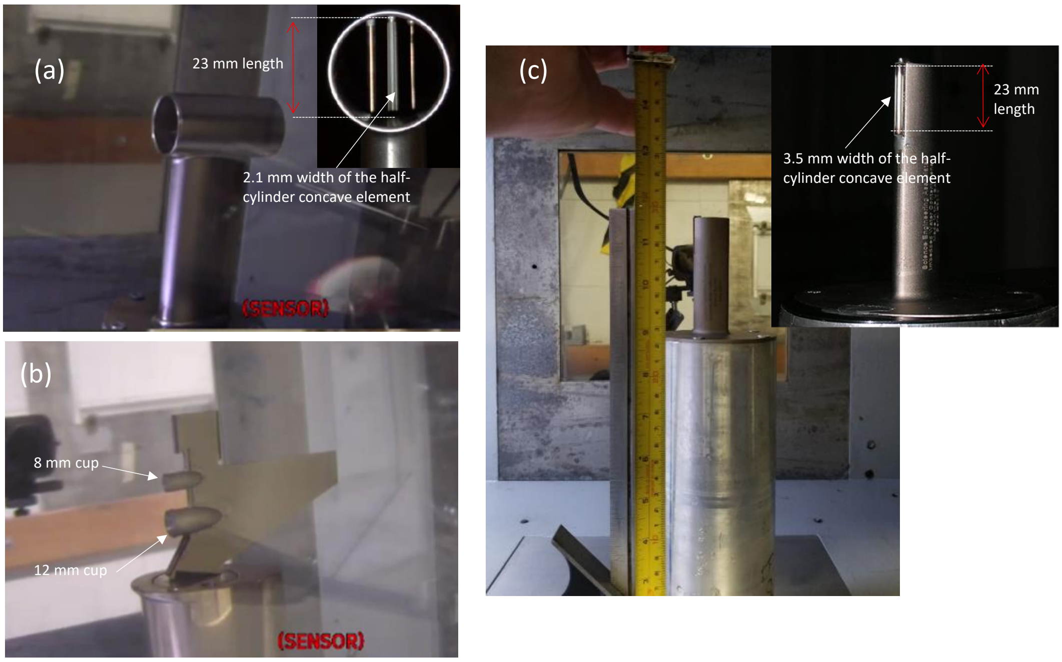



*Figure 9: TWC/LWC hotwire instrumentation comparison at NRCC-AIWT. Different hotwire techniques aligned with the test section centreline: SEA Ext-Multi (a); Nevzorov two-cup (b); SEA Robust Probe (c).*

The post-processing and data analysis that are currently ongoing will address the study of the response of each hot-wire sensor will be described as function of MVD at quasi-constant LWC (Table 2, MVDs sweeps), as will the response of the probes as function of LWC at low, intermediate, and max MVDs (Table 2, LWC sweeps). The tunnel airspeed was set at 80 m $s^{-1}$ for most of the conditions while the static air temperature at -10 °C was problematic for the icing onset on the edge of Nevzorov sensing element. To avoid this issue, static temperature at -5 °C has been considered for all the test campaign. Some conditions were also collected at 40 m $s^{-1}$ and at maximum airspeed to check the probes' collection efficiency at different droplet's impact on sensing element. Up to 30 test conditions were considered in this study with 15% of those repeated five times to verify both tunnel and probes repeatability. SEA M300 system have been used to acquire all the hot-wire probes. Data were collected for two minutes for each test point and presence of re-circulation after the spray off has been checked between two conditions. Sampling frequency at 10 Hz have been used for all the hot-wire probes except for Nevzorov two-cup that collected data at 100 Hz.

| | Test point | VTAS | Static T | LWC | MVD |
|---|---|---|---|---|---|
| | | m/s | °C | g/m3 | microns |
| LWC sweep at 20 microns | 2 | 80 | -5 | 0,5 | 20 |
| | 3 | 80 | -5 | 1 | 20 |
| | 4 | 80 | -5 | 1,5 | 20 |
| | 5 | 80 | -5 | 2 | 20 |
| | 6 | 80 | -5 | 2,5 | 20 |
| | 7 | 80 | -5 | 3 | 20 |
| | | | | | |
| LWC sweep at 100 microns | 13 | 80 | -5 | 0,25 | 100 |
| | 14 | 80 | -5 | 0,5 | 100 |
| | 15 | 80 | -5 | 0,75 | 100 |
| | 16 | 80 | -5 | 1 | 100 |
| | | | | | |
| LWC sweep at 250 microns | 20 | 80 | -5 | 0,25 | 250 |
| | 21 | 80 | -5 | 0,5 | 250 |
| | 22 | 80 | -5 | 0,75 | 250 |
| | 23 | 80 | -5 | 1 | 250 |
| | | | | | |
| MVDs sweep at LWC 0.5 | 1 | 80 | -5 | 0,5 | 15 |
| | 8 | 80 | -5 | 0,5 | 28 |
| | 9 | 80 | -5 | 0,5 | 40 |
| | 10 | 80 | -5 | 0,5 | 60 |
| | 11 | 80 | -5 | 0,5 | 55 |
| | 12 | 80 | -5 | 0,5 | 81 |
| | 17 | 80 | -5 | 0,5 | 126 |
| | 18 | 80 | -5 | 0,5 | 187 |
| | 19 | 80 | -5 | 0,5 | 236 |
| | 24 | 80 | -5 | 0,5 | 314 |
| | | | | | |
| 40 m/s | S4I 13 CM | 40 | -5 | 0,42 | 20 |
| | S4I 18 IM | 40 | -5 | 1,2 | 28 |
| 100 m/s | FRL 16 | 100 | -5 | 0,7 | 10 |
| | FRL 27 | 100 | -5 | 0,2 | 30 |
| | FRL 25 | 100 | -5 | 0,2 | 200 |
| | FRL 26 | 100 | -5 | 0,2 | max |

*Table 2: Test matrix points used for this experiment. NRCC-AIWT MVDs are derived from their Malvern measurements while the LWCs from rotating cylinder and C-SIRO King hot-wire probe.*

Overall preliminary results are very encouraging even if must be considered that at moment are without applying any significant corrections other than subtracting the offset in cases of wind speed change. It is expected to complete the data processing and analysis within this year and to update in a next version of this Deliverable with results. These results will be useful for CIRA to select the best option for the LWC measurements on the base of their response, whether in Appendix C or Appendix O. As for the hot-wire techniques, both Robust probe (RP) and multi-wire (MW) represent two important options for CIRA in consideration of the results available from the HAIC program showing a good agreement between the RP and CU-IKP in App. C, and for the wide use of MW and Nevzorov probes in several facilities (facilities harmonization process). The next Section will show the main characteristics of RP with an example of results collected from the HAIC program and of recent measurements collected in CIRA-IWT.

**CIRA Robust probe in Appendix C conditions**

The robust sensor was specifically designed to have sufficient mechanical sensor strength for high IWC measurement at high speed. Conventional sensors have not been able to withstand the kinetic energy of impact of ice particles in high concentrations at speeds in excess of 150 m/s. Its sensing element geometry with 3.5 mm half cylinder concave (Figure 10c) were conceived specially to trap ice particles. This design could also be functional to improve the LWC measurement uncertainty for SLD clouds to increase the response with respect to the conventional cylinder wire, especially at high speed such as achievable in CIRA-IWT and at higher concentrations of larger droplets in the PSDs, such as for the FZDZ and FZRA conditions. No specific investigation on the performance of this probe under SLD conditions has been done in the W/T.

All particles that enter in the concave hot element would impact and evaporate, thereby providing a measurement of the total water content (TWC). The electronics of the robust probe will attempt to keep the sensor wire at a constant temperature. Normally a temperature of 150 °C or higher is used.

This probe operates with same principle of hot-wire sensing element described in sect. 3.2 using the same SEA WCM-2000 power control system as for Multi-wire. The power dissipated by the wire while maintaining constant temperature is due to dry convective heat loss in the colder air, and warming, (melting), evaporation of water droplets and ice particles in the wire capture volume. So, total water content (TWC) as the sum of the LWC and the ice water content (IWC) can be determine. The robust probe is unable to distinguish between ice and water, and in fact, an uncertainty arises in mixed phase due to the unequal collection efficiency for ice particles and water droplets. This should not be a major issue for liquid clouds in W/T because they are expected to be composed mostly of liquid drops, assuming preliminary mitigation of droplet freeze-out phenomena.

As showed reported in Section 3.2 the total power dissipated by the wire, can be written as sum of two contributions: power due to the dry-air convective heat loss across the wire (to be calculated from dry-air parametrization) and power across the wire due to the liquid and ice particles ($P_{TWC}$). From this relation can be derived $P_{TWC}$ as differences between the basic power measurement of the probe ($T_t$ in Section 3.2) and $P_{dry}$, that will be calculated from an empirical relationship for dry-air heat loss. Finally, the TWC is directly proportional to the value of PTWC.

System sensor heads are well de-iced with constant-temperature (~50 °C, programmable) control. This hot-wire capability eliminates common trouble with “full-on” heater systems (e.g. burned out heaters when not turned off at low speed). Moreover, the strut temperature and the de-ice power are used for diagnostic purposes only. Typically, these be calculated and displayed as a real-time quality control of proper probe operation.

The WCM-2000 electronics provide sufficient power to the robust sensor for high LWC/IWC measurement at high speed conditions, where other probes electronically saturate at these levels.

**Robust probe results**

The Robust probe response has already been investigating within the HAIC project where a direct comparison with CU-IKP probe was performed at Cranfield Uncivility wind tunnel. The Cranfield icing wind tunnel test section is 760x760mm. The tunnel runs at atmospheric pressure with the capability to reach 130 m/s. The tunnel total temperature can go as low as -25 to -30 °C. Below are summarized the results showing the comparisons between the Robust probe and the CU-IKP under Appendix C conditions at low airspeed.

The experiments were conducted between the 11th and 14th march 2014. Both probes were positioned around the center of the tunnel test section (longitudinally and horizontally). Both probes were installed within the tunnel test section with firstly a separation 63 mm (See Figure 10 below). Another series of tests were performed with a probe separation of 32 mm to check potentially measurement difference due to cloud homogeneity or probes’ interferences into their sampling volume.


*Figure 10: Instrumentation layout in CU tunnel test section and separation distance between RP and CU-IKP.*

In addition to measurements with the CU-IKP and the RP, an Icing blade was used to determine the cloud non-uniformity of LWC to better assess the differences in probe measurements due to the uncertainty of W/T cloud homogeneity. The blade was made of aluminium and was 760 mm long (as the tests Section wide), 20 mm deep and 6 mm thick.

The icing blade was positioned in such a way that when inserted, the blade is a few centimeters in front of both probes and at the same height. The method consists of exposing the blade to water spray, accreting rime ice (0.88 g cm-3 is the supposed ice density) for a period of time function of expected maximum thickness, and measuring the ice thickness to calculate the liquid water content This means that, when icing blade measurements are taken, LWC measurements of IKP and RP can be affected. However, icing blade measurements were performed for only short period of time thus not affecting significantly any averaged LWC measured by the IKP and RP. For the RP, periods of icing blade insertion were removed from averaging data when LWC measurements were affected too strongly. For the IKP, icing blade insertion did not affect LWC measurements so that all data was kept for LWC averaging.

The test conditions were chosen with the aim of having a range of droplet sizes (20, 32 and 40 µm), two tunnel total temperatures (-5 and -20 deg. C) and a single tunnel speed of 50m/s. The LWC tested ranged from 0.2 g/m3 up to about 5 g/m$^3$.

The first data set were collected at tunnel total air temperature (TAT) of -20 °C. Three mean droplet sizes were tested for a LWC ranging from 0.5 g/m$^3$ to 4.57 g/m$^3$ according to the RP or 6.86 g/m$^3$ according to the IKP. This graph in Figure 11 only uses the measurement from each probe without any correction due to the non-uniformity of the cloud. Overall, Figure 11 shows a good agreement between each probe for LWC lower than 3 g/m$^3$. When taking the cloud non-uniformity into account, the discrepancy is generally less than 20% (excluding 2 outliers showing more than 40% difference) and some points (4 points) have up to 33% difference. For the three points with higher LWC than 3 g/m$^3$, the difference is no more than 25 %. As the LWC increases, there is a clear tendency of higher LWC measurement made by the IKP. One potential issues of these measurement at -20 °C TAT was the stabilization of cloud uniformity during the run especially for smaller MVD (20 µm).

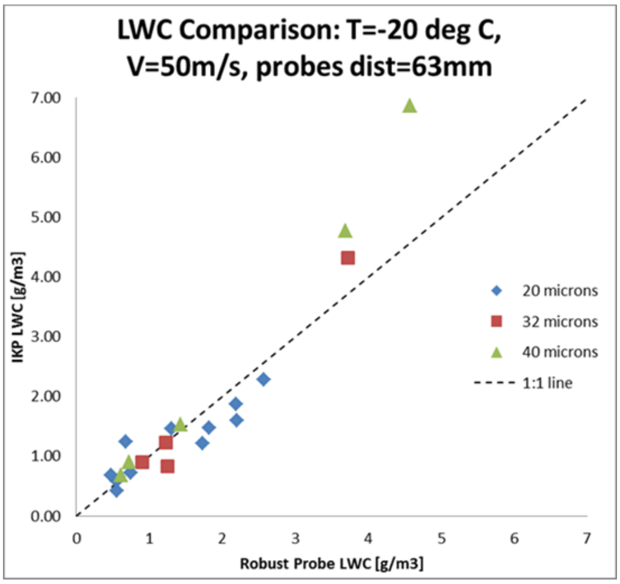



*Figure 11: LWC comparison at a tunnel temperature of -20 °C.*

Figure 12 shows LWC measurements for a tunnel total temperature of -5 deg. C. In this series of tests two probe distances were used (63 and 32 mm probe separations). Figure 13, discriminates the results for each probe separation. The conclusion is that probe separation was not a determining factor for LWC measurement discrepancy since no clear trends can be found in Figure 13.

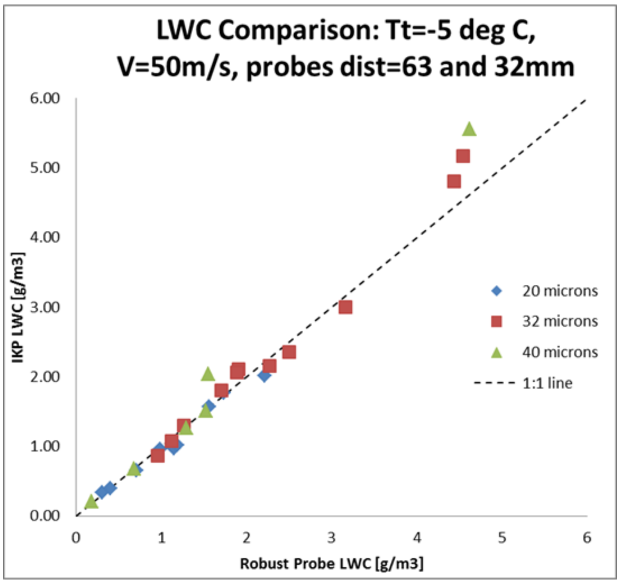



*Figure 12: LWC comparison at a tunnel temperature of -5 °C.*

Since the test series was performed at -5 °C, it was not possible to use the icing blade for checking the cloud non-uniformity. However, the result obtained shows less discrepancy compared to the -20 °C test series. The percentage difference is less than 18 % except for the test point at higher LWC where a difference of 24 % was shown. It can clearly be seen on Figure 13 that discrepancy is lesser when compared to the -20 °C test series. One remarkable result is that for all the 20 µm test cases at -5 °C, for LWC below 3 g/m$^3$, the agreement between the probes is improved, showing each test point on the 1:1 line or much closer to it. Similarly, to the tests at -20 °C, there is an over-reading trend of the IKP toward higher LWC.

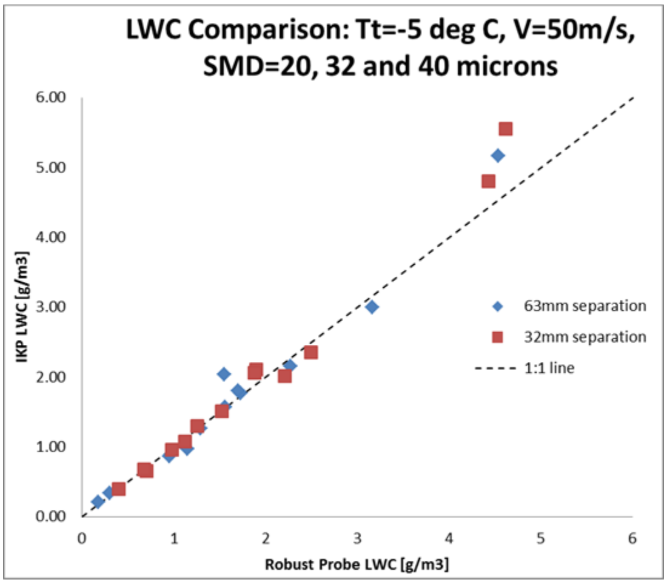



*Figure 13: LWC comparison at a tunnel temperature of -5 °C.*

To confirm the agreement at 20 µm for the Appendix C conditions, in January 2020, the RP has been compared with standard Icing Blade (IB) used as a reference in CIRA-IWT for LWC measurements during the cloud calibrations. The LWC sweep from 0.15 g/m$^3$ to 1.32 g/m$^3$ at 140 m/s and constant 20 µm MVD have been measured with RP collection efficiency close to one as for the large droplets. Results were compared with analytical data derived from Icing Blade measurement, showing an agreement within the ± 10% as reported in Figure 14.

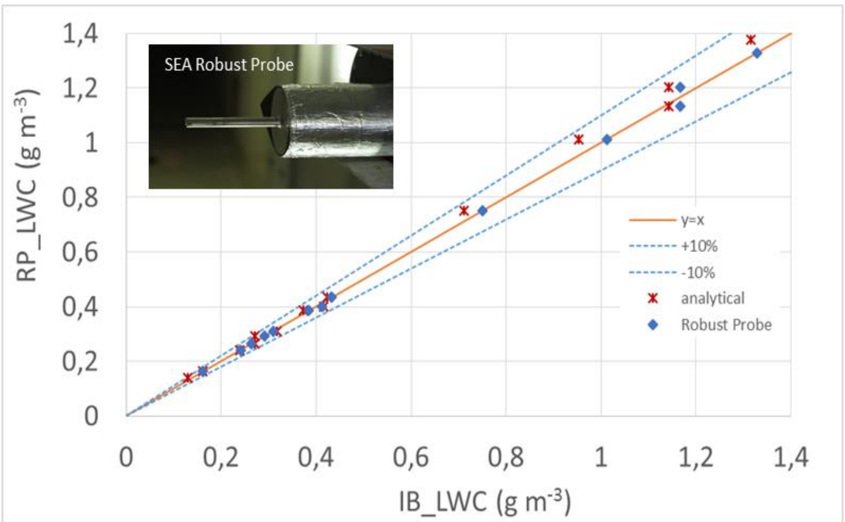



*Figure 14: Robust probe response in CIRA-IWT for LWC conditions at 20 µm MVD, 140 m/s and -8°C.*

Further conclusions on RP performance are expected to coming up from the NRC-AIWT instrumentation comparison campaign. Collection efficiency estimated with numerical simulation will be verified for both the Robust probe and Multi-wire.

## 4.2 Comparison of different LWC sensors in App. O FZDZ

RTA uses the standard Icing Blade for the calibration of the LWC in Appendix C conditions, where the blade should have an uncertainty of less than ±10%. Measurements in Appendix O FZDZ conditions have also been performed using the Icing Blade, here the largest uncertainty is the unknown collection efficiency, as splashing effects could influence the result.

Preliminary calibration measurements using the WCM-2000 (only TWC – halfpipe element was used), a Nevzorov probe and the CU IKP have been performed in Appendix C and Appendix O FZDZ / FZRA conditions. In addition, the LWC was estimated based on the measured total water flow and a reference area, which was derived from uniformity measurements (Equation 1). For FZDZ MVD > 40 µm the resulting LWCs are 0.98 g $m^{-3}$, 0.59 g $m^{-3}$ and 0.49 g $m^{-3}$ for 30 m $s^{-1}$, 50 m $s^{-1}$, and 60 m $s^{-1}$ respectively.

$$LWC\ \left[\frac{g}{m^3}\right] = \frac{total\ water\ massflow\ [g/s]}{v\ \left[\frac{m}{s}\right] * A_{ref}\ [m^2]} \qquad 3$$

Figure 15 shows a summary of the results from different measurement methods for FZDZ MVD > 40 µm. The results are compared to the calibration curve derived from WCM2000 measurements in October 2018 using the 2mm TWC half pipe sensing element.

For the icing blade FZDZ measurements, a collection efficiency of 0.98 was used to account for the lower collection efficiency of the small mode, for the large mode a collection efficiency of 1 was assumed. No post processing was applied to the WCM2000 measurement results, assuming a collection efficiency of exactly 1. In Steen et al. (2016) it is mentioned that the correction is only 1-2% for 100 µm MVD distributions above 100 kts, based on the collection efficiency determined from numerical simulations (Rigby et al., 2014). In the simulations, the effect of splashing was considered, but only for droplets with a size of 100 µm.

For FZDZ MVD > 40 µm, the individual results show a relatively good agreement with deviations of about ±25% from the WCM2000, the IKP showed the highest water contents and the Nevzorov probe TWC12 cone the lowest. The estimation based on the water flow is about 10 to 20 % higher than WCM2000. The measurements were performed at different airspeeds and locations in the test section, due to variations of the cloud uniformity (in the range of ~25%) a certain spread was expected. Here, it has to be mentioned that only the TWC8 sensor from the Nevzorov probe should be used for the comparison.

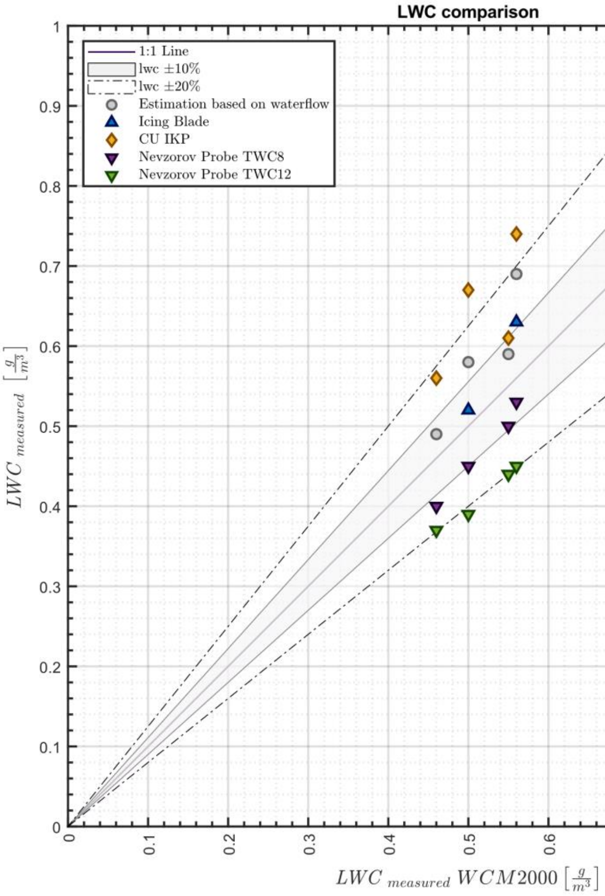



*Figure 15: Appendix O FZDZ MVD > 40 µm, MVD ~100 µm measurement results in the RTA IWT: Comparison of instruments versus WCM2000. Shown is a mean of all test points per LWC and instrument.*

For the multi-instrument tests at the RTA IWT it is useful to calculate a mean value of available test points averaged over all instruments for each measured LWC in order to show the ability of the IWT to generate Appendix O FZDZ conditions. The results are displayed in Figure 16. Additionally, the deviation of individual instruments from the mean LWC for all instruments is listed in Table 3.

| **Measurement device** | **deviation from the mean LWC (%)** |
|---|---|
| **Icing Blade** | +5.50 |
| **WCM2000 TWC half pipe element** | +0.60 |
| **Nevzorov TWC8 cone** | -4.70 |
| | |
| **CU-IKP** | +25.50 |

*Table 3: Deviation of each instrument from the mean LWC in Appendix O FZDZ > 40 µm MVD in RTA IWT.*

Figure 15 shows the instruments deviation from the calculated mean between ± 25 %. The IKP overestimates LWC compared to the mean and the Nevzorov underestimates values with a deviation of less than 10 %. The WCM2000 shows the best results in comparison to the other methods with a small deviation of less than 1 %. It can be stated the RTA IWT is able to generate Appendix O FZDZ conditions with MVD > 40 µm. The instrument deviations are between ± 25 % which can be explained with different positions in the test section and different measurement days. The three sensors WCM2000, Nevzorov probe and CU-IKP are able to perform the measurements in these conditions. Best agreement of < 1% was found for the WCM2000 with respect to the multi instrument mean. Up to 10% deviations were derived for the Nevzorov 8 mm cone and the icing blade. The estimates from the water flow method agreed within 12% to the multi instrument mean. Compared to the multi instrument mean, the IKP tends to exceed the mean LWC value by ~20% for the measurement conditions between 0.4 and 0.6 g/m³ of LWC. However, the instrument position may significantly contribute to this bias. Also, the uncertainty with respect to background correction is to be mentioned. As an outcome of this instrument comparison, it was suggested to perform the W/T calibration at RTA with the three instruments to collect more data and evaluate the spray conditions of the IWT as well as the instrument uncertainties. Besides the fact of a general good agreement of the measurement results from Nevzorov probe and WCM2000 together with the calculation of the water flow in FZDZ conditions, an underestimation of the LWC value derived from WCM2000 or Nevzorov compared to the CU-IKP can currently not be finally ruled out.

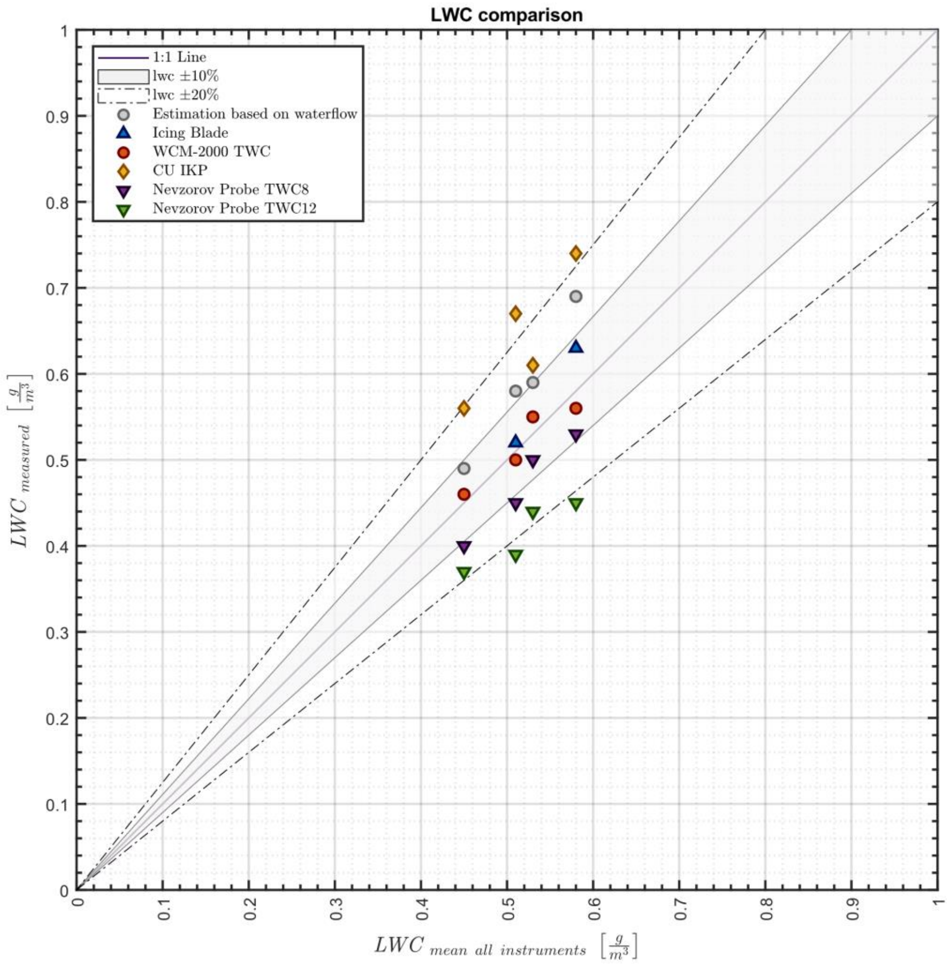



*Figure 16: Appendix O FZDZ MVD ~100 µm: Comparison of LWC from several instruments versus the LWC mean of all instruments in RTA IWT.*

## 4.3 Correction methods

**CU-IKP: TWC measurement and Iso-kineticity corrections**

Inherent to the current design of the IKP instrument, the maximum mass flow rate is limited. This leads to a maximum IKP inlet velocity of about 120-130 m $s^{-1}$ in the conditions tested. However, in 2 of the 4 facilities, it is required to measure the water content to speeds up to 230 m $s^{-1}$. In these conditions, the iso-kinetic behaviour at the probe inlet cannot be maintained. In such sub iso-kinetic conditions (the IKP sucking air at a lesser speed than the tunnel air speed), the IKP would not ingest enough air relative to the water ingestion leading to an overestimation of the TWC. To cater for this limitation and still allow measurement at higher tunnel speed, it is possible to estimate the correction factor to apply to correct the non iso-kinetic behaviour at the probe inlet. This correction factor is based on the percentage difference between the IKP inlet speed and the actual tunnel speed. In addition, the correction factor is directly dependent on the local air density. This means that the correction factor to apply varies when the tunnel test conditions changes such as the static pressure and the static temperature. However, this correction factor is calculated on a theoretical basis only and assumes that the large majority of the ice content (in term of mass) is not significantly deviated by the air flow when entering the IKP inlet. This assumption would be justified as most of the water droplets produced have a large MVD (typically larger than 100 µm) thus would be less affected by the air stream.

The correction factor is calculated as follows. For three air mass flows (200, 160 and 120 nL $min^{-1}$), the theoretical TWC is calculated for a constant water mass flow (here set at 2 g $min^{-1}$). The first air mass flow is considered the iso-kinetic condition (with a corresponding TWC) while the second and third air mass flow corresponds to -20% and -40% sub iso-kinetic conditions respectively. This gives two TWC corresponding to a -20% and -40% sub iso-kinetic condition.

This provides the first correction factor for a given air density. The procedure is repeated for a few different air densities to obtain the variation of the correction factor with respect to the air density.

The results are shown in Figure 17.

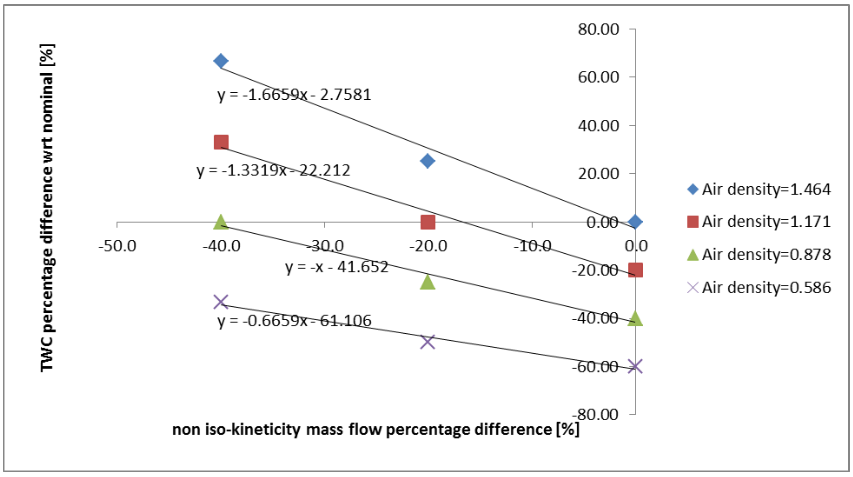



*Figure 17: Percentage TWC difference vs. air mass flow percentage difference for 4 air densities.*

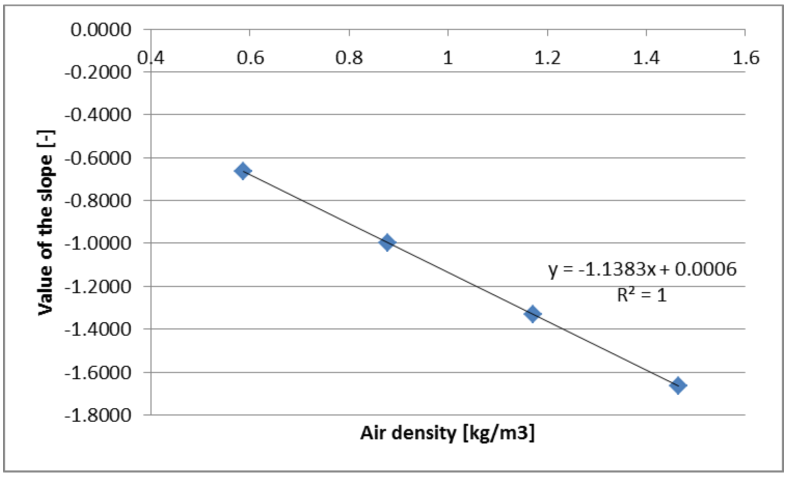



*Figure 18: Variation of the slope value with respect to the air density*

Finally, we can retrieve the equation that will be used to calculate the correction factor to apply based on a known tunnel air density.

$$Slope = -1.1383 * Rho_{air} + 0.0006 \tag{4}$$

As an example, if the IKP measures 8.8 g $m^{-3}$ with a non iso-kinetic difference of -6.6% (%non_isokinetic) at an air density of 1.237 kg $m^{-3}$. The slope is given by (1) as slope = -1.41. Thus the actual correction factor to apply is:

$$Correction\ factor = \%non\_isokinetic\ * slope \tag{5}$$

This equals to 9.2 % in our example.

The final step to obtain the corrected TWC from the measured TWC is:

$$LWC_{Corrected} = LWC_{measure} * \left(\frac{LWC_{measured} * Correction\ factor}{100}\right) \tag{6}$$

In our example LWC corrected is 7.99 g $m^{-3}$.

This procedure is subsequently applied for all the measurements made when there is a speed difference between the IKP inlet and the tunnel speed.

The IKP measures both the background humidity and the TWC at the same time and at roughly the same location within the test section. So, in principle any changes in background humidity caused by a change of inlet conditions are measured and considered by the IKP to extract the final TWC. The accuracy of the absolute background humidity concentration will impact the overall accuracy of the IKP especially at the low TWC concentration. As of now, there is not enough data at low TWC (less than 0.4 g $m^{-3}$) to establish any significant potential accuracy degradation at low TWC. However, the data obtained, so far in Appendix C, when compared to the WCM2000 show good agreement from 1 data point.

With the IKP, it is only possible to set one speed at the inlet of the probe. The IKP is considered iso-kinetic when the tunnel air velocity matches the IKP inlet velocity. At this time, there is no consideration or correction in place to account for the sprayed particle size distribution. Essentially, it is assumed a collection efficiency of 1 whatever the size distribution. The effect of such assumption on the global instrument accuracy is still unclear.

**DLR Nevzorov probe**

The sensors of the Nevzorov probe have a phase discrimination capability that results from the different behaviour of small and large liquid and solid particles impacting with the sensor surface (Korolev et al., 1998). Small liquid droplets flatten on the surface of LWC and TWC sensors and evaporate completely. Ice particles and large droplets should remain inside the cone of the TWC sensors until they melt and evaporate. From the convex surface of the LWC sensor ice particles break away with a very small heat expansion. Large liquid droplets tend to shed from the LWC surface and evaporate incompletely.

The collection efficiency of each sensor depends on particle size but also on the individual geometry and shape. Collection efficiencies of the Nevzorov probe can be taken from literature but they are only available for a limited number of cases. For the LWC wire the cylindrical shape made it possible to theoretically calculate the collection efficiency. In Korolev et al. (1998) the calculation for small liquid droplets are based on Voloshchuk (1971). For the drizzle size range, Schwarzenboeck et al. (2009) proposed a parameterization based on the 1.8 mm LWC wire.

For the TWC cones empirical data are available (Korolev et al., 1998; Schwarzenboeck et al., 2009) or calculations based on a two-dimensional shape simulating the side view of the TWC sensor generated by the NASA LEWICE model (Strapp et al., 2003).

The correction of the collection efficiency does not correct any effects from splashing or shattering of droplets on the sensor head.

The collection efficiency depends on the true air speed as it was shown in Strapp et al. (2003). This effect is more important for small particles in the Appendix C particle size range. For MVD larger than 40 µm this will be neglected.

## 4.4 Uncertainty assessment

**CU-IKP**

The main sources of uncertainty for the CU-IKP are:

- inlet air mass flow measurement
  - The mass flow is measured to ensure iso-kineticity at the probe inlet. Error in this measurement is directly proportional to the water concentration error. The estimated error is 1-2 %.
- water concentration measurement
  - The water concentration is measured by the LICOR7000. Errors can come from a miss-calibration or drift in the calibration. Also, differences in measurements cells temperature and pressure leads to water content error. The error is estimated to be up to 10%.
- completeness of evaporation process
  - Accurate measurement of water content is based on a full evaporation of the condensed water upon entry of the probe. Large uncertainty appears if full evaporation is not achieved. This issue would normally happen only for large water content ingestion rate at the probe inlet. Within the context of App. O conditions, the water content is low and evaporation issues are not expected to happen.

The overall accuracy of the probe in App C. conditions is estimated to be generally within 15% when compared to other instruments such as Icing blade, Robust probe, WCM2000 and Nevzorov probes. For Appendix O conditions, the estimated accuracy is not yet established due to the lack of inter-comparison data. A larger uncertainty is expected for App. O conditions at low LWC, as the error in the determination of the water vapour concentration affects the IKP LWC results in particular for low LWC.

**DLR Nevzorov probe**

The primary sources for measurement errors of the Nevzorov sensor are (Korolev et al., 1998; Baumgardner et al., 2017):

- measurement of the probe sensor area,
- estimate of the resistance of the sensor wire,
- estimation of empirical constants in heat transfer equations,
- estimation of the collection efficiency,
- incomplete evaporation of large droplets, and
- bouncing or pooling in the concave elements.

The overall instrument uncertainty accounts for the several effects explained before. By using the law of error propagation an uncertainty of ± 11 % for both, the LWC wire and TWC8 cone, is found. This is valid for using the LWC wire for droplets with a MVD between 20 and 40 µm and the TWC8 cone for droplets with a MVD between 50 µm and 800 µm.

Besides the instrument uncertainty, the whole measurement uncertainty is influenced by the specific W/T conditions und specifications. Accuracy of airspeed, air pressure, and air temperature are already included in the accuracy of the collection efficiency but might have a larger impact. Important points that have to be considered are the cloud uniformity within the W/T test section and the reproducibility of measurements in the W/T.

**The WCM2000**

As the WCM2000 has been rented for the tests and has been delivered back to the manufacturer, the uncertainty assessment is based on literature data. The uncertainty for the WCM2000 used for measurements in the RTA IWT based on literature data is 10 to 15 %. For FZDZ, the mean of 12.5 % is applied in this report.

# 5 Conclusions

Deliverable D4.2 summarizes the work that was performed in task 4.2 within the ICE GENESIS project. The task was to review and select the best appropriate instrumentation to measure LWC in Appendix C and O conditions in W/T facilities. The discussion also includes correction methods for the data analysis and an uncertainty assessment for the selected instruments.

The requirements include the capability of the instrument to measure LWC between less than 0.1 g $m^{-3}$ and 3 g $m^{-3}$ with a good efficiency for both, small droplets and supercooled large droplets. The droplet sizes can vary between 1 µm and 500 µm (FZDZ) or even exceed 1000 µm (FZRA). If necessary, appropriate correction methods have to be applied to consider different collection efficiencies for various droplet sizes. The required instrumental uncertainty (D3.1) equal or lower than ±10 % might be reconsidered in sight of the results from this deliverable.

In a first step, the LWC instrumentation from all WP partners taking part in task 4.2 was reviewed. The existing state-of-the-art instrumentation capable to measure liquid or total water content is based on bulk measurement devices where the LWC is derived as an integral over the whole droplet spectrum. Commonly used techniques are the hot-wire of cup technique (e.g. Nevzorov probe, Robust Probe, WCM-2000), the inlet-based evaporation (e.g. IKP) or ice accretion (e.g. Icing Blade). The selected instruments will be used for the W/T SLD calibration (FZDZ) in task 6.4 in the following facilities: CIRA, MinDef, RTA (CIAM, TsAGI).

While instrument uncertainties are given for all instruments, three instruments were selected and have shown good performance for icing W/T measurements in Appendix C conditions. Results from the experiments performed for D4.2 show that the Isokinetic Probe IKP, the WCM-2000 and the Nevzorov probe agree within better than 10% for LWC measurements in Appendix C conditions at RTA W/T for LWC between 0.4 and 2.4 g/m³. Therefore, the CU-IKP, the WCM2000 and the Nevzorov probe can be recommended for LWC measurements in Appendix C conditions.

Tests with bimodal particle size distributions in Appendix O FZDZ conditions with MVD > 40 µm performed at RTA at LWC between 0.4 and 0.6 g/m³ generally show a sufficient agreement between the different probes within ± 25 %. This deviation can be explained by the fact that the measurements were performed at different airspeeds and locations in the probably heterogeneous test section. In addition, data from different campaigns are intercompared. Hence particularly, the variations in the cloud uniformity (in the range of 25 %) may lead to a certain spread in the measurement results. Considering these limitations and the individual instrument uncertainties between ± 10 % and ± 15 %, the results are promising. With respect to the multi instrument mean, the best agreement of < 1% was found for the WCM2000. This multi instrument mean is used in this Deliverable as reference LWC value from several campaigns to enable an indirect comparison of the instruments. This value may not present the true LWC value. Up to 10% deviations were detected for the Nevzorov 8 mm cone and the icing blade. Compared to the multi instrument mean, the IKP tends to overestimate the LWC by ~20% as explained by the effects mentioned above. In addition, challenges in subtracting high levels of water vapour from the signal for background correction may contribute to this bias. Thus, additional measurements are required to better constrain the observations. To enhance data statistics and generate more comparison data additional measurements at RTA W/T are planned. The CU-IKP will be used to measure LWC in specific locations within the test sections. For the WCM2000 and the Nevzorov probe it is planned to make measurements on a traversing unit to capture test points in the whole IWT test section.

The CU-IKP will then also be used for W/T calibrations at MinDef and TsAGI which gives a good opportunity to compare the different facilities. At MinDef additionally, a WCM2000 will perform LWC measurements to evaluate the IKP results and the performance of both instruments in this facility.

The W/T SLD calibration will be performed just for FZDZ conditions (task 6.4). Therefore, test measurements in FZRA conditions are shown in the Appendix. The deviations between several instrument devices are larger than ± 25 %. This might also be explained with a low data statistics and different test conditions during the measurements. Nevertheless, none of the tested instruments is fully characterized for the measurements in FZRA conditions. Therefore, it is recommended to perform additional tests before a preferred instrument for these conditions can be selected.

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# 7 Appendix

**LWC test measurements at RTA IWT in Appendix O FZRA conditions (MVD > 40 µm)**

Besides Appendix C and Appendix O FZDZ conditions, measurements with FZRA conditions were performed at the RTA IWT during two test campaigns in October 2018 and April 2019. The conditions were the same as for the FZDZ measurements: wind tunnel airspeed of 50 and 60 m $s^{-1}$, temperature of -5°C (see Sections 4.1.1 and 4.1.2).

RTA estimates the LWC based on the measured total waterflow and a reference area, which was derived from uniformity measurements (Equation 1). For FZRA MVD > 40 µm LWCs of 0.27 g $m^{-3}$ (at 60 m $s^{-1}$) and 0.325 g $m^{-3}$ (at 50 m $s^{-1}$) were derived. Additionally, the LWC was also derived from a rime ice accretion test on a NACA0012 wing Section. The test was performed at a SAT of -15.7°C (in order to get a freezing fraction of 1) and a test section airspeed of 60 m $s^{-1}$, the icing duration was approximately 13 minutes and 33 seconds. The measured ice accretion thickness on the stagnation line was between 11.5 and 12.0 mm (Figure 19). This amount of ice accretion would correspond to an LWC of about 0.26 g $m^{-3}$, based on the "Langmuir and Blodgett" approach described in (Anderson & Tsao, 2008).

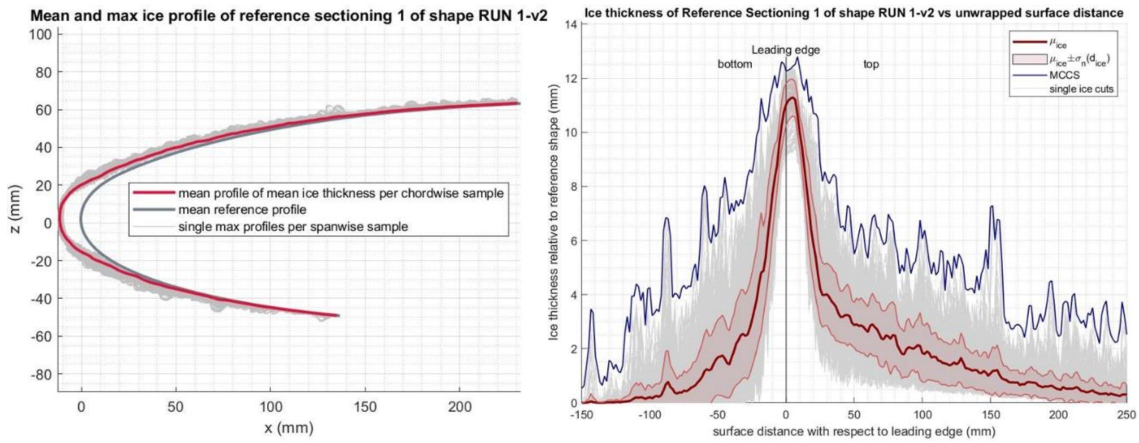


*Figure 19: FZRA MVD > 40 µm rime ice accretion on NACA0012 wing Section, 3D scan performed by AIIS.*

As for FZDZ conditions, also in FZRA conditions the following instruments performed measurements: WCM2000 and CU-IKP in October 2018, DLR Nevzorov probe in April 2019. The results are summarized in Figure 20 where the CU-IKP is used as reference instrument. A larger spread between the instruments is observed compared to FZDZ conditions. The IKP again indicated the highest LWCs and the TWC element of the WCM2000 showed very low values (about 40% lower than the IKP). Only the TWC12 sensor element of the Nevzorov probe was used for the comparison (the TWC8 element showed a large variation and unreasonable results at the different airspeeds), the indicated water contents were about 10% to 25% lower, when compared to the IKP results but were very close to the estimations based on the waterflow and the ice accretion test. From these results it is suggested not to use the WCM2000 for LWC measurements in FZRA conditions. The absolute TWC values indicate that not all particles, especially very large particles about 1 mm size, were detected by this device. The other measurement techniques (Nevzorov TWC12, Waterflow estimation, IKP, Ice Accretion test) show discrepancies up to at least ± 30 %. The low data statistics and possible differences in the results coming from different test days and positions in the test section may lead to further discrepancies and uncertainties. Therefore, it is recommended to perform more tests under FZRA conditions. For both, the CU-IKP and the Nevzorov probe, the shown test points are the only available data in FZRA conditions. Additional measurements for a better characterization regarding instrument uncertainty and collection efficiency are needed.

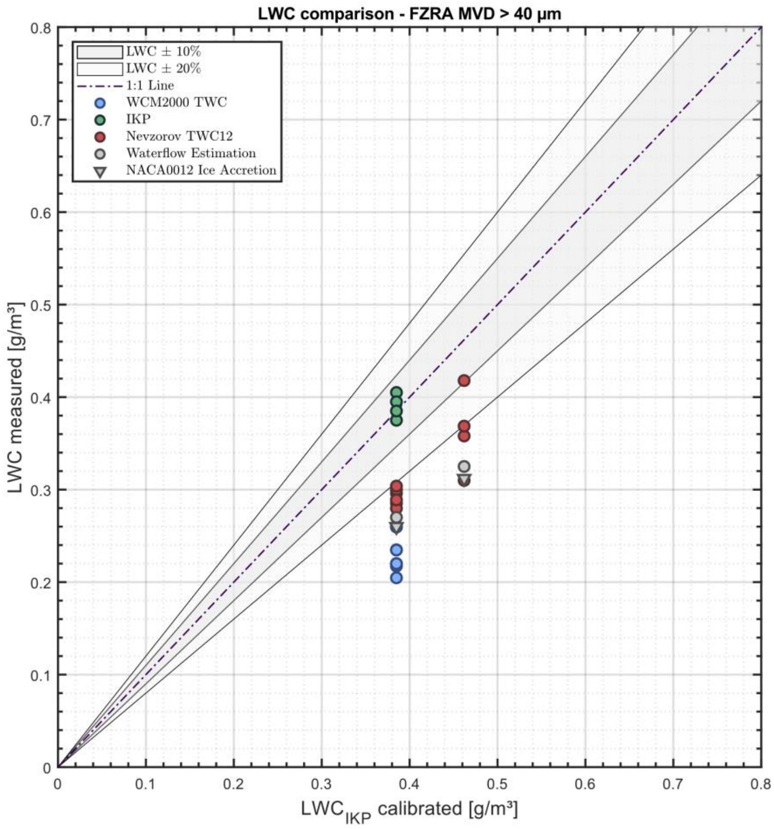


*Figure 20: Appendix O FZRA MVD ~550 µm measurement results in the RTA IWT: Comparison of WCM2000, Nevzorov, Ice Accreation versus CU-IKP. Shown are single test points per LWC and instrument.*