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CIRA Icing Wind Tunnel Facility: Capability Assessment for Hybrid Aircraft TMS Testing

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Abstract

In the frame of EU-funded AMBER project, [1], the Italian Aerospace Research Center-CIRA is involved in a specific task focused on the experimental tests of the Thermal Management System (TMS), currently under design and development in AMBER project's coordinator, Avio Aero. The objectives of the experimental tests are to evaluate the overall TMS performance in real flow conditions, taking into account for its critical role in a hybrid aircraft.
To match this objective, CIRA is developing an upgrade of its Icing Wind Tunnel (IWT), [2], taking advance from the large IWT test section dimensions, and from the possibility to combine altitude/temperature simulation with a wide operating mass flow rate range (1.5 -55 kg/s mass flow rate).
The use of the IWT facility allows to test full-scale TMS with powers up to the order of 0,5 MW, in conditions that are representative of real flight environment in terms of temperature and mass flow rate, giving in this way advantages in terms of TMS characterization and optimization.
This paper summarizes the overall on-going upgrades to the experimental IWT facility in terms of necessary equipment/subsystems, and the needs for a TMS experimental characterization.
A preliminary IWT design of the operative envelope with respect to its main driving parameters has been derived. The final goal, represented by the upgrading of the IWT facility, will permit to realistically simulate the operating conditions of a hybrid aircraft, allowing specific tests on thermal performance subsystems, in environments with appropriate freestream temperatures and mass flow rates.

1. Introduction

To meet the climate goals of the Paris Agreement and the EU Green Deal, the aviation sector is under pressure to adopt cleaner technologies and more sustainable operational practices. Aviation accounts for approximately 2.5% of global CO_2 emissions [3], without considering the climate-altering effect of condensation trails and nitrogen oxide (NOx) emissions [4], or Airplane Contrails [5] which amplify the overall greenhouse effect of the sector. This trend is expected to grow due to increased air traffic.
According to the latest IATA report [6], the global airline industry aims to reach net-zero carbon emissions by 2050; in this perspective hybrid-electric and all-electric propulsion systems are gaining attention as viable solutions for reducing emissions—particularly for short-haul and regional flights. The Alliance for Zero Emission Aviation (AZEA), supported by EUROCONTROL, has recently launched its vision on enabling the operation of hydrogen-powered and electric flights in Europe. The vision sets an ambitious objective to have 36% to 68% of intra-EU flights operated by these new aircraft configurations by 2050 and underlines the aviation ecosystem's determination to become more climate-friendly and to invest in the technologies of the future [7].
However, 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 [8], [9].

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In this scenario one of the most critical aspects is represented by the thermal management systems (TMS), devoted to maintaining the optimal operating temperatures of critical aircraft components and systems within their specified limits, assuring then safe and efficient aircraft operations.
The hybrid vehicle's dual powertrain—a blend of traditional combustion engines and electric propulsion—generates a complex thermal landscape. 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, with a performance reduction, resulting in reduced range, lower power output, and potentially permanent damage.
Furthermore, electric powertrains generate less waste heat compared to combustion engines, leading to challenges in cold climates, where thermal energy is necessary to heat the vehicle's cabin and keep the battery at an optimal temperature. Hence, the need to balance heat generation and dissipation across the hybrid powertrain necessitates advanced TMS that can manage varying thermal loads efficiently.
In addition to improving efficiency, effective thermal management is crucial for vehicle safety. Overheating or failure to properly regulate temperatures in power electronics, batteries, or engines can result in component failure or, in extreme cases, catastrophic events like fires. The complexity of modern hybrid aircraft requires TMS that can react quickly to changing conditions and ensure consistent operation under diverse flying conditions, from regional flights to high-performance demands or in extreme weather conditions.
Given the critical link between effective thermal management and aircraft safety, performance and longevity, 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.

1.1 Testing Thermal Management System

The characterization of the TMS performances in hybrid vehicles requires extensive testing to ensure the systems perform reliably under all operating conditions. The process typically involves simulation and physical testing of vehicle components in various thermal scenarios, including temperature extremes, transient load conditions, and thermal cycling. However, physical testing often faces limitations, especially when it comes to simulating complex real-world environments where hybrid vehicles operate.
In Table 1 some reference values of aircraft Thermal Management System for a propulsion system up to 1 MW size fed by a PEM (Proton Exchange Membrane) Fuel Cell or a Li-Ion battery system are summarized.

Table 1: Typical TMS aircaft reference values

Layout	**Energy conversion system Efficiency**	**Heat Power dissipation with TMS [kW_{th}]**	**Ref.**
Low Temperature – PEM FC	39 % (cruise) 49 % (take-off)	500 (single stack of FC)	[11]
2 Liquid heat exchangers, external radiators – PEM FC	50 %	1000 (Complete heat load to be dissipated)	[12]
Liquid heat exchanger, external radiator - FC	60 %	1000 (Complete heat load to be dissipated)	[13]
Liquid heat exchanger, external radiator – PEM FC	55 %	80 (single module under continuous load)	[14]
Liquid heat exchanger, external radiator with forced air cooling – HT PEM FC	50 %	1000 (Complete heat load to be dissipated)	[15]
Li-ion battery	90 %	135 kW	[16]

The data shown in the above table are obtained from the numerical models presented in [11]-[16] made for the correct TMS sizing or the analysis of other accompanying fluid dynamic effects [15].

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It is clear that the testing possibilities are different, ranging from the analysis of the TMS system performance based on the aircraft mission profile, to the fluid dynamics analysis of the system's cooling terminal, either in air or within the aircraft fuselage, inside the wing or in any portion of the aircraft where the TMS has been integrated both in full scale for light and ultralight aircraft, or in reduced scales for larger aircraft.
The upgrade of the IWT at CIRA will allow the opening of a new scenario, being able to test a full scale TMS prototype in a relevant simulated flight environment in terms of wind speed, temperature, pressure and even the presence of clouds, and then providing the possibility of correlating the experimental data with the real flight conditions.
The planned upgrade of the wind tunnel facility will enable testing of thermal management system prototypes, either integrated into the airframe or standalone, within a relevant environment up to Technology Readiness Level (TRL) 6 or 7, [17]. This capability will support the transition toward final aircraft integration by providing not only numerical data but also experimental validation under realistic operating conditions.

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, [2].
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).



Figure 1 - 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. An overall Layout of the Icing Wind Tunnel is shown in Figure 2.

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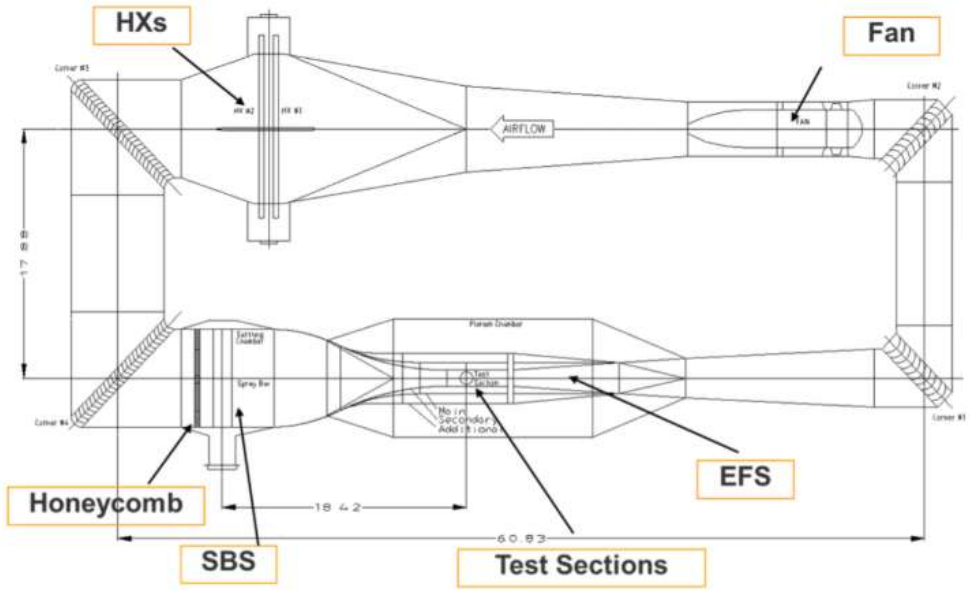


Figure 2 - IWT layout and main subsystems

The IWT 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 × 2.35 m² (STS) up to 3.6 × 2.35 m² (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 °C in the STS and −32 °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 located 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.
In Table 2 are summarized the main characteristics of each test section.

Table 2 - IWT test sections main characteristics

	Main	Secondary	Additional	Open Jet
Height [m]	2.35	2.35	2.35	2.35
Width [m]	2.25	1.15	3.60	2.25
Length [m]	7.00	5.00	8.30	7.00
Mach	0.41	0.70	0.25	<0.4
Minimum Static Temp. [°C]	-32	-40	-32	-32
Maximum Altitude [m]	7000	7000	7000	7000

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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°, enabling comprehensive aerodynamic analyses under various angles of incidence.
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 Upgrade of CIRA Icing Wind Tunnel

The inclusion of a Thermal Load Management System (TMS) in aircraft components entails the need to conduct verification and validation tests of the component prior to flight use. The Italian Aerospace Research Center, CIRA, aims to offer a real environment in which to experiment with different thermal load requirements at cruise altitude depending on the dissipation load required by the propulsion system through the TMS system being tested. To do this the IWT facility is expanding its fluid conditioning capabilities to serve the test section, already equipped with spray bars for simulating ice formation and hot air systems for anti-icing testing. In detail, a thermal generation station will be set up, capable of producing up to 500 kW of thermal power in the form of water-glycol mixture, at a pressure of 10 bar and 1200 l/m to be supplied to the components under test in the tunnel. These may include liquid to air exchanger or more innovative systems such as structure-integrated heat exchangers, such as skin heat exchangers [9] or nanofluid-based system [10] designed to enhance the thermal conductivity of the base heat transfer fluid.

The Heat Generation system will 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.

The winning feature is represented by the possibility of testing the TMS system in a relevant environment capable of simulating both the speed of the aircraft, and also the altitude with the variation of operating pressure, temperature and, if necessary, the presence of clouds and icing on the exchanger surface.
Figure 3 shows a basic layout explaining the system's function. The system is composed of an electrical heating unit that sends a flow rate of heat transfer fluid to the test section under specific temperature and pressure conditions, which can be set directly through the control system.
The unit has been designed to simulate the hot flow of coolant coming from the electric motor, from the energy storage and/or conversion system (batteries or fuel cells) and from the electronic control system. This would let the test being performed in a relevant environment in term of dissipation for the TMS component under investigation.
Table 3 shows the system operating range and the maximum heat output that can be delivered to the fluid for operation of the wind tunnel test article.

Table 3 - Operating conditions and accuracy of the heat load simulation system

Heat load simulator operating conditions	
Maximum heat power	500 kW
Maximum continuous operating temperature	120 °C
Maximum operating temperature (peak only)	130 °C
Maximum operating pressure	10 bar
Maximum mass flow rate	1200 l/min
Accuracy of the control system	
Temperature control accuracy	± 1 °C
Flow rate control accuracy (based on set value)	± 2%
Pressure control accuracy	± 0.2 bar
Minimum adjustable thermal power	10 kW

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To ensure precise control of the temperature, pressure and flow rate of the refrigerant, the system has been equipped with pressure sensors (PT in Figure 3) for absolute pressure measurement, PDI for differential pressure measurement and temperature sensors (TT in Figure 3) 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 Figure 3), 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 section during testing.

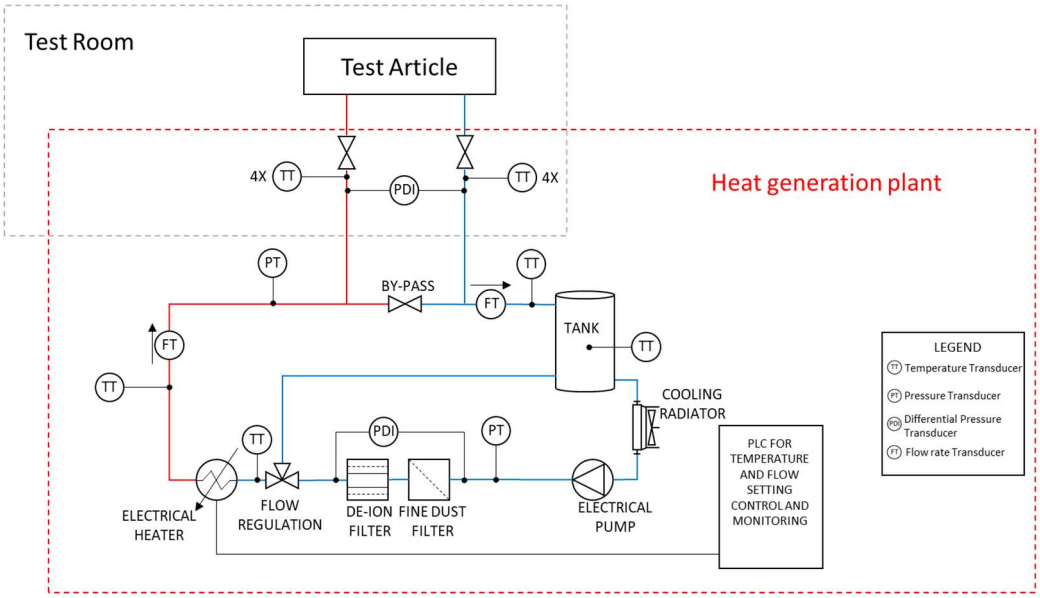


Figure 3 - Layout of the main components of the heat generation system.

A filtering system for the heat transfer fluid is included to prevent the accumulation of dust and scaling deposits on the electric resistances or in the article during the tests. 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 3 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.

2.2 Control and measurement system

The thermal generation system employed for simulating the aircraft thermal load is equipped with an electronic control unit that enables the configuration of set-point values, temperature ramp times, and the acquisition of fluid delivery and overall system data. This setup is designed to prevent potential errors or anomalies during data acquisition. Temperature and pressure sensors are strategically installed at all critical points of the plant, with particular attention to the test section, in proximity to the test article, where temperature is measured via four probes to enhance data accuracy. Considering the system may operate at high pressures (up to 10 bar), two flow meters are positioned upstream and downstream of the branch leading to the test section, as shown in Figure 3. This configuration allows the identification of leaks within the tunnel, should a discrepancy in measured flow rates occur, thus permitting timely test interruption to avoid anomalies or the acquisition of invalid data. All pressure, temperature, and flow rate measurements, as well as the system's operational status, are transmitted to the wind tunnel control room, thereby enabling real-time data integration and comprehensive experimental analysis. In particular, the electronic control system:

a. allows for the configuration of temperature, pressure, flow rate, and/or thermal power transferred to the fluid (depending on the experimental condition), as well as reference times for any transient variations occurring during the test. The system autonomously manages all operations required to achieve the desired target conditions.

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b. allows manual control commands for the independent operation of each actuator, at the operator's discretion, within the safety limits of the system's operating conditions.
c. provides the operator with a user interface for the visualization of the plant's operating parameters acquired during operation, as well as those related to the operational status of the control system itself.
d. logs all measurement and operational data relevant to the experiment, as well as to the identification of potential anomalies (alarms and warnings), both locally and remotely, enabling data access and sharing from the wind tunnel control room.

3. TMS simulation capabilities of the IWT facility

Being able to carry out tests in simulated altitude conditions allows the identification of the right trade-off between a decrease in temperature and a decrease in air density, necessary for the correct sizing of the dissipation unit, for the benefit of the overall weight of the system. Considering for example a classic crossflow exchanger, sized to dispose of 300 kW in ambient air conditions. The same exchanger, operating at 2000 or 6000 meters altitude conditions, despite the decrease in air density, the simultaneous decrease in temperature benefits the thermal exchange, reaching a dissipation of up to 500 kW with the same exchanger. These calculations, although generally suitable for preliminary sizing, were carried out considering a real starting exchanger, keeping the flow rate and the hot side inlet temperature unchanged and varying the temperature and density of the air that theoretically hits the exchange surface. The equations used were 1 and 2 [18], while the next Table 4 shows the starting conditions.

$$Q = U \times A \times f\Delta T_{ml} \tag{1}$$

$$Q = m_w \times c_{p_w} \times \Delta T_w = m_{air} \times c_{p_a} \times \Delta T_{air} \tag{2}$$

Table 4 – Typical operating conditions of a real exchanger

Real Exchanger data	
Fluid Hot side	Water/glycol (50/50% v/v)
Mass flow rate Hot side	600 l/min
Q	300 kW
T1	75 °C
T2	67,2 °C
T3	35 °C
T4	55 °C
Air Velocity	10 m/s
UA[1]	12 000 W/K

[1] *- The UA value shown in the above and in the next table has been obtained with the ε-NTU method [18], [19].*

Table 5 shows the results obtained in terms of minimum UA value, gained with the ε-NTU method [18], [19] in the different operating conditions (air flow rate and air temperature), to obtain the new characteristics of the exchanger in terms of heat exchange coefficient and exchange area in the new operating conditions.

Table 5 - Results of a preliminary design for a closs-flow heat exhanger at different altitude

Data Input	**2000 meters altitude**	**6000 meters altitude**
Air Velocity	10 m/s	10 m/s
Mass flow rate Hot side	600 l/m	600 l/min
T1	75 °C	75 °C
T3	2 °C	-24 °C
Air density	1,01 kg/m^3	0,66 kg/m^3
Results		
UA value for 300 kW dissipation	5,27 kW/K	4,32 kW/K

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From the results, even if in this discussion represent only a preliminary sizing, it emerges that an exchanger, sized to dispose of 300 kW on the ground level, might be able to dispose a greater value of heat power at higher altitudes, despite the decrease in air density. This can translate into the use of smaller exchangers, provided that the mission profile for the aircraft includes the point of maximum thermal load to be disposed at top climb altitude. Being able to verify in real like environment the decrease in the UA value, compatible with the aircraft's mission profile, would allow the evaluation of a significant saving in the size and weight of the cooling system, a critical issue today in the diffusion of electric propulsion systems powered by batteries or fuel cells.

3. Conclusions

This paper has detailed the critical need for advanced Thermal Management Systems in the development of next-generation hybrid-electric aircraft, a key pathway towards achieving stringent emissions reduction targets in the aviation sector. The EU-funded AMBER project, focused on maturing megawatt-class hybrid electric propulsion, underscores this necessity. Within this framework, the Italian Aerospace Research Centre is undertaking a significant upgrade of its Icing Wind Tunnel facility. This enhancement, centered around a new heat generation system capable of delivering up to 1MW of thermal power with precise control over temperature, pressure, and flow rate, will enable comprehensive experimental characterization of full-scale TMS components.
The upgraded IWT will provide a unique capability to test these 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, a crucial step before aircraft integration.
By enabling the experimental validation of TMS in conditions representative of an actual flight envelope, including the complex interplay of varying air density and temperature at altitude, this upgraded infrastructure will offer invaluable data for optimizing TMS design. Preliminary analyses indicate that testing at altitude could reveal opportunities for significant reductions in the size and weight of cooling systems, which is paramount for the viability of hybrid-electric powertrains. So, the enhanced CIRA IWT will serve as a cornerstone for de-risking new thermal technologies, accelerating their adoption, and supporting the European aerospace industry's transition towards greener and more energy-efficient aircraft, in line with global environmental objectives.

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Acronyms and Abbreviations

A	Heat exchange area
AMBER	InnovAtive DeMonstrator for hyBrid-Electric Regional Application
AZEA	Alliance for Zero Emission Aviation
cp_a	Specific heat capacity of cold fluid
cp_w	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
f	Exchanger shape correction factor
FC	Fuel Cell
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
m_{air}	Cold mass flow rate
m_w	Hot mass flow rate
MVD	Median Volume Diameter
NOx	Nitrogen Oxides
PEMFC	Proton Exchange Membrane Fuel Cell
PDI	Pressure Differential Indicator
PT	Pressure Transmitter
Q	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
U	Heat transfer coefficient

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