



The CIRA Icing Wind Tunnel Facility: Expanding Capabilities for Hybrid-Electric Aircraft TMS Testing

CIRA – Italian Aerospace Research Center*

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Abstract: The Icing Wind Tunnel (IWT) of the Italian Aerospace Research Center (CIRA) is one of the largest refrigerated wind tunnels in service worldwide, capable of reproducing realistic altitude, temperature, pressure and icing conditions in a controlled environment for compliance with aviation regulations.

It has been extensively used in national and international research and industrial programs, supporting aircraft and rotorcraft icing certification, aerodynamics research, and system testing. The IWT is designed to simulate atmospheric icing effects up to an altitude of 7000 m, with static temperatures down to about -40 °C and static pressures between 0.39 and 1.45 bar; different multiple interchangeable test sections and an open-jet configuration are available, in order to accommodate a wide range of test models and conditions. The facility can also support aerodynamic investigations in low and high subsonic regimes by varying flow temperature, pressure, and Reynolds number.

Within the EU-funded AMBER project (European Commission, 2022), coordinated by Avio Aero, the facility is currently being upgraded to support the integration and performance assessment of full-scale TMS components under realistic flow conditions relevant to hybrid aircraft applications. In this framework, the main emphasis has been placed on exploiting the large test-section dimensions and the capability to combine altitude and temperature simulation with a wide operating mass-flow-rate range, from 1.5 to 55 kg/s. These features allow testing full-scale TMS configurations with power levels up to the order of 500 kW, under conditions representative of real flight in terms of freestream temperature and mass flow rate.

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1 Introduction

Aircraft icing remains a critical safety concern in aviation, as the accretion of ice on aerodynamic surfaces can profoundly degrade lift, increase drag, alter stall behavior, and compromise control effectiveness. The formation of ice on wings, tail surfaces, and control surfaces can lead to catastrophic failures if not properly understood and mitigated. To ensure the safety and performance of aircraft in cold weather conditions, comprehensive research and qualification testing are essential. Icing wind tunnels are crucial research infrastructures in aerospace science and technology, providing a controlled, repeatable environment for studying the complex physical phenomena associated with ice accretion and for testing ice protection systems critical to flight safety and performance (Huanyu et al., 2020). They enable the simulation of atmospheric icing conditions encountered by aircraft during flight - such as supercooled liquid water clouds, temperature and pressure variations - and support the compliance verification of anti-icing and de-icing systems with airworthiness regulations under well-defined flow parameters (Baumert et al., 2018).

Regarding regulations compliance, they require that aircraft undergo thorough testing to demonstrate that they can safely operate in known icing conditions, including the performance of anti-icing and de-icing systems and the aircraft's stall characteristics with ice accumulation on surfaces. The testing must also ensure the aircraft meets minimum performance standards for handling and safety under icing conditions, with practical impact due to the influence on the design and qualification of protection systems for airframes, rotors and engine inlets.

Beyond certification support, icing tunnels play a central role in fundamental research on ice accretion mechanisms and the aerodynamic effects of icing. Wind tunnel data are routinely used to develop and validate predictive icing codes (e.g., NASA LEWICE, FENSAP-ICE, CIRA's Multi-ICE), as well as to assess new materials and surface treatments, sensors, and mitigation strategies under controlled laboratory conditions.

In this scenario, the Icing Wind Tunnel (IWT) operated by the Italian Aerospace Research Centre (CIRA), represents one of the world's most advanced facilities for such testing. It is a closed-loop, refrigerated and pressurized wind tunnel capable of reproducing altitude, temperature and cloud microphysical conditions up to approximately 7000 m of simulated flight and static temperatures down to -40 °C, with interchangeable test sections and open-jet configurations to accommodate diverse testing needs (Vecchione et al., 2003).

Currently, the aviation industry is rapidly progressing toward hybrid-electric and electrified propulsion architectures as essential enablers of reduced fuel consumption and lower emissions, in line with emerging environmental goals such as Flightpath 2050 and other long-term sustainability targets.

In this context, while the electrification of propulsion systems (with powers of the order of 1 MW) is regarded as a viable strategy to reduce the environmental impact of aviation, it introduces new and interesting technological challenges chief among them being the efficient management and dissipation of thermal loads generated by batteries, fuel cells, electric motors, and high-power electrical components (Coutinho et al., 2023).

While internal combustion engines typically operate at high temperatures and require cooling to avoid overheating, electric motors and batteries are sensitive to both high and low temperatures, which can reduce range and power output, and potentially cause permanent damage.

Given the critical link between effective thermal management and vehicle safety, performance, and longevity in hybrid vehicles, the experimental testing of TMS is of paramount importance. Simulation and modeling play a vital role in the design phase, but they must be validated and complemented by real-world testing under controlled conditions.

Currently, the IWT is undergoing strategic enhancement to enable the experimental investigation and characterization of Thermal Management Systems (TMS) targeted at hybrid and electric aircraft applications (Invigorito et al., 2025).

Ground experimentation, particularly within controlled large-scale test facilities, remains crucial for advancing these technologies. The upgrade leverages the facility's large test section, broad mass-flow range and environmental simulation capabilities, allowing realistic TMS component integration and performance evaluation under relevant flow and thermal conditions. The upgraded IWT will extend its role from icing and aerodynamic testing into thermal management and integrated energy systems research, fostering innovation and optimization of advanced aircraft subsystems.

Currently, the IWT is being strategically upgraded to enable experimental investigation of Thermal Management Systems (TMS) for hybrid and electric aircraft (Invigorito et al., 2025). Leveraging its large test section, broad mass-flow range, and environmental simulation capabilities, the upgraded facility will support full-scale TMS integration testing and performance evaluation under realistic flow and thermal conditions, bridging the gap between conceptual design and operational validation, and accelerating the transition toward certification and practical application of TMS architectures for hybrid and electric aircraft.

2 Overview of CIRA IWT facility

The Icing Wind Tunnel (IWT) at the Italian Aerospace Research Centre (CIRA) is a state-of-the-art, closed-loop, refrigerated, and pressurized wind tunnel, specifically designed to reproduce in-flight atmospheric icing phenomena for aeronautical applications (Vecchione et al., 2003; Chanetz et al., 2020). Historically, the primary objective of the IWT has been to ensure the safety and performance of aircraft by evaluating how ice forms on wings and other essential components under controlled and repeatable flight conditions.

Officially inaugurated in September 2002, the IWT is one of the most advanced icing tunnels in the world (Figure 1 – CIRA Icing Wind Tunnel aerial view).

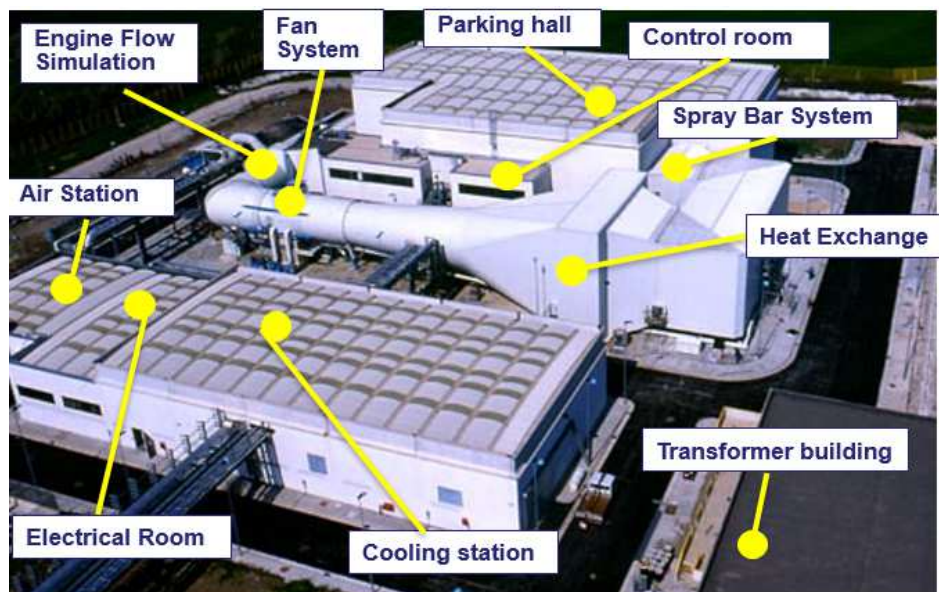


Figure 1 – CIRA Icing Wind Tunnel aerial view

Its unique capabilities include being the largest refrigerated wind tunnel currently in service, the highest-speed icing tunnel (up to Mach 0.7), and the only facility worldwide that combines simultaneous simulation of both altitude and temperature making it an exceptionally versatile tool for both aerodynamic and icing-related experimentation.

The IWT supports qualification and certification tests for a wide variety of anti-ice and de-ice systems, such as pneumatic boots, hot bleed air, and thermal resistance solutions. A dedicated engine flow simulation system further extends testing capabilities to include icing on air intakes of both airplanes and helicopters across a wide operational envelope.

The next Figure 1 shows the overall layout of the Icing Wind Tunnel.

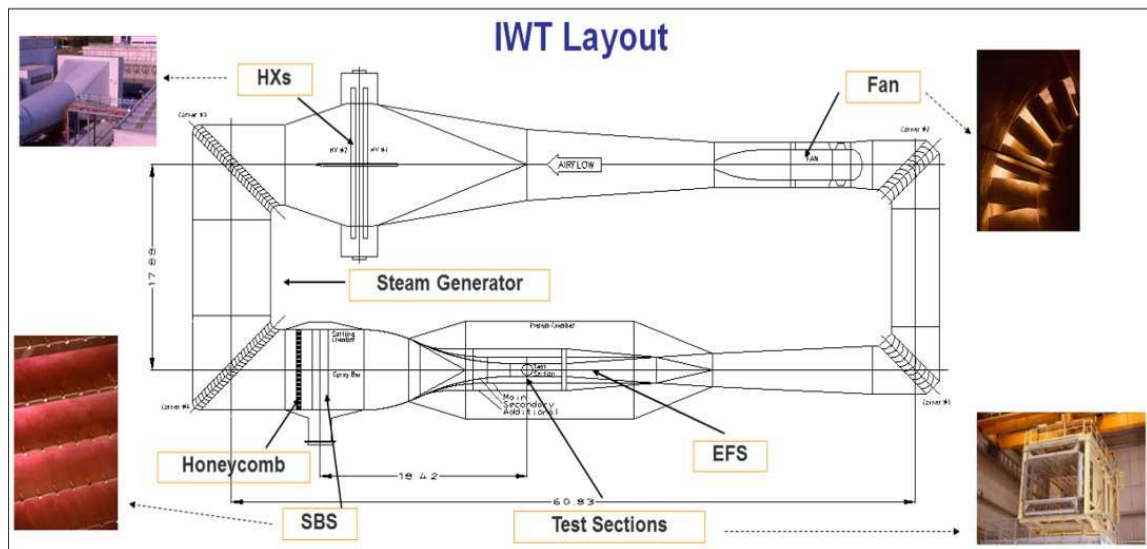


Figure 2 – IWT layout and main subsystems

The circuit is equipped with three interchangeable test sections – Main Test Section (MTS), Secondary Test Section (STS), and Additional Test Section (ATS) – along with an Open Jet configuration. These configurations provide a versatile experimental environment for a wide range of aerodynamic and icing tests, with test section cross-sections ranging from $1.15 \times 2.35 \text{ m}^2$ (STS) up to $3.6 \times 2.35 \text{ m}^2$ (ATS). The maximum attainable Mach numbers are 0.70 in the STS, 0.40 in the MTS, and 0.25 in the ATS. Test sections can have both closed and slotted walls (7% porosity). Airflow refrigeration is obtained via a twin row heat exchanger enabling minimum static temperatures of $-40 \text{ }^\circ\text{C}$ in the STS and $-32 \text{ }^\circ\text{C}$ in other configurations. A dedicated evacuation and pressurization air system allows static pressure being regulated between 39 kPa, corresponding to an altitude of about 7000 m, and 145 kPa, for high Reynolds number aerodynamic tests.

The generation of the artificial cloud is performed by the Spray Bar System (SBS), consisting of up to 20 aerodynamically shaped stainless-steel bars, each capable of hosting up to 50 spray nozzles, for a total of up to 1,000 nozzles. These are in the settling chamber upstream of the test section and are connected to pressurized water and air supply lines. The long contraction length of 18 meters between the settling chamber and the test section ensures thermal equilibrium of water droplets with the cold airflow before reaching the test object, creating a stable and realistic icing environment. The SBS enables precise control over droplet size (Median Volume Diameter, MVD) and Liquid Water Content (LWC), covering a wide range of regulatory icing envelopes, including those defined in CS-25/29 Appendix C and selected Supercooled Large Droplet (SLD) conditions. With its unique integration of aerodynamic fidelity, environmental control, and icing simulation capabilities, the CIRA IWT stands as a benchmark facility in Europe and globally for both experimental research and certification testing of aircraft components subjected to in-flight icing conditions.

2.1 Test Section and operating conditions

The CIRA Icing Wind Tunnel (IWT) features four distinct test section configurations: the Main (MTS), Secondary (STS), Additional (ATS), and Open-Jet sections, designed to satisfy varied requirements for speed, cloud uniformity, and model scale. Three of these closed configurations utilize slotted walls with 7% porosity to host high-blockage models while maintaining 80% optical access for non-intrusive measurements. Operating conditions within these sections are highly versatile, simulating altitudes up to 7,000 meters with pressures ranging from 0.39 to 1.45 bars. The facility can achieve a maximum speed of Mach 0.7 in the Secondary Test Section and maintain air temperatures from a maximum of +40 °C down to -40 °C. Additionally, the IWT controls relative humidity between 70% and 100% and produces icing clouds that comply with FAR 25/29 Appendix C and O, including Super-cooled Large Droplets (SLD) for freezing drizzle simulation. Specialized systems also allow for engine flow simulation with mass flows between 1 and 55 kg/s, supporting a wide range of qualification tests for aircraft and helicopter intakes. In Table 1 are summarized the main characteristics of the facility for the different IWT test section.

Table 1 – IWT test sections main characteristics

TEST SECTION	Dimension [m]	Max Speed* (Mach)	Temperature* [°C]	Altitude* [m]
MAIN	2.25 x 2.35	0.41	-32 < Ts < +40	0÷7000
SECONDARY	1.15 x 2.35	0.70	-40 < Ts < +40	0÷7000
ADDITIONAL	3.60 x 2.35	0.25	-32 < Ts < +40	0÷7000
OPEN-JET	2.25 x 2.35	0.34	-32 < Ts < +40	0÷7000

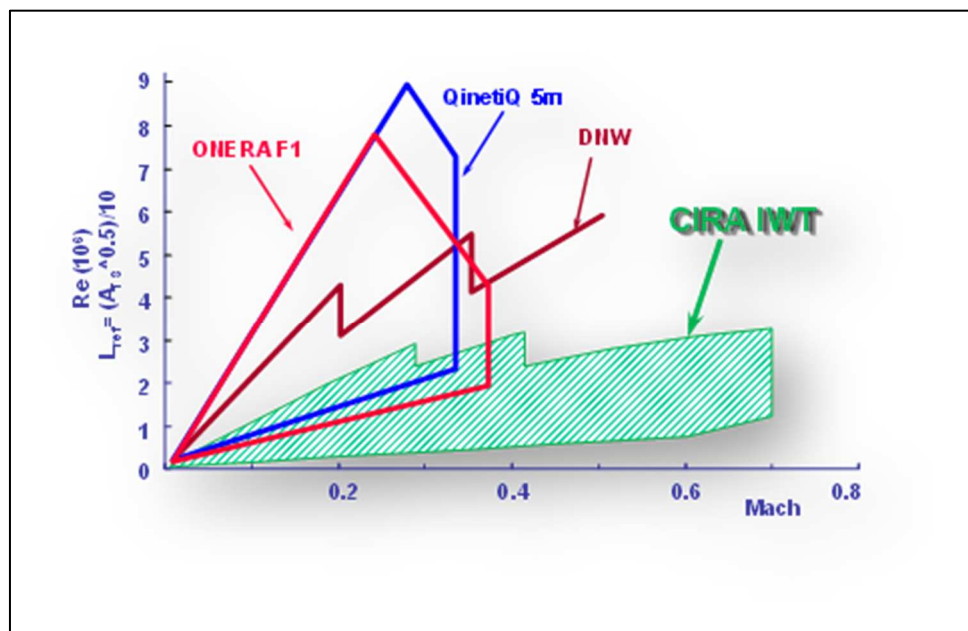


Figure 3 – Operational IWT envelope for Mach-Reynolds (comparison with ONERA F1 and German-Dutch DNW)

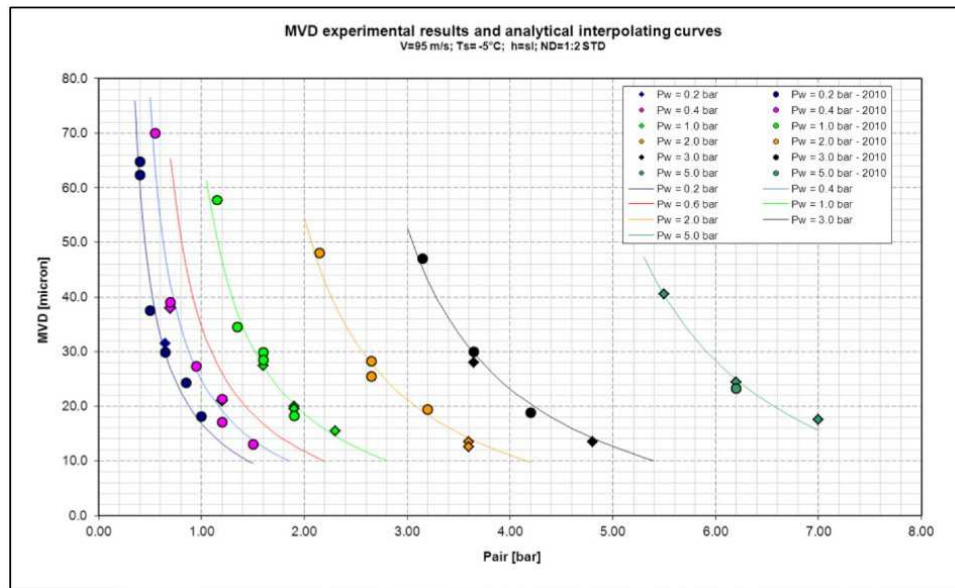


Figure 4 – Typical MVD calibration curves of IWT facility

The above Figure 4 presents experimental measurements and analytical interpolating curves for the Median Volumetric Diameter (MVD) of supercooled water droplets in the IWT facility as a function of atomizing air pressure (Pair) at fixed water/vapor pressures (Pv, ranging from 0.2 to 5.0 bar).

Tests were conducted at airflow velocity $V = 95$ m/s, static temperature $T_s = -5$ °C, with nozzle distribution $ND = 1:2$ STD. Analytical curves (continuous lines) provide smooth empirical fits, enabling accurate prediction of MVD for untested spray-bar operating conditions. The calibration envelope supports reproducible generation of Appendix C icing clouds (MVD 10–50 μm) and limited SLD conditions, demonstrating the IWT capability to achieve a wide MVD range by modulating air and water pressures, critical for simulating realistic droplet impingement and ice accretion physics.

2.2 Main Facility Sub-Systems

The CIRA Icing Wind Tunnel (IWT) infrastructure is composed of the wind tunnel circuit, an office building, a parking hall, and an auxiliary systems building. The auxiliary systems building, situated near the wind tunnel, houses the critical air and cooling plants. Centrally located within the wind tunnel circuit is a three-floor building that serves as the operational hub, hosting the facility control room, operating team offices, and a laser room on the ground floor. The control room, located on the first floor, provides direct access to the test section through a specialized air lock chamber. To support logistics and testing setup, a large parking hall measuring 18 by 54 meters is used to store interchangeable components and provides a dedicated rigging area for model installation and private workshop areas for customers. This complex is integrated into the broader Italian Aerospace Research Centre, which includes additional support infrastructure such as an electrical power station, cooling towers, and a thermo-refrigerating plant.

The CIRA Icing Wind Tunnel is an advanced facility designed to simulate flight conditions in icing environments, with capabilities to test aircraft and their components under extreme conditions. The facility is composed of various subsystems, each playing a crucial role in accurately simulating the effects of ice formation on aerodynamic surfaces and the overall performance of the aircraft.

Test Sections

- The IWT can be configured with four different test sections (Main, Secondary, Additional, and Open-Jet) to satisfy requirements for speed and model size.
- Three configurations feature slotted walls with 7% porosity to host high-blockage models while maintaining 80% optical access for non-intrusive measurements.
- Synchronized turntable platforms (2 meters in diameter) are installed in all configurations to set precise model orientation relative to the airflow.



Figure 5 – Main and secondary IWT test section icing grid (Esposito et al., 2003; Ragni et al., 2005)

Cooling System

- This subsystem removes heat generated by various sources to maintain constant air temperatures via a twin-row heat exchanger.
- It achieves minimum temperatures of $-32\text{ }^{\circ}\text{C}$ in the Main/Additional sections and $-40\text{ }^{\circ}\text{C}$ in the Secondary Test Section with $\pm 0.1\text{ }^{\circ}\text{C}$ accuracy.
- The system also controls relative humidity between 70% and 100% and provides a dedicated mode for automated tunnel defrosting.

Fan System

- Airspeed is driven by a 24-blade, 3.9-meter diameter fan unit equipped with variable blade pitch angle settings.
- The 4 MW motor is electronically managed by an inverter to reach a maximum fan speed of 750 rpm under FMS control.
- A 35% power margin is reserved to compensate for air pressure losses caused by ice build-up on tunnel surfaces during testing.

Air Plant

- A 0.7 MW centrifugal compressor regulates tunnel pressure between 0.39 and 1.45 bars to simulate altitudes up to 7,000 meters.

- A dedicated 1.2 MW axial unit supplies the Spray Bar System, while separate compressors support hot air and pneumatic boot de-icing systems.
- The plant additionally provides 7.5 bar instrument air at several positions throughout the buildings and inside the plenum chamber.

Flow Reference System

- The FRS acquires real-time data from stilling chamber sensors to calculate flow speed, Mach number, altitude, and relative humidity.
- Measurement is performed using high-accuracy MENSOR pressure systems and BFGoodrich temperature probes with integrated de-icing capability.
- The resulting parameters are utilized by the FMS to set and control precise test conditions and auxiliary operations.

Spray Bar System

- Located in the stilling chamber, the SBS generates icing clouds covering FAR 25/29 Appendix C and selected Appendix O (SLD) conditions.
- The system utilizes 20 aerodynamic bars equipped with 500 active, remotely controlled nozzles to optimize cloud coverage and uniformity.
- Closed-loop control managed by the FMS allows for fast switching between Maximum Continuous and Max Intermittent icing conditions.

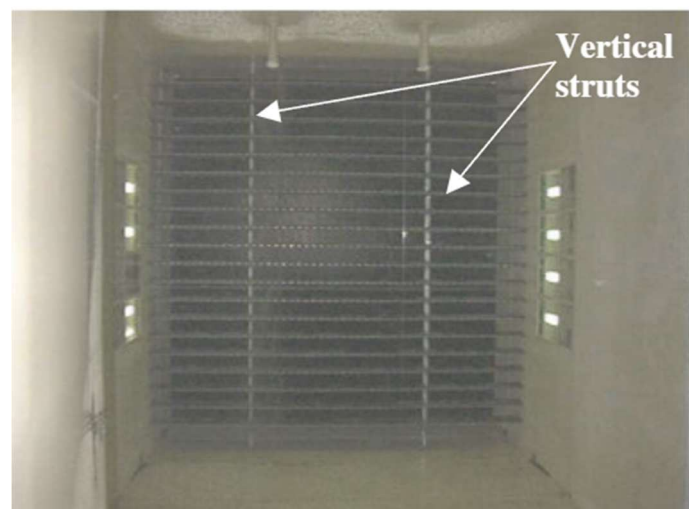


Figure 6 – Spray bar view from the test section (Esposito et al., 2003)

Engine Flow Simulator System

- The EFS uses high-pressure fans to extract and re-inject air, reproducing the air intake flow inside an engine nacelle.
- It operates within the full range of tunnel temperatures and pressures with mass flows ranging between 1 and 55 kg/s.

- A twin calibrated Venturi system meters air mass flow with a maximum error margin of approximately 1%.



Figure 7 – IWT Engine flow simulator

Facility Management System

- The FMS is the primary software architecture designed to monitor and manage all facility subsystems and test parameters.
- Built on the Talent kernel, it operates on a distributed PC network to provide manual, automatic, or integrated control modes.
- Core functions include test automation via scripts, data acquisition, video monitoring, and overall facility safety supervision

2.3 Overview of IWT Instrumentation

The IWT is fully instrumented with a modern data acquisition and control system. The Facility Management System (FMS) oversees all subsystems—including the main fan, refrigeration system, pressure control and spray systems—while real-time test monitoring is performed by the Flow Reference System (FRS), which delivers accurate measurements of Mach number, airspeed, pressure, total temperature, and humidity. Model attitude can be precisely adjusted using motorized turntables with a rotation range from -100° to $+250^\circ$, enabling comprehensive aerodynamic analyses under various angles of incidence.

The Facility Management System (FMS) serves as the primary architecture for monitoring and managing all parameters within the CIRA Icing Wind Tunnel. It operates on a distributed PC network utilizing a 1Gb/sec Ethernet LAN, with an industrial Ethernet interface connecting to low-level PLC control systems. The control software is built upon the Talent kernel, which provides a Graphic User Interface (GUI) for high-level facility management in manual, automatic, or integrated modes.

Centrally, the FMS is divided into facility management and test article management functions. The Test Automation Subsystem acts as the core of the FMS during campaigns, utilizing Test Automated Scripts (TAS) to control procedures for the start-up, testing, and shutdown phases. The system provides real-time status displays for all wind tunnel subsystems and manages critical control loops for air stream parameters.

Monitoring is supported by a dedicated Flow Reference System (FRS) and various internal probes that track temperature and pressure across the tunnel circuit. For test article measurement, the Data Acquisition System (DAS) acquires both analog and digital data, specifically utilizing the IMC

Spartan-R system for model sensors and an electronically scanned pressure system. Visual monitoring is provided by an extensive video imaging system comprising 16 IP-HD cameras positioned within the plenum and along the tunnel circuit to document model behavior and facility safety. Finally, the Data Processing System (DPS) manages both on-line and off-line processing to deliver raw and post-processed data in user-required formats.

Particle Sizing Measurement Methods

CIRA ITW utilizes a suite of advanced technologies to characterize the diameter and velocity of atomized water droplets.

<i>Technique</i>	<i>Description</i>
Instrumentation	Includes phase Doppler systems, spectrometer probes, and high-speed imaging technologies.
Updates	Methods are continuously updated to address challenges like out-of-focus imagery and depth of field uncertainty (Lilie et al., 2023; Esposito et al., 2024)

Phase Doppler Particle Analyser (PDPA) Technique

Advanced technique for in-situ and non-intrusive measurements of water droplets

<i>Feature</i>	<i>Details</i>
Instrumentation	Airborne Droplet Analyzer (ADA) and modular PDPA system (Esposito et al., 2007; Esposito et al. 2011)
Measurement range	Light scattering interferometer principle, using light wavelength as a scale - From 0.5 μm to 2000 μm , depending on optical configuration.

Forward Scattering Spectrometer Probe (FSSP)

Technology for determining droplet diameter by measuring scattered light power

<i>Feature</i>	<i>Details</i>
Instrumentation/model	FSSP-100ER
Measurement range	From 5 μm to 95 μm
Laser	5 mW helium-neon laser

Optical Array Probe (OAP)

Optical instrument for measuring droplets larger than 100 μm using a shadow-based imaging technique

<i>Feature</i>	<i>Details</i>
Instrumentation/model	DMT OAP-260X, OAP-2DGC and SEA OAP-1D2D (Esposito et al., 2007; Esposito et al. 2011, Esposito et al., 2024)
Measurement range	Up to 960 μm

Technology	Shadow-based imaging technique with hardware correction of out-of-focus imaging.
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High-Speed Imaging (HSI) updated to Particle Imaging Systems (P-I)

High-speed imaging technique used to capture fast-moving particles (Esposito et al., 2019)

<i>Feature</i>	<i>Details</i>
System used	2D CMOS array imaging system with multi-beam illumination
Pulsed laser	Pulse duration as short as 12.5 ns
Resolution	3.8 μm/pixel, detecting particles from 7 μm to 1820 μm.

Liquid Water Content (LWC) Measurement Methods

Techniques for accurate measurement of Liquid Water Content (LWC).

<i>Feature</i>	<i>Details/description</i>
Instrumentation/ Measurement methods	Mechanical ice collection and heated-wire sensor techniques.
Note	Crucial for calibrating simulated icing clouds to meet certification requirements.

Icing Blade System

Standard method for LWC calibration using a stainless steel icing blade

<i>Feature</i>	<i>Details</i>
Instrumentation/model	300mm stainless steel blade
Working principle	Measuring the ice thickness accumulated on the blade after exposure to the cloud.
Test temperature	Typically -20 °C or lower.

Hot-Wire LWC Probe

Probe for calculating LWC based on the electrical power required to maintain a constant temperature.

<i>Feature</i>	<i>Details</i>
Instrumentation	Hot-Wire LWC Probe
Measurement principle	Electrical power required to vaporize droplets and maintain sensor temperature.
Operational range	LWC range from 0 to 3.0 g/m ³ at airspeeds from 140 to 230 miles per hour.

SEA Hot-Wire Probes

System using heated elements to distinguish between liquid water and total condensed phase water (including ice crystals in mixed-phase clouds)

<i>Feature</i>	<i>Details</i>
Instrumentation	SEA Hot-Wire Probe
Technology	Convex elements collect liquid water and concave (half cylinder) elements to capture both ice and water (Baumert et al., 2015; Scott et al., 2015)
Special probes used	“Robust” probes to minimize measurement uncertainty under Appendix O (SLD) conditions

Liquid Water Content Uniformity Measurement Methods

Methods for measuring the uniformity and coverage area of the generated icing cloud.

<i>Feature/Method</i>	<i>Description</i>
Icing Grid system	Mesh of stainless-steel bars connected to an external frame.
LWC measurement	Data normalized to the test section center to create an LWC distribution map in the cross-section.



(a)



(b)

Figure 8 – Some IWT measurement Instrumentation, Airborne Droplet Analyzer ADA probe (a), icing blade installation in the IWT STS (b)

3 Advancing CIRA IWT capabilities

The integration of a Thermal Management System (TMS) in aircraft requires reliability testing prior to flight certification. This need is particularly relevant for hybrid-electric and fully electric aircraft, where thermal loads from batteries, power electronics, and electric propulsion systems are significantly higher and variable. In this context, the on-going CIRA IWT upgrades provide a realistic experimental environment for ground testing, capable of replicating cruise-altitude

thermal loads while varying both the dissipation system demands and specific mission profiles (e.g., as shown in Figure 9).

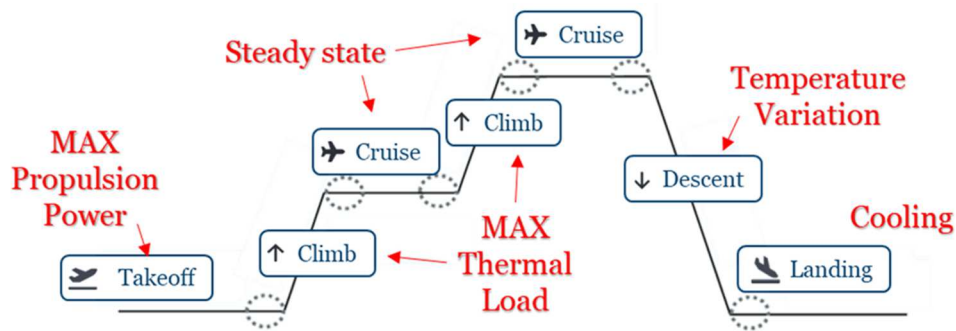


Figure 9 – Schematic mission profile of a regional size aircraft

Testing of different configurations will be enabled, encompassing Thermal Management System (TMS) performance under representative flight conditions and detailed fluid-dynamic analysis of various cooling terminal arrangements (e.g., fuselage-integrated, wing-mounted, or other ram-air systems). The upgraded facility will provide a flexible framework for technology validation while allowing verification of system sizing, control strategy validation, and safety margin assessment under realistic operating conditions, for both full-scale configurations (such as light or ultralight aircraft) and scaled demonstrators.

3.1 Reference TMS power levels

The thermal power generation system for the IWT upgrade has been sized at 500 kW, based on thermal load levels reported in the literature for hybrid-electric vehicle applications. Several studies provide representative estimates of heat rejection and thermal power demand under typical operating conditions, which have been used as a reliable reference for preliminary system dimensioning. **Fehler! Verweisquelle konnte nicht gefunden werden.** summarizes some used reference values of aircraft Thermal Management System, related to a propulsion system up to 1 MW size fed with a PEM (Proton Exchange Membrane) Fuel Cell, including also a TMS for Li-Ion battery system.

Table 2 – Reference aircraft TMS values

Layout	Nominal Efficiency	Electric Power [kW]	Heat Power dissipation [kW]	Reference
Low Temp. - PEMFC	39 % (cruise)	312	500	Schröder et al., 2024
High Temp. - PEMFC	50 %	300	300	Simpleflying 2024
2 Liquid heat exchangers, ext. radiators	55 %	1000	450 (Fuel Cell stack)	Frey et al., 2024
			370 (Power elect., electric motors)	

Liquid heat exchanger, ext. radiator	55 %	500	400	Schlittenhardt et al., 2025
Liquid heat exchanger, ext. radiator	55 %	250	200	Wright et al., 2022
Liquid heat exchanger, ext. radiator - forced air cooling	55 %	1000	820	Adam et al., 2025
Li-ion battery	90-95%	1000	50-100 kW	Kellermann et al., 2022

The above data have been derived from numerical models as detailed in the related referenced studies, specifically developed for proper Thermal Management System (TMS) sizing and for analyzing associated fluid-dynamic effects (Adam et al., 2025).

Direct correlation between numerical models and experimental data, by testing prototypes in a relevant simulated flight environment (wind speed, temperature, pressure, and cloud/icing conditions) will be enabled from the upgrade of CIRA IWT.

Technological assessment of Thermal Management System (TMS) prototypes – airframe-integrated or standalone – up to Technology Readiness Level (TRL) 6 or 7 (ESA, 2025) will provides a bridge toward final aircraft integration by combining numerical predictions with high-fidelity experimental validation under realistic operating conditions.

3.2 System description

The above-mentioned thermal generation system is currently being implemented at the IWT facility. It has been designed to deliver up to 500 kW of thermal power using a water-glycol mixture, supplied to the test articles at a maximum pressure of 10 bar and with a flow rate of up to 1200 litres per minute.

The test article will include liquid to air exchanger or more innovative cooling systems such as structure-integrated heat exchangers, skin heat exchanger or nanofluid-based system designed to enhance the thermal conductivity of the base heat transfer fluid (Heerden et al., 2022; Wiriyasart et al., 2020).

The Heat Generation system has been designed to allow:

- precise thermal loading of electrical components during test campaigns,
- monitoring of flow rate, pressure, and temperature,
- validation of cooling strategies and component performance under thermal stress.

A basic layout illustrating the system's function is shown in **Fehler! Verweisquelle konnte nicht gefunden werden.**, where an electrical heating unit circulates the heat transfer fluid (water-glycol mixture) to the test section, providing controlled flow rates at precisely adjustable temperature and pressure conditions, directly regulated through the control system.

To ensure precise control of the temperature, pressure and flow rate of the refrigerant, the system has been equipped with pressure (PT in 10 for absolute pressure measurement, PDI for differential pressure measurement) and temperature sensor (TT in 10 at all the key points, particularly upstream and downstream of each component within the setup, in order to thermally characterize each individual component. It will also include flow meters (FT in 10), both to directly measure the fluid flow rate towards the test section – providing feedback to the electronic control unit – and to ensure that there are no leaks inside the test room during testing.

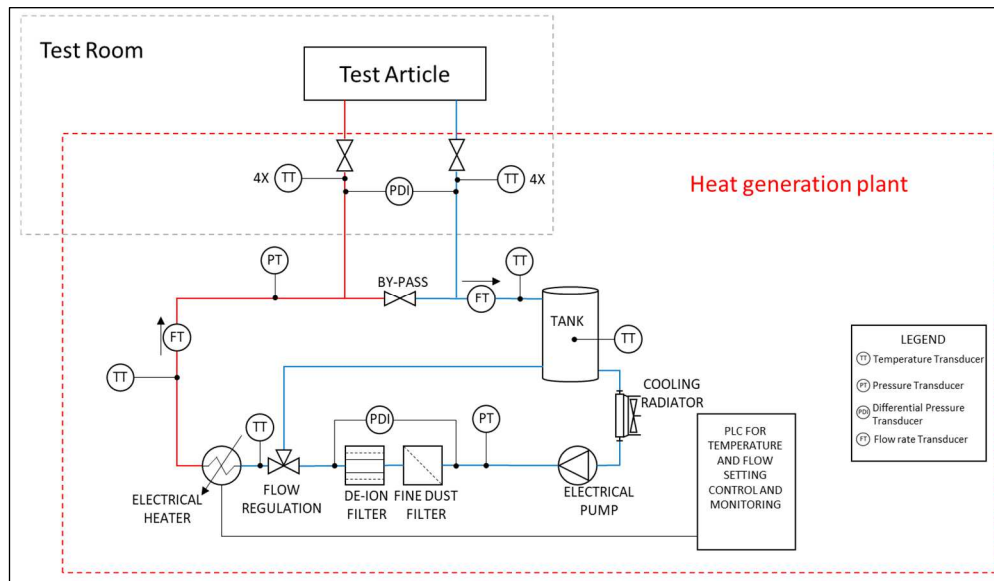


Figure 10 – Layout of the main components of the heat generation system.

Since the system is built with adequate thermal insulation to minimize heat losses to the environment during the test, an electro-fan radiator, referred in the Figure as the "Cooling Radiator", has been included to facilitate rapid cooling of the heat transfer fluid and be able to quickly repeat tests such as cold start transients from ambient temperature up to maximum operating temperature without using the tunnel or the test article to cool the fluid to initial conditions.

Table 3 shows the maximum operating conditions of the system, that are the maximum heat output that can be delivered to the fluid for operation of the wind tunnel test article.

Table 3 – Heat Load Simulation System: Maximum Operating Conditions and Accuracy

Maximum operating conditions	
Heat power	500 kW
Hot fluid line, max continuous temperature	120 °C
Hot fluid line, peak temperature	130 °C
Fluid lines, max operating pressure	10 bar
Liquid max Mass flow rate	1200 l/min
Target setpoint accuracy	
Temperature	± 1 °C
Flow rate	± 2%
Pressure	± 0.2 bar
Minimum adjustable thermal power	10 kW

3.3 Control and measurement system

The thermal generation system used to simulate aircraft thermal loads is equipped with an electronic control unit that allows the configuration of temperature set-points, ramp times, and operating parameters while acquiring system and fluid delivery data. Temperature, pressure, and flow sensors are foreseen to be installed at key locations – particularly near the test article – to

ensure accurate monitoring, while dual flow meters upstream and downstream of the test section enable leak detection when operating at pressures up to 10 bar. All measurements and system status data are transmitted to the IWT control room, allowing operation within safety limits, providing real-time visualization of operating parameters, and logs experimental and diagnostic data for analysis and anomaly detection.

3.4 Additional IWT experimental testing capabilities

The implementation of an active Thermal Management System (TMS) in the upgraded CIRA Icing Wind Tunnel will enable additional sophisticated testing capabilities for advanced aircraft heat exchangers (HX) and anti-icing systems. Future experiments could include advanced studies on hybrid- and electric-propulsion-related ice growth dynamics (Timmermann et al., 2018) and performance degradation due to frosting (Wei et al., 2022). Additional applications may involve precise drag assessment using force-balance and flow diagnostics (Habermann et al., 2023), separation of friction and pressure losses (Broatch et al., 2024), and evaluation of the Meredith effect through measurements of momentum and enthalpy changes across ram-air ducts. These capabilities, combined with CFD, will allow optimization of HX and duct designs across realistic flight envelopes, supporting the validation of innovative aero-thermal solutions.

4 Conclusions

The CIRA Icing Wind Tunnel represents a unique and highly versatile experimental infrastructure, historically recognized for its role in aircraft icing research, certification support, and aerodynamic investigations. The IWT is designed to simulate atmospheric icing effects up to an altitude of 7000 m, with static temperatures down to about -40 °C and static pressures between 0.39 and 1.45 bar; different multiple interchangeable test sections and an open-jet configuration are available, in order to accommodate a wide range of test models and conditions. The facility can also support aerodynamic investigations in low and high subsonic regimes by varying flow temperature, pressure and Reynolds number.

Currently, the facility is undergoing an upgrade as part of the EU-funded AMBER project focused on maturing megawatt-class hybrid-electric propulsion. This enhancement significantly expands the IWT capabilities beyond traditional icing applications, positioning the facility as a key reference test environment for the experimental investigation of Thermal Management Systems (TMS) in hybrid and electric aircraft.

The upgraded IWT will provide a unique capability to test systems under realistic flight conditions, including simulated altitude, temperature, and airflow, thereby validating TMS performance and integration up to a Technology Readiness Level of 6.

By combining large-scale test sections, wide mass-flow-rate operability, and the ability to reproduce realistic altitude and thermal conditions, the upgraded IWT enables the integration and testing of full-scale TMS components at power levels up to the megawatt range under flight-representative conditions. This advancement provides a critical experimental bridge between numerical design tools and real-world operational requirements, supporting the validation, optimization, and de-risking of innovative thermal architectures. Ultimately, the enhanced IWT will contribute to accelerating the development, certification, and deployment of efficient and reliable thermal management solutions, thereby supporting the broader transition toward sustainable, low-emission aviation technologies.

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Acronyms and Abbreviations

<i>A</i>	Heat exchange area
AMBER	InnovActive DeMonstrator for hybrid-Electric Regional Application
ATS	Additional Test Section
AZEA	Alliance for Zero Emission Aviation
<i>c_{pa}</i>	Specific heat capacity of cold fluid
<i>c_{pw}</i>	Specific heat capacity of hot fluid
ΔT_{air}	Cold side Temperature difference
ΔT_{ml}	Mean logarithmic Temperature difference for the exchanger
ΔT_w	Hot side Temperature difference
<i>f</i>	Exchanger shape correction factor
FMS	Facility Management System
FRS	Flow Reference System
FT	Flow Transmitter (o Flowmeter)
IATA	International Air Transport Association
IWT	Icing Wind Tunnel
LWC	Liquid Water Content
<i>m_{air}</i>	Cold mass flow rate
<i>m_w</i>	Hot mass flow rate
MTS	Main Test Section
MVD	Median Volume Diameter
NO _x	Nitrogen Oxides
PEMFC	Proton Exchange Membrane Fuel Cell
PDI	Pressure Differential Indicator
PT	Pressure Transmitter
<i>Q</i>	Thermal power released from the hot fluid (water and glycol) to the cold fluid (air)
T1	Hot side inlet temperature
T2	Hot side outlet temperature
T3	Cold side inlet temperature
T4	Cold side outlet temperature
TMS	Thermal Management System
<i>U</i>	Heat transfer coefficient

References

- Baumert A., Bansmer S., Trontin P., Villedieu P. (2018). Experimental and numerical investigations on aircraft icing at mixed phase conditions. *International Journal of Heat and Mass Transfer* 123, 957-978. ISSN 0017-9310
- Baumert A., Pervier H., Esposito B. M., Bansmer S. (2015). Calibration of the Icing Wind Tunnel Braunschweig with Respect to Mixed Phase and Glaciated Icing Conditions. *SAE 2015 International Conference on Icing of Aircraft, Engines, and Structures*, Prague, Czech Republic.
- Broatch A., García-Tíscar J., Quintero P., Felgueroso A. (2024). Rapid aerodynamic characterization of surface heat exchangers for turbofan aeroengines through optical techniques and additive manufacturing. *Thermal Science and Engineering Progress* 55, 102966.
- Chanetz B., Délery J., Gilliéron P., Gnemmi P., Gowree E. R., & Perrier P. (2020). Experimental Aerodynamics: An Introductory Guide (1st ed.). *Springer Nature Switzerland AG*, Subsonic Wind Tunnels Chapter, 51-95. <https://doi.org/10.1007/978-3-030-35562-3>
- Coutinho M. et al. (2023). A review on the recent developments in thermal management systems for hybrid-electric aircraft. *Applied Thermal Engineering* 227, 120427. <https://doi.org/10.1016/j.applthermaleng.2023.120427>
- ESA (2025). <https://sci.esa.int/web/sci-ft/-/50124-technology-readiness-level> (Accessed on 05/05/2025)
- Esposito B. M., Bachalo W., Leroy D., Schwarzenboeck A. et al. (2019). Wind Tunnel Measurements of Simulated Glaciated Cloud Conditions to Evaluate Newly Developed 2D Imaging Probes. *SAE Technical Paper*, 2019-01-1981. <https://doi.org/10.4271/2019-01-1981>
- Esposito B. M., Brown K. J., Bachalo W. D. (2011). Application of Optical Methods for Icing Wind Tunnel Cloud Simulation Extension to Supercooled Large Droplets. ILASS Americas, *23rd Annual Conference on Liquid Atomization and Spray Systems*, Ventura, May 2011, CA.
- Esposito B. M., Lilie L. E., Timko E., Acosta L., Strapp J. W., Bansemer A. (2024). Wind Tunnel PSD and MVD Characterization Using New 1D2D Optical Array Probes. *AIAA Aviation Forum And Ascend*, AIAA 2024-4246. <https://doi.org/10.2514/6.2024-4246>
- Esposito B. M., Lilie L. E., Timko E. N., Hux L. E., Strapp J. W., Bansemer A. (2024). Wind Tunnel PSD and MVD Characterization Using New 1D2D Optical Array Probes. *AIAA Atmospheric and Space Environments Conference*, AIAA 2024-4246, Las Vegas.
- Esposito B. M., Marrazzo M. (2007). Application of PDPA System with Different Optical Configuration to the IWT Calibration. *AIAA Conference*, AIAA 2007-1094, Reno, NV.
- Esposito B. M., Ragni A., Ferrigno F., Vecchione L. (2003). Cloud Calibration Update of the CIRA Icing Wind Tunnel, *SAE Technical Paper Series*.
- European Commission (2022). AMBER project: Innovative demonstrator for hybrid-electric regional application. Project ID 101102020, CORDIS. <https://cordis.europa.eu/project/id/101102020>
- Frey A. C., Bosak D., Stonham J., Sangan C. M., Pountney O. J. (2024). Liquid Cooling of Fuel Cell Powered Aircraft: The Effect of Coolants on Thermal Management. *ASME. J. Eng. Gas Turbines Power*, November 2024, 146(11), 111021. <https://doi.org/10.1115/1.4066047>
- Frey A. C., Stonham J., Bosak D., Sangan C. M., Pountney O. J. (2025). Radiators in fuel cell powered aircraft: The effect of heat rejection on drag. *Applied Thermal Engineering*, 274, Part C, 126697. <https://doi.org/10.1016/j.applthermaleng.2025.126697>

- Habermann A. L., Khot A., Lampl D. E., Perren C. (2023). Aerodynamic effects of a wing surface heat exchanger. *Aerospace* 10(5), 407.
- Huanyu D., Shinan C., Mengjie S. (2020). The optimization of simulated icing environment by adjusting the arrangement of nozzles in an atomization equipment for the anti-icing and deicing of aircrafts. *International Journal of Heat and Mass Transfer* 155, 119720. ISSN 0017-9310
- Invigorito M., Serpico M., Mercurio U., Caputo C., Elia G. (2025). CIRA Icing Wind Tunnel Facility: Capability Assessment for Hybrid Aircraft TMS Testing. *11TH European Conference for Aeronautics And Space Sciences (EUCASS)*, 30 June - 4 July Rome, Italy. <https://doi.org/10.13009/EUCASS2025-073>
- Kellermann H. et al. (2022). Design of a battery cooling system for hybrid electric aircraft. *Journal of Propulsion and Power* 38.5, 736-751, [16].
- Lilie L., Bouley D., Sivo C., Esposito B. et al. (2023). A New 1D2D Optical Array Particle Imaging Probe for Airborne and Ground Simulation Cloud Measurements. *SAE Technical Paper*, 2023-01-1415. doi:10.4271/2023-01-1415
- Ragni A., Esposito B., Marrazzo M., Bellucci M., Vecchione L. (2005). Calibration of the CIRA IWT in the High Speed Configuration. *43rd AIAA Aerospace Sciences Meeting and Exhibit*, AIAA 2005-471, Reno, NV.
- Schlittenhardt J. et al. (2025). Preliminary Design of Regional Aircraft—Integration of a Fuel Cell-Electric Energy Network in SUAVE. *Aerospace* 12.3, 249.
- Schröder M., Becker F., Gentner C. (2024). Optimal design of proton exchange membrane fuel cell systems for regional aircraft. *Energy Conversion and Management* 308, 118338, [10].
- Simpleflying 2024. <https://simpleflying.com/high-temperature-fuel-cells-in-sustainable-aviation/> (Accessed on 05/05/2024)
- Stott I., Howard G., Esposito B. M., Pervier H. (2015). Improvements Made to the GKN Icing Wind Tunnel with Respect to Glaciated and Mixed Phase Icing Conditions. *SAE 2015 International Conference on Icing of Aircraft, Engines, and Structures*, Prague, Czech Republic, June 22-25, 2015
- Timmermann M. A. S., Kaviyani M., Barbosa Jr. J. R. (2018). Thermal performance of peripheral-finned tube evaporators under frosting. *International Journal of Heat and Mass Transfer* 116, 194-207.
- Van Heerden A., Judt D., Jafari S., Lawson C., Nikolaidis T., Bosak D. (2022). Aircraft thermal management: Practices, technology, system architectures, future challenges, and opportunities. *Prog. Aerospace Science*, 128, 100767, <http://dx.doi.org/10.1016/j.paerosci.2021.100767>
- Vecchione L., De Matteis P. P., Leone G. (2003, January). An Overview of the CIRA Icing Wind Tunnel. *AIAA Conference: 43th Sciences Meeting and Exhibit at Reno, Nevada, USA*.
- Wei H., Dong W., Yang X., Guo X., Li Z., Tang Z., Fu C. (2022). Experimental studies on the frosting and defrosting performance of compact heat exchanger under moderate humidity condition. *Energy Reports* 8, 1321–1338.
- Wiriyasart S., Hommalee C., Sirikasemsuk S., Prurapark R., Naphon P. (2020). Thermal management system with nanofluids for electric vehicle battery cooling modules. *Case Stud. Therm. Eng.* 18, 100583. <http://dx.doi.org/10.1016/j.csite.2020.100583>

Wright S., Aaltonen J. (2022). Fuel cells and novel thermal management advancements required for aviation. 33rd *Congress of the International Council of the Aeronautical Sciences 2022*.