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NEW LONG-RANGE CABIN MOCK-UP ENABLING THE SIMULATION OF FLIGHT CASES BY MEANS OF TEMPERED FUSELAGE ELEMENTS

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ABSTRACT:

A new full-scale cabin mock-up is set up to experimentally analyse the performance of novel ventilation concepts for long-range airliners. It enables the simulation of thermodynamically realistic boundary conditions by means of temperature-controlled fuselage elements taking static and dynamic operational conditions for different flight phases into account. In addition to the latest measurement techniques, such as velocity field measurements, local probes and tracer gas analysis, thermal manikins will be used to simulate the sensible heat impact as well as the CO_2 accumulation caused by passengers. Moreover, the mock-up is designed for human subject tests to validate the objective data.

1. INTRODUCTION

Climate change and the urgency of decarbonising the global environment are the driving force for technological innovations especially in the aviation industry. In case of civil aircraft, the Environmental Control System (ECS) consumes large amounts of energy during long-range flights, which reinforces the demand for energy-efficient HVAC and air distribution systems. To overcome the drawbacks of conventional mixing ventilation systems regarding energy efficiency, thermal passenger comfort and air quality, alternative and novel ventilation concepts have attracted the aircraft industry for decades. In this context, novel concepts, which promise energy- and weight-saving potential as well as a higher level of thermal comfort, are analysed numerically and experimentally using ground-based cabin mock-ups. The following section provides a short overview of the existing literature on the experimental analysis of novel ventilation concepts for aircraft cabins conducted in test benches at ground level. However, most of the investigations were related to single-aisle cabin configurations [1], [2], [3]. Advanced studies of different air distribution modes on dual-aisle airplane cabins included experimental tests in a seven-row 767-300 mock-up section [4]. However, only five rows of the test facility were equipped with heated passenger manikins.

To determine the efficiency of ventilation systems regarding the air quality in terms of contaminant transport or distribution, tracer gas measurements in aircraft cabin airflows are a common approach. Here, some measurements were carried out in ground-based test facilities, i.e. in a 767-300 mock-up [5], a four-row, dual-aisle mock-up section [6] or in a five-row section of a MD-82 [7].

Generally, the existing experimental studies either focused on single-aisle configurations or were conducted in dual-aisle configured test benches too simplified to allow for conclusions on operational scenarios (e.g. very short cabin sections). Furthermore, there are no studies addressing the performance of novel ventilation concepts under dynamic, non-ideal boundary conditions. The test facility described in [8] is the only mock-up section allowing temperature control via a thermostatic chamber. However, dynamic changes of the thermodynamic boundary conditions in a range covering relevant temperatures and time scales are still lacking.

The aim of the ADVENT project is to set up a new long-range cabin mock-up for testing novel ventilation systems under static and dynamic conditions. The mock-up allowing the installation of different cabin geometries on a 1:1 scale and is capable of integrating novel ventilation concepts. Furthermore, the new test bench provides thermodynamically realistic boundary conditions for the experimental simulation of different flight phases (e.g. hot-day-on-ground, climb and cruise), which can be changed on operationally relevant time scales. In addition to the latest measurement techniques, thermal manikins will be used during the experimental investigations to simulate the passenger´s heat load and obstruction as well as the exhalation. The latter is realised by equipping each manikin with a CO_2 release system. Additionally, the mock-up is designed in such a way that even human subject tests can be

performed.
In summary, the new test facility is designed to study novel, energy-efficient and comfortable ventilation systems and thus directly addresses the conference topic: “Research infrastructure for greener and safer aviation”.

2. TECHNICAL APPROACH AND IMPLEMENTATION

2.1. Thermodynamic Boundary Conditions

As mentioned in section 1, the main feature of the new cabin mock-up is the provision of thermodynamically realistic boundary conditions facilitating the experimental simulation of different operational phases (e.g. hot-day-on-ground, climb or cruise) under static and dynamic conditions. Therefore, the interior lining elements as well as the floor of the cabin are tempered.

Technical Background

To evaluate the performance of the cabin air conditioning system during different flight phases in terms of energy efficiency and thermal passenger comfort, the surface temperature distribution at the cabin lining and the corresponding heat transfer coefficients are crucial factors.
Therefore, the selected position of the temperature control system, which is based on temperature-controlled capillary tubes mounted on aluminium sheets, is located in the “gap” between the primary and secondary insulation of a typical aircraft fuselage, see Fig. 1.

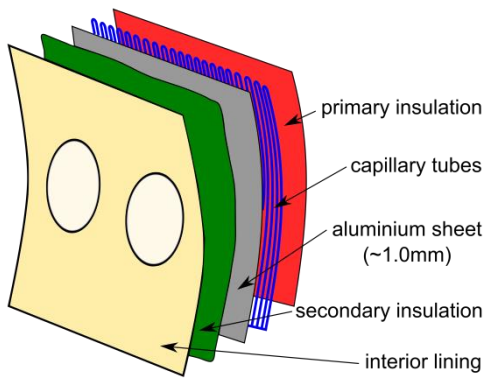

Figure 1. Illustration of the cabin structure with temperature control system.

Thus, real interior parts of an Airbus A340 are used taking the correct heat transfer coefficients through the lining into account. The mentioned capillary tubes are characterised by large volume flows but comparatively small tube diameters. Further, the system based on close-spacing capillary tubes in combination with the aluminium sheets ensures a uniform and homogeneous temperature distribution behind the interior lining. While the air temperature in the stratosphere is about -55°C and the related outer surface temperatures of the fuselage amount to approx. -28°C due to aerodynamic heating (recovery temperature), the temperature distribution between the two insulation layers turns out to be much more moderate and thus significantly reduces the requirements of the temperatures to be controlled. Hence, the effort and the resulting costs for operating the temperature control technique are considerably reduced. The resulting gap temperature values of the corresponding cabin parts (sidewalls, crown and floor) used for this purpose are summarised in Tab. 1. In that sense, the front and rear side of the cabin mock-up is not temperature-controlled and kept under adiabatic thermal conditions using sufficiently thick insulation (30 mm). The data given in Tab.1 is based on measured interior surface temperatures during various flight tests carried out in the DLR test aircraft ATRA [9].

Table 1. Gap temperature range depending on the corresponding cabin sections/parts.

Cabin zones/parts	Temperature range
Floor	10°C – 40°C
Sidewalls	10°C – 30°C
Ceiling	10°C – 30°C
Overhead bins	10°C – 30°C

Test and Implementation

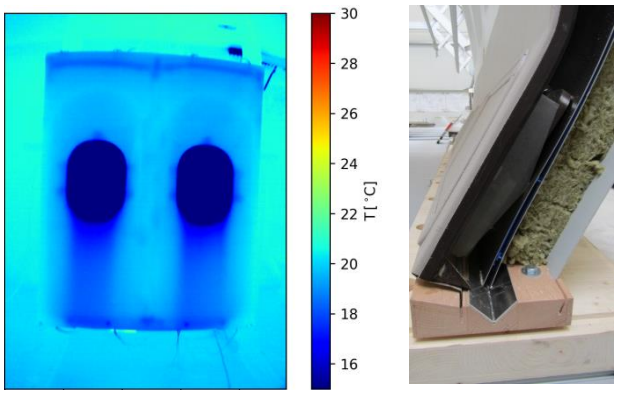

Figure 2. Temperature-controlled fuselage elements. Left: IR picture of a sidewall for cold gap temperatures. Right: Implementation in the sidewall of the new mock-up.

Before implementing the temperature control system in the new long-range cabin mock-up, a demonstrator was tested in order to verify this technique: As described above, a single sidewall

element including secondary insulation was enhanced with capillary tubes attached to an aluminium sheet and the primary insulation (expanded polystyrene). In combination with a water-glycol temperature control unit, the element was tested for cold and warm gap temperatures. As an example, Fig. 2 (left) shows the resulting inner surface temperatures of the lining for cooling captured using infrared (IR) thermography. After successful testing, the mock-up´s sidewalls, crown and floor were equipped with such a system. Fig. 2 (right) shows an original dado lining with a temperature control system covered by the primary and secondary insulation. By operating at least four different temperature control units, the corresponding cabin parts of the new long-range mock-up can be controlled individually.

2.2. Support Structure

The final cabin simulator is principally based on two sub-systems: the support structure and the actual cabin mock-up. The support structure is made of aluminium system profiles and serves as an external framework for the cabin mock-up, allowing to bear all occurring loads caused by interior cabin parts, the ducting of the HVAC, the tubing of the temperature control system and the installed measurement systems in the cabin. Generally, the support structure allows the installation of cabin geometries on a 1:1 scale enabling dimensions up to 7.0 x 10.0 x 3.0 m (W x L x H). Fig. 3 displays a CAD model of the final support structure.

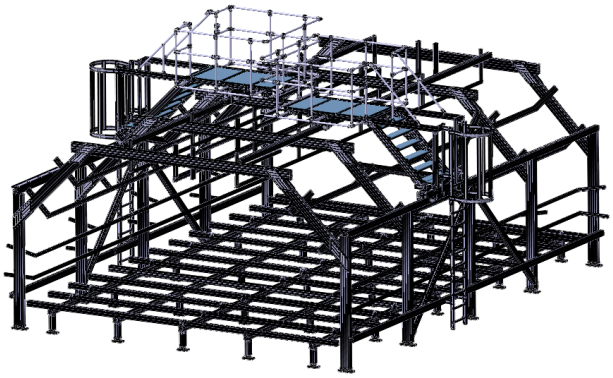

Figure 3. CAD model of the support structure.

As shown in Fig. 3, the support structure also comprises an elevated base plate consisting of aluminium profiles, which is not directly connected to the framework. It serves as a mounting platform for the floor and lining elements. Additionally, the base plate rests on 25 articulated feet in order to provide a well-balanced weight distribution in accordance with the laboratory limitations. Further components of the support structure are two sliding maintenance platforms on the top to facilitate the implementation of different ventilation concepts and the switching process between them.

2.3. Modularity

In order to cover the widest potential spectrum of existing and planned cabin cross-sections, the cabin mock-up was designed with the best possible modularity. This is achieved by using aluminium system profiles enabling the flexible installation of individual cabin parts. The sidewall and ceiling linings as well as the overhead bins are adjustable mounted to sliding holding elements (aluminium system profile), which in turn are screwed to the struts of the supporting structure. By using system profiles, flexible moving and adjusting of brackets is possible at any time. Fig. 4 schematically illustrates the installation of different cabin geometries (highlighted in black and light grey) in the support structure thanks to the flexible mounting system (indicated by red arrows). The remaining space between the support structure and cabin structure can be used very flexibly for the air supply systems of the different ventilation concepts.

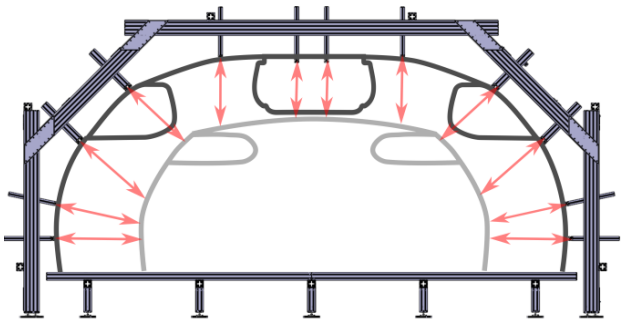

Figure 4. Sketch to illustrate the modularity regarding the implementation of different cabin cross-sections. Black: large twin-aisle cabin, grey: smaller single-aisle cabin geometry.

Furthermore, the floor of the cabin mock-up consists of 144 single segments (see Fig. 5), where the temperature can be adjusted/controlled individually. In addition, a large number of floor segments are equipped with insulated openings (blue dots in Fig. 5). Here, the power supply of manikins, supply hoses for media and other cables for the different measurement techniques can be

easily inserted into the cabin. Additionally, the cabin mock-up features eight moveable seat rails offering the possibility to easily switch between different seating configurations (i.e. 8-, 10- or even 11-abreast seating with flexible seat pitch) and seating classes.

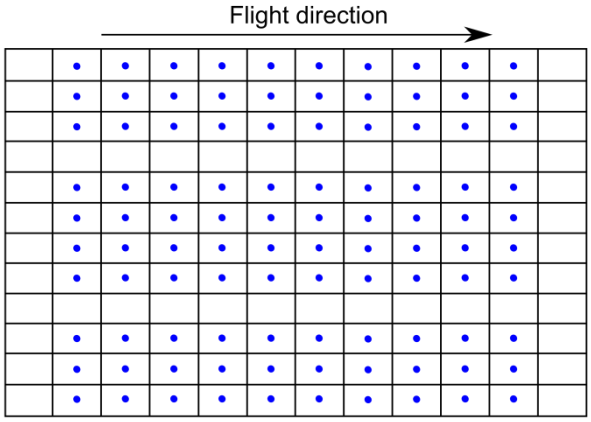

Figure 5. Modular construction of the floor consisting of individual segments.

Another important feature regarding the modularity of the cabin mock-up is the operation with different air distribution systems. To analyse alternative ventilation concepts for different cabin geometries, a maximum flexibility in terms of the air supply and air exhaust is required. For this reason, the mock-up as well as the corresponding ducting system are designed for a multitude of air inlet and outlet configurations. Fig. 6 gives an overview of the different air inlet (blue arrows) and outlet (red arrows) positions provided by the mock-up structure.

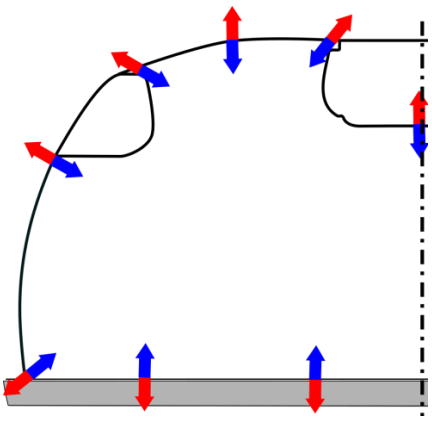

Figure 6. Sketch of different possible air inlet and outlet configurations.

Depending on the studied ventilation scenario, the corresponding air inlets/outlets are connected to the air supply and air extraction system, respectively. This enables the possibility to switch between or to combine different ventilation systems on the fly.

2.4. Long-Range Cabin Layout

The advantages of ultra-long-haul routes, such as shorter travel times and lower kerosene consumption are offset by considerable disadvantages like higher take-off weight and greater strain on passengers. Innovative ventilation concepts can alleviate these problems through their potential to provide greater passenger satisfaction. In that sense, by increasing ventilation efficiency it might be possible to reduce the necessary quantities of fresh air to fulfil the legal limits for CO, CO_2 and O_3 [10]. Consequently, the very energy-intensive bleed air requirement can be decreased. Moreover, by using an intelligent, innovative structuring of the air supply concept, the number and length of pipes and components can be drastically reduced. These are just a few reasons for choosing a long-range cabin layout for the new full-size test facility.

Figure 7. New long-range cabin mock-up with original interior parts.

Generally, the cabin model is set up in a dual-aisle configuration, characteristic for modern long-range aircraft. As shown in Fig. 7, the entire interior lining such as dado parts, sidewalls, overhead bins and ceiling linings consists of second-hand interior parts, thus ensuring realistic thermodynamic characteristics in terms of heat capacity and thermal conductivity.
In total, 10 seat rows are installed, each separated by a 32" seat pitch, see Fig. 8. Here, the base case provides a 3-4-3 seating configuration, which is already established in large four-engine airliners (e.g. B747 or A380) and can also be found in large twin-engine jets such as the B777 and the slightly smaller A350XWB. As a result, the starting configuration of the new cabin model offers a passenger capacity of 100 in total.

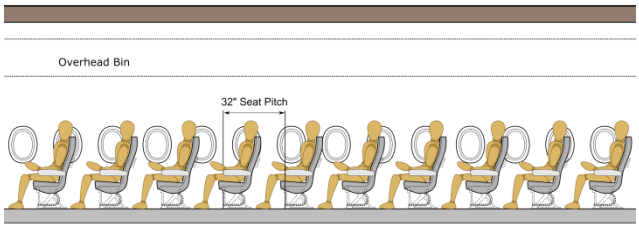

Figure 8. Sketch of the cabin model with 10 seat rows and 32" seat pitch, side view.

2.5. HVAC and Air Distribution

To provide the long-range cabin mock-up with the necessary chilled inlet air, a sophisticated HVAC system is essential. Fortunately, an existing HVAC installation is available which already supplies the Do728 experimental test bench [1]. As the nominal capacity of the existing HVAC was intended for a cabin volume comprising 75 passengers, it had to be extended to fulfil the capacity increase to 100 passengers for the presented long-range cabin mock-up. The resulting volume flows of at least 1000 l/s as well as cabin inlet temperatures between 10°C and 55°C can therefore be realised with only slight adaptions. The revised facility is illustrated in Fig. 9 in form of a flow chart.

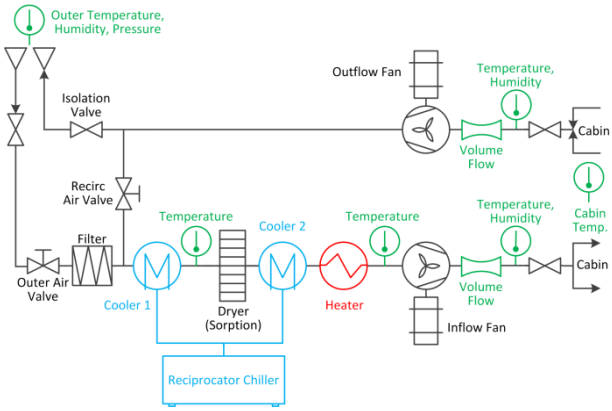

Figure 9. Flow chart of the adapted HVAC with the included components.

It can be seen that the HVAC system does not only meet the thermodynamic requirements but also allows the use of recirculated air as well as the supply of pure chilled fresh air depending on the demands of the project. By opening the recirculation air valve, a part of the outlet air is used as inlet air as in a real aircraft ECS. This reduces the cooling demand for the HVAC but additionally allows the simulation of realistic distribution ways of the cabin's CO_2 exposure. Fig. 9 does not illustrate the detailed air ducting system for the dedicated air supply and exhaust configurations of the new cabin mock-up. Here, a multitude of volume flow measurement systems are installed in order to determine and control volume flow rates as well as air temperatures independently for at least a group of air inlet and outlet tubes. This enables experimental measurements under highly precise boundary conditions.

3. MEASUREMENT TECHNIQUES

This section summarises the measurement techniques used for the experimental studies in the new long-range cabin mock-up to evaluate characteristic quantities in order to compare and rate the efficiency and performance of novel ventilation concepts of future aircraft under static and dynamic boundary conditions. The used techniques are selected and designed to quantify and analyse the following parameters: boundary conditions, cabin air temperature, efficiency of the ventilation concept, thermal comfort, velocity fields and air quality.

3.1. Thermal Manikins

In order to study novel ventilation systems operating in the mixed or natural convection regime, the simulation of the passenger´s heat impact and obstruction is crucial. For this reason, thermal manikins (TMs) are used during experimental studies, see Fig. 10.

Figure 10. Thermal manikins in the new cabin mock-up.

Design and Functioning

To simulate sitting passengers during experimental investigations, TMs are employed in the ground-based test facility. Fig. 11 displays the shape of a single manikin. The TMs are made of a non-combustible foam core, which is wrapped with a resistance wire followed by a thin layer of black heat-conductive aluminium. As a result, they have the shape of normal sitting passengers and provide a similar blockage and heat release as real humans. The use of external adjustable power supplies (part of the peripheral equipment of the

new long-range cabin mock-up) allows the variation of the emitted sensible heat of each single TM in a range of 0 to about 150 W.
In addition, these TMs undergo on-going development activities to provide even more features, which are discussed in the following.

Figure 11. Thermal manikin. Left: Picture of the TM. Right: Rendering of CAD model [11].

Human Comfort Manikin

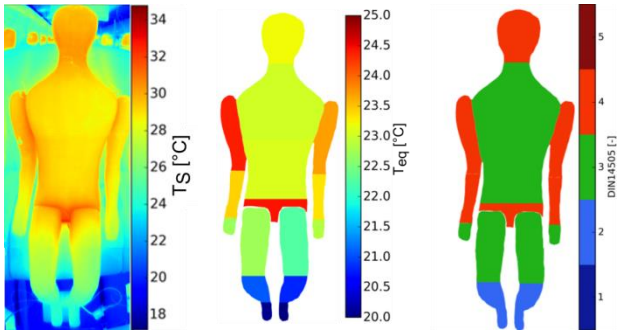

Figure 12. Sample results of a human comfort manikin. Left: TM's surface temperatures. Centre: local T_{eq} values. Right: Comfort analysis based on [12].

Since the TMs are operated with a constant heat flux density, they can be used to quantify thermal passenger comfort based on the acquisition of local equivalent temperatures (T_{eq}). However, a thorough calibration process is necessary beforehand. The TM is calibrated at constant heat release in a temperature-controlled box providing isothermal conditions according to [12]. Using high-definition infrared (IR) thermography, body-part related surface temperatures of the manikin are measured for different ambient temperatures within the box. For a state of equilibrium, the mean ambient temperature in the calibration environment corresponds to T_{eq}, as defined in [12]. As a result, calibration curves are captured, which allow the calculation of local equivalent temperature values based on segmented surface temperatures for TMs operated under constant heat flux conditions. In accordance with the appraisal suggested in [12], the corresponding T_{eq} values are rated on a scale of 1 (very cold) to 5 (too warm) with regard to thermal passenger comfort. Fig. 12 shows exemplarily the evaluation of the thermal passenger comfort for mixing ventilation in the DLR's Do728 test facility.
Detailed information about the calibration process is given in [11].

Simulation of CO_2 Exhalation

Since the CO_2 concentration in the air has a significant influence on the passenger's well-being, the impact of CO_2 accumulation caused by the breathing of passengers is of great interest, especially in terms of cabin air quality. Therefore, the TMs used during the experimental investigations will be equipped with a CO_2 release system simulating the exhalation of passengers. In a first step, the CO_2 quantities typical for an adult are blown out continuously at the position of the nose. Since the required volume flow is very low (≈0.29 l/min/PAX) [13], a reliable pressure control system must be implemented ensuring low volume flows without deviations. In this context, the radius of a pipe has a decisive influence on the pressure drop. Hence, the use of capillaries with a very small diameter (0.18 mm) is of great benefit. For this purpose polyetheretherketone (PEEK) capillaries are glued in a gas-tight manner into a standard hose system and ending in a generic nose, which is attached to the TM's face, see Fig. 13.

Figure 13. Generic nose of the TM for supplying CO_2.

The immediate transition to an established standard hose system provides a reliable supply system for all 100 equipped TMs in the cabin.

During preliminary tests the volume flows through capillaries have shown only small deviations for a relatively large range of differential pressure. Fig. 14 shows the growth of the volume flow in comparison with the broad pressure range. This allows a precise control of the volume flow due to the large pressure drop in each nose. Even pressure deviations of a few 100 Pa caused by the supply tubes will only have minor influence on the volume flow.

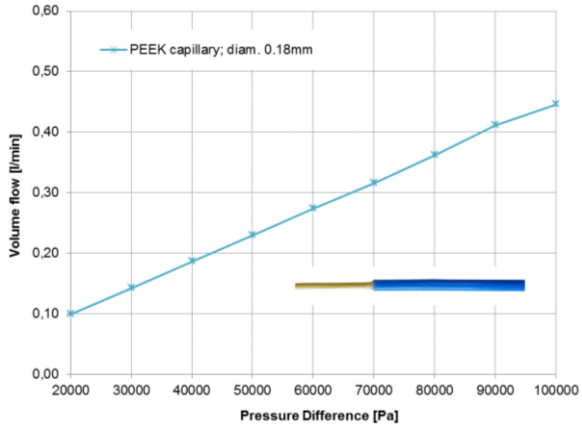

Figure 14. Volume flow of CO_2 depending on the pressure difference.

On average, the volume flow only increases by 0.04 l/min per 10000 Pa. Thus, the volume flow of CO_2 will only be measured integrated for all 100 TM's noses at once due to cost reasons and the very low volume flow through a single exhaust. The resulting CO_2 concentrations during the tests are determined at different positions in the cabin using stationary industrial sensors at multiple locations (with an accuracy of ±30 ppm + 3%) as well as a high-precision 6-point sampler gas analysis system.

3.2. Infrared Thermography

As indicated in section 3.1, IR thermography is used to acquire the surface temperatures of the human comfort manikin: Two IR cameras with a sensitivity of 0.13 K are mounted in front of the calibrated TM ensuring the optical accessibility for the whole TM's body. In addition, an automatically rotatable IR camera set-up is placed in the centre of the new cabin mock-up in order to capture the surface temperatures of the cabin interior (e.g. inner linings, seats, etc.). This set-up provides the opportunity to capture a thermal fingerprint of the whole cabin with a further high-sensitive IR camera (sensitivity of 0.08 K).

3.3. Local Probes

A comprehensive sensor system based on local probes will be assembled and installed to capture the relevant flow parameters (e.g. air velocity, air and surface temperatures) and comfort-governing quantities (e.g. temperature stratifications, humidity, draft rate etc.). Of course, the knowledge of previous studies in ground-based test facilities [1], [14] is taken into account to determine the optimal sensor positions.

Temperature Sensors

Resistance temperature detectors (RTD) will be used to capture and monitor the temperatures of the temperature-controlled sidewalls, the in- and outflowing air, the inner surfaces as well as the fluid temperatures within the cabin and close to the TMs. Generally, RTDs with an accuracy of ±0.15 K are used.

As mentioned in section 2.1, the new cabin mock-up provides the opportunity to simulate different flight cases (e.g. hot-day-on-ground, climb and cruise) by means of temperature-controlled sidewalls and floor elements. For optimal adjustment and monitoring of the gap temperature, in total 39 resistance temperature detectors (RTD) were installed on the aluminium sheets (ambient temperature T_A). These sensors are divided into three cross-sections located in the front, middle and rear of the cabin. The detailed position of each probe depends on the number of temperature-controlled interior parts (e.g. sidewall lining, ceiling lining, overhead bins, etc.) installed in a cross-section. Further probes are placed centrally under each seat and in the middle of each aisle, see Fig. 15.

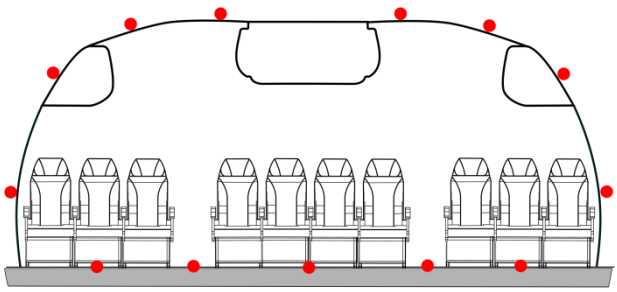

Figure 15. Sketch of cross-section with positions of RTDs (red dots) used to control the gap temperature.

In order to control the overall in- and outflow temperatures and to determine the energy balance, one RTD is required for every air inlet and air outlet. Depending on the installed ventilation

concept, the amount of installed RTDs in the air inlets/outlets varies between 20 and 75 probes. Furthermore, to analyse the local temperatures and temperature stratifications with regard to thermal passenger comfort, fluid temperatures are measured near the TMs (at a distance of 5 cm). Therefore, ten measurement racks with RTDs at six height levels (see Fig. 16) will be installed near the manikins in a selected seat row.

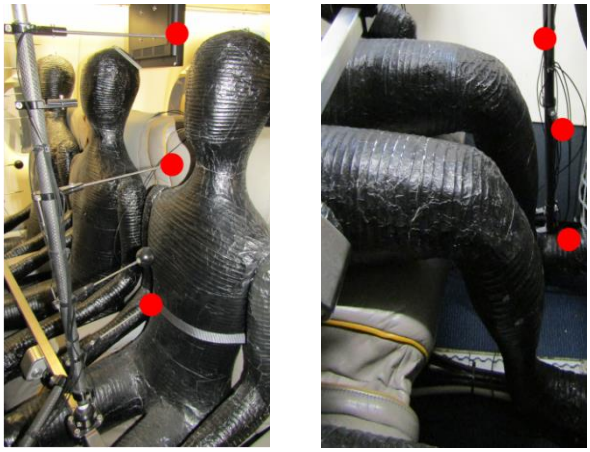

Figure 16. Picture of measurement rack for capturing fluid temperatures near the TM in the DLR's Do728 test facility. Left: Upper body. Right: Lower body.

Two further racks, with sensors mounted at different heights, will be positioned in the aisle sections of the cabin mock-up. Additionally, more probes at chest level will be placed in front of all TMs in order to analyse the temperature homogeneity in longitudinal direction.

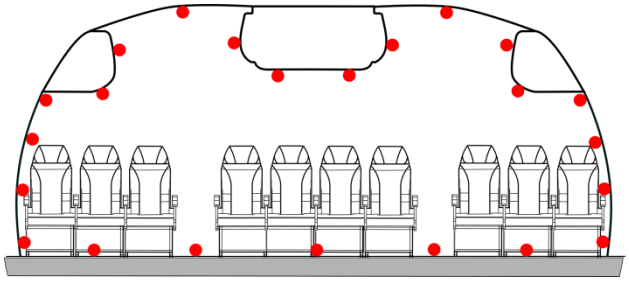

Figure 17. Sketch of the cross-section with positions of RTDs (red dots) for measuring surface temperatures.

To get an overview of the inner surface temperatures, 23 RTDs are planned to be installed in a cross section in the centre of the mock-up. Two further sections (in the front and rear of the cabin) will be equipped with a reduced number of probes. Fig. 17 shows a simplified sketch of the sensor positions for the acquisition of the inner surface temperatures in the centre section.
In total, more than 400 local temperature probes are intended to be installed in the new cabin mock-up.

Omnidirectional Velocity Probes
Another key parameter regarding thermal passenger comfort is the air velocity. Hence, fluid velocities will be measured using high-precision draft rate sensors in the vicinity of the TMs. All 10 seats of one selected seat row are going to be equipped with these combined velocity and temperature probes. Here, the probes are positioned next to the ankle, knee, and head at a distance of 5 cm from the manikin´s surface. Further five sensors at different height levels will be mounted on racks, which can be installed in the aisle. The used omnidirectional draft rate probes provide an accuracy of 0.04 m/s within the measurement range of 0.05 m/s ≤ u ≤ 1.0 m/s.

Humidity Sensors
To examine the humidity of in- and outflowing air as a boundary condition with a strong influence on the thermal passenger comfort, humidity probes will be installed in air inlets and outlets. Furthermore, condensation effects during the different studied flight phases will be acquired with portable humidity sensors.

3.4. Air Quality

The quality of the air is a crucial factor for the well-being (comfort and health) of passengers during flights. Here, the mixing behaviour of fresh and used air as well as the propagation of pollutants (e.g. odours, CO_2 or pathogens) determines the air quality. A performance indicator to characterise the air change effectiveness is the so-called local ventilation efficiency, which is defined by the nominal air exchange rate and the local mean age of air [15]. The latter describes the mean time required by the supply air to reach a certain point in the compartment. Using the tracer gas technique in a step-down measurement approach, the ventilation efficiency will be investigated experimentally [15]. The multi-gas monitoring system in use can be equipped with sulphur hexafluoride (SF6), freon 134a (R134a) or carbon dioxide (CO_2) as tracer gas and provides an accuracy of dosage of ±2%. By means of this measurement technique, further experiments should clarify how much fresh air is actually required for the analysed concepts in order to be

able to comply with the thresholds of CO_2 concentrations specified in [10].

3.5. Analysing Velocity Fields

Understanding physical flow mechanisms is essential to analyse the performance of new ventilation concepts regarding their energy efficiency and thermal passenger comfort. Hence, a further measurement technique, called particle image velocimetry (PIV), will be employed within the cabin. With PIV, large-scale instantaneous velocity fields can be determined in a complete cross section using small tracer particles (e.g. oil droplets or helium-filled soap bubbles) in combination with a light source to illuminate the particles. The latter are based on a pulsed laser system or light-emitted diodes (LEDs). The post-processing comprises image analysis algorithms to finally obtain instantaneous large-scale flow fields with a high spatial and temporal resolution [16]. Fig. 18 displays the results of a PIV measurement in the DLR's single-aisle cabin test facility.

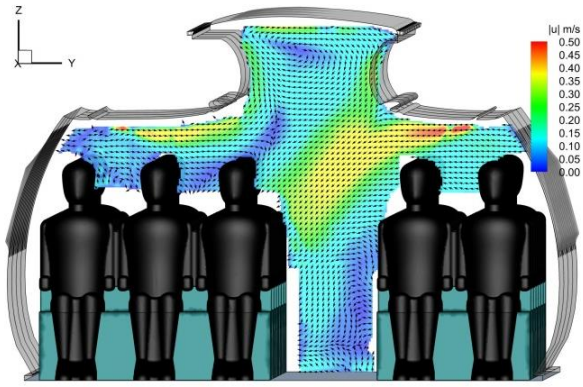

Figure 18. Instantaneous velocity field (magnitudes and vectors) evaluated using PIV [17].

3.6. Human Subject Tests

To verify the objective thermal comfort measurements, tests with human subjects are feasible in the new cabin mock-up and planned for future applications. During these tests, thoroughly selected test persons, representing a cross-section of adult passengers, will occupy the 100 seats in the cabin mock-up. The experimental test procedure will comprise the investigation of selected ventilation concepts for different temperature scenarios under static and transient thermal boundary conditions. Using specified questionnaires, the subjects' climate and comfort sensation is determined based on the evaluation of many different parameters. The subjects have to fill out the questionnaires at the end of each scenario. The human subject tests at DLR Göttingen will be realised in cooperation with the psychologist from the Institute of Aerospace Medicine of the DLR. In this case we can already benefit from experience from other areas of cabin research at the DLR [13], [18].

3.7. Heating and Cooling Efficiency

In order to evaluate the performance and efficiency of novel aircraft cabin ventilation concepts for different flight cases and boundary conditions, some quantities are required. First, the heat removal efficiency (*HRE*) is a measure to evaluate the efficient removal of heat loads [19]. It is defined by Eq. 1, where the inflowing air temperature (T_{in}), the temperature of the outflowing air (T_{out}) and the mean cabin temperature (T_{cabin}) are considered:

$$HRE = 0.5\frac{T_{out}-T_{in}}{T_{cabin}-T_{in}} \quad (1)$$

As a result, perfectly mixed air, which is indicated by T_{out}=T_{cabin}, reaches an *HRE* of 0.5. The latest tests of alternative ventilation systems for aircraft cabins have shown the potential regarding higher heat removal efficiencies [1].
In order to improve the energetic efficiency of new ventilation systems, the temperature control efficiency η is defined as the ratio of the air enthalpy flow to the passenger (corrected for its own heating power) and the air enthalpy flow into the cabin [20]:

$$\eta = \frac{T_{eq}-T_A-P_H/(q_V\varrho c_p)}{T_{in}-T_A} \quad (2)$$

Here, P_H, q_V, ϱ and c_p represent the total heat load, the volume flow rate as well as the density and specific heat capacity of the air, respectively. It must be noted, that this quantity is limited to the actual set point of the system defined by the heat loads, volume flow rate and ambient temperature. On the basis of η, the actual enthalpy flow $\dot{H}$, required to reach a comfortable temperature level (e.g. $T_{eq} = 23°C$), can be calculated by Eq. 3.

$$\dot{H} = (T_{in} - T_A)q_V\varrho c_p = \frac{(T_{eq}-T_A)q_V\varrho c_p - P_H}{\eta} + T_A \quad (3)$$

4. CONCLUSIONS AND OUTLOOK

This report introduces the new aircraft cabin mock-up, assembled at the German Aerospace Center in Göttingen, which will be used for experimental investigations of novel and innovative ventilation concepts at ground level. The new test bench

reproduces the geometrical constraints of a passenger cabin typical for modern long-range airliners on a scale of 1:1. As a first geometry, a dual-aisle cabin layout is realised offering space for a total of 100 passengers in 10 seat rows. In order to study novel air distribution and ventilation systems under realistic thermodynamic conditions, the fuselage elements – based on original aircraft linings and overhead bins - are temperature-controlled. Further, the test facility allows for dynamic changes of the inner surface temperatures in a range covering the operationally relevant temperatures and time scales in order to experimentally simulate different flight phases, e.g. hot-day-on-ground, climb or cruise. Consequently, time- and cost-efficient test sequences under real operational (static and dynamic) thermal conditions can be performed. Furthermore, the design of the cabin model allows the integration of different ventilation concepts with a high degree of flexibility. This also enables the possibility to switch between or even combine different ventilation scenarios with reasonable effort. Moreover, the test bench facilitates the installation of different aircraft cabin geometries and layouts thanks to the flexible and adjustable mounting system. Accordingly, the spectrum of our research is not limited to studies addressing long-range aircraft cabins only.

In order to analyse promising ventilation concepts regarding energy efficiency, thermal passenger comfort and air quality, thermal manikins are installed in the cabin. They can simulate the blockage, the heat release and the CO_2 exhalation of passengers. With a wide range of the latest measurement techniques including tracer gas analysis, optical methods for velocity field and surface temperature measurements as well as high-resolution local probes, the performance of ventilation concepts will be investigated for steady and non-ideal thermodynamic boundary conditions. To validate the objective measurements, human subject test with questionnaires are planned in the new cabin mock-up ensuring a comprehensive evaluation of the studied ventilation scenarios.

5. CLOSING REMARK

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7. REFERENCES

1. Bosbach, J. (2013). *Alternative Ventilation Concepts for Aircraft Cabins.* CEAS Aeronautic Journal 4, pp 301-313.

2. Müller, D., Schmidt & M., Müller, B. (2011). *Application of displacement ventilation systems for air flow distribution in aircraft cabins.* AST. Hamburg, Germany.

3. Schmidt, M., Müller, D., Gores, I. & Markwart, M. (2008). *Numerical study of different air distribution systems for aircraft cabins.* Internat. Conference for Indoor Environment and Energy. Techn. Univ. of Denmark

4. Zhang, T., Li, P., Zhao, Y. & Wang, S. (2013). *Various air distribution modes on commercial airplanes. Part 1: Experimental measurements.* HVACR Res., vol. 19, no. 3, pp268-282

5. Yan, W., Zhang, Y., Sun, Y. & Li, D. (2009). *Experimental and CFD study of unsteady airbone pullutant transport within aircraft cabin mock-up.* Build. Environ. vol.44, no.1, pp34-43

6. Zhang, Z., Chen, X., Mazumdar, S., Zhang, T. & Chen, Q. (2009). *Experimental and numerical investigation of airflow and contaminant transport in an airliner cabin mock up.* Build. Environ. vol.44, no.1, pp85-94

7. Li, B., Duan, R., Li, J. Huang, Y., Yin, H., Lin, C., Wie, D., Shen, X., Liu, J. & Chen, Q. (2016). *Experimental studies of thermal environment and contaminant transport in a commercial aircraft cabin with gaspers on.* Indoor Air, vol.26, no.5, pp806-819

8. Zhu, X., Liu, J., Cao, X. & Li, J. (2015). *2D-PIV Experimental Study on the Air Distribution with Natural Convection Effect of Passengers in an Air Cabin Mockup.* Procedia Eng., vol.121, pp.866-874

9. Dehne, T., Bosbach, J. & Heider, A. (2014). *Comparison of surface temperatures and cooling rates for different ventilation concepts in an A320 aircraft cabin under flight conditions.* Proceedings of 13th CSCANVAC Roomvent, Sao Paulo, Brazil

10. Code of Federal Regulations (2011). Aeronautics and Space. §25.831 Ventilation. pp 458-459

11. Lange, P., Westhoff, A., Schmeling, D., & Bosbach, J. (2018). *Cost-effective human comfort manikin with realistic thermal loads for studies of convection-driven ventilation systems.* Roomvent & Ventilation Conference, Espoo, Finland. ISBN: 978-952-5236-48-4, pages 367-372

12. EN ISO 14505-2 (2006). *Evaluation of thermal environments in vehicles – Part 2: Determination of equivalent temperature*.

13. Pasch, T., Krayer, S. & Brunner, H.R. (1994). *Grundzüge der Beatmung. Definition und Messgrößen der akuten respiratorischen Insuffizienz: Ventilation, Gasaustausch, Atemtechnik.* Springer, Berlin, pp95-108

14. Schmeling, D. & Bosbach, J. (2017). *On the influence of sensible heat release on displacement ventilation in a train compartment.* Build. Environ. 125, pp 248-260

15. Han, H. (2012). *Ventilation effectiveness measurements using tracer gas technique.* Fluid Dynamics, Computational Modeling an Application. Chapter 3, pp 41-66.

16. Raffel, M., Willert, C.E., Scarano, F., Kähler, C.J., Wereley, S.T. & Kompenhans, J. (2018). *Particle Image Velocimetry – A practical Guide.* 3rd Edition. Springer International Publishing.

17. Bosbach, J., Misol, M., Heider, A. & Webel, O. (2013). *Auslegung und Verifikation neuer Verfahren der Kabinenbelüftung für Verkehrsflugzeuge.* DLR: Project Report Ref: FKZ20K0806D

18. Winzen, J., Marggraf-Micheel, C. & Soll, H. (2013). *Thermal comfort in an aircraft mock-up when using displacement ventilation.* Deutscher Luft- und Raumfahrtkongress

19. Wick, A. (2010). *Ventilation efficiency and thermal comfort.* Airbus: Internal Report Ref:N21D10027368

20. Dehne, T., Lange, P., Volkmann, A., Schmeling, D., Konstantinov, M. & Bosbach, J. (2017). *Vertical Ventilation Concepts for Future Passenger Cars.* Build. Environ. 129, pp 142-153