33RD CONGRESS
OF THE INTERNATIONAL COUNCIL
OF THE AERONAUTICAL SCIENCES
STOCKHOLM, SWEDEN, 4-9 SEPTEMBER, 2022

ICAS 2022 SWEDEN

USE OF THE FLIGHT TEST FACILITY MOCK-UPS IN THE EUROPEAN CLEAN SKY 2 PROGRAM

Victor Norrefeldt, Florian Mayer, Arnav Pathak, Marie Pschirer, Max Kienberger, Andreas Lindner, Sabine Johann, Anna Nagele-Renzl, Michael Buschhaus, Gunnar Grün

[1]Fraunhofer Institute for Building Physics IBP, Fraunhoferstr. 10, D-83626 Valley, Germany

Corresponding author: victor.norrefeldt@ibp.fraunhofer.de

Abstract

The Clean Sky 2 program unites all major European players in the aeronautical sector to conduct research on future, more energy efficient aircrafts with lower environmental footprint. Besides technologies developments, the demonstration of technologies in dedicated test environments is a key element of this research program. The Fraunhofer Flight Test Facility is such a platform for technology demonstration. Located in Holzkirchen, south of Munich, it hosts several aircraft fuselage structures and allows for indoor environmental tests under realistic temperature, moisture and pressure conditions. In this paper, demonstrations performed within Clean Sky 2 are highlighted. These include an adaptive ECS system, environmentally friendly fire protection, model validation tests for ETOPS considerations and cleaning and disinfection demonstrations.

Keywords: technology demonstration, ground test, environmental test, Clean Sky

1. Introduction

The major aim of the Clean Sky program is the development of cleaner air transport technologies. To achieve this, the European Union, Industry, Research and Academia formed a Joint Undertaking striving to reach climatic goals and creating a competitive aeronautic industry. Within this research agenda, the Fraunhofer Fight Test Facility plays an important role as a platform for technology demonstration. The special focus of this research facility is the indoor climate in aircrafts. In this scope, indoor climate focusses on different aspects like thermal management, passenger comfort and safety, agent distribution and air quality.

The heart of the Flight Test Facility is a low pressure vessel of 9.6 m diameter and 30 m length (Figure 1). This low pressure vessel is able to operate at pressures down to 750 hPa with people and 116 hPa without human beings inside. Through this, subject tests at a realistic pressure equivalent of 8000 ft, corresponding to 750 hPa, as implemented in today's airliner pressure control system [1] can be conducted.

This publication aims to provide an overview of the involvement of the aircraft mock-ups in the Clean Sky 2 programme.

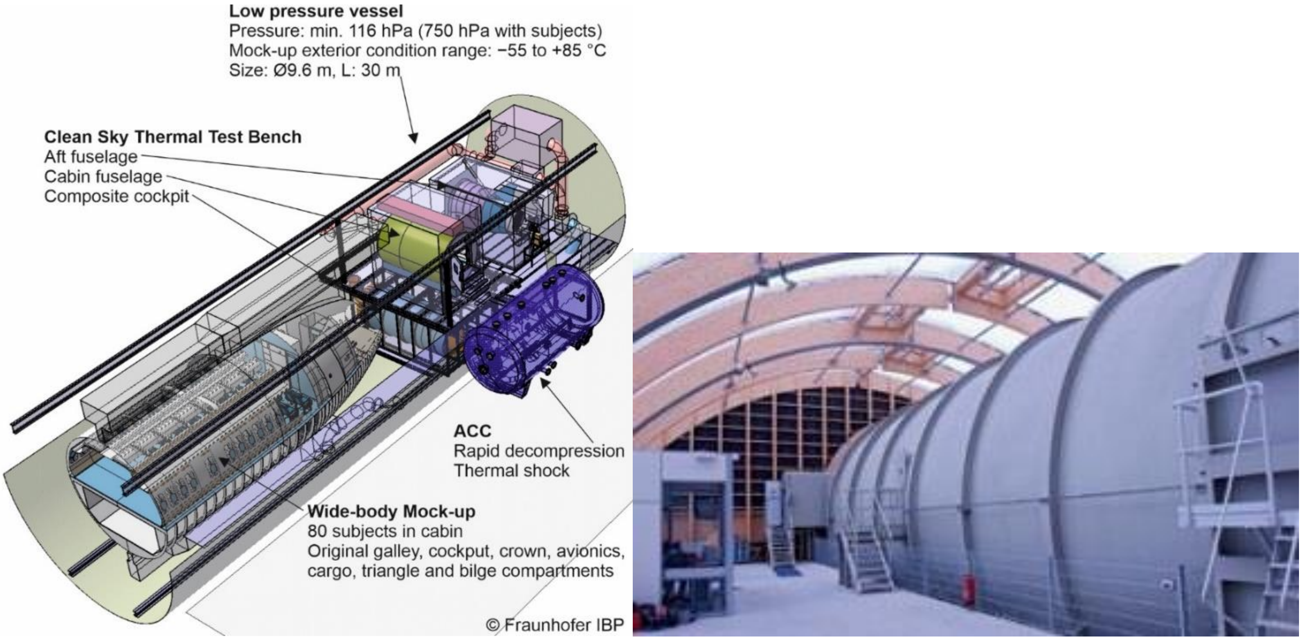


Figure 1: Flight test facility

1.1 Wide-body mockup

The low pressure vessel integrates several mock-ups. The largest one is a former in-service wide-body aircraft. After end of service, it was cut at the front wing box and integrated into the Flight Test Facility in 2005 (Figure 2). In the underfloor, the mock-up consists of the forward cargo bay with the adjacent triangle areas, bilge and the avionics compartment. The main deck consists of the cabin, galley, lavatory, crown and cabin with space for up to ten rows of a 2-4-2 seat arrangement. Hence, up to 80 subjects fit into the mock-up. The mock-up is ventilated by a dedicated ECS emulation system. In this system the fresh air is freezed to -20 °C and then reheated in order to simulate the dry air in cruise. The air enters a mixing chamber, where it is mixed with recirc air and supplied to the cabin through original ceiling air inlets and refurbished inlets below the stow bins. Furthermore, the galley/door area and the cockpit can be supplied with air from the mixer unit. Cabin air overflows below the dado panels into the triangle areas. From there, the recirc air is aspired and HEPA-filtered before being resupplied to the mixer unit. The exhaust air overflows behind the cargo liner into the bilge area from where it is extracted (Figure 3).

Figure 2: Fuselage integration in low pressure vessel

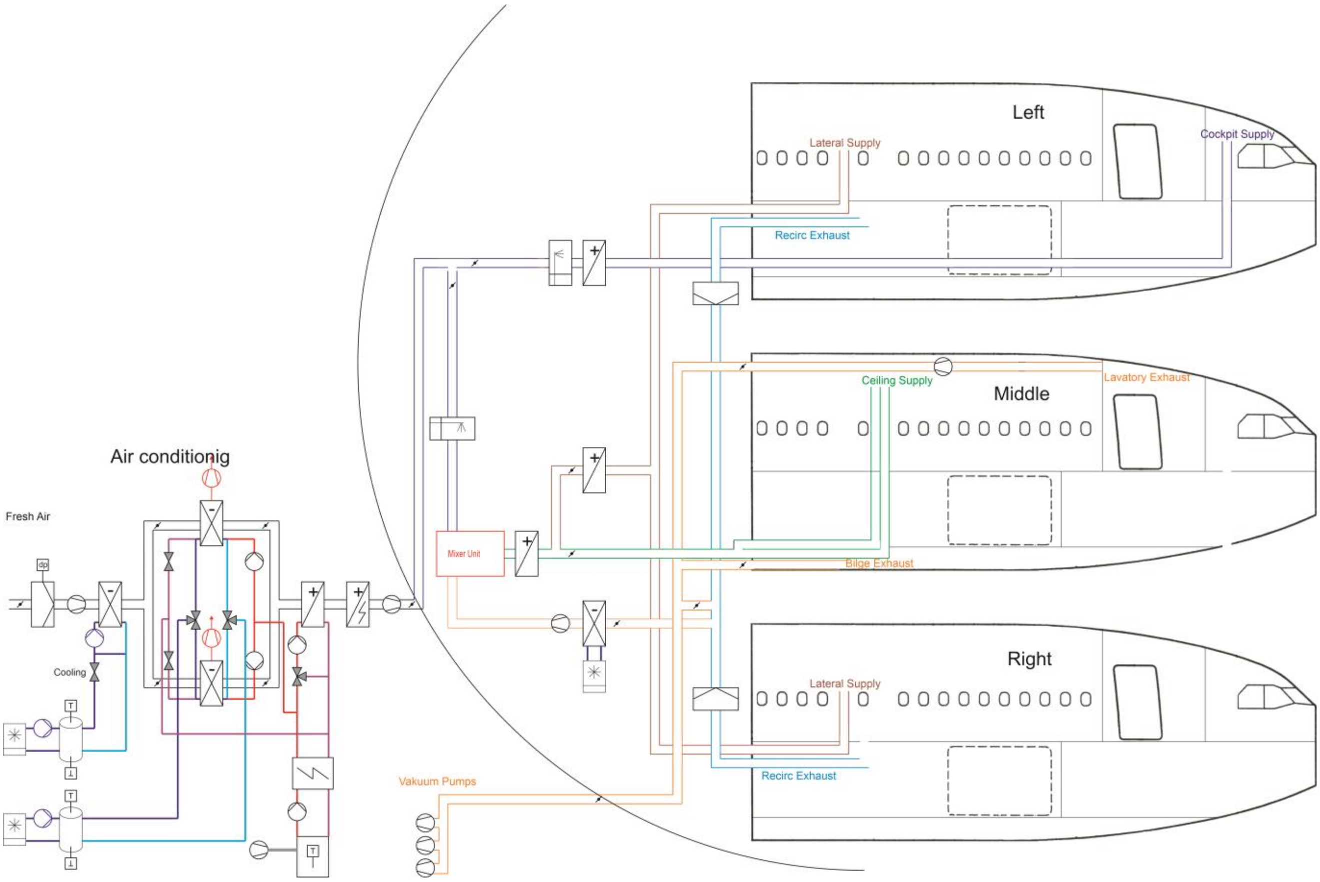


Figure 3: Ventilation pattern of the wide-body mock up

In order to generate low temperature exterior conditions, a second skin is built around the mockup leaving a 2" air gap. This gap is flushed with conditioned air and allows cooling the fuselage surface down to temperatures between -20 to -30 °C (Figure 4). With operable flaps, the distribution of cold air can be optimized to the actual test requirement.

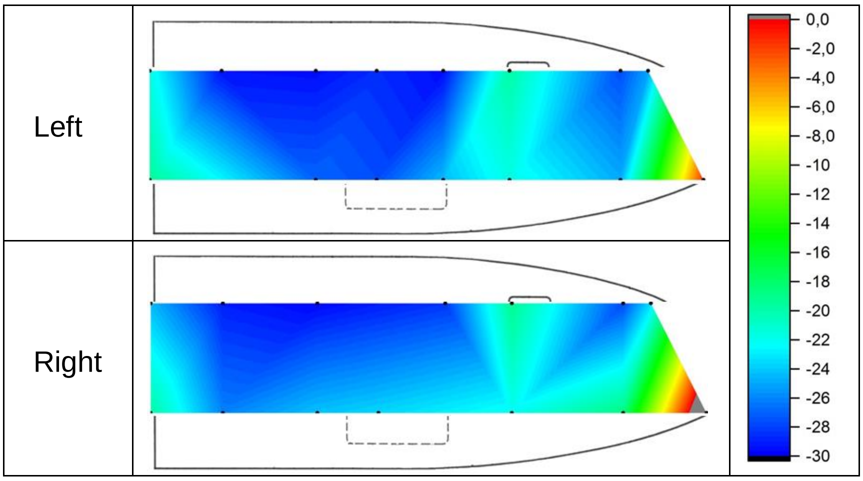


Figure 4: Cocoon ventilation temperature distribution

1.2 Business Jet Mockups

Within Clean Sky Eco-Design for Systems, three business jet mock-ups provided by Dassault Aviation were integrated in the Flight Test Facility (Figure 5):

- 80% scaled composite cockpit section

- Business Jet Cabin section
- Empennage incl. avionics bay

These mock-ups are equipped with an ECS emulation system and a cocoon ventilation, allowing cooling the exterior fuselage down to -50 °C. Here, a lower temperature is achieved due to the smaller size of the mock-ups.

Figure 5: Business Jet Mock-Ups

1.3 Aircraft Calorimeter (ACC)

The AirCraft Calorimeter (ACC) is a second low pressure vessel connected to the evacuation system of the large low pressure vessel. Through this, very dynamic pressure changes are achieved down to 5 hPa. Its size is 3.2 m in diameter and 5.5 m in length. The ACC integrates a heat exchanger with 500 kg steel that can be pre-cooled down to -60 °C and hence allows creating a thermal shock inside the chamber. The inner walls of the vessel are insulated in order to minimize conductive losses. Through this approach, accurate energy balancing is possible. Typical applications of the chamber are high gradient cooling tests, like e.g. skin heat exchangers or test of rapid decompression / thermal shock according to DO160F and their effect on the thermal system.

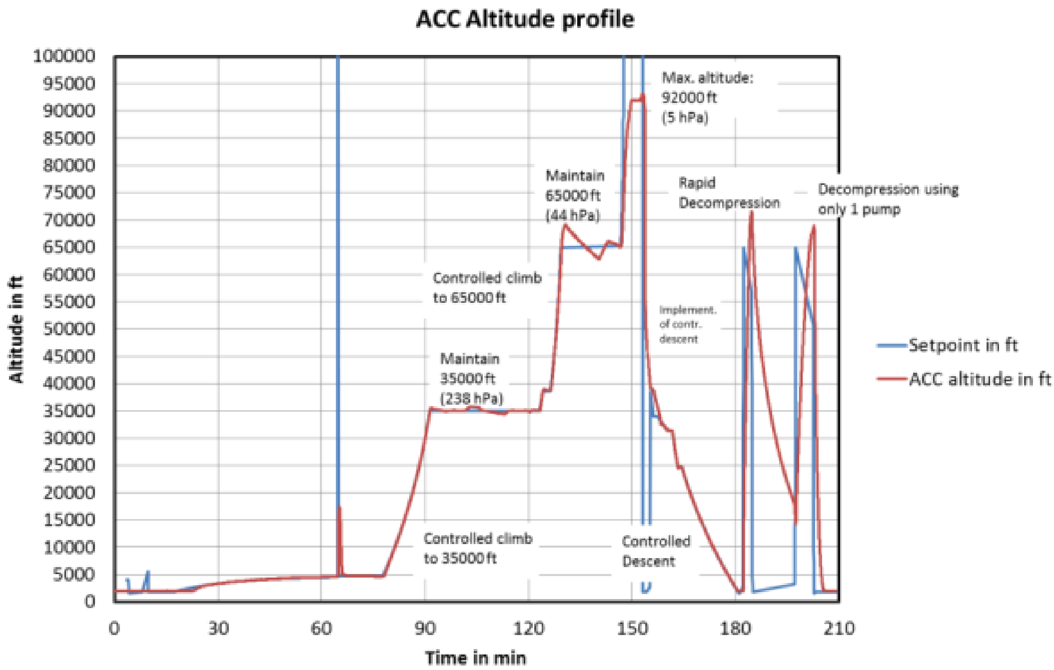


Figure 6: ACC pressure profile for controlled pressures and rapid decompression

1.4 Regional Passenger Cabin Ground Demonstrator

The Passenger Cabin Ground Demonstrator, a full-scale fuselage section of a future Regional aircraft consisting of the door/galley area and five rows of seats, is currently under development.

The demonstrator's aim is to validate innovative systems and human centered design concepts within the CleanSky2 Regional project. The Passenger Cabin is a Clean Sky JU Leader LEONARDO Aircraft Demonstrator for all aspects concerning research, technological maturation, design, manufacturing and integration. It will, in the course of the project, be transferred to Fraunhofer for thermal testing. Within Fraunhofer, the demonstrator will be equipped with an ECS emulation system and an exterior conditioning to be able to thermally imitate the operation of the cabin section over a flight cycle. A sketch of the current planning status is shown in Figure 7.

Figure 7: 3D printed model of the Passenger Cabin Ground Demonstrator

2. Clean Sky 2 projects conducted in the FTF

2.1 ComAir: Investigation of the Adaptive Environmental Control System

Subject tests were conducted in the wide-body cabin mock-up to determine comfort perceptions in an adaptive environmental control system [2]. In 12 sessions, the fresh/recirculation airflow ratio was altered from today's typically applied fractions (Baseline, 5.2 l/s fresh air leading to slightly above 1200ppm CO_2) to up to 88% recirculation fraction.

Table 1: Overview of ComAir test conditions

Test condition	Rationale	Fresh airflow rate (l/s per passenger)	Recirculation airflow rate (l/s per passenger)	Tests performed
Baseline	Replicate today's typical CO_2-concentration of ~1300 ppm [3–5]	5.2	4.2	2x half booked 1x fully booked
ASHRAE	Min. required fresh airflow rate [1]	3.5	5.7	
ASHRAE half	Half of min. required fresh airflow rate	1.8	7.6	
Max. CO_2	High CO_2 level but exposure below limit of 5000 ppm	1.1	8.3	
VOC / CO2 dosing	Separate dosing of CO_2, VOC or both into cabin to artificially replicate conditions	5.2	4.2	4x half booked

The major results of this study can be summarized:

- Relative humidity, CO_2 and TVOC clearly increase with decreasing outdoor airflow rate
- Singular events like the use of a cleaning agent showed higher impact on the TVOC levels than the airflow regime
- Neither a trained sensory panel nor subjects could differentiate smell or acceptability for the different recirculation airflow conditions. Only in a fully booked cabin slightly worse votes were given at lower outdoor air intake.
- The occupancy (half vs. fully booked) showed to play a major role for subject's wellbeeing [6].
- When the amount of outdoor air becomes too low, additional cooling capacity is needed in the recirculation path. This would result in a possible need for redesign of the ECS compared to today's architecture. In the study, such cooling capacity was added in the ECS emulation system.
- The tests allowed developing a mixture of VOCs that can be dosed in future tests to represent human emissions. This mixture includes Ethanol, Acetonitrile, Acetone, 2-Propanol, Acetic acid, Hexanal, Nonanal, 1-Propanol, Toluene, Ethyl acetatate, 6-Methyl-5-hepten-2-one and Limonene.

Figure 8: Exemplary subject test in wide-body mock-up

The project was conducted together with the Ludwig-Maximilians-Universität München (LMU) and Danske Tekniske Universitet (DTU) under the topic management by Collins Aerospace (formerly UTRC). Special thanks are attributed to PD Dr. phil. Dipl.-Psych. Britta Herbig and Associate Professor Pawel Wargocki.

This study received funding from the Clean Sky 2 Joint Undertaking under the European Union's Horizon 2020 research and innovation programme under grant agreement No. 820872-ComAir-H2020-CS2-CFP07-2017-02.

2.2 Environmentally Friendly Fire Protection

The goal is the replacement of today's cargo fire extinguishing agent Halon, a substance with high global warming potential of 7100. In the "Environmentally Friendly Fire Protection" project, the distribution of new, environmentally friendly fire extinguishing agents and systems for the cargo area are experimentally validated. Discharge characteristics and concentration profiles are investigated under various climatic conditions. The aim is to prove that the design concentration in the entire cargo area is reliably maintained over the entire flight cycle until landing. For this, the wide-body mockup's cargo hold was entirely refurbished (Figure 9). A door seal leakage emulation was integrated inline with the minimum performance standard (MPS) for agent distribution testing [7]. New liners and the pressure management system were installed, that allows attaining the pressure equilibrium during climb and descent as well as during agent release. Furthermore, the agent distribution line together with the cavity and injection nozzles were integrated.

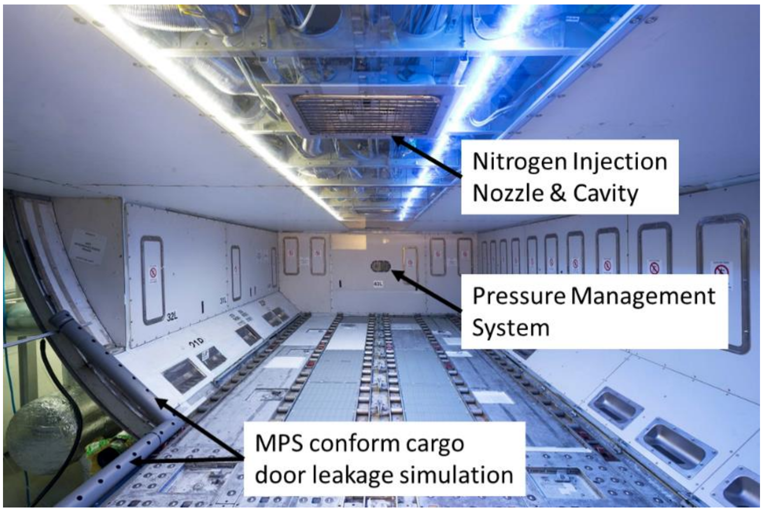


Figure 9: Refurbished wide-body cargo hold

To ensure the system operability over a wide range of conditions, several tests were conducted varying

- Cargo hold initial temperature and pressure
- Cargo hold load density (empty vs. containerized loads)
- Storage bottle's temperature
- Amount of agent injected

The low pressure vessel allows the application of a realistic cabin pressure profile, taking into account the ingress of fresh air during descent due to repressurization. This ingress leads to dilution of the suppression agent by fresh air. Furthermore, the agent concentration was measured in the cabin to ensure that passengers and crew are safe despite activation of the cargo fire suppression system.

Together with our project partners various demonstrations were performed in the Flight Test Facility for innovative, environmentally friendly Halon replacements:

- Nitrogen suppression system
- Use of the On-Board Inert Gas Generation System (OBIGGS), a technology derived from fuel tank inerting [8]
- High-boiling point suppression agent

Besides the experimental campaign, Fraunhofer researchers validated model based design approaches to predict the agent distribution in the cargo hold. The models implement the zonal decomposition of the cargo hold, an agent distribution model and a CFD domain of the injection region. Such models enable the scalability of the test results achieved on the wide-body demonstrator to other aircraft platforms or transient mission profiles [9].

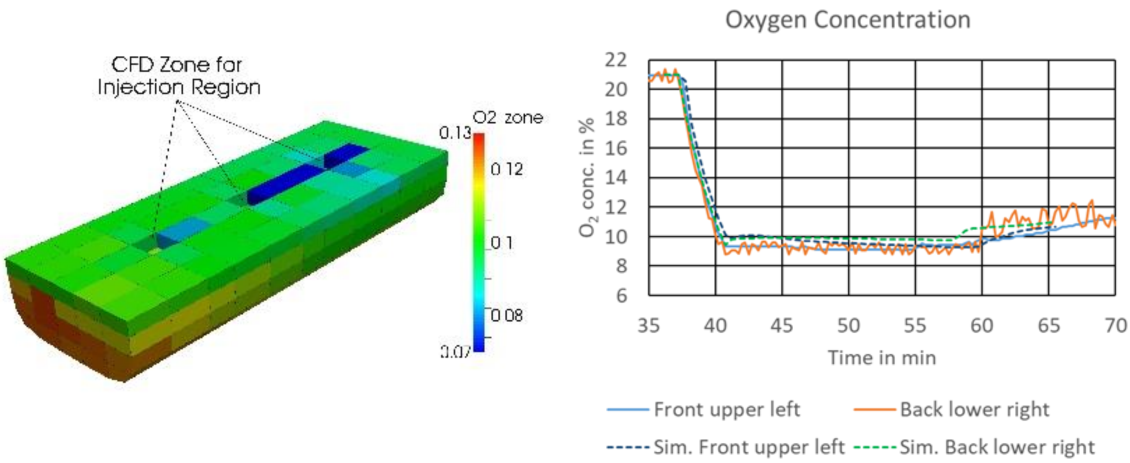


Figure 10: Zonal prediction of O2 concentrations for a nitrogen based fire suppression system (left) and model validation results (right).

The air tightness of the cargo liners is a major contributor to the fire suppression system performance. Leakages in the liner contribute to dilution of the agent and hence require larger amounts of agent supply. The so called Blower Door Method has been adapted to detect and seal leakages in the cargo liners – and hence probable locations of fresh air ingress leading to dilution of the fire suppression agent [10]. For this, the cargo hold is heated with electrical fans and a low pressure is generated by an air extraction system. On the thermal image the ingressing air leaves a thermal footprint indicating leakages by cold "noses" close to seams.

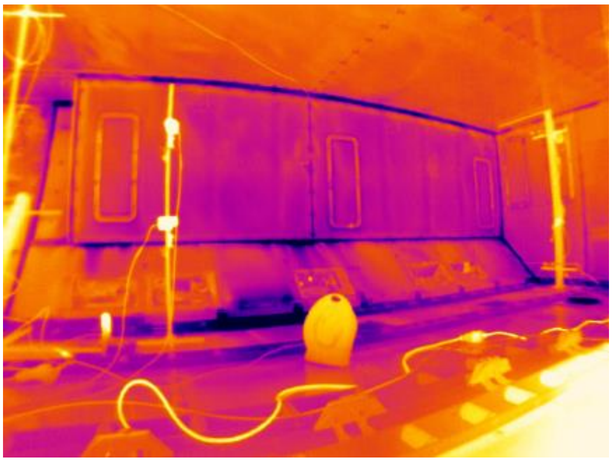


Figure 11: Thermal image showing leakages at the seam between the vertical and inclined liner.

As a result of the tests and simulations conducted within the Flight Test Facility, novel fire suppression systems could be raised to TRL 6.

The work was conducted with financial support from the Clean Sky 2 program under Grant Agreement number: LPA-IADP CS2-LPA-GAM-2020-2021-01.

2.3 Novel Certification

Within the Airframe A - Novel Certification approach, the possibility to use model based design for the assessment of thermal hazard cases was investigated. The underlying question is whether a loss of the ECS in an exterior thermal environment of -50 °C can be sustained for an ETOPS (Extended Operation) time of 3 h. This means that the aircraft may operate up to 3 h from away from the nearest airport. As pass criterion, the threshold of a cabin air temperature of 0 °C was applied. For this, a zonal simulation model [11,12] of the business jet cabin was set up. From a normal flight case, the loss of ECS was simulated resulting in a gradual reduction of temperature in the cabin. Thermal inertia was integrated into the model.

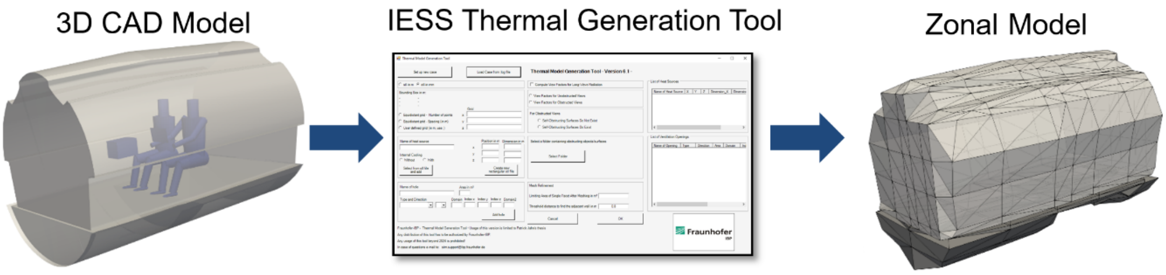
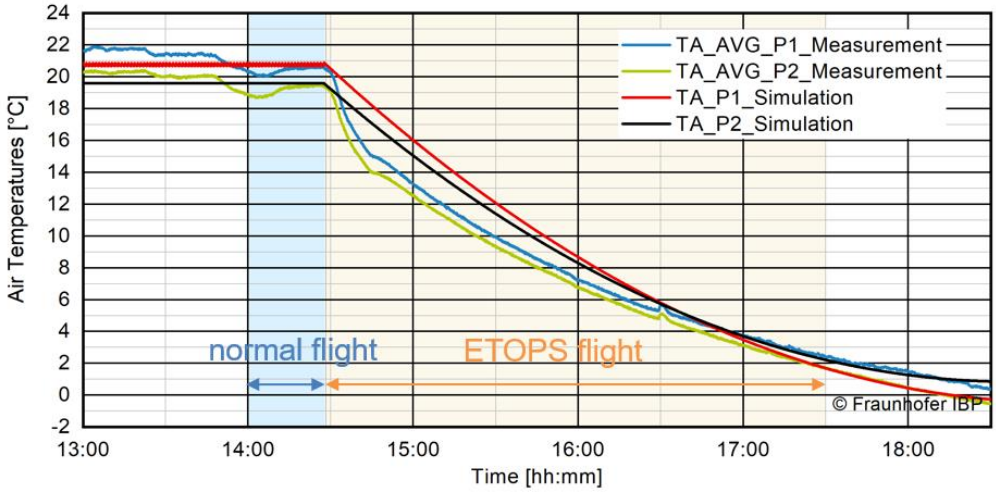


Figure 12: Generation of a zonal airflow model from the business jet CAD geometry

Accordingly, a test setup was integrated into the Business Jet Cabin Demonstrator. Thermal loads from laptop, passengers and in-cabin systems were installed along with temperature sensors in two positions (P1, close to seat, P2, distant from seat).

Figure 13: Business jet cabin demonstrator test setup

The model and the test prove that after 3 h, the interior cabin temperature is predicted with an accuracy of 1 °C. Hence, the zonal model proved its ability to solve such certification relevant thermal considerations by simulation.



The work was conducted with financial support from the Clean Sky 2 program under Grant Agreement number: GAM AIR 2020-2021/945521.

2.4 Cabin Air Disinfection

In the light of the Covid-pandemic, the Business Jet Mock-Up was additionally used to investigate the spread of virus within the cabin and the effect of air purification by an ion generator. For this, a breathing head was connected to an aerosol generator to replicate the human particle emission through the mouth (Figure 14). The aerosol consisted of a buffer solution with phi6-phagus. This phagus is a virus only attacking selected bacteria and hence not harmful to animals and humans. It has a representative structure of the Sars-CoV-2 virus. Air and wipe samples were taken at breathing height of the opposite passenger and on the table. Furthermore, a method to contaminate and measure the impact of cleaning devices on smooth structures like the carpet was developed. Here, a defined amount of viral solution is spread with drops on the carpet. After exposure, the carpet is cut around these five droplets and soaked in a thinning solution to dissolve the remaining viral load. The plague assay method was used to determine the load of infectious virus in the solutions extracted from the samples.

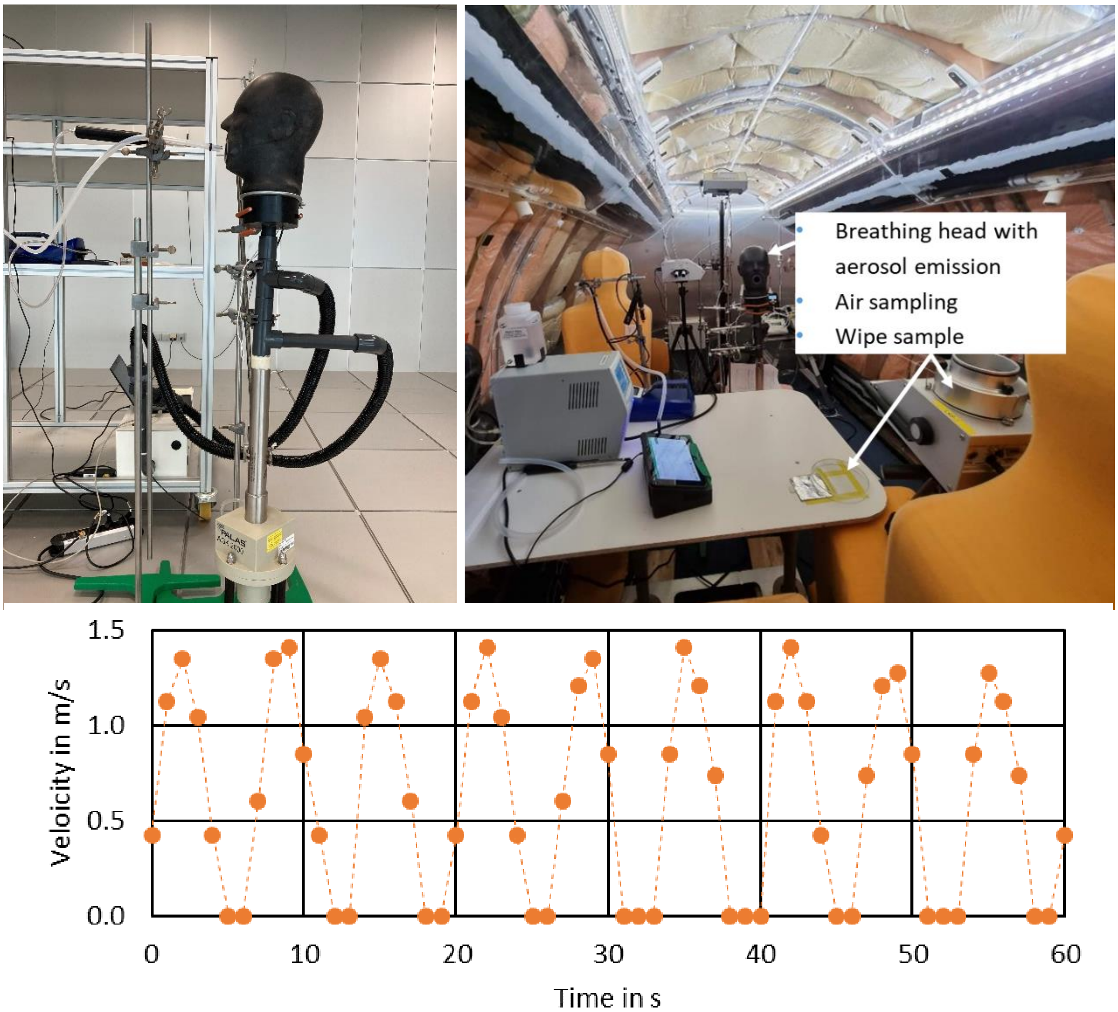


Figure 14: Breathing head apparatus (lop left), Test setup in Business Jet demonstrator (top Right), Characterization of airflow velocity in mouth of head (bottom)

As a proof of concept, the combination of increased airflow and ion emission proved to actively reduce the viral load both in air and on surfaces (Figure 15). For all three samples (air, table and carpet) a reduction of viral load by approx. 80% could be achieved.

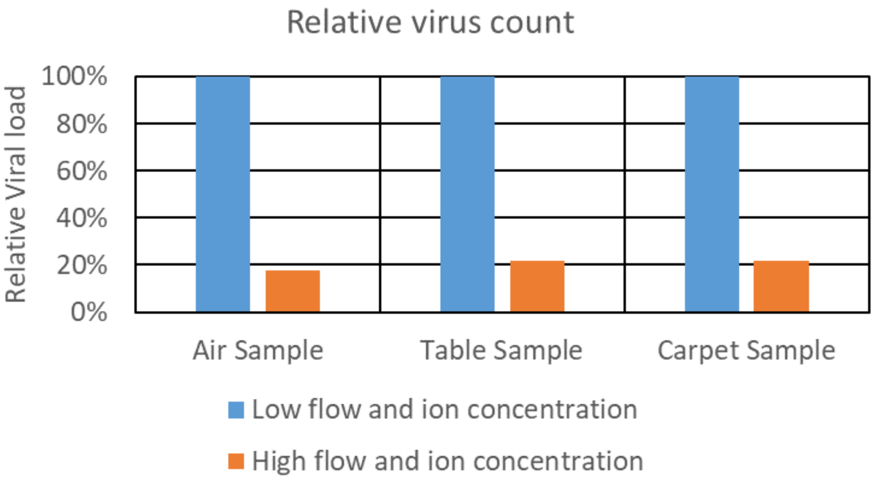


Figure 15: Effect of increase airflow and ion dosing on viral load

The work was conducted with financial support from the Clean Sky 2 program under Grant Agreement number: GAM AIR 2020-2021/945521.

2.5 Demonstrations for the Regional Aircraft

Within the Regional IADP, Fraunhofer performs demonstrations of different technological bricks for the new Regional aircraft. One such brick is an innovative recirculation air-cleaning device provided by the project partner Diehl Aviation. This device reduces VOCs in the recirc air through a non-thermal plasma generation device, followed by an active activated carbon filter to remove ozone. A demonstrator is currently integrated in the recirc air path of the wide-body demonstrator (Figure 16) to assess its matureness for use in the Regional Demonstrator. The VOC mixture developed within the ComAir project (§2.1) is dosed by a syringe pump into the cabin supply air. It contains ethanol, acetonitrile, acetone, 2-Propanol, acetic acid, hexanal, nonanal, 1-Propanol, toluene, ethyl acetate, 6-Methyl-5-hepten-2-one and limonene. Its smell is a bit fruity, soapy and sweaty. A PID is placed in the cabin to monitor the TVOC concentration.

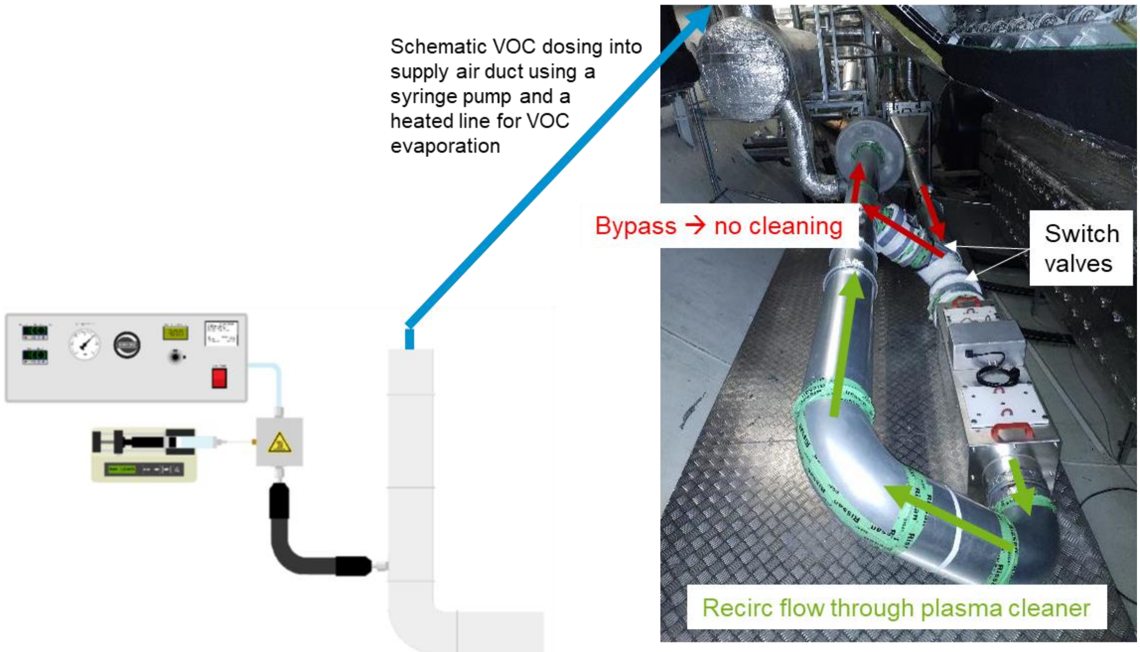


Figure 16: Integrated air cleaning demonstrator

The test is conducted in three phases. In phase 1, the TVOC concentration is built up without the demonstrator operated (8:30 – 10:30). During this phase, the switch valve is set for air to shortcut the demonstrator. Then, the valves are adjusted to guide air through the demonstrator but the plasma source remains inactivated (10:30 – 12:30). Hence, the effect of only the activated carbon filter is shown. In the last phase, the plasma source is switched on (12:30 – 14:30). At 14:30, the VOC injection is switched off and the decline of VOC is monitored for 30 min.

Figure 17 shows the result of the measurement. It is obvious that the cleaner has the potential to reduce the VOC load in the cabin. However, whether the non-thermal plasma source took over this task when switched on or whether the activated carbon filter remained the sink for VOCs cannot be discerned.

To exclude ozone exposure by the non-thermal plasma source, additionally this parameter was measured. The maximum increase of ozone level during operation was found to be 4 ppb and thus can be considered negligible compared to the limit of 100 ppb set out in ASHRAE 161 [1].

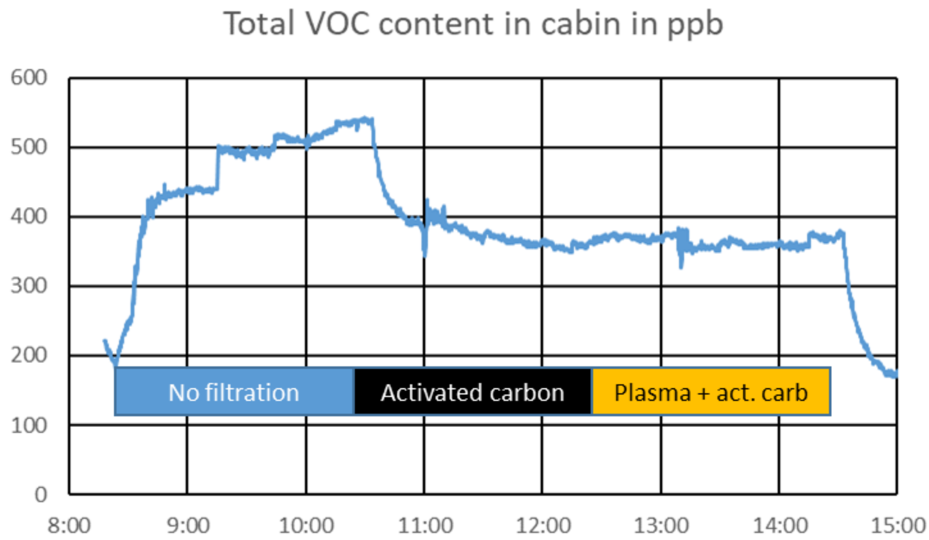


Figure 17: Measured VOC concentration in the cabin

This study was funded by the Clean Sky 2 Regional IADP under grant agreement No. 945548. The demonstrator was provided by Diehl Aviation and funded by the Clean Sky 2 NADiA project under grant agreement No. 831716.

3. Conclusion

This paper highlights the value the Fraunhofer Flight Test Facility brings to the Clean Sky 2 program. It gives an overview of the projects that have been realized within this program covering different thematic fields like

- Passenger comfort related to air quality and occupancy
- Environmentally friendly fire suppression system for the cargo hold
- Hazard and comfort considerations in the business jet aircraft for model based ETOPS certification
- Covid-risk reduction in the cabin
- Technologies demonstration for the future regional aircraft.

4. Acknowledgements

We want to thank the Clean Sky 2 program for the various projects we were able to realize within the Flight Test Facility. Grant numbers are provided in the project sections. The authors are responsible for the content of this publication.

5. Copyright Statement

References

References

[1] ANSI/AHSHRAE. ASHRAE Standarad 161 - 2007: Air quality within commercial aircraft.

[2] Norrefeldt, V.; Mayer, F.; Herbig, B.; Ströhlein, R.; Wargocki, P.; Lei, F. Effect of Increased Cabin Recirculation Airflow Fraction on Relative Humidity, CO2 and TVOC. Aerospace 2021, 8, 15, doi:10.3390/aerospace8010015.

[3] Giaconia, C.; Orioli, A.; Di Gangi, A. Air quality and relative humidity in commercial aircrafts: An experimental investigation on short-haul domestic flights. Building and Environment 2013, 67, 69–81, doi:10.1016/j.buildenv.2013.05.006.

[4] Cao, X.; Zevitas, C.D.; Spengler, J.D.; Coull, B.; McNeely, E.; Jones, B.; Loo, S.M.; MacNaughton, P.; Allen, J.G. The on-board carbon dioxide concentrations and ventilation performance in passenger cabins of US domestic flights. Indoor and Built Environment 2019, 28, 761–771, doi:10.1177/1420326X18793997.

[5] Chen, R.; Fang, L.; Liu, J.; Herbig, B.; Norrefeldt, V.; Mayer, F.; Fox, R.; Wargocki, P. Cabin air quality on non-smoking commercial flights: A review of published data on airborne pollutants. Indoor Air 2021, 31, 926–957, doi:10.1111/ina.12831.

[6] Herbig, B.; Ströhlein, R.; Ivandic, I.; Norrefeldt, V.; Mayer, F.; Wargocki, P.; Fang, L. Impact of different ventilation strategies on aircraft cabin air quality and passengers' comfort and wellbeing - the ComAir study. In . ICES - 50th International Conference on Environmental Systems, 2020.

[7] Reinhardt, J.W. Minimum Performance Standard for Aircraft Cargo Compartment Halon Replacement Fire Suppression Systems, 2nd Update. US Department of Transportation Federal Aviation Administration, June 2005.

[8] Yangyang, W.; Yu, Z. Research on nitrogen enriched air flow of on-board inert gas generating system. In CSAA/IET International Conference on Aircraft Utility Systems (AUS 2020). CSAA/IET International Conference on Aircraft Utility Systems (AUS 2020), Online Conference, 18-21 September 2020; Institution of Engineering and Technology, 2021; pp 1027–1031, ISBN 978-1-83953-419-5.

[9] Pathak, A.; Norrefeldt, V.; Pschirer, M. Validation of a Simulation Tool for an Environmentally Friendly Aircraft Cargo Fire Protection System. Aerospace 2021, 8, 35, doi:10.3390/aerospace8020035.

[10] Norrefeldt, V.; Lindner, A.; Pschirer, M. Anpassung der Blower-Door Methode für die Leckagesuche im Flugzeug-Cargobereich. In 12. International BUILDAIR-Symposium, Hannover, Germany, 25.-26. June 2021, 2021.

[11] Norrefeldt, V.; Pathak, A.; Siede, M.; Lemouedda, A. Thermal Model and Thermal Model Generation Tool for Business Jet Applications. In Proceedings of the Greener Aviation Conference, Brussels, Belgium, 12–14 March 2014.

[12] Norrefeldt, V.; Grün, G.; Sedlbauer, K. VEPZO – Velocity propagating zonal model for the estimation of the airflow pattern and temperature distribution in a confined space. Building and Environment 2012, 48, 183–194, doi:10.1016/j.buildenv.2011.09.007.