

ICE GENESIS

Creating the next generation of 3D simulation means for icing

Type of action: Research and Innovation Action

Call identifier: H2020-MG-2018-SingleStage

Topic: MG-2-5-2018 Innovative technologies for improving aviation safety and certification in icing conditions

Deliverable D2.5

Synthesis of Results and Way Forward

EC Grant Agreement number:

824310

Start date of project: 1 January 2019

Duration: 60 months

Lead beneficiary of this deliverable:

AIRBUS

Due date of deliverable: 31/12/2023

Actual submission date: 12/03/2024

Version #: R0.2

Project funded by the European Commission within the H2020 Programme (2014-2020)		
Type		
R	Document, report excluding the periodic and final reports	X
DEM	Demonstrator, pilot, prototype	
DEC	Websites, patents filing, press & media actions, videos, etc.	
OTHER	Software, technical diagram, etc.	
ETHICS	Ethics requirement	
ORDP	Open Research Data Pilot	
Dissemination level		
PU	PUBLIC, fully open, no embargo e.g. web	X
PU+E1	PUBLIC after embargo of 12 months from date of publication	
PU+E3	PUBLIC after embargo of 3 years after the project's end	
RE	RESTRICTED, only for certain members of the consortium (including the Commission Services): specify here which consortium members have access to the document	
CO	CONFIDENTIAL, only for members of the consortium (including the Commission Services)	
CO+IGAB	CONFIDENTIAL, only for members of the consortium (including the Commission Services) and for the ICE GENESIS Advisory Board	

Revision History

V #	Date	Description / Reason of change	Author
R0.1	31/01/2024	New deliverable	E. LAINE (AIRBUS)
R0.2	16/02/2024	Update following internal review at AIRBUS	E. LAINE (AIRBUS)
R1.0	22/02/2024	Update following comments from reviewers	E. LAINE (AIRBUS)
R2.0	07/03/2024	Update with full list of publications	E. LAINE (AIRBUS)

Deliverable Contributors

Authors

Organisation	Authors' name	Export control status date	Export control status
AIRBUS	Estelle LAINE	16/02/2024	"No data subject to export control"

Contributors

Organisation	Authors' name	Export control status date	Export control status
N/A	N/A	N/A	N/A

Export Control Status

Author / Contributor	Type of data	Position in document of concerned text/data*	Jurisdiction and ECCN under this jurisdiction	Status of authorization
Estelle LAINE	Literature, test data, computational data	All document	"no data subject to export control"	Not Applicable

****To be checked by the Owner of the document before delivery of the document!***

Internal Reviewers

Organisation	Internal Reviewers' name
AIRBUS HELICOPTERS	Fabien DEZITTER
RTA	Hermann FERSCHITZ

Table of Contents

Table des matières

1	Glossary.....	5
2	Executive Summary.....	7
3	Introduction.....	10
4	Reminder of ICE GENESIS context, objectives and workplan.....	11
4.1	Context of ICE GENESIS	11
4.1.1	Liquid Water Icing Context.....	11
4.1.2	Snow Context	12
4.2	Objectives of ICE GENESIS	13
4.3	Workplan structure of ICE GENESIS.....	13
5	Main results of ICE GENESIS.....	15
5.1	Faced Challenges.....	15
5.2	Main results on Supercooled Liquid Water	15
5.2.1	Main results on Icing Wind Tunnel Test Capabilities.....	15
5.2.2	Main results on Icing Numerical Capabilities.....	17
5.3	Main results on Snow	20
5.3.1	Outcomes on the characterization of falling snow conditions.....	20
5.3.2	Main results on Snow Wind Tunnel Test Capabilities.....	21
5.3.3	Main Results on Snow Numerical Capabilities	24
5.4	Common experimental database.....	25
5.5	Standardization activities.....	26
5.6	Main dissemination activities.....	26
6	Exploitation of ICE GENESIS results.....	27
6.1.1	Exploitation of WP4 Instrumentation for Liquid Icing Conditions Results.....	27
6.1.2	Exploitation of WP5 Instrumentation for Snow and Microphysical Properties Results	27
6.1.3	Exploitation of WP6 Supercooled Large Drops Test Capability Results	27
6.1.4	Exploitation of WP7 Snow Test Capability Results.....	27
6.1.5	Exploitation of WP8 Wind Tunnel Tests for Liquid Icing and Snow Conditions Results	28
6.1.6	Exploitation of WP9 Numerical Capability Development for Liquid Icing Conditions Results.....	28
6.1.7	Exploitation of WP10 Numerical Capability Development for Snow Results ...	28
6.1.8	Exploitation of WP11 Numerical Tools Validation in Industrial Environment Results	28
7	Way Forward after ICE GENESIS.....	29

7.1	Way forward for Supercooled Large Drops	29
7.2	Way forward for Snow	29
8	Conclusions.....	31
9	Bibliography	32
10	Appendix 1 - List of ICE GENESIS Public Deliverables	34
11	Appendix 2 - List of ICE GENESIS Publications	35

Table of Tables

Table 1	The 4 drop distributions of Appendix O conditions, built from DOT/FAA/AR-09/10	11
Table 2	Common 2D test cases used by the industrial partners for the validation of the upgraded tools in SLD conditions.....	19
Table 3	Comparison of falling snow generated at RTA and NRC through snow accretion tests on a NACA0012	22
Table 4	Capability of the snow wind tunnel test facilities at the end of ICE GENESIS.....	23
Table 5	Range of conditions covered by the ICE GENESIS database.....	25

Table of Figures

Figure 1	H175 Flight Tests in snow conditions; credit: Airbus Helicopters.....	12
Figure 2	A400M snow tests with a snow gun; credit: Airbus Defence & Space	13
Figure 3	ICE GENESIS Work Plan Structure	14
Figure 4	Example of 3D scan of an ice shape generated in icing wind tunnel.....	16
Figure 5	The business jet 3D wing tested in Appendices C & O in CIRA IWT.....	16
Figure 6	The 2 mock-ups tested only in Appendix C during ICE GENESIS: cascade rig in Cranfield IWT (left) and fan rotor in NRC IWT (right)	17
Figure 7	Experimental observation of the altitude effect on droplet impact (D0: drop diameter; Vair: airspeed; Tair: air temperature; Pair: ambient pressure).....	18
Figure 8	Validation results from the different partners on the FZDZ (left) and FZRA (right) 2D test cases from Table 2.....	19
Figure 9	ATR42 snow field campaign at Les Eplatures (Swiss Jura) - 01/2024	21
Figure 10	IAG SnowFall snow generation system into RTA Climatic Wind Tunnel and calibration.....	22
Figure 11	Comparison of falling snow generated at RTA and NRC through snow accretion tests on a NACA0012	23
Figure 12	Physical phenomena related to snow. All but shedding were addressed in ICE GENESIS....	24
Figure 13	Simulation comparison for each industrial partner with 4 NRC snow accretion test cases .25	

1 Glossary

Abbreviation / Acronym	Description/meaning
2D-S	2D Stereo Probe
AIAA	American Institute of Aeronautics and Astronautics
APU	Auxiliary Power Units
ARP	Aerospace Recommended Practice
CFD	Computational Fluid Dynamics
CIRA	Centro Italiano Ricerche Aerospaziali (Italy)
CNRS	Centre National de la Recherche Scientifique (France)
CPI	Cloud Particle Imager
CU	Cranfield University (United Kingdom)
CVI	Counterflow Virtual Impactor
CWC	Condensed Water Content
EASA	European union Aviation Safety Agency
FAA	Federal Aviation Administration (USA)
FZDZ	Freezing Drizzle
FZRA	Freezing Rain
HTC	Heat Transfer Coefficient
HSI	High Speed Imaging
IAG	Industrie Automatisierungs GmbH (Austria)
ICC	Ice Capture Cylinder
IKP	Iso Kinetic Probe
IWC	Ice Water Content
IWT	Icing Wind Tunnel
LWC	Liquid Water Content
MASC	Multi Angle Snowflake Camera
MinDEF	Ministère de la Défense (France)
MMD	Median Mass Diameter
MVD	Median Volumetric Diameter
NACA	National Advisory Committee for Aeronautics
NASA	National Aeronautics and Space Administration
NRC	National Research Council (Canada)
PIP	Particle Imaging Probe
R&T	Research and Technology
RTA	Rail Tec Arsenal (Austria)
SAE	Society of Automotive Engineers

Abbreviation / Acronym	Description/meaning
SLD	Supercooled Large Drops
TRL	Technology Readiness Level
TWC	Total Water Content
WP	Work Package

2 Executive Summary

ICE GENESIS is an EU-funded project in the Horizon 2020 framework (project number 824310) which started in January 2019 and ended in December 2023, with the main objective to create the next generation of 3D simulation means for icing. A need for this project arose since, with the forthcoming disruptive architectures for air vehicles and propulsive systems, it will no longer be possible to rely on the existing design methodologies mainly based on experience and comparative analysis. These difficulties would moreover be increased with the recent changes in certification regulations, in particular regarding Supercooled Large Drops (SLD). Snow was also identified as a specific challenge to be addressed for the certification of turbine engines and APUs, with little development and certification compliance means available apart from flight testing. There was therefore a strong need for more mature tools to support the development and certification of aircraft, rotorcraft and engines in supercooled liquid water and snow conditions. To cover this need, the top-level objective of ICE GENESIS was to provide the European aeronautical industry with a validated new generation of 3D icing engineering tools (numerical simulation tools and upgraded test capabilities), addressing Appendix C, Appendix O and snow conditions, for safe, efficient, right first time, and cost-effective design and certification of future regional, business and large aircraft, rotorcraft and engines.

ICE GENESIS faced several challenges during its execution phase. Two of them had sufficiently notable impacts to be mentioned in this report: the COVID-19 crisis, which led to an extension of the project duration, and the termination, for geopolitical reasons, of an international partnership around which some major activities of the project were articulated. Some mitigation means were found to continue the project, but with some impacts on its overall scope and outcomes.

Supercooled Liquid Icing in ICE GENESIS

During ICE GENESIS, efforts on supercooled liquid icing have been concentrated on the upgrade and validation of test facilities for Supercooled Large Drops (SLD) conditions and on the improvement of numerical tools to perform 3D icing simulations and model SLD conditions.

First of all, the requirements targeting at the reproduction of SLD conditions in ground wind tunnel facilities were defined. The most appropriate instrumentation for SLD wind tunnel calibration was then selected. Further to the selection of the appropriate instrumentation, a calibration methodology for SLD test facilities was derived from the SAE ARP 5905. In particular, relevant parameters and acceptance criteria for SLD cloud calibration were updated. With that respect, ICE GENESIS enabled to achieve upgraded icing wind tunnel test capabilities in freezing drizzle conditions, both at CIRA (Italy) and RTA (Austria). A preliminary capability for freezing rain was even demonstrated at RTA. In terms of maturity assessment for freezing drizzle conditions, RTA achieved the TRL5 maturity targeted at the end of the project, while CIRA achieved a TRL4. The lack of calibration of the CIRA icing wind tunnel in its complete broad envelope covering altitude and high speed is the main reason why CIRA could not achieve TRL5. This calibration work is to be continued through other projects. On top of the upgrading of the test facilities, some trials were performed to characterize the droplet temperature in the wind tunnel, as it is a parameter that is believed to play a role in the accretion process. This was a first time for a European project and it provided encouraging results. It was also the first time that extensive 3D scanning of ice shapes was performed. The scanned ice shapes have been stored in the ICE GENESIS common database and can later be used for tool validation. Although the freezing drizzle capabilities of CIRA and RTA icing wind tunnels were significantly increased over the course of ICE GENESIS, some gaps remain to achieve a full freezing drizzle capability. Indeed, there are still some issues with the cloud uniformity and the Liquid Water Content (LWC) achieved is often too high compared to the certification requirements. Moreover, the effect of droplet temperature on the ice accretions needs to be further characterized. Some standardization efforts on the instrumentation for particle size distribution and LWC measurement are also required to ensure more consistency on the calibration of different test facilities. Furthermore, in order to use the test capabilities for industrial applications, the efficiency of the SLD set-up will have to be improved and it will be necessary to find a way to switch easily between Appendices C and O. At the end of ICE GENESIS, the upgraded icing

wind tunnel capabilities for Appendix O conditions provide more possibilities of testing but they are not yet at a level that would enable their use as a comprehensive means of compliance for aircraft certification.

As for the test facilities, a set of target requirements for the 3D icing numerical tools were defined at the beginning of the project, including requirements for the SLD capability. At the end of ICE GENESIS, some numerical capabilities were demonstrated in freezing drizzle based on the initial target requirements. In particular, some models were developed to simulate drop impact and mass deposition after splashing, as well as droplet re-emission. Moreover, a 3D capability was demonstrated with new methodologies for remeshing or multi-step processes. In consideration of this progress, the numerical tools for supercooled liquid icing, and in particular for SLD icing, achieved a TRL4. A TRL5 assessment was also performed but was not conclusive due to the remaining model limitations and the lack of industrialization of the tools. It was recommended to continue the research to improve SLD models, in particular addressing altitude and high-speed effects, which were identified in the course of the project. A significant gap was as well highlighted on roughness modelling. Recommendations also insisted on the need to further work on automation, user-friendliness, robustness and accuracy of 3D algorithms for predictor/corrector and/or multi-stepping method to allow their use to non-expert users. Finally, there is a lack of reliable experimental data to properly assess the models. For instance, experimental data enabling to properly differentiate the contributions of each individual phenomena is missing, as well as test data on more complex configurations. Overall major progress on numerical tools for liquid icing has been done during ICE GENESIS. However, the maturity of the tools upgraded with SLD models is not yet sufficient for them to be used as certification means of compliance. Some efforts are still needed to provide a better level of acceptance of these tools as certification means of compliance, as it is the case today for Appendix C. Considering the complexity and dimension of the topic, collaborative research efforts will be mandatory.

Snow in ICE GENESIS

During ICE GENESIS, efforts on snow have been concentrated on the characterization of falling snow conditions, on the upgrade and validation of test facilities and on the improvement of numerical tools. One of the first achievements of ICE GENESIS regarding snow was the characterization of falling snow conditions through field campaigns, during which valuable data was gathered thanks to developed synergies between the flight test aircraft, ground in-situ measurements and ground remote sensing (winter 2020/21). Considerable efforts were made on the data processing to retrieve the snow microphysical properties. The results were later used in the project as a support for the development of snow test and numerical capabilities.

The target requirements for snow test facilities were defined at the beginning of ICE GENESIS. These requirements were aiming at the reproduction of natural-like falling and blowing snow conditions in ground wind tunnel facilities. The most appropriate instrumentation for snow wind tunnel calibration was then selected. Further to the selection of the appropriate instrumentation, a calibration methodology for snow test facilities was derived from the SAE ARP 5905. In particular, relevant parameters and acceptance criteria for snow cloud calibration were updated. ICE GENESIS enabled the development of snow generation systems in RTA and NRC, with the capability to change the particle melt. The wind tunnel test facilities upgraded with these capabilities were then calibrated following the methodology previously defined. Though the snow generation systems used by the two facilities are based on different principles, they both enabled to achieve comparable results which provided a good confidence on the calibration of both facilities. Even though the maturity of the snow generation system in RTA was significantly increased during the project, it still needs to be upscaled in order to achieve the regulatory Total Water Content ($TWC > 1\text{g/m}^3$) as defined in AC29 or AMC25.1093(b). Moreover, the efficiency and operability of the snow generation systems will have to be improved for industrial use. Finally, it will be necessary to use the upgraded test facilities to generate a validation database on representative industrial configurations (turbo propeller or helicopter engine air inlet) to be used to assess the numerical capabilities.

Some target requirements for the snow numerical tools were defined at the beginning of the project, complementing those defined for supercooled liquid water since the same tools were expected to integrate both the snow and supercooled liquid water capability. Several physical phenomena related to snow were modelled during ICE GENESIS, starting from ice crystals models developed in the framework of the HAIC and MUSIC-HAIC projects. The physical phenomena addressed were drag, melting, erosion and sticking efficiency. The modelling of the particle trajectories (drag and melting) was assessed as sufficiently mature to achieve a TRL4 based on the good correlation with the experimental database. On the opposite, the erosion and sticking models obtained are only preliminary, equivalent to a TRL3 maturity. The snow models were then implemented into industrial 2D/3D icing tools, which were assessed by comparison with experimental results from the CSTB, NRC and RTA databases. The TRL5 assessment for snow numerical tools was not conclusive due to several remaining gaps which are listed hereafter. The snow accretion modelling is less mature than the snowflake trajectory modelling. In particular, models of snowflake impact and accretion will need more development. The case of snow accretion on heated surfaces will also have to be considered. Moreover, ice shedding and snow saltation should be further modelled. Finally, the numerical capabilities could not be properly assessed due to the lack of experimental data on complex 3D cases. This will have to be done in the future. Nevertheless, the panel recommended to proceed, since the progress made was significant and seemed to tend in the right direction. Achievements within ICE GENESIS provide already major improvement compared to the state of the art especially with regards to the transport model and efforts are to be continued.

ICE GENESIS common experimental database

One of the main outcomes of ICE GENESIS is the generation of a common experimental database, that gathers data from previous projects worldwide (example: NASA SLD Database) as well as ICE GENESIS data. The database contains Appendix C and Appendix O icing test cases, which represent in total 390 individual icing runs on 17 different test objects.

Conclusion

ICE GENESIS enabled significant progress on wind tunnel test facilities for the simulation of SLD and Snow conditions. The project also led to an improved understanding and modelling of SLD and Snow physics, though some progress remains necessary on the new models in order to use them as certification means of compliance. All along the project, the international cooperation has been beneficial and is to be continued.

Further efforts are necessary to achieve workable means of compliance for the future generation of disruptive products. They could take the shape of collaborative research activities feeding two separate roadmaps focusing respectively on supercooled large drops and snow & ice crystals. Launching the necessary activities to achieve the targets of these roadmaps will be critical to enable the development and certification of low-CO₂ aircraft and engines. Some coordination efforts are currently ongoing at international level to define in more details the scope of the required future activities and to identify the best funding opportunities in the coming years.

3 Introduction

ICE GENESIS is an EU-funded project in the Horizon 2020 framework (project number 824310) which started in January 2019 and ended in December 2023, with the main objective to create the next generation of 3D simulation means for icing.

This document is the public synthesis of ICE GENESIS. After reminding the context and main objectives of the project, the document will present its main outcomes. In particular, the outcomes regarding icing wind tunnel test facilities and numerical tools will be addressed for both supercooled liquid water icing (Appendices C and O) and snow.

Finally, the exploitation of ICE GENESIS' results and the way forward after the project will be discussed.

4 Reminder of ICE GENESIS context, objectives and workplan

4.1 Context of ICE GENESIS

Icing usually occurs when an air vehicle flies through clouds in which supercooled droplets are suspended. A supercooled droplet is a drop of liquid water with a temperature below the freezing point. This is an unstable state for water, and aircraft surfaces naturally act as freezing nuclei, turning the water into its more stable ice phase upon impingement. Icing can also happen when flying through glaciated clouds or precipitations, where accretion from ice crystals will be more likely in areas with warm air flow or warm surfaces. Air vehicle icing can lead to a reduction of visibility, damage due to ice shedding, interference with probes and static vents, reduced flight performance and handling, adverse aerodynamic effects, engine power loss, etc. In order to comply with certification regulation rules, air vehicle and engine manufacturers must demonstrate safe operation under icing conditions, as defined per CS23/25/27/29/E. This demonstration is performed through a combined use of numerical simulations, theoretical analyses, laboratory tests (wind tunnel dry or icing tests) or flight tests.

Current design methodologies used to characterise ice accretion and its effects on air vehicle components and power plant systems are mainly based on empirical methods, comparative analysis, 2D simulation tools calibrated for Appendix C icing and past experience gained on in-service products. Due to the associated uncertainties, cautious design margins are used, leading to conservative and non-optimised solutions. As future air vehicle and propulsive system architectures introduce radical design changes, it will no longer be possible to rely on the existing design methodologies, making future development extremely difficult to accomplish efficiently and within short development cycles that are demanded by customers and desired by industry. These difficulties are increased by the recent changes in certification regulations, in particular for Supercooled Large Drops (SLD), which require manufacturers to certify their products against more stringent requirements. Snow is also a challenge, especially for turbine engines and APUs. Further details on liquid water icing and snow contexts are provided respectively in sections 4.1.1 and 4.1.2.

4.1.1 Liquid Water Icing Context

For future aircraft or engine certification, two different types of liquid icing conditions have to be addressed. These are described by the following Appendices in the regulations:

- CS25 / Part 25 Appendix C, defining clouds with small supercooled droplets (MVD typically smaller than 50 μ m) and long-established in the regulations.
- CS25 / Part 25 Appendix O, defining Supercooled Large Drops (SLD) and introduced more recently in the regulations (CS25 Amendment 16, March 2015). SLD conditions include freezing drizzle (FZDZ) and freezing rain (FZRA). They are further described in Table 1, where the subcategories "In" and "Out" refer to conditions found more often for In Cloud (In), and for Out of Cloud (Out) droplets.

Defintion	MVD Range	Maximum Diameter Range	MVD	Maximum Diameter	LWCmax
FZDZ In	< 40 μ m	100 – 500 μ m	20 μ m	389 μ m	0.44 g/m ³
FZDZ Out	> 40 μ m	100 – 500 μ m	110 μ m	474 μ m	0.27 g/m ³
FZRA In	< 40 μ m	> 500 μ m	19 μ m	1553 μ m	0.31 g/m ³
FZRA Out	> 40 μ m	> 500 μ m	526 μ m	2229 μ m	0.26 g/m ³

Table 1 The 4 drop distributions of Appendix O conditions, built from DOT/FAA/AR-09/10

At the start of ICE GENESIS, the icing wind tunnel test capabilities regarding the generation of SLD conditions is quite limited (TRL2). This is also the case for icing simulation tools which are overly-

conservative when dealing with large drops and not properly validated. Indeed, specific physical phenomena related to large drops like bouncing and splashing and likely to reduce the water collection efficiency are not sufficiently well represented. The preliminary SLD models implemented in some of the numerical tools used by the industrials are at TRL2.

The low maturity of both icing wind tunnel test facilities and numerical tools regarding Appendix O represents a significant limitation for the development of future aircraft and powerplant installations. In particular, the need for disruptive architectures to tackle the CO₂ emission reduction challenge implies less possibilities to use comparative analysis and more extensive use of wind tunnel testing and numerical simulations. There is therefore a need for upgraded icing wind tunnel test and numerical tools capabilities for Appendix O.

On top of these specific needs for Appendix O, a 3D icing capability covering both Appendix C and Appendix O is necessary for faster and more efficient design and certification of complex aircraft or powerplant geometries.

4.1.2 Snow Context

Rotorcraft manufacturers need to demonstrate safe operations in falling and blowing snow conditions. The demonstration is performed at the end of the program development during certification flights (Figure 1). The 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 regulation's Acceptable Means of Compliance (AMC). 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. Similar issues can be faced by turbo-propeller A/C or APUs. Finally, there is a growing interest for large A/C because of increased exposure to heavy snow conditions.



Figure 1 H175 Flight Tests in snow conditions; credit: Airbus Helicopters

There is therefore a need to develop snow test and numerical capabilities to de-risk power plant system design before in-flight demonstration and as such, secure future program development and certification.

On top of the need identified for rotorcraft or turbo-propeller powerplants, a need for snow capabilities will also arise on the disruptive aircraft engine configurations.

Some attempts have been made in the past to use snow guns on ground in order to de-risk some engine inlet designs (Figure 2). However, the snow generated by the snow guns is not fully representative of the snow encountered in flight, which limits the benefit of the test. AC29 specifically mentions "Artificially produced snow should not be used as the sole means of showing compliance."

A preliminary snow capability was also available in the RTA icing wind tunnel before the start of ICE GENESIS (based on a snow gun at TRL1/TRL2) but a new more representative capability needed to be implemented to be used as a robust development and certification means.



Figure 2 A400M snow tests with a snow gun; credit: Airbus Defence & Space

4.2 Objectives of ICE GENESIS

The top-level objective of ICE GENESIS was to provide the European aeronautical industry with a validated new generation of 3D icing engineering tools (numerical simulation tools and upgraded test capabilities), addressing Appendix C, Appendix O and snow conditions, for safe, efficient, right first time, and cost-effective design and certification of future regional, business and large aircraft, rotorcraft and engines.

Three technical objectives were further defined to achieve the project's main goal:

1. Improve and validate existing 3D numerical tools to predict ice accretion in Appendix C, Appendix O and Snow conditions.
2. Upgrade and calibrate icing wind tunnels to allow reproduction of:
 - Supercooled Large Drops in Freezing drizzle conditions
 - Snow icing conditions
 Additionally, assess the potential of current icing wind tunnels to represent Supercooled Large Drops in Freezing rain conditions.
3. Build a large-scale experimental database on representative 3D configurations to be used as a solid reference ("ground truth") for future numerical tools validation.

Through the achievement of these objectives, ICE GENESIS would permit weather hazards to be more precisely evaluated and properly mitigated thanks to adapted design or optimised protection through either active or passive means. Furthermore, ICE GENESIS would pave the way for 3D digital tools to be used in the future as acceptable means of compliance by the regulation authorities. Overall, ICE GENESIS would contribute to flight safety, reduced certification costs and increased operability.

4.3 Workplan structure of ICE GENESIS

In order to achieve the objectives of the project, a workplan structure of 11 work packages and 3 streams was defined (Figure 3). Two streams were dedicated to supercooled liquid icing, one to address the specifics of Appendix O conditions and the other focused on the 3D numerical capability in Appendix C. A third stream addressed snow conditions. The two first work packages were dedicated respectively to the project management (WP1) and to the dissemination and exploitation (WP2). They were independent of the streams. A first technical work package (WP3) focused on the consolidation of specifications and test plans for the three streams. Some specifications were defined for the wind tunnel test capabilities for SLD and snow conditions and for the numerical capabilities. The next work package (WP4) focused on the selection of the appropriate instrumentation to characterize liquid icing conditions. A similar work package (WP5) was intended at selecting the instrumentation for the characterization of snow conditions. It also included some activities to characterize the microphysical properties of snow, notably through field campaigns. The two following work-packages were respectively dedicated to the improvement and validation of the SLD (WP6) and snow (WP7) wind tunnel test capabilities. After the upgrade of the facilities, work package 8 hosted the different test campaigns that were performed for each of the three streams. As for the activities on the

instrumentation, the development of the numerical capabilities was separated into two work packages, one of them addressing supercooled liquid icing conditions (WP9) and the other addressing snow conditions (WP10). Finally, WP11 focused on the validation of the numerical tools in industrial environment and covered all of the three streams. Each work package was coordinated by a different partner of the project.

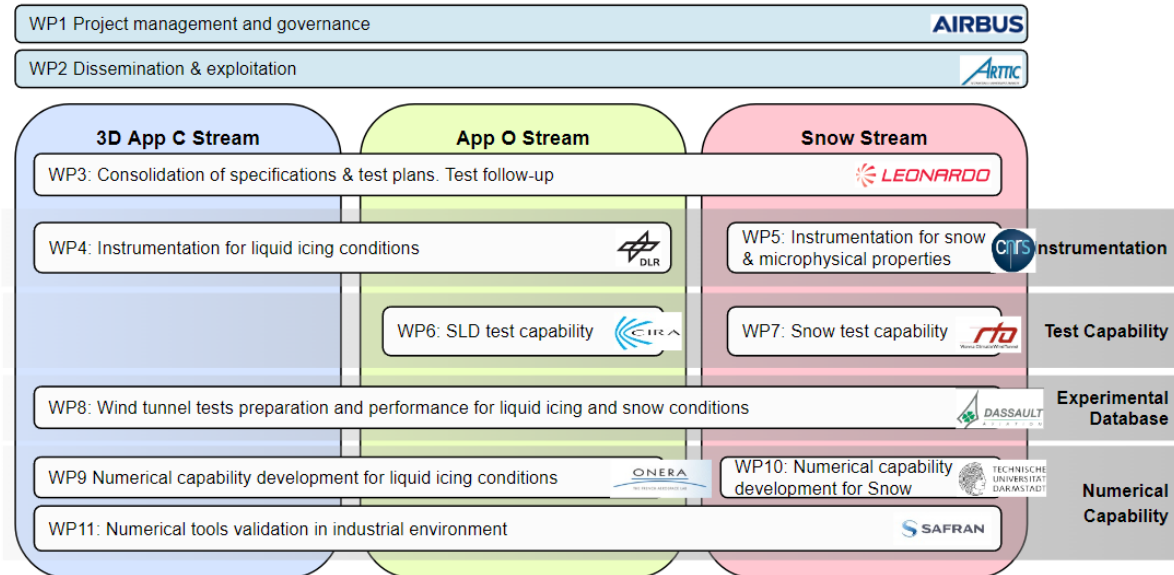


Figure 3 ICE GENESIS Work Plan Structure

5 Main results of ICE GENESIS

5.1 Faced Challenges

ICE GENESIS faced several challenges during its execution phase. Two of them had sufficiently notable impacts to be mentioned in this report.

First of all, the COVID-19 crisis led to a delay in some of the activities. In order to compensate, the end of the project was delayed by one year (December 2023).

Moreover, the project was articulated around a partnership with Russian partners that were supposed to bring some necessary test data (WP8) for further validation of the numerical tools (WP11), both in supercooled liquid icing and snow conditions. The partnership stopped in 2022 for geopolitical reasons. As a result, some mitigations had to be found for the validation of the numerical tools with other existing data. This event nevertheless had impacts on the project's scope and outcomes.

5.2 Main results on Supercooled Liquid Water

The main results of the two ICE GENESIS streams focusing on supercooled liquid icing capabilities mainly concern icing wind tunnels and numerical tools. They will be respectively detailed in sections 5.2.1 and 5.2.2.

5.2.1 Main results on Icing Wind Tunnel Test Capabilities

5.2.1.1 Outcomes on Icing Wind Tunnel Test Capabilities

The first activity of ICE GENESIS related to supercooled liquid water was to define the target requirements in Appendix O for the test facilities in the framework of WP3. This activity was also an opportunity to make a status of the test facilities in terms of SLD calibration, that highlighted the gaps to be covered by each facility in the framework of WP4 and WP6 [1].

Since instrumentation is a key player in the calibration of the test facilities, a specific focus was made in WP4 on the selection of the most appropriate instrumentation for experiments in Appendices C and O icing conditions. The following parameters were considered:

- Particle Size Distribution [3]. The instrumentation was selected to enable the determination of the MVD for a droplet size spectrum between 40 to 2500 μm .
- Liquid Water Content [4]. The range to be covered was $0.1 \text{ g/m}^3 \leq \text{LWC} \leq 3 \text{ g/m}^3$.
- Droplet temperature [5]. The target was to validate that the droplets were supercooled in the wind tunnel test section. This measurement was performed with a Global Rainbow Technique (GRT) which was a first time for a European project.
- Cloud Homogeneity [7]
- Ice shape [6]. The goal was to characterize surface roughness and ice density. Ice shapes were acquired through an innovative 3D scanning process which was a first time for a European project (Figure 4).

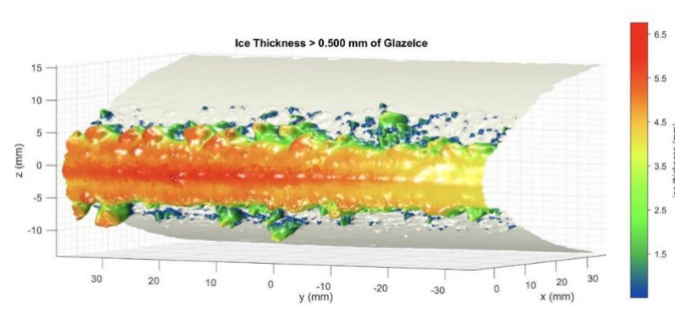


Figure 4 Example of 3D scan of an ice shape generated in icing wind tunnel

The instrumentation selected was first calibrated and characterized in laboratory, before being used for the calibration of the test facilities in the framework of WP6. The Appendix O calibration was performed following a procedure defined in the course of the project and further described in reference [7]. This calibration effort enabled to achieve and validate upgraded capabilities in Appendix O for the CIRA and RTA test facilities [8][9]. In particular, the capabilities in freezing drizzle conditions were improved both at CIRA and RTA. A preliminary capability for freezing rain was even demonstrated at RTA. In terms of maturity assessment for FZDZ, RTA achieved the TRL5 maturity targeted at the end of the project, while CIRA achieved a TRL4 and performed a TRL5 assessment. Some gaps to TRL5 were identified and will be discussed in §5.2.1.2.

The upgraded capability at CIRA was used in the framework of WP8 to perform tests on a business jet 3D outer-wing mock-up in Appendix C and O conditions (Figure 5). The mock-up included a high lift device (slat) which could be retracted or extended and a hot air anti-icing capability. A total of 22 test runs were performed, including a number of Appendix O conditions in FZDZ and ice protection system runs. The ice shapes were scanned so that they could be further used for the validation of the numerical tools (Figure 4). Moreover, some tests were performed in Appendix C in the Cranfield icing wind tunnel (cascade rig [10]) and in the NRC icing wind tunnel (fan rotor) (Figure 6). These tests were also meant to populate the common database of validation test cases for the 3D icing tools developed in ICE GENESIS. As explained in §5.1, some challenges lead to the reduction of the icing wind tunnel test campaigns planned during the project and these 3 test campaigns were finally the only ones available.



Figure 5 The business jet 3D wing tested in Appendices C & O in CIRA IWT

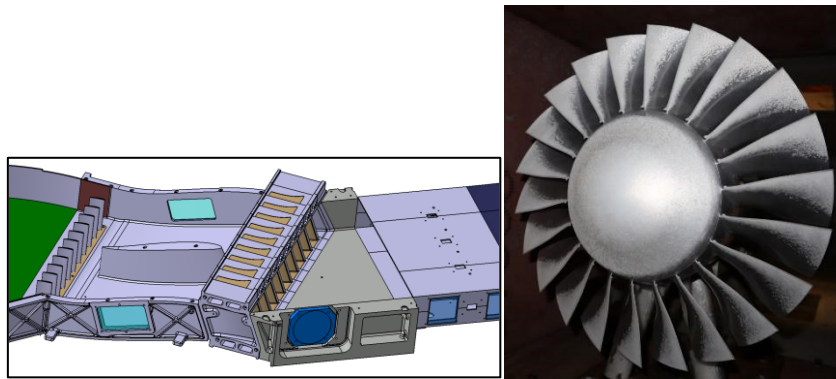


Figure 6 The 2 mock-ups tested only in Appendix C during ICE GENESIS: cascade rig in Cranfield IWT (left) and fan rotor in NRC IWT (right)

5.2.1.2 Remaining Gaps on Icing Wind Tunnel Test Capabilities

Although the freezing drizzle capabilities of CIRA and RTA icing wind tunnels were significantly increased over the course of ICE GENESIS, some gaps remain to achieve a full freezing drizzle capability. Indeed, there are still some issues with the cloud uniformity and the LWC achieved is often too high compared to the certification requirements. Moreover, the effect of droplet temperature on the ice accretions needs to be further characterized. Some standardization efforts on the instrumentation for particle size distribution and LWC measurement are also required to ensure more consistency on the calibration of different test facilities. Furthermore, in order to use the test capabilities for industrial applications, the efficiency of the SLD set-up will have to be improved and it will be necessary to find a way to switch easily between Appendices C and O.

Finally, the CIRA icing wind tunnel needs to be calibrated in its broad envelope covering altitude and high speed. These are indeed two parameters that are of high interest for industrials. This lack of calibration in a broader range is the main reason why CIRA did not achieve TRL5. Part of the work is currently in progress thanks to national funded projects to improve the calibration.

At the end of ICE GENESIS, the upgraded icing wind tunnel capabilities for Appendix O conditions provide more possibilities of testing but they are not yet at a level that would enable their use as a comprehensive means of compliance for aircraft certification.

The improvements required to achieve a full FZDZ capability in each facility could be achieved through self or national funding. However, a collaborative project could be necessary to finalize the standardization efforts started in ICE GENESIS. Regarding FZRA, the challenges to have a full capability are more numerous. There could even be some physical barriers preventing the existing facilities to achieve such capability (droplet breakup or supercooling). Some further studies will therefore be required to define a clear way forward.

5.2.2 Main results on Icing Numerical Capabilities

5.2.2.1 Outcomes on Icing Numerical Capabilities

As for the test facilities, the target requirements for the numerical tools regarding supercooled liquid icing (Appendices C and O) were formulated by the industrial partners at the beginning of ICE GENESIS (WP3)[2]. The definition of these requirements started with an overview of already existing models and techniques but also of available experimental data for model development purposes. The review focused on numerical methods for meshing (immersed boundary methods, mesh deformation, automatic remeshing), roughness models (characterization in Appendices C and O, boundary layers on rough walls), supercooled large drops models (secondary/re-emitted droplets, partial deposit and sticking efficiency) and ice density models. On top of the different necessary models and their expected level of accuracy, the requirements also insisted on the tools' capabilities (transient simulation, compute system heat requirements necessary to fulfil a given criterion...), their computational performance, and their user-friendliness.

The activities necessary to achieve the target specifications for the numerical capabilities were performed in WP9 [13]. It focused on three main aspects: experimental investigations, modelling of the physical phenomena observed in the experiments, and development of numerical methods to enable an efficient use of the models in the tools. The experimental investigations and modelling mainly turned around SLD impact on a surface. It included the investigation over several phenomena like drop deformation, drop impact regime, mass deposition, accretion, and secondary droplets. This activity was also the opportunity to observe unexpected behaviours like altitude (Figure 7) or erosion effects. These will require further investigation and modelling beyond ICE GENESIS. Some experiments and modelling attempts were also performed on roughness. However, the maturity of the roughness models proved to be lower than expected and requiring work beyond what would be achievable during the project. It was therefore decided to concentrate the efforts on drop impact models. Due to a lack of test data consequent to the challenges described in §5.1, the activities on liquid film were as well drastically reduced. Regarding numerical methods, the work performed in ICE GENESIS consisted in improving the capabilities of 3D solvers for liquid icing conditions. In particular, numerical methods for 3D Predictor-Corrector and Multi-Step calculations [11][12] were developed. This part of the activity also included the integration of the SLD models into the 3D tools. The solvers were then evaluated on common ice accretion test cases on NACA profiles from the Ice Prediction Workshop database and achieved a TRL4 (SLD Impact models and 3D ice accretion, roughness excluded).

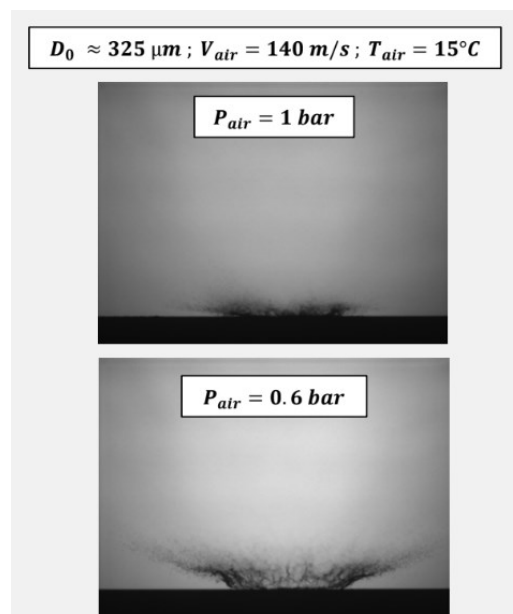


Figure 7 Experimental observation of the altitude effect on droplet impact
(D_0 : drop diameter; V_{air} : airspeed; T_{air} : air temperature; P_{air} : ambient pressure)

Following the achievement of the TRL4, the updated 3D icing tools were integrated into the different environments of the industrial partners. In some cases, the SLD models were directly implemented into the in-house tools of the partners. The icing tools with their new capabilities were then further evaluated on a validation database, which included partner-specific and common test cases. For Appendix O, the 2D test cases were selected from a test campaign performed at RTA on a NACA0012 airfoil in the framework of another project (Table 2). For appendix C, 2D test cases were selected from a campaign performed during ICE GENESIS at TUBS on a HMDI profile [13]. The 3D test cases were selected from the 3D wing test campaign performed at CIRA in WP8. This activity performed in the framework of WP11 was targeting at validating the ability of each industrial partner to perform simulations in SLD conditions (FZDZ & FZRA) and to perform 3D simulations in liquid conditions. It was also an opportunity for each partner to define some best practices for the usage of the tools [27]. The 2D validation test cases in FZDZ were correctly predicted, though there was still room for improvement. The FZRA shapes were however presenting more discrepancies with the tests. The 3D

simulations could be run by some partners, who however encountered more challenges that will be discussed in §5.2.2.2. The numerical tools for supercooled liquid icing, and in particular for SLD icing, achieved a TRL4 at the end of ICE GENESIS. A TRL5 assessment was also performed but was not conclusive due to the remaining model limitations and the lack of industrialization of the tools. These gaps will be further discussed in §5.2.2.2. However, the recommendation of the panel was to proceed since major progress was made during the project and more achievements could be expected by continuing the efforts in the same direction.

Test article	Chord [m]	SLD Cond.	SAT [°C]	Altitude [m]	Airspeed [m/s]	Mach []	AoA [°]	MVD [µm]	LWC [g/m ³]	Exposure time [min]
NACA0012	1	FZDZ	-11.4	0	60	0.19	0	87.9	0.48	7.5
NACA0012	1	FZRA	-11.5	0	60	0.19	0	535	0.33	10

Table 2 Common 2D test cases used by the industrial partners for the validation of the upgraded tools in SLD conditions.

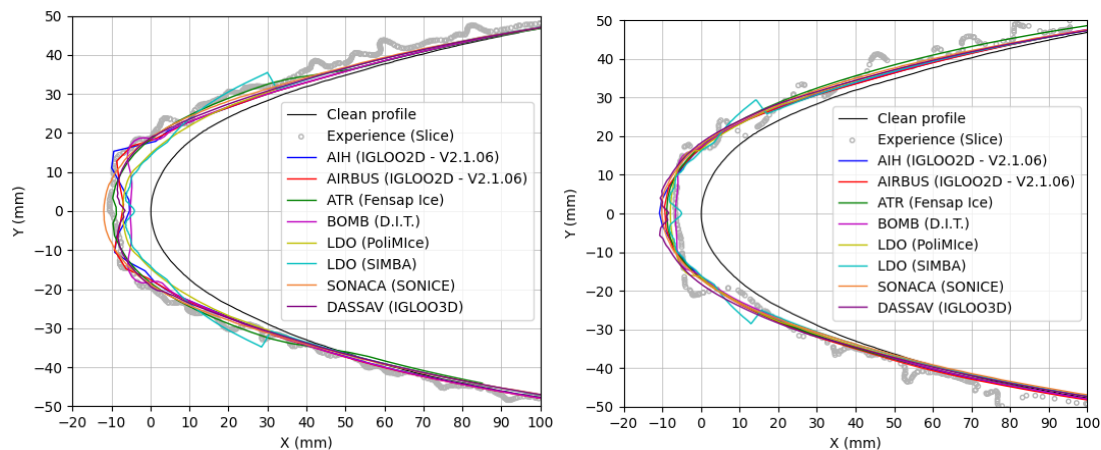


Figure 8 Validation results from the different partners on the FZDZ (left) and FZRA (right) 2D test cases from Table 2

To summarize, some numerical capabilities were demonstrated in freezing drizzle through ICE GENESIS. In particular, some models were developed to simulate drop impact and mass deposition after splashing, as well as droplet re-emission. Moreover, a 3D capability was demonstrated with new methodologies for remeshing or multi-step processes. Nevertheless, the capability still presents some limitations that will be discussed in §5.2.2.2.

5.2.2.2 Remaining Gaps on Icing Numerical Capabilities

At the end of ICE GENESIS, the full freezing drizzle capability is missing in numerical tools. This has been highlighted by the TRL5 assessment of the tools in industrial environment, which was not conclusive. There is also still a lack of modelling for freezing rain conditions, which was out of the scope of the project. This means the maturity of the numerical tools upgraded with SLD models is not yet sufficient for them to be used as sole certification means of compliance. Some efforts are still needed so that these tools and models could have an acceptability from airworthiness authorities equivalent to those used for Appendix C certification. Areas of improvement and possible means have already been identified. Indeed, the recommendation of the TRL5 was to proceed and continue the efforts deployed through ICE GENESIS to address the remaining gaps. These are mainly related to the three following topics: SLD specifics, roughness modelling and 3D re-meshing capabilities.

Regarding SLD topics, some physical phenomena identified during ICE GENESIS like altitude or high-speed/erosion effects need to be further understood, quantified and modelled. The secondary droplet re-emission models also require some improvements. Furthermore, the impact of SLD on wet or rough iced surfaces should be characterized. On top of the understanding and modelling, there is a lack of reliable experimental data to properly assess the models. For instance, experimental data enabling to properly differentiate the contributions of each individual phenomena is missing, as well as test data on more complex configurations. Some test data in FZRA conditions will also be necessary.

Regarding roughness and heat transfer coefficient (HTC) prediction, a significant gap remains worldwide that will need to be further addressed by some testing efforts in different conditions and at different scales. It will be required to better model the accretion process, especially in mixed and glaze conditions.

Finally, concerning the 3D re-meshing capabilities, it is necessary to better industrialize the tools so that they can be used by non-expert users with reasonable pre- and post-processing efforts. This means reducing human intervention in the remeshing process, reducing mesh dependency and improving the handling of ice shape / geometry interaction. This shall be possible for complex designs like a full aircraft or rotating components.

In order to fill those gaps, international collaboration will be key. Indeed, it will involve significant testing and modelling efforts that could not be achievable in a reasonable timeframe by single entities. The collaboration will also bring some benefits in the validation of the models and the definition of best practises. A future collaborative project is therefore highly desirable to continue the efforts of ICE GENESIS on the SLD numerical capabilities.

5.3 Main results on Snow

The main results of the snow stream concerned the characterization of falling snow conditions, snow wind tunnel test capabilities and numerical tools. They will be respectively detailed in sections 5.3.1, 5.3.2 and 5.3.3.

5.3.1 Outcomes on the characterization of falling snow conditions

One of the first achievements of ICE GENESIS regarding snow conditions was the characterization of falling snow conditions through field campaigns in the framework of WP5. Valuable falling snow data was gathered during winter 2020/21 [16]. The flight test campaign relied on developed synergies between the flying aircraft (SAFIRE ATR42), ground in-situ measurements (MASC) and ground remote sensing (X, W-band radar) in order to quantify the microphysical properties of snow (Figure 9). In preparation of the flight test campaign a study enabled to select the most relevant instrumentation for the test aircraft [17]. Considerable efforts were made on the data processing to retrieve the snow characteristics. For instance, machine learning techniques [18] were used to re-construct 3D descriptors of the snowflakes 2D images taken from the MASC or to retrieve the morphological classes of the snowflakes from the 2D-S and PIP probes installed on the aircraft. A deep learning method was also used to post-process the radar measurements [19]. The intention of the snow campaigns was not to be exhaustive, which would have been out of reach in terms of time and budget, but rather to capture some samples of possible snow conditions and to correlate different types of measures for a same condition. The results of these field campaigns were later used in the project as a support for the development of snow test and numerical capabilities.



Figure 9 ATR42 snow field campaign at Les Eplatures (Swiss Jura) - 01/2024

5.3.2 Main results on Snow Wind Tunnel Test Capabilities

5.3.2.1 Outcomes on Snow Wind Tunnel Test Capabilities

The target requirements for snow test facilities were defined at the beginning of ICE GENESIS in the framework of WP3 [14]. These requirements were targeting at the reproduction of natural-like falling and blowing snow conditions in ground wind tunnel facilities, with the goal to cover all the different parts of the rotorcraft and aircraft affected by snow with a focus on power plant system. The defined requirements and associated priority level were used as a guideline for the selection of improvements and upgrades of the test rigs, procedures and controls in the framework of WP7.

A specific focus was made in the framework of WP5 on the selection of the most appropriate instrumentation for snow wind tunnel calibration [20]. The following criteria were considered:

- 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
- 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
- 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...
- Ensure cloud homogeneity in IWT measurement section (e.g. with laser sheet technology, grid mesh, etc...)

Further to the selection of the appropriate instrumentation, a calibration methodology for snow test facilities was defined in the framework of WP7 [21]. It was derived from the SAE ARP 5905 [28]. In particular, relevant parameters and acceptance criteria for snow cloud calibration were updated. Moreover, a continuity check test was 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.

Through WP7 activities, ICE GENESIS enabled the development of snow generation systems in RTA (Figure 10) and NRC, with the capability to change the particle melt. The snow generation systems used by the two facilities are based on different principles. The SnowFall technology used at RTA and developed by IAG generates snowflakes by icing/riming a rotating cylinder under specific and adjustable conditions and scraping off flakes with a blade. The cylinder is integrated into a housing which itself is installed in the wind tunnel. For further control of the wetness or the Liquid Water Ratio (LWR) of the snow, humidification nozzles are used to spray liquid water onto the falling particles [22]. The snow maker installed in the NRC RATFac creates snow particles by agglomerating small ice

particles. It also has the ability to change the particle melt. The wind tunnel test facilities upgraded with these capabilities were calibrated following the methodology described above. After the calibration phase, a same NACA0012 test article was tested in both facilities in order to compare the snow generation systems. For scaling purposes, it was attempted to match the total water content multiplied by the exposure duration as much as possible (Table 3). The results show good agreement in impingement limits, thickness, shape and TWC growth rate, which provides a good confidence on the calibration of both facilities (Figure 11).



Figure 10 IAG SnowFall snow generation system into RTA Climatic Wind Tunnel and calibration

Parameter	RTA (IAG SnowFall)	NRC RATFac (Snow Maker)
TAS [m/s]	40	40
SAT [°C]	-0.8	-0.3
MVD [μm]	2180	2000
TWC [g/m^3]	0.41	2.2
Duration [s]	600	120
TWC*Duration [$\text{g.s}/\text{m}^3$]	246	264

Table 3 Comparison of falling snow generated at RTA and NRC through snow accretion tests on a NACA0012

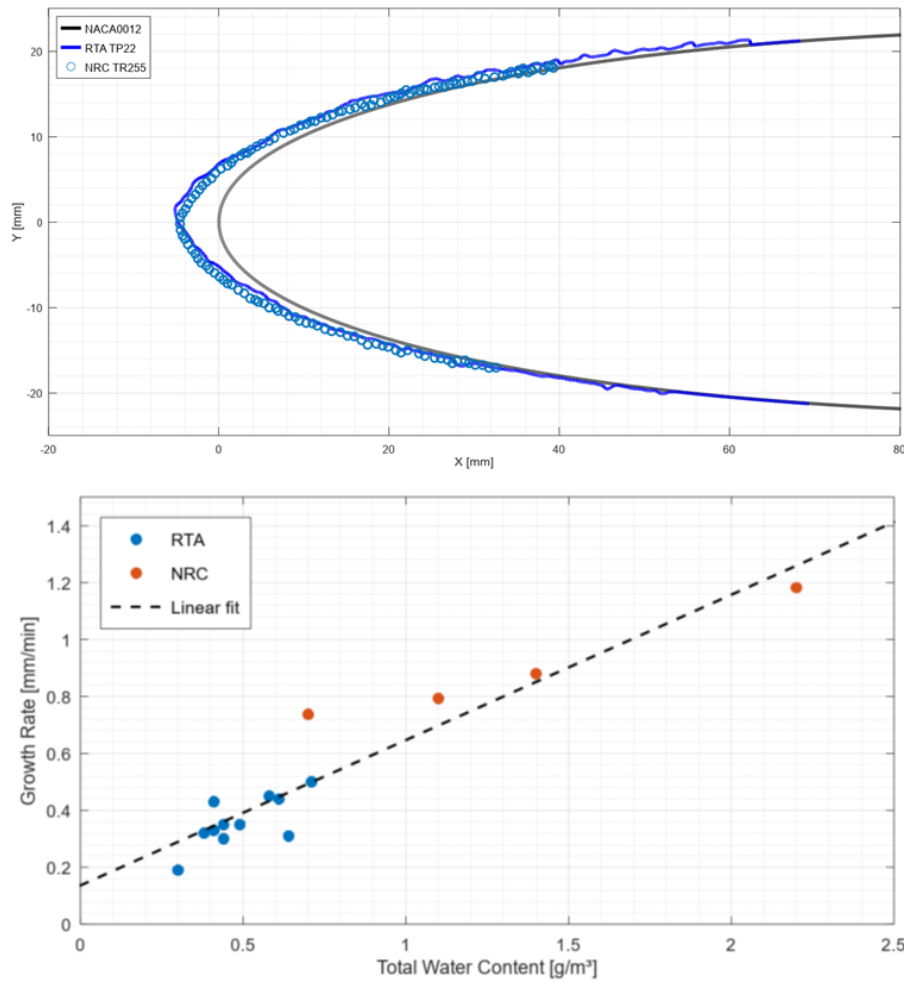


Figure 11 Comparison of falling snow generated at RTA and NRC through snow accretion tests on a NACA0012

At the end of the project, RTA achieved the targeted TRL4 level, while NRC RATFac was in between TRL4 and TRL5. The capabilities of each snow test facility at the end of ICE GENESIS are presented in Table 4.

Parameter	RTA (IAG SnowFall)	NRC RATFac (Snow Maker)
MMD or MVD [μm]	550 < MMD < 650	1000 < MVD < 4000
TWC at 40 m/s [g/m^3]	0.2 < TWC < 0.6	0.2 < TWC < 2.5
TWC at 80 m/s [g/m^3]	0.3 < max TWC < 0.4	Not Applicable
Independent particle melt change	YES	YES
TRL Level Achieved	TRL4	TRL4/5

Table 4 Capability of the snow wind tunnel test facilities at the end of ICE GENESIS

5.3.2.2 Remaining Gaps on Snow Wind Tunnel Test Capabilities

Even though the maturity of the snow generation system in RTA was significantly increased during the project, it still needs to be upscaled in order to achieve the regulatory Total Water Content ($1\text{g}/\text{m}^3$) in the area of interest ($\sim 1\text{m}^2$). Moreover, the efficiency and operability of the snow generation systems will have to be improved for industrial use.

Finally, it will be necessary to use the upgraded test facilities to generate a validation database on representative industrial configurations (turbo propeller or helicopter engine air inlet). It will be used to assess the numerical capabilities (§5.3.3.2).

5.3.3 Main Results on Snow Numerical Capabilities

5.3.3.1 Outcomes on Snow Numerical Capabilities

As for the snow wind tunnel facilities, the target requirements for the snow numerical tools were defined in the framework of WP3 [15]. The requirements complemented those defined for supercooled liquid water within D3.4 [3] since the same tools were expected to integrate both the snow and supercooled liquid water capability.

Several physical phenomena related to snow were modelled during ICE GENESIS (Figure 12), starting from ice crystals models developed in the framework of the HAIC and MUSIC-HAIC projects [24].

In order to model snowflakes' drag and melting during the transport phase, the snowflakes were approximated by prolate or oblate spheroids. The HAIC drag and melting models were then adapted based on this approximation [25][26], with a good correlation with the experiments (+/-30%). Regarding the accretion part, the ONERA ice crystal erosion and sticking models were used and compared with snow experiments performed at CSTB and RTA. The model's parameters were then optimized allowing to improve comparison with experimental results. However, the accuracy of the sticking and erosion models is not yet at the expected level, so they are considered as only preliminary models and equivalent to a TRL3 maturity. The modelling of the particle trajectories (drag and melting) was on the opposite assessed as sufficiently mature to achieve a TRL4 based on the good correlation with the experimental database.

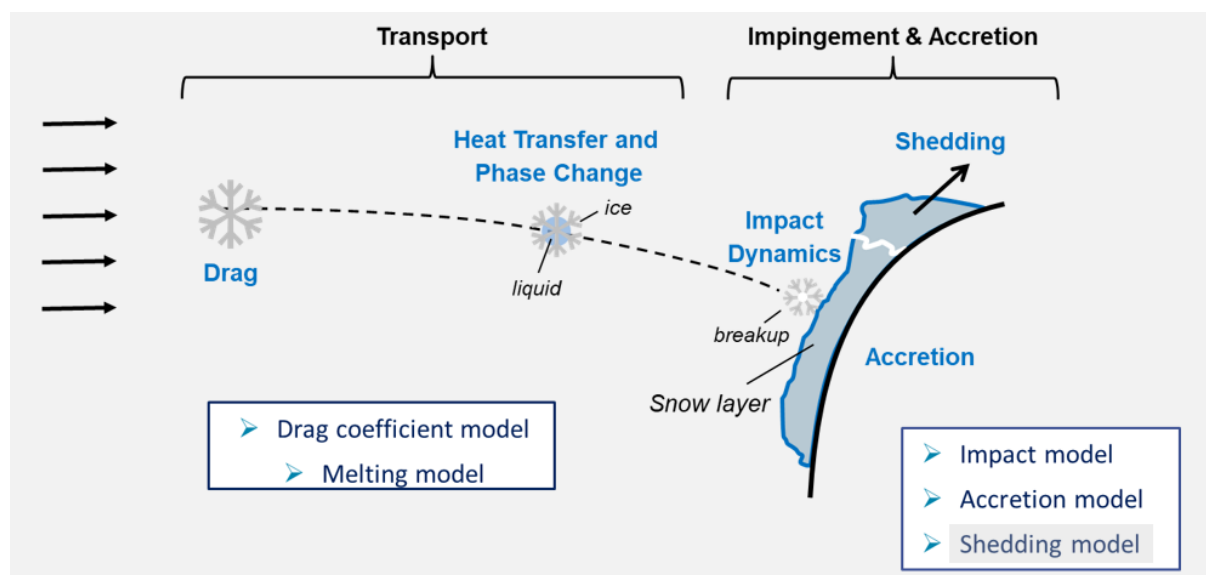


Figure 12 Physical phenomena related to snow. All but shedding were addressed in ICE GENESIS.

These snow transport and accretion models were then implemented into industrial 2D/3D icing tools at Airbus, Airbus Helicopters (AIH), General Electrics (GE) and Rolls Royce (RR). An additional optimization of sticking and erosion model coefficients was performed at industrial level, as well as a sensitivity study to numerical setting. The industrial tools were then assessed by comparison with experimental results from the CSTB (WP10), NRC and RTA (WP7) databases (Figure 13), [27]. Altogether, these 3 databases covered snow accretions on a NACA0012 airfoil for dry, medium and wet snow. The TRL5 assessment for snow numerical tools was not conclusive due to several gaps that will be further discussed in §5.3.3.2. Nevertheless, the panel recommended to proceed, since the progress made was significant and seemed to tend in the right direction. Achievements within ICE GENESIS provide already major improvement compared to the state of the art especially with regards to the transport model.

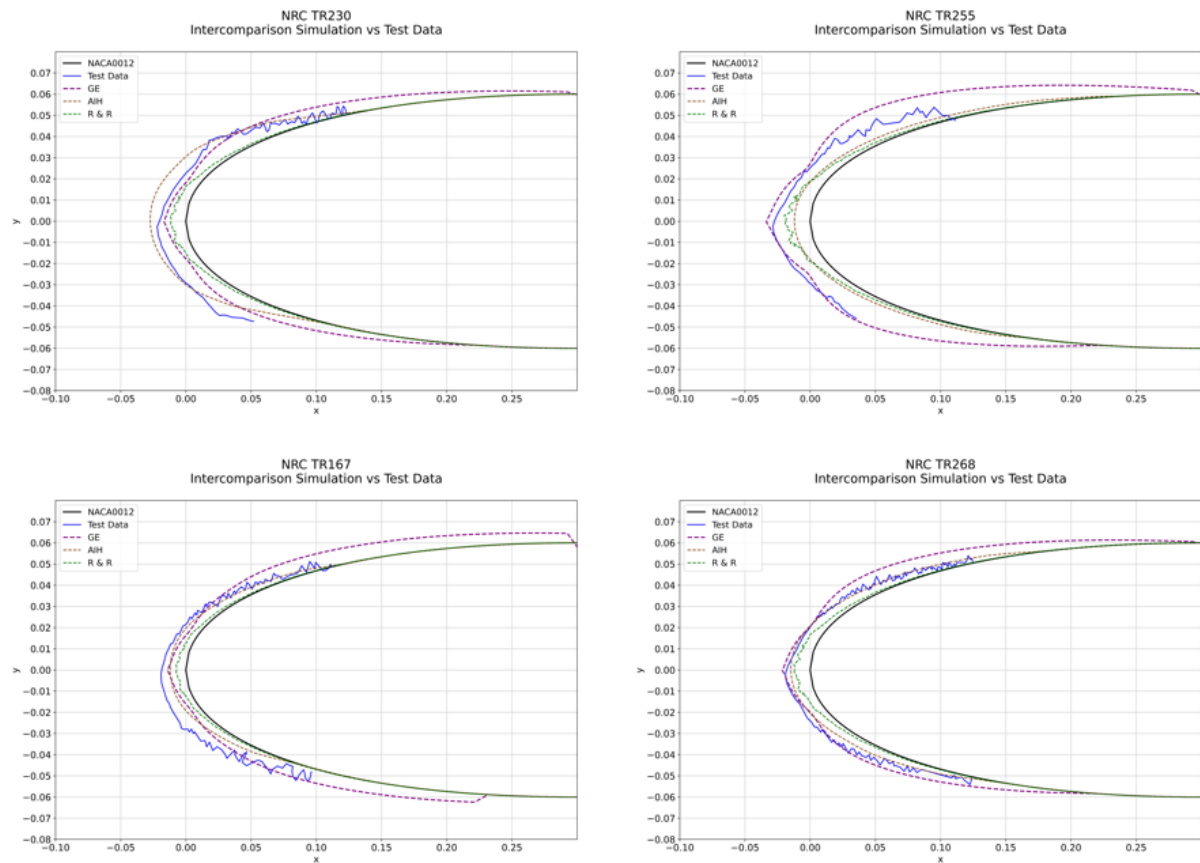


Figure 13 Simulation comparison for each industrial partner with 4 NRC snow accretion test cases

5.3.3.2 Remaining Gaps on Snow Numerical Capabilities

As highlighted by the TRL assessments, the snow accretion modelling is less mature than the snowflake trajectory modelling. In particular, models of snowflake impact, accretion and erosion will need more development. The case of snow accretion on heated surfaces will also have to be considered. Moreover, ice shedding and snow saltation should be further modelled.

Finally, the numerical capabilities could not be properly assessed due to the lack of experimental data on complex 3D cases (§5.3.2.2). This will have to be done in the future.

5.4 Common experimental database

One of the outcomes of ICE GENESIS is the generation of a common experimental database, that gathers data from previous projects worldwide (example: NASA SLD Database) as well as ICE GENESIS data [23]. The database contains Appendix C and Appendix O icing test cases, which represent in total 390 individual icing runs on 17 different test objects (Table 5).

Parameter	Minimum	Maximum
Velocity spectrum	40 m/s (78 kts)	205 m/s (400 kts)
SAT spectrum	-25 °C	-2.5 °C
LWC spectrum	0.12 g/m ³	1.53 g/m ³
MVD spectrum	15 µm	225 µm
Icing duration	1 min	2 h 45 min

Table 5 Range of conditions covered by the ICE GENESIS database

Part of the database is publicly available and can be used by industrials or researchers for tools validation purposes. The remaining test cases are restricted to the ICE GENESIS consortium.

The database is accessible at the following address: <https://www.icing-database.eu/>

5.5 Standardization activities

The effort performed through WP3 in order to define some specifications for the test facilities and numerical tools, both on liquid icing and snow, could be re-used as a starting point for future research programmes. Indeed, the specifications gather the needs of a representative panel of industrials (manufacturers of large/regional aircraft, business jets, rotorcraft, engines and systems), test centres and academics [1][2][14][15].

Moreover, a calibration procedure of icing wind tunnels for supercooled large drops was proposed in WP6 [7]. This methodology could be a proposal for SAE AIR6341, “SLD capabilities of icing wind tunnels” or the extension of ARP5905, “Calibration and Acceptance of Icing Wind Tunnels” [28], for Appendix O conditions. It establishes certain standards and acceptance criteria that could also be reviewed within the SAE AC-9C Aircraft Icing Technology Committee.

Finally, a calibration procedure of icing wind tunnels for snow was proposed in WP7 [21]. This methodology could be a proposal for the extension of ARP5905, “Calibration and Acceptance of Icing Wind Tunnels”, for snow conditions.

5.6 Main dissemination activities

ICE GENESIS communicated with the aeronautical community as a whole using means such as:

- conference presentations (including SAE 2019 and 2023 International Conference on Icing of Aircraft, Engines, and Structures, and AIAA 2020 and 2021 Aviation forums),
- presentations at partner project events (MUSIC-HAIC and SENS4ICE),
- ICE GENESIS Public Events,
- articles,
- working groups (SAE AC9C),
- the public website (<https://www.ICE GENESIS.eu/>)

Many scientific papers were published during the course of the project (27 publications in conference proceedings and 25 publications in journals). The project also liaised with international experts in particular through the ICE GENESIS Advisory Board (including FAA and EASA representative). FAA and EASA representatives were also involved as panel members for the TRL assessments.

6 Exploitation of ICE GENESIS results

6.1.1 Exploitation of WP4 Instrumentation for Liquid Icing Conditions Results

A detailed review and assessment of the instrumentation for liquid icing conditions was performed in ICE GENESIS. This work led to the selection of the most relevant instrumentation for the measurement of PSD [3], LWC [4], droplet temperature and cloud homogeneity [5] and finally ice shapes acquisition [6]. It was further used to feed the calibration methodology for FZDZ developed in WP6. As such, it will contribute to the harmonization of practices in terms of test facility calibration for FZDZ conditions (see §6.1.3). Moreover, the 3D scanning methodology developed to acquire the ice shapes generated in icing wind tunnel can now be used to store more complete and accurate data in icing wind tunnel test campaigns, enabling a more extensive usage of the results and facilitating the tool validation activities afterwards. The experience acquired during the project will also enable a better usage of the instrumentation means in future research activities.

6.1.2 Exploitation of WP5 Instrumentation for Snow and Microphysical Properties Results

A detailed review and assessment of the instrumentation for snow conditions was performed in ICE GENESIS, both for flight tests [17] and icing wind tunnel tests [20]. This work led to the selection of the most relevant instrumentation for the measurement of PSD, IWC and morphology of the snowflakes. Some specific post-processing methodologies were also implemented to retrieve some valuable data from the measurements. The instrumentation review was further used to feed the calibration methodology for snow developed in WP7. As such, it will contribute to the harmonization of practices in terms of test facility calibration for snow conditions (see §6.1.4). The post-processing methodologies defined during ICE GENESIS to analyse the data from the field campaigns could also be re-used as a standard for future flight test campaigns. Moreover, the experience acquired during the project will also enable a better usage of the instrumentation means and data post processing in future research activities.

Finally, the data acquired during the field campaigns in the framework of ICE GENESIS WP5 will be a useful reference for future research activities on snow since it provided an extensive characterization of a sample of natural snow conditions.

6.1.3 Exploitation of WP6 Supercooled Large Drops Test Capability Results

In ICE GENESIS WP6, a calibration procedure of icing wind tunnels for supercooled large drops was proposed [7]. This methodology could be a proposal for SAE AIR6341, "SLD capabilities of icing wind tunnels" or the extension of ARP5905, "Calibration and Acceptance of Icing Wind Tunnels" [28], for Appendix O conditions. It establishes certain standards and acceptance criteria that could also be reviewed within the SAE AC-9C Aircraft Icing Technology Committee.

Moreover, some upgrades of the CIRA and RTA facilities regarding the generation of SLD conditions were achieved and/or validated through the WP6. These upgrades can now be promoted to aerospace customers for their future commercial testing activities. The achieved capabilities can indeed already be used for preliminary industrial tests, even though they are not yet at the expected level to be used as certification means of compliance. The improved facilities can also be used for further research activities in order to continue their development and to support the validation of the numerical tools on more complex configurations.

6.1.4 Exploitation of WP7 Snow Test Capability Results

In ICE GENESIS WP7, a calibration procedure of icing wind tunnels for snow was proposed [21]. This methodology could be a proposal for the extension of ARP5905, “Calibration and Acceptance of Icing Wind Tunnels” [28], for snow conditions.

Moreover, some upgrades of the RTA and NRC facilities regarding the generation of snow conditions were achieved and/or validated through the WP7. These upgrades can now be promoted to aerospace customers for their future commercial testing activities. The achieved capabilities can indeed already be used for preliminary industrial tests. The improved facilities can also be used for further research activities in order to continue their development and to support the validation of the numerical tools on more complex configurations.

6.1.5 Exploitation of WP8 Wind Tunnel Tests for Liquid Icing and Snow Conditions Results

The different tests performed in icing wind tunnel with the SLD or snow upgraded capabilities have been added into the ICE GENESIS common database. This database will remain available for the partners and can be used to continue the validation effort of the numerical tools.

Moreover, the ICE GENESIS database also includes a public part which gathers public data from several past projects in a single place. This public database can already be used by academics and industrials as a common validation database for their icing numerical tools.

6.1.6 Exploitation of WP9 Numerical Capability Development for Liquid Icing Conditions Results

The activities performed in ICE GENESIS WP9 enabled to update the SLD models into the numerical tools. Moreover, some new 3D capabilities have been implemented into the tools. The possibilities of these new capabilities can now be used to perform some sensitivity studies on the parameters, that could help in defining the next improvements of the test facilities, or even the numerical tools themselves. On top of the capabilities delivered through WP9, some new physical phenomena like altitude or erosion effects were observed. The preliminary observations gathered during ICE GENESIS will serve as a basis for the implementation of more specific experiments to characterize these new phenomena in future research activities.

6.1.7 Exploitation of WP10 Numerical Capability Development for Snow Results

The approach used in ICE GENESIS WP10 to model snow phenomena based on existing ice crystals models has proved to be promising. Future research efforts will most likely continue to investigate in that direction and to further optimize the coefficients of the ice crystals models for snow applications. The synergies identified during ICE GENESIS will therefore be beneficial for the future progress on both ice crystals and snow.

6.1.8 Exploitation of WP11 Numerical Tools Validation in Industrial Environment Results

The new numerical capabilities developed through ICE GENESIS on supercooled liquid icing and snow can now be used by industrials for exploratory purposes. They can, for instance, perform some sensitivity studies or preliminary design assessments, within the limits identified for the tools in WP11. Beyond the work performed in ICE GENESIS, some additional validation efforts could be performed by each partner on private data, when available. However, a collaborative activity based on commonly accessible data on 3D complex test cases would be beneficial to reach a more accurate validation and conclude on their acceptability as certification means of compliance. This will be the purpose of future research works.

7 Way Forward after ICE GENESIS

7.1 Way forward for Supercooled Large Drops

As far as supercooled large drops are concerned, the context for the aeronautical industry remains quite challenging. Indeed, the climate evolution means increasing weather hazards. Moreover, the new generation of aircraft and engines achieving reduced CO₂ emissions will have disruptive configurations whose behaviour in SLD conditions will have to be assessed. Finally, to date, no clean sheet design has been certified since Appendix O was added to CS25. There are currently no direct means that enable to comply with the rules or to achieve compliance without being over-conservative, which becomes a showstopper for the disruptive and optimised concepts. As a result, the future clean and sustainable aviation products cannot be certified without further research.

For this purpose, the next collaborative research efforts are currently being discussed. The potential activities to be pursued will be scoped from the results of ICE GENESIS. They need to be further detailed and consolidated, but could include the following tasks, mainly deriving from the Manufacturer Icing Certification Group (MICG) white paper:

- Definition of probabilistic icing scenarios for SLD using the original flight test data that lead to the release of Appendix O as well as flight tests and climate models that anticipate climate change. This could be an important entry point to consider a definition of more realistic scenarios of SLD encounters in the regulations.
- Improvement of large icing wind tunnels (CIRA, RTA) capabilities for FZDZ icing domain. This would particularly involve productivity improvement in changing from Appendix C to Appendix O settings, and for CIRA a calibration over a wider range of the domain available (speed, altitude). Investigation of scaling methodologies would also bring better understanding of sensitivities, and for FZRA especially allow for more usable experimental means.
- Generation of generic SLD ice shapes in large facilities. The considered test articles shall enable to perform trades on wing thickness, sweep, and high lift devices (flaps) so that the aerodynamics effect of SLD conditions on disruptive configurations could be assessed. It also includes testing with an active ice protection system.
- Update of the numerical tools with state-of-the-art physics to avoid over-conservatism leading to over-sizing of the ice protections systems, or even leading to over-sized aircraft that may miss their environmental targets.

Some additional flight tests are also considered to validate and compare the ice shapes with the test facilities and numerical tools, as well as to enable further atmospheric characterization. However, the benefit of these tests compared to their cost is not yet unanimously acknowledged.

The expected outcomes would be to have workable means of compliance for SLD icing for application to future products design, enabling certification at horizon 2030+.

Even though the next steps still need to be consolidated, it appears already clearly that collaborative efforts will be highly desirable to achieve the target.

7.2 Way forward for Snow

As far as snow and ice crystals are concerned, the context for the aeronautical industry remains quite challenging. Indeed, the climate evolution means increasing weather hazards. Moreover, the new generation of aircraft with reduced CO₂ emissions will have disruptive engine and powerplant configurations whose behaviour in snow and ice crystal conditions will have to be assessed. Finally, the level of the certification requirements to be complied with or the expectations of airworthiness authorities when showing compliance also tends to increase. This means that additional research in snow and ice crystals icing is required to enhance computational methods and tools. The new testing capabilities developed within ICE GENESIS also need to be used and especially assessed on more complex configurations to advance to higher TRL maturity.

For this purpose, the outlines of a new collaborative project on snow and ice crystals are currently under definition. The decision to combine snow and ice crystals in a single project is based on the potential synergies existing in the modelling of these two conditions.

The scope of the future research effort would be focusing on three main aspects:

- Finding a unified approach to handle snow and ice crystals by a combined effort of extending the experimental database and implementing state of the art physics for improved numerical capabilities including rotating systems, heated and unheated surfaces, altitude effects, ice shedding and wet operability
- Upscaling snow test capabilities in collaboration with Europe and NRC
- Implementing complex validation cases in collaboration with Europe, NRC and NASA like a multi stage compressor water ingestion rig for the study of steady state and transient wet operability (stage by stage heavily instrumented) and an engine air inlet that incorporate design features prone to snow accumulation

The expected outcomes of the future research efforts would be to have engineering tools / means of compliance ready to support the design and certification of future products regarding ice crystals and snow.

8 Conclusions

ICE GENESIS enabled significant progress on wind tunnel test facilities for the simulation of SLD and Snow conditions. In particular, the project created a worldwide first with validated large icing tunnel spray bar systems for the generation of SLD particle size distribution and LWC. Considerable efforts with state-of-the-art techniques were also made to characterize and reproduce natural snow conditions. Furthermore, ICE GENESIS led to an improved understanding and modelling of SLD and Snow physics.

All along the project, the international cooperation has been beneficial and is to be continued for further research efforts. It indeed enhanced the impact of the project, fostering harmonization and scientific excellence.

The capabilities developed during ICE GENESIS can now be used to progress on the understanding of the effects of SLD and snow on industrial configurations and perform some preliminary design assessments. Nevertheless, further improvements of the models and validation of the tools on representative configurations are needed to achieve a sufficient maturity for application in industrial products' development and certification processes. The test capabilities also require some upgrades and further calibration to be formally used in a certification process but can already host some preliminary industrial tests that will, in particular, support the validation of the tools.

Further efforts are necessary to achieve workable means of compliance for the future generation of disruptive products. They could take the shape of collaborative research activities feeding two separate roadmaps focusing respectively on supercooled large drops and snow & ice crystals. Launching the necessary activities to achieve the targets of these roadmaps will be critical to enable the development and certification of low-CO₂ aircraft and engines. Some coordination efforts are currently ongoing at international level to define in more details the scope of the required future activities and to identify the best funding opportunities in the coming years.

Overall, the progress made within ICE GENESIS will pave the way for future research activities at National and European level in order to further mature numerical and test capabilities and provide European aeronautical industry with necessary engineering tools for development and certification of future low emission products.

9 Bibliography

- [1] Esposito B., "Definition of the target requirements for test facilities operating envelopes for App O" ICE GENESIS Public Deliverable D3.1
- [2] Caminade F., Frazza L., Rouzaud O., Trontin P., "Definition of Numerical Capability Requirements for Liquid Icing Conditions", ICE GENESIS Public Deliverable D3.4
- [3] "Report on the review, assessment and selection of instrumentation for PSD", ICE GENESIS Public Deliverable D4.1
- [4] "Report on the review, assessment and selection of instrumentation for LWC", ICE GENESIS Public Deliverable D4.2
- [5] "Report on the review, assessment and selection of instrumentation/model for droplet temperature measurement and homogeneity characterization", ICE GENESIS Public Deliverable D4.3
- [6] Kozomara D., Neubauer T., Puffing R., "Instrumentation for 3D Scanning of ice shapes - Report on the development and assessment of 3D scanning systems and associated evaluation tool", ICE GENESIS Public Deliverable D4.4
- [7] Breitfuss W., Heller R., Esposito B., "Proposal of calibration instruments and procedures for FZDZ & FZRA", ICE GENESIS Public Deliverable D6.1/D6.2.
- [8] Esposito B., "Assessment of improved FZDZ capabilities for each IWT involved in the project", ICE GENESIS Public Deliverable D6.3.
- [9] "Assessment of FZRA capabilities for each IWT involved in the project", ICE GENESIS Public Deliverable D6.5.
- [10] Pervier, H., Vénuat, C., and Neubauer, T., "Engine Cascade Rig Design Tests and Results in App C Conditions," SAE Technical Paper 2023-01-1419, 2023, doi:10.4271/2023-01-1419.
- [11] de Rosa, D., Capizzano, F., and Cinquegrana, D., "Multi-Step Ice Accretion by Immersed Boundaries," SAE Technical Paper 2023-01-1484, 2023, doi:10.4271/2023-01-1484.
- [12] Donizetti, A., Rausa, A., Bellostà, T., Re, B. et al., "A Three-Dimensional Level-Set Front Tracking Technique for Automatic Multi-Step Simulations of In-Flight Ice Accretion," SAE Technical Paper 2023-01-1467, 2023, doi:10.4271/2023-01-1467.
- [13] "Public synthesis of liquid icing physics models and tools improvement", ICE GENESIS Public Deliverable D9.5
- [14] Dezitter F., "Definition of the target requirements for test facilities operating envelopes for snow", ICE GENESIS Public Deliverable D3.5
- [15] Dezitter F., "Definition of numerical capability requirements for snow", ICE GENESIS Public Deliverable D3.6
- [16] Jaffeux, L., Schwarzenboeck, A., Coutris, P., Febvre, G. et al., "Snow Particle Characterization. Part A: Statistics of Microphysical Properties of Snow Crystal Populations from Recent Observations Performed during the ICE GENESIS Project," SAE Technical Paper 2023-01-1492, 2023, doi:10.4271/2023-01-1492.
- [17] Schwarzenboeck A., Dezitter F., "Selection of most suitable instrumentation for F/T" ICE GENESIS Public Deliverable D5.1
- [18] Jaffeux, L., Coutris, P., Schwarzenboeck, A., and Dezitter, F., "Snow Particle Characterization. Part B: Morphology Dependent Study of Snow Crystal 3D Properties Using a Convolutional Neural Network (CNN)," SAE Technical Paper 2023-01-1486, 2023, doi:10.4271/2023-01-1486.
- [19] "Synthesis & Characterization of snow microphysical properties", ICE GENESIS Public Deliverable D5.7
- [20] Schwarzenboeck A., "Selection of most suitable instrumentation for IWT/T calibration" ICE GENESIS Public Deliverable D5.8
- [21] Dezitter F., "Calibration methodology for snow test facility", ICE GENESIS Public Deliverable D7.1

- [22] Breitfuß, W., Ferschitz, H., Schwarzenboeck, A., Heller, R. et al., "Experimental Simulation of Natural-Like Snow Conditions in the Rail Tec Arsenal (RTA) Icing Wind Tunnel," SAE Technical Paper 2023-01-1407, 2023, doi:10.4271/2023-01-1407.
- [23] Neubauer, T. and Puffing, R., "Introduction of an Online Ice Accretion Database," SAE Technical Paper 2023-01-1464, 2023, doi:10.4271/2023-01-1464.
- [24] "Public synthesis of snow icing physics models and tools improvement", ICE GENESIS Public Deliverable D10.4
- [25] B. Aguilar, P. Trontin, L. Reitter, K. Köbschall, F. Dezitter, I. Roisman and P. Villedieu, "Ice Crystal Drag Model Extension to Snowflakes: Experimental," AIAA Journal, vol. 60, no. 12, 2022.
- [26] B.Aguilar et al "Experimental investigation and semi-empirical modeling of snowflake melting", International Journal of Heat and Mass Transfer, Volume 209, 1 August 2023
- [27] "Report on the validation test main conclusions and best numerical practices", ICE GENESIS Public Deliverable D11.4
- [28] Aerospace Recommended Practice SAE ARP5905, "Calibration and Acceptance of Icing Wind Tunnels," SAE International, Sep. 2015.

10 Appendix 1 – List of ICE GENESIS Public Deliverables

#	Title
D2.4	ICE GENESIS Public Website
D2.5	ICE GENESIS – synthesis of results and way forward
D3.1	Definition of the target requirements for test facilities operating envelopes for App O
D3.4	Definition of numerical capability requirements for liquid icing conditions
D3.5	Definition of the target requirements for test facilities operating envelopes for snow
D3.6	Definition of numerical capability requirements for snow
D4.1	Report on the review, assessment and selection of instrumentation for PSD
D4.2	Report on the review, assessment and selection of instrumentation for LWC
D4.3	Report on the review, assessment and selection of instrumentation/model for droplet temperature measurement and homogeneity characterization
D4.4	Report on the development and assessment of 3D-scanning systems and associated evaluation tool
D5.1	Selection of most suitable instrumentation for F/T
D5.7	Synthesis & Characterization of snow microphysical properties
D5.8	Selection of most suitable instrumentation for IWT/T calibration
D6.1-1	Proposal of calibration instruments and procedures for FZDZ & FZRA v1
D6.1-2	Proposal of calibration instruments and procedures for FZDZ & FZRA v2
D6.3	Assessment of improved FZDZ capabilities for each IWT involved in the project
D6.5	Assessment of FZRA capabilities for each IWT involved in the project
D7.1	Calibration methodology for snow test facility
D9.5	Public synthesis of liquid icing physics models and tools improvement
D10.4	Public synthesis of snow icing physics models and tools improvement
D11.4	Report on the validation test main conclusions and best numerical practices

Public Website: <https://www.ICE GENESIS.eu/>

Public Database: <https://www.icing-database.eu/>

11 Appendix 2 – List of ICE GENESIS Publications

No.	Title	Authors	Title of the Journal/Proc./Book	Number, date or freq. of the Journal/Proc./Book	Repository Link
1	A CIRA 3D Ice Accretion Code for Multiple Cloud Conditions Simulations	D. Cinquegrana, F. D'Aniello, D. de Rosa, A. Carozza et al.	SAE Technical Paper	June 20 - 22, 2023	10.4271/2023-01-1461
2	A new approach to simulate aerosol effects on cirrus clouds in EMAC v2.54	Mattia Righi, Johannes Hendricks, Ulrike Lohmann, Christof Gerhard Beer, Valerian Hahn, Bernd Heinold, Romy Heller, Martina Krämer, Christian Rolf, Ina Tegen, and Christiane Voigt	Geoscientific Model Development Discussions	September 2019	10.5194/gmd-2019-212
3	A Three-Dimensional Level-Set Front Tracking Technique for Automatic Multi-Step Simulations of In-Flight Ice Accretion	Alessandro Donizetti, Tommaso Bellosta and Alberto Guardone	SAE Technical Paper	June 20 - 22, 2023	10.4271/2023-01-1467
4	Assessing Mixed-Phase Conditions during the ICE GENESIS Snow Measurement Campaign	Coutris, Pierre & Febvre, Guy & Jaffeux, Louis & Schwarzenboeck, Alfons & Dezitter, Fabien & Billault-Roux, Anne-Claire & Grazioli, Jacopo & Berne, Alexis & Jorquera, Susana & Delanoë, Julien	SAE Icing conference	June 20 - 22, 2023	https://doi.org/10.4271/2023-01-1494
5	Assessment of Ice Shape Roughness via Automatic Spacing of Codebook Vectors in a Two-Dimensional Self-Organizing Map	Thomas Neubauer, Reinhard Puffing	AIAA AVIATION 2020 FORUM	June 2020	https://arc.aiaa.org/doi/10.2514/6.2020-2806
6	Assessment of the PoliMIce toolkit from the 1st AIAA Ice Prediction Workshop	Myles Morelli, Tommaso Bellosta, Alessandro Donizetti, and Alberto Guardone	AIAA AVIATION 2022 Forum	AIAA 2022-3307 June 27-July 1, 2022	10.2514/6.2022-3307
7	Automatic Classification Tool for Optical Array Probes to Understand Ice Cloud Mechanisms	Jaffeux, Louis	UCA library		-
8	Automatic roughness characterization of simulated ice shapes	Gallia, Mariachiara, Tommaso Bellosta, and Alberto Guardone	Journal of Computational and Applied Mathematics	427, 2023	10.1016/j.cam.2023.115114

No.	Title	Authors	Title of the Journal/Proc./Book	Number, date or freq. of the Journal/Proc./Book	Repository Link
9	Calibration Transfer Methodology for Cloud Radars Based on Ice Cloud Observations	Susana Jorquera , Felipe Toledo Bittner, Julien Delanoë, Alexis Berne, Anne-Claire Billault-Roux, Alfons Schwarzenboeck, Fabien Dezitter, Nicolas Viltard, and Audrey Martini	AMS		https://doi.org/10.1175/JTECH-D-22-0087.1
10	Comparison of different droplet measurement techniques in the Braunschweig Icing Wind Tunnel	Knop, I., Bansmer, S., Hahn, V., and Voigt, C	Atmospheric Measurement Techniques - Discussions	9 March 2020	10.5194/amt-2019-494
11	Coupling aerosols to (cirrus) clouds in the global EMAC-MADE3 aerosol-climate model	Mattia Righi; Johannes Hendricks; Ulrike Lohmann; Christof Gerhard Beer; Valerian Hahn; Bernd Heindel; Romy Heller; Martina Krämer; Michael Ponater; Christian Rolf; Ina Tegen; Christiane Voigt	Geoscientific Model Development	1	10.3929/ethz-b-000410306
12	Distinct secondary ice production processes observed in radar Doppler spectra: insights from a case study	Billault-Roux, A.-C., P. Georgakaki, J. Gehring, L. Jaffeux, A. Schwarzenboeck, P. Coutris, A. Nenes and A. Berne	Atmospheric Chemistry and Physics	vol. 23(17)	10.5194/acp-23-10207-2023
13	Dual-frequency spectral radar retrieval of snowfall microphysics: a physically constrained deep learning approach	Billault-Roux, A.-C., G. Ghiggi , L. Jaffeux, A. Martini, N. Viltard and A. Berne	Atmospheric Measurement Techniques	vol. 16(4)	10.5194/amt-16-911-2023
14	Dual-frequency spectral radar retrieval of snowfall microphysics: a physically constrained deep learning approach	Billault-Roux, Anne-Claire & Ghiggi, Gionata & Jaffeux, Louis & Martini, Audrey & Viltard, Nicolas & Berne, Alexis	AMT		10.5194/amt-2022-199
15	Efficient radial basis function mesh deformation methods for aircraft icing	Myles Morelli, Tommaso Bellosta, Alberto Guardone	Journal of Computational and Applied Mathematics	392,2021	10.1016/j.cam.2021.113492
16	Engine Cascade Rig Design Tests and Results in App C Conditions	Hugo Pervier, Clément Vénuat, Thomas Neubauer		45078	https://www.sae.org/publications/technical-papers/content/2023-01-1419/
17	Etude expérimentale et modélisation numérique des phénomènes d'accrétion de particules de neige à l'origine de la formation d'accrétions sur des structures aéronautiques ou de génie civil	Boris Aguilar			-
18	Experimental and numerical investigations of snow accretion.	Boris Aguilar; Kilian Köbschall; Louis M. Reitter; Pierre Trontin; Fabien Dezitter; Jan Breitenbach; Ilia V. Roisman; Olivier Rouzaud; Philippe Villedieu	AIAA AVIATION 2021 FORUM	1	10.2514/6.2021-2684
19	Experimental investigation and semi-empirical modeling of snowflake melting	Aguilar, B., Trontin, P., Köbschall, K., Dezitter, F., Hussong, J., & Villedieu, P.	International Journal of Heat and Mass Transfer	209, 1 August 2023	https://doi.org/10.1016/j.ijhmas.2023.124117
20	Experimental Simulation of Natural-Like Snow Conditions in the Rail Tec Arsenal (RTA) Icing Wind Tunnel	Breitfuß, W., Ferschitz, H., Schwarzenboeck, A., Heller, R. et al	Aerospace	June 15, 2023	https://doi.org/10.4271/2023-01-1407

No.	Title	Authors	Title of the Journal/Proc./Book	Number, date or freq. of the Journal/Proc./Book	Repository Link
21	Extending the Impingement Capabilities of a Cartesian Solver towards Super-Cooled Large Droplets (SLD)	F. Capizzano and D. de Rosa	SAE Technical Paper	June 20 - 22, 2023	10.4271/2023-01-1470
22	Geometric descriptors for the prediction of snowflake drag	Köbschall, K., Breitenbach, J., Roisman, I. V., Tropea, C., & Hussong, J.	Experiments in Fluids	64(1), December 2022	https://doi.org/10.1007/s00348-022-03539-x
23	Ice accretion compositions in ice crystal icing. International	Malik, Y. A., Köbschall, K., Bansmer, S., Tropea, C., Hussong, J., & Villedieu, P.	Journal of Heat and Mass Transfer	220, March 2024	https://doi.org/10.1016/j.ijhe.2023.124910
24	Ice crystal drag model extension to snowflakes: Experimental and numerical investigations	Aguilar, B., Trontin, P., Reitter, L., Köbschall, K., Dezitter, F., Roisman, I., & Villedieu, P.	AIAA Journal	60(12), 9 Sep 2022	https://doi.org/10.2514/1.J062122
25	Ice crystal images from optical array probes: classification with convolutional neural networks	Jaffeux, Louis & Schwarzenboeck, Alfons & Coutris, Pierre & Duroure, Christophe	AMT		10.5194/amt-15-5141-2022
26	ICE GENESIS: Synergetic Aircraft and Ground-Based Remote Sensing and In Situ Measurements of Snowfall Microphysical Properties	Billault-Roux, Anne-Claire & Grazioli, Jacopo & Delanoë, Julien & Jorquera, Susana & Pauwels, Nicolas & Viltard, Nicolas & Martini, Audrey & Mariage, Vincent & Gac, Christophe & Caudoux, Christophe & Aubry, Clémantyne & Bertrand, Fabrice & Schwarzenboeck, Alfons & Jaffeux, Louis & Coutris, Pierre & Febvre, Guy & Pichon, Jean & Dezitter, Fabien & Gehring, Josué & Berne, Alexis	BAMS		https://doi.org/10.1175/BAMS-D-21-0184.1
27	Ice Shape Convergence in Multi-Step Ice Accretion Simulation over Straight Wings	Alessandro Donizetti, Andrea Rausa, Tommaso Bellosta, Barbara Re and Alberto Guardone	AIAA AVIATION 2024 Forum	AIAA 2024-2679 8-12 January 2024	10.2514/6.2024-2679
28	Ice Shape Roughness Assessment Based on a Three-Dimensional Self-Organizing Map Approach	Thomas Neubauer, Wolfgang Hassler, Reinhard Puffing	AIAA AVIATION 2020 FORUM		https://arc.aiaa.org/doi/10.2514/6.2020-2805
29	Influence of Realistic Aircraft Conditions on Accretion of Supercooled Large Droplet	B. Déjean, T. Alary, Q. Duchayne, Berthoumieu P.	SAE Technical Paper	No. 2023-01-1408	https://doi.org/10.4271/2023-01-1408
30	Instrumentation for Measuring Supercooled Large Droplet Cloud Distributions in Icing Wind Tunnels	Venkateshwar Reddy Bora, Inken Knop, Johannes Lucke, Tina Jurkat-Witschas	AIAA SciTech Forum 2023	AIAA 2023-2286	https://doi.org/10.2514/6.2023-2286
31	Integrated water vapor and liquid water path retrieval using a single-channel radiometer	Anne-Claire Billault-Roux; Alexis Berne	Atmospheric Measurement Techniques	Volume 14, issue 4	10.5194/amt-2020-311

No.	Title	Authors	Title of the Journal/Proc./Book	Number, date or freq. of the Journal/Proc./Book	Repository Link
32	Introduction of an online ice accretion database	Neubauer, T., & Puffing, R.	International Conference on Icing of Aircraft, Engines, and Structures	June 2023	10.4271/2023-01-1464
33	Investigation of the Influence of Aero-Thermal Non-equilibrium Conditions of an SLD Cloud on Airfoil Icing	Venkateshwar Reddy Bora, Mariachiara Gallia, Inken Knop, Alberto Guardone	SAE Technical Paper	June 20 - 22, 2023	10.4271/2023-01-1406
34	Lagrangian and Eulerian algorithms for water droplets in in-flight ice accretion	Tommaso Bellosta, Giacomo Baldan, Giuseppe Sirianni, Alberto Guardone	Journal of Computational and Applied Mathematics	429. 2023	10.1016/j.cam.2023.115230
35	Level-Set Mass-Conservative Front-Tracking Technique for Multistep Simulations of In-Flight Ice Accretion	Alessandro Donizetti, Tommaso Bellosta, Andrea Rausa, Barbara Re and Alberto Guardone	Journal of Aircraft	4, 2023	10.2514/1.C037027
36	MASCDB, a database of images, descriptors and microphysical properties of individual snowflakes in free fall	Jacopo Grazioli, Gionata Ghiggi, Anne-Claire Billault-Roux & Alexis Berne	Nature	Article number: 186 (2022)	
37	Melting of and Imbibition in a Granular Ice Layer on a Heated Substrate	Kilian Köbschall, Jan Oberreuter, Jan Breitenbach, Ilia V. Roisman, Cameron Tropea and Jeanette Hussong	AIAA AVIATION 2021 FORUM		10.2514/6.2021-2682
38	Melting of fractal snowflakes: Experiments and modeling	Köbschall, K., Traut, B., Roisman, I. V., Tropea, C., & Hussong, J.	International Journal of Heat and Mass Transfer	212, 15 September 2023	https://doi.org/10.1016/j.ijhe.2023.124254
39	Modeling In-Flight Ice Accretion Under Uncertain Conditions	Giulio Gori https://orcid.org/0000-0001-7442-2773 , Pietro M. Congedo, Olivier Le Maître, Tommaso Bellosta https://orcid.org/0000-0002-7745-6052 and Alberto Guardone	Journal of Aircraft	May 2022	10.2514/1.C036545
40	Modelling the Secondary Impingement of Supercooled Large Droplets in an Eulerian Environment	P. Catalano and B. Mele	SAE Technical Paper	June 20 - 22, 2023	10.4271/2023-01-1459
41	Multi-sensor measurements of cloud and snowfall properties at near-freezing temperatures during ICEGENESIS	Billault-Roux, A.-C., J. Grazioli*, J. Delanöe, S. Jorquera, N. Pauwels, N. Viltard, A. Martini, V. Mariage, C. Le Gac, C. Caudoux, C. Aubry, F. Bertrand, A. Schwarzenboek, L. Jaffeux, P. Coutris, G. Febvre, J.-M. Pichon, F. Dezitter, J. Gehring, A. Untersee, C. Calas, J. Figueras i Ventura, B. Vie, A. Peyrat, V. Curat, S. Rebouissoux and A. Berne	Bulletin of the American Meteorological Society	vol. 104(2)	10.1175/BAMS-D-21-0184.1
42	Multi-Step Ice Accretion by Immersed Boundaries	D. de Rosa, F. Capizzano and D. Cinquegrana	SAE Technical Paper	June 20 - 22, 2023	10.4271/2023-01-1484

No.	Title	Authors	Title of the Journal/Proc./Book	Number, date or freq. of the Journal/Proc./Book	Repository Link
43	Numerical and experimental investigations on rough airfoil in icing conditions	Denis Sotomayor-Zakharov	Forschungsbericht Niedersächsisches Forschungszentrum für Luftfahrt	Bd. 2023-12 (29.01.2024)	https://doi.org/10.24355/dbbs_084-202401191241-0
44	Poly-dispersed Eulerian-Lagrangian particle tracking for in-flight icing applications	Giuseppe A. Sirianni, Tommaso Bellosta, Barbara Re and Alberto Guardone	AIAA AVIATION 2022 Forum	AIAA 2022-3695 June 27-July 1, 2022	10.2514/6.2022-3695
45	RTA SLD CALIBRATION RESULTS	Breitfuß, W.,		November 22, 2022	https://www.ice-genesis.eu/media/articles/files/2nd_Public_Workshop/ICE_GENESIS_Public_Forum_RTASLD_Test_CAPABILITY_R1.0.pdf
46	RTA snow test capability	Ferschitz, H. Breitfuß, W.,		November 22, 2022	https://www.ice-genesis.eu/media/articles/files/2nd_Public_Workshop/ICE_GENESIS_WP7_RTAPublicWorkshop_R1.1.pdf
47	Shape Evolution of a Melting Snowflake.	Köbschall, K., Traut, B., Aguilar, B., Roisman, I. V., Tropea, C., & Hussong, J.	AIAA AVIATION 2022 Forum	AIAA 2022-3371, 20 Jun 2022	https://doi.org/10.2514/6.2022-3371
48	Snow Particle Characterization. Part A: Statistics of Microphysical Properties of Snow Crystal Populations from Recent Observations Performed during the ICE GENESIS Project	Jaffeux, Louis & Schwarzenboeck, Alfons & Coutris, Pierre & Febvre, Guy & Dezitter, Fabien & Aguilar, Boris & billault-Roux, Anne-claire & Grazioli, Jacopo & Berne, Alexis & Köbschall, Kilian & Jorquera, Susana & Delanoë, Julien	SAE Icing conference	June 20 - 22, 2023	https://doi.org/10.4271/2023-01-1492
49	Snow Particle Characterization. Part B: Morphology Dependent Study of Snow Crystal 3D Properties Using a Convolutional Neural Network (CNN)	Jaffeux, Louis & Coutris, Pierre & Schwarzenboeck, Alfons & Dezitter, Fabien	SAE Icing conference	June 20 - 22, 2023	https://doi.org/10.4271/2023-01-1486
50	Snowflakes shape characterization via bayesian inference: exploring the challenges	Giulio Gori; Alessio Raimondi; Alberto Guardone	AIAA AVIATION 2021 FORUM	1	10.2514/6.2021-2683
51	Statistical Analysis of the Surface Roughness on Aircraft Icing	Denis Sotomayor-Zakharov, Emmanuel Radenac, Mariachiara Gallia, Alberto Guardone, Inken Knop	Journal of Aircraft	61, 2024	https://doi.org/10.2514/1.C037403

No.	Title	Authors	Title of the Journal/Proc./Book	Number, date or freq. of the Journal/Proc./Book	Repository Link
52	Supercooled large droplet (SLD) impact on ice at high velocity splashing characterization	T. Alary, B. Déjean, P. Berthoumieu, P. Trontin	AIAA AVIATION 2022 Forum	AIAA Paper 2022-4116	https://doi.org/10.2514/6.2022-4116
53	Uncertainty quantification for in-flight ice accretion under Appendix-C and Appendix-O conditions	Tommaso Bellosta, Alberto Guardone, Giulio Gori, Pietro Congedo and Olivier le Maitre	AIAA Aviation 2021 Forum	AIAA 2021-2645 August 2-6, 2021	10.2514/6.2021-2645
54	Validation of Ice Roughness Analysis Based on 3D-Scanning and Self-Organizing Maps	Thomas Neubauer, David Kozomara, Reinhard Puffing, Wolfgang Hassler	SAE Technical Paper Series	2019-01-1992	10.4271/2019-01-1992
55	Workflow for predictor–corrector simulations of in-flight ice accretion, with applications on swept wings	E. Radenac, G. Blanchard, T. Renaud et Q. Duchayne	Engineering with Computers	2023	https://doi.org/10.1007/s00366-023-01910-y