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MEASUREMENT OF NOISE AND INDOOR CLIMATE ON BOARD A TURBOPROP AIRPLANE FLIGHT

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Abstract

On Nov. 3rd 2021 two subject test round flights were conducted on a turboprop airplane (ATR 72) with measurement equipment to assess the noise, CO_2-concentration, cabin pressure, relative humidity, temperature and stratification in a close to fully booked cabin. The flights took off at Rotterdam, flew a round over the North Sea and landed in Rotterdam again. Additionally, the flight mission of the aircraft back to its base in Lübeck was accompanied. This paper presents the transient measurements of cabin noise and cabin indoor climate. Such dates serves for future benchmarking of the research and development conducted on the new generation regional aircraft within the Clean Sky 2 project.

Keywords: cabin climate, cabin noise, turboprob aircraft, regional aircraft

1. Introduction

The environmental control system (ECS) ensuring a safe and healthy indoor climate for passengers and crew is one of the major non-propulsive loads in the aircraft. Hence, optimizations of the ECS can directly impact fuel burn and operation efficiency. The limit of such optimizations currently are set out be the regulatory bodies. For example, requirements for the cabin indoor environment are set out in [1] stating that cabin temperature shall be contained within 18.3 to 26.7 °C with a maximum temperature gradient between air and surfaces of 5.6 K (65, 80 and 10 °F respectively). The minimum fresh air rate shall be 3.5 l/s per passenger (7.5 cfm). Cabin pressurization shall not exceed the equivalent altitude of 8.000 ft, corresponding to 750 hPa. CO_2 concentration shall not exceed 5000 ppm.

Measurements of CO_2 in the operated jet aircraft cabin by [2] and [3] reveal typical levels around 1353 ± 290 ppm or 925 and 1449 ppm in cruise respectively. The sources of CO2 are the atmospheric background concentration (typically 350-500 ppm depending on location) and the exhalation by passengers. The major source of moisture in the aircraft cabin is the water vapor emitted by passengers. In [4], a literature review concluded that the average cabin relative humidity level amounts to 16% with a minimum of 0.9%, hence the span is rather wide. At low humidity levels of 10% the perception of dryness significantly increases after 90 min [5]. In [3], measurements were performed on domestic short-haul flights and found relative humidity levels in the cabin between 17.9% and 27%. The wide span of reported humidity levels potentially result from different occupancy and flight durations. For short-haul flights, a higher average humidity level is expected because the fraction of low-altitude operation is higher and hence the exterior source of humidity from ambient air is more dominant. In contrast, during long cruise times, the air in the cabin has been entirely renewed with dry bleed air aspired from outside, where temperatures typically is around -25 °C for the typical cruise altitude of 20000 ft [6] where turboprops operate. Hence only low amount of water vapor is contained in the air. In terms of temperature, [4] show a wide spread of reported temperatures ranging from approx. 17 °C to above 30 °C. The average is 23.5 °C and hence in a comfortable range. The reason for such spread is again a large variety of different environmental conditions of operation, different occupancy of the aircraft and the possibility of the crew to select the temperature setpoint for the cabin. [7] measured noise in two A321 cabins and concluded that noise level in cruise amounts to 80-85 dB(A) with some peaks between 81-88 dB(A). [8] compared noise measurements in the cockpit of an A319 (jet) and a Dash 8Q-400 (turboprop) aircraft and concluded that average noise is a bit lower than 80 dB(A) for both aircrafts' cockpit.

The passenger experience in the cabin is governed by multifactorial influences such as the indoor climate, sedentary and space comfort, noise perception and on-board services. [9,10] exposed passengers to a flow adaptive ECS setting in a simulated flight under a fully booked and half booked condition. Despite the higher flow rate for the fully booked conditions, the effects on thermal perception of subjects were of small size, whereas a big size effect was measured on satisfaction with privacy and space. In line with this [11] report the leg space and personnel space the two worst rated comfort parameters, whereas climate rated nr. 10 of 14 criteria.

This paper presents the environmental data of the investigated round flights. A first evaluation of subject votes has additionally been published [12]. Here, noise, vibration and the seat were reported the three most frequent factors influencing subject's discomfort whereas temperature, light and space were reported the three most frequent contributors to comfort.

To the authors' knowledge, this paper for the first time publishes a full set of indoor environmental measurements from the operated cabin of a turboprop aircraft.

2. Method

Two round flights from Rotterdam airport over the North Sea were accompanied. The flights each had a total duration of 70 minutes, with a cruise phase of 30 minutes at 17000 ft altitude. The aircraft is a normal in-service ATR 72 with a 2-2 seat abreast interiors arrangement. In total, 15 rows are present in the aircraft (numbering 1-12 and 14-16). 52 and 45 passengers together with three crew members were in the cabin on flights no. 1 and 2.

Figure 1: Aircraft and cabin interiors

The test staff member carrying out the indoor climate measurement was located in row 9 on the right seats. Here, a logger for CO_2, temperature and relative humidity was placed in the newspaper holder. Furthermore, temperature sensors were mounted 0.1, 0.6 and 1.1 m above the floor and humidity and absolute pressure is measured. The acoustic microphone was also placed in row 9 on the right seats at ear height.

The following sensors were used (Figure 2):

- CO_2: Rotronic CP11
    - CO_2: 0-5000 ppm, with accuracy of ±30 ppm / ±5%
    - Temperature: -20-60°C, with accuracy of ±0.3 °C
    - Humidity: 10-90%, with accuracy of ±2%
- Temperature and pressure: MSR145:
    - +5 to +45 °C with accuracy of ±0.1 °C
    - 750 to 1100 mbar with accuracy of ±2.5 mbar

- Acoustic spot measurements were carried out in the aisle during the cruise phase of flight 1 using a sound level meter B&K TYPE 2270 SOUND LEVEL METER (Class I) (https://www.bksv.com/en/instruments/handheld/sound-level-meters/2270-series).
- Acoustics (only used in flight 2): calibrated Sennheiser Ambeo VR Mic (first order ambisonics) with calibrated Sound Devices MixPre-6 II recording device. Recording resolution: 24 bit, Sample-Rate: 44.1 kHz.
- To assess the temperature distribution of the floor, a FLIR One IR-camera for smartphones was used.

Figure 2: Measurement equipment. Left: CO_2 & RH, middle: temperatures and pressure, right: acoustics

The absolute humidity of the air was computed with equation (1) [13]:

$$x = \frac{6.112 \cdot e^{\frac{17.67 \cdot T}{T+243.5}} \cdot RH \cdot 2.1674}{273.15+T} \tag{1}$$

CO_2 readings were pressure compensated according to equation (2) assuming air behaves like an ideal gas within the relevant pressure and temperature range.

$$c_{CO_2} = c_{CO_2,raw} \cdot \frac{10113}{p} \cdot \frac{T}{298.15} \tag{2}$$

To assess the fresh airflow rate V_{fresh} per passenger, equation (3) is solved under steady state conditions using the CO_2 measurement in the cabin.

$$\dot{V}_{fresh} \cdot \left(c_{cabin} - c_{fresh}\right) - N \dot{\cdot} V_{Prod} = 0 \tag{3}$$

where c_{cabin} is the measured steady-state cabin concentration, c_{fresh} is the ingress by fresh air (assumed 380 ppm), N is the number of occupants in the cabin, V_{prod} is the internal production rate per passenger (18 l/h CO_2 [14]).

3. Results of in cabin measurements

In this section, the results of the in-cabin measurements are provided. As mentioned, the measurements were mounted at the two right places (D/F) of row 9.

3.1 Pressure

The pressure profile is very similar for both flights (Figure 3). It seems at minute 2, the ventilation system is activated translating into a small pressure peak. During taxi and takeoff, an oscillating control behavior of the cabin pressurization is obvious. In the climb phase, a relatively linear decrease of cabin pressure to a constant value of 900 hPa during cruise is visible. In the descent, cabin pressure is built up to ground pressure again and the stop of climatization is seen by a slight drop of cabin pressure in minute 77. The cabin pressure of 900 hPa is above regulatory limits of 750 hPa [1].

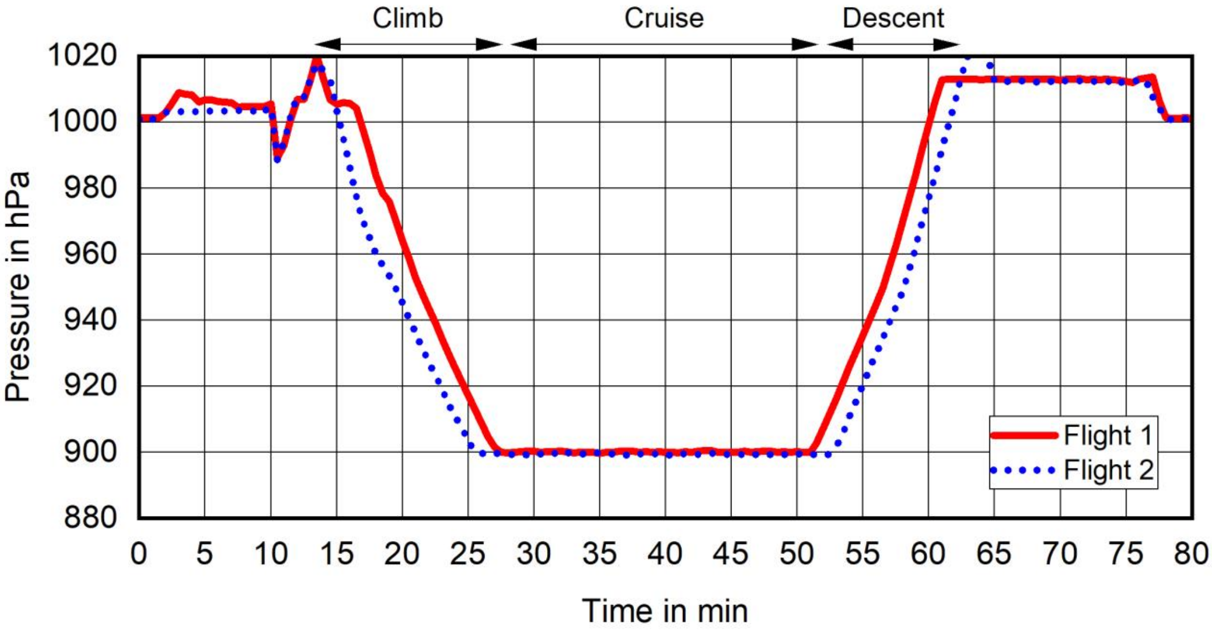

Figure 3: Pressure profile in cabin

3.2 Temperature and Stratification

It can be seen that flight 1 was cold soaked because the initial temperature is noticeably lower than flight two (Figure 4). Only after approx. 15 minutes into the measurement, the floor seems to have reached a somewhat steady condition, indicated by the transition of the measurement at 0.1 m above floor from increasing to stable temperature. At the end of flight 1, a spike at 0.6 m temperature is visible (minute 70-75). It is assumed that the operational personnel may have approached the sensor hence measuring human influenced micro-climate. Generally, flight 2 was measured warmer than flight 1. Nevertheless, temperatures mostly remain within the limits of 18.3 to 26.7 °C set out in [1].

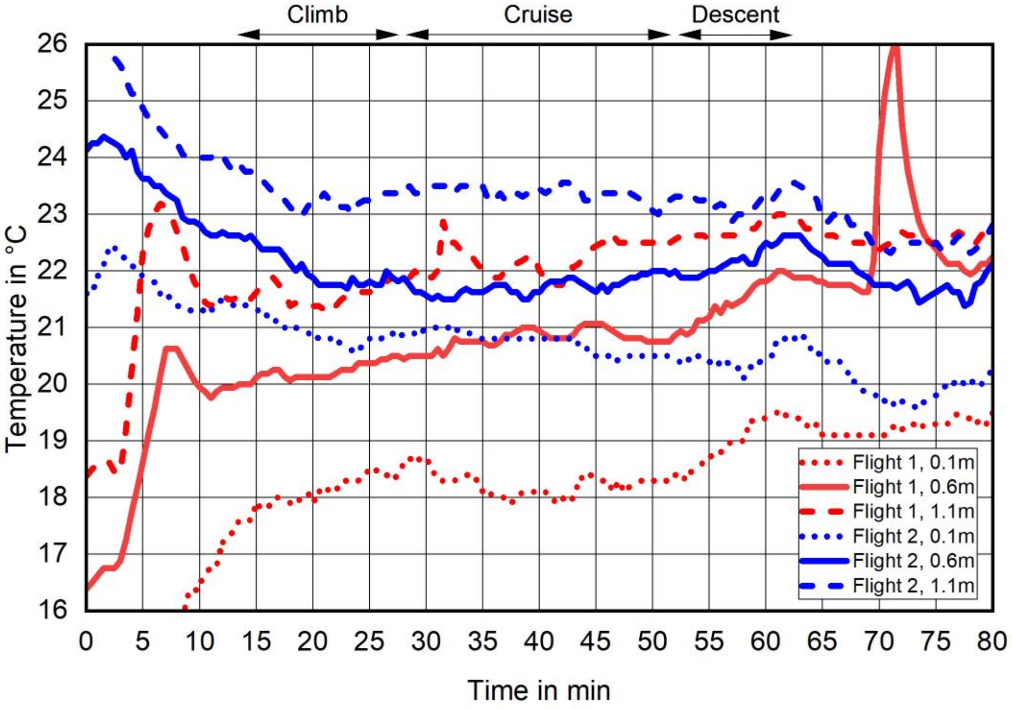

Figure 4: Temperatures in 0.1, 0.6 and 1.1m above floor

Figure 5 shows the thermal stratification between the sensor at 1.1 m and 0.1 m above floor. During the flight, the stratification stabilizes at 3.1-4.2 K for flight 1 and below 3 K for flight 2. This is below the max. acceptable stratification of 5.6 K set out by [1], however partially above the stratification of 4 K typically accepted in the built environment [15]. It is believed that a colder floor temperature in flight 1 led to the higher thermal stratification. Figure 6 gives an indication that the floor had time to heat up for flight 2, whereas it was still cold in flight 1. As the color scheme of the camera automatically adapts and the spot measures an area of gradient, care should be taken to not overinterpret the indicated temperatures.

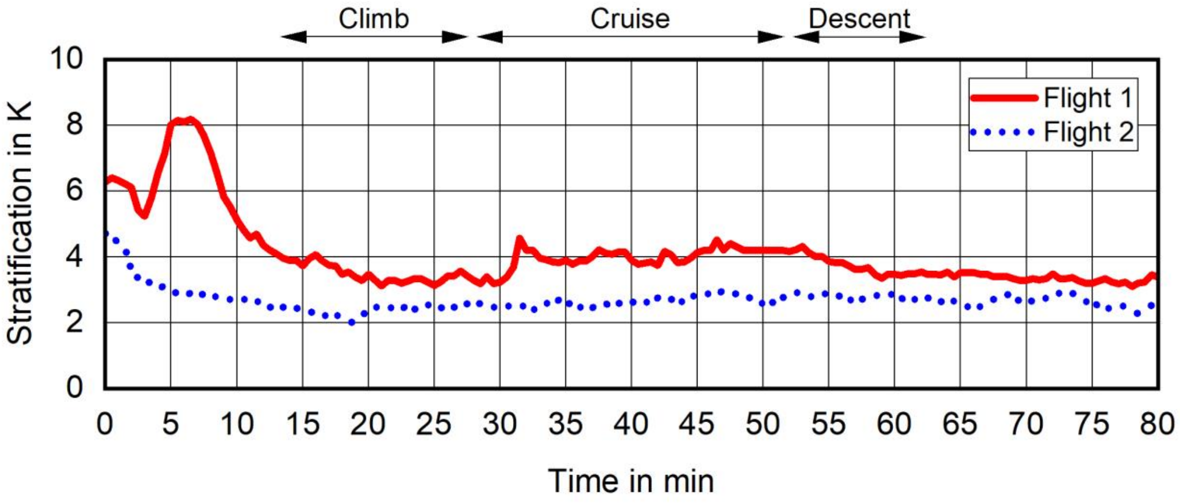

Figure 5: Temperature stratification

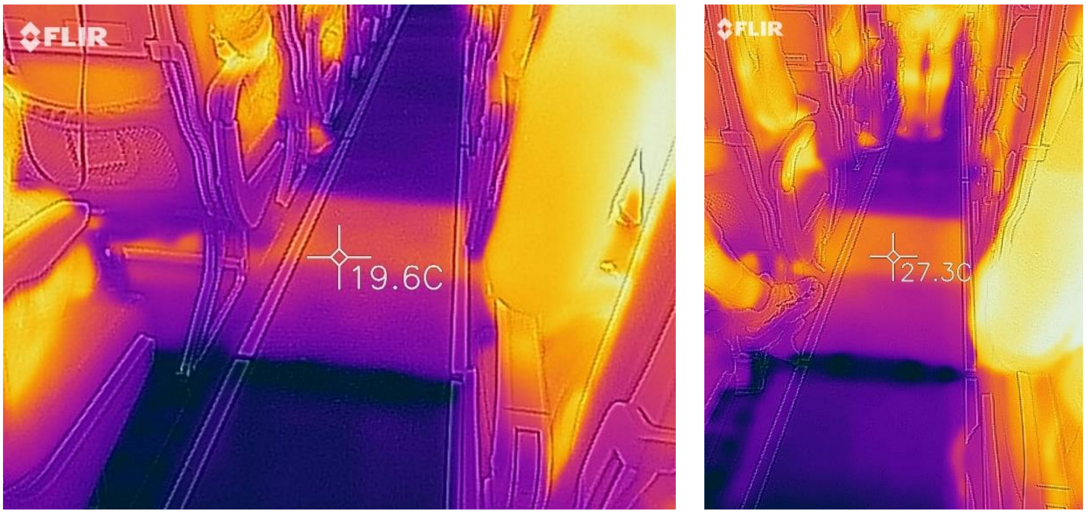

Figure 6: Comparison of floor IR image for flight 1 (left) and 2 (right)

During the first flight, some wider surface IR pictures were made. Measurements show that the surface temperatures are within the range requirement of 5.6 K difference from air temperature [1]. Generally, no discomfort would be expected from surface temperatures between 18.6 °C at the ceiling and 21 to 24.4 °C on the sidewalls (Figure 7). In flight 2, more detailed images were made of the window section (Figure 8). It is obvious that the window pane and its surrounding is colder, however due to the limited size and hence the low view factor for long-wave radiation, its impact is considered minor.

Figure 7: Interiors surface temperatures (Flight 1)

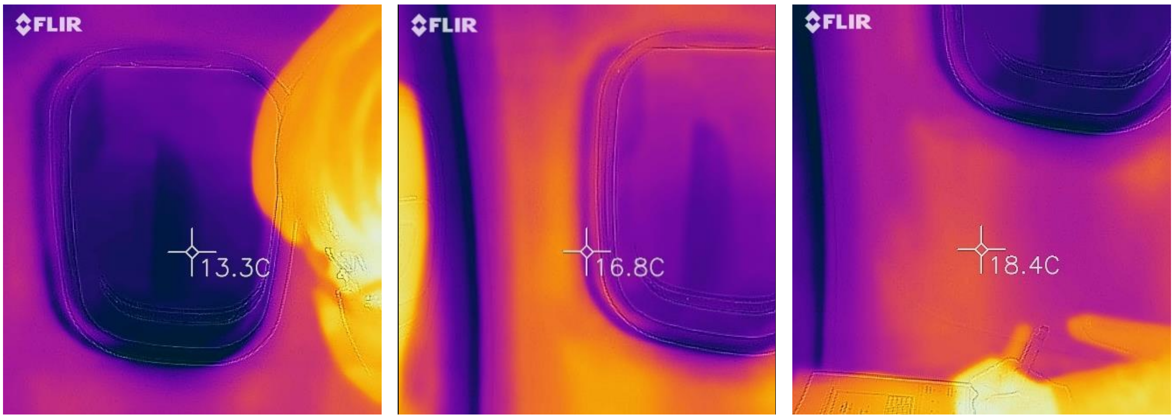

Figure 8: Detailed IR images around window (Flight 2)

3.3 Humidity

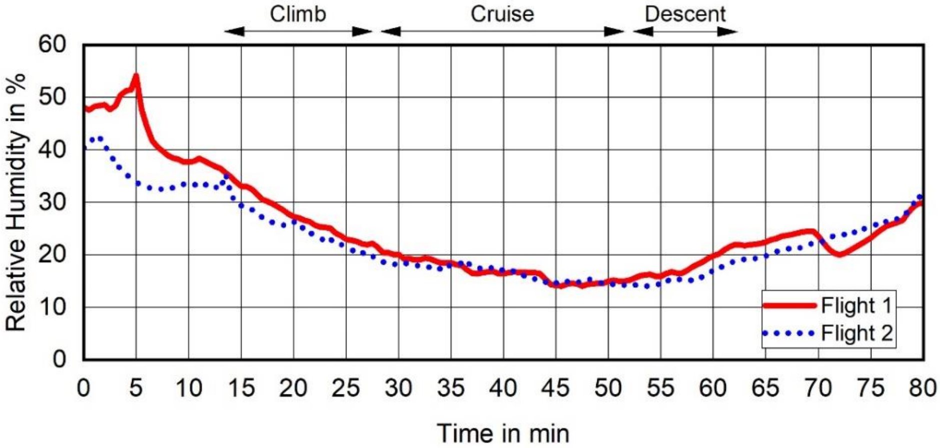

Figure 9: Cabin relative humidity

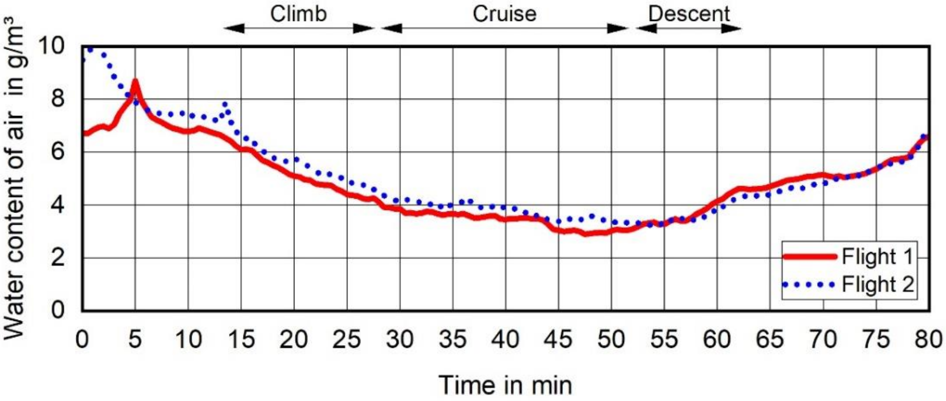

Figure 10: Cabin air water content

3.4 CO_2

Figure 11 shows the pressure corrected cabin CO_2 concentration profile. Before the ventilation starts (min. 0-2), the concentration steeply increases to 4000 ppm and more during boarding. Once the ECS operates, the concentration decreases below 2000 ppm within approx. 5 minutes. During cruise a stable CO_2 concentration around 1200 ppm is observed, that increases to 1600 ppm during descent, where probably less bleed is supplied due to the engines operating in idle mode.

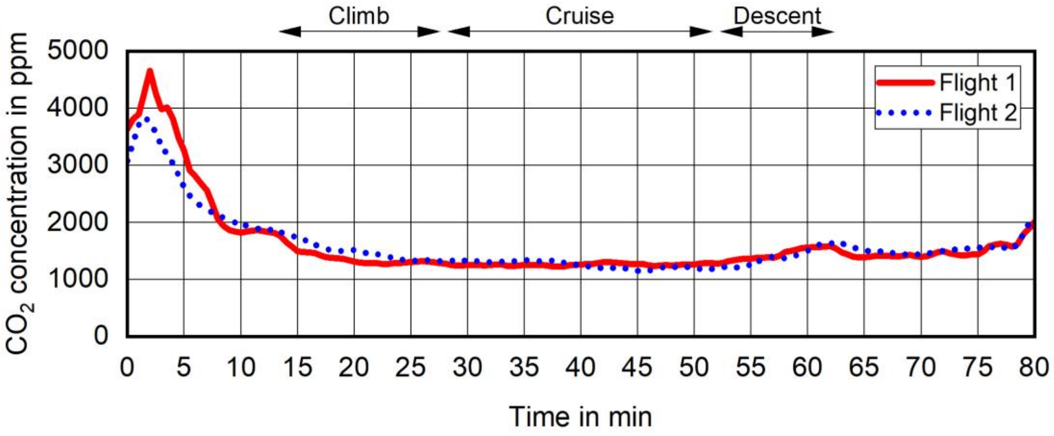

Figure 11: Cabin CO_2 concentration (pressure corrected)

For the final cruise phase, the cabin fresh airflow rate is deduced from the CO_2 balance using equation (3). Table 1 summarizes the input data and results from this calculation. It is obvious, that the regulatory requirement of 3.5 l/s per passenger [1] is exceeded.

Table 1: Cabin fresh flow rate computation

	Flight 1	Flight 2
CO_2 exhalation per passenger	18 l/h	
Exterior CO_2 concentration	380 ppm	
Number of occupants in cabin	52+3	45+3
Average concentration in cabin	1252 ppm	1191 ppm
Fresh airflow rate total	0,32 m^3/s	0.30 m^3/s
Fresh airflow rate / Passenger	5.7 l/s	6.2 l/s

3.5 Continuous noise

In the second flight, the noise was continuously recorded between seats 9D/F (Figure 12). The highest peak of 89 dB(A) was measured during takeoff. At cruise, the cabin noise mostly remained around 81 dB(A). Higher sound pressure levels were found in the middle rows than front and rear. A detailed analysis about the sound pressure levels at different positions in the cabin can be found in section 3.9. Generally, the highest sound level was recorded in the middle row, while front and rear showed lower sound pressure level. The soundfile included sounds of service and speech from passengers. This could explain some of the peaks in sound pressure level during cruise. All the following evaluations show only the pressure channel of the Ambisonics microphone. A more detailed, directional evaluation will follow in the further analysis of the data.

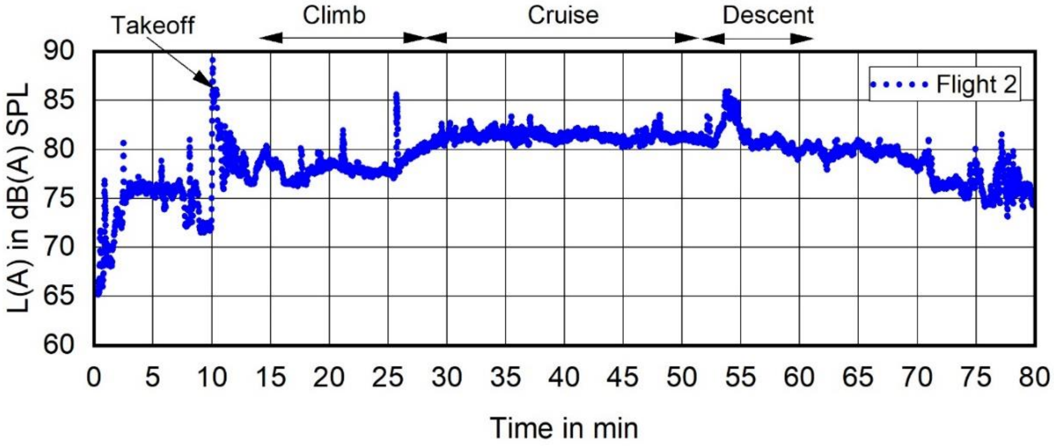

Figure 12: Transient noise measurement on Seats 9D/F

3.6 Spectral analysis

A 1/12 octave spectral analysis was performed during representative noise sections on ground (Figure 13) and in flight (Figure 14). The continuous energy equivalent sound level $L_{A,eq}$ was 76 dB(A) before takeoff, 88 dB(A) during takeoff, 81 dB(A) during flight, 80 dB(A) during landing, and 76 dB(A) after landing at the representative noise sections. Middle and high-frequency tonal components could be detected in the spectrum, which were also clearly audible during the flight. In addition, the tonal rotational noise around 100 Hz could be clearly recognized, especially during takeoff and cruise. The peak at 100 Hz corresponds to engine speed of 1000 rpm with a 6-blade propeller. The same peak also showed up in the vibration data that was collected during the flight. The engine speed for the engines is rated as maximum of 1200 so would be 120 Hz for a 6-blade propeller which corresponds to takeoff peak.

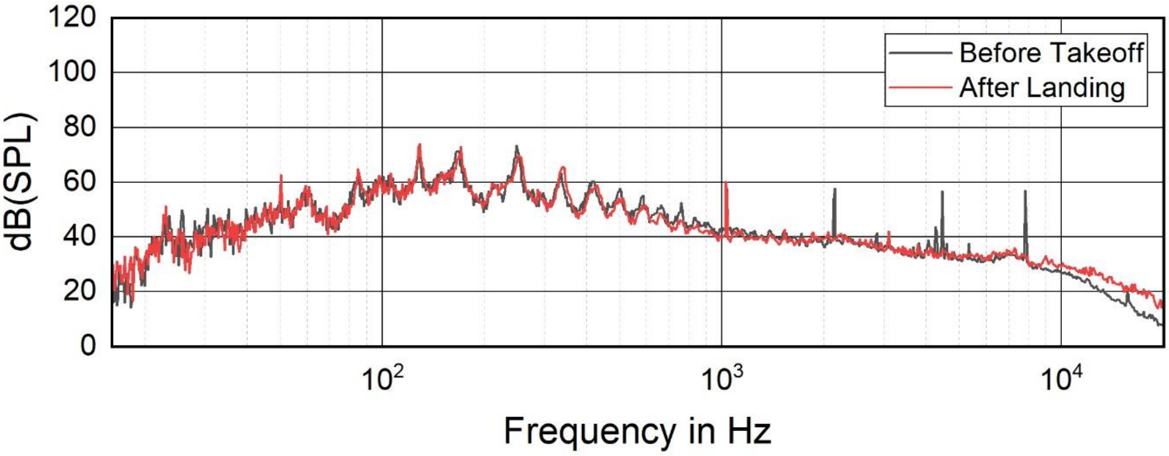

Figure 13: 1/12 octave spectral analysis during different ground phases

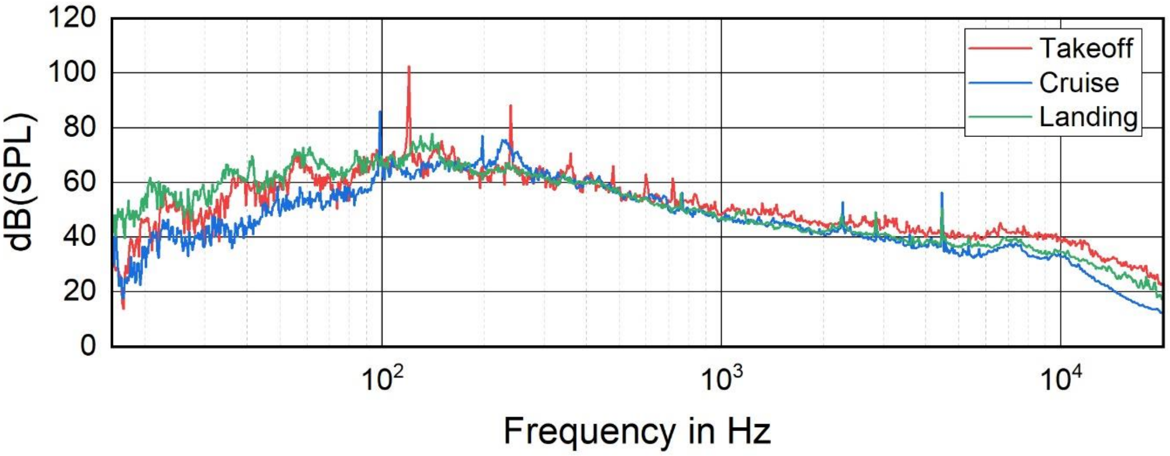

Figure 14: 1/12 octave spectral analysis during different flight phases

3.7 Speech Intelligibility Index

A Speech Intelligibility Index (SII) analysis (settings for analysis: 1m distance, time interval for analysis 300ms, standard speech spectrum, frequency resolution 1/3 octave) was performed for the entire duration of the second flight. Since at normal speech level the speech intelligibility during the flight was below 0%, the following representation in Figure 15 is done with raised speech level. In addition, Table 2 shows the SII values for normal, raised, loud, and screaming speech levels during the various phases of flight before takeoff, during takeoff, during cruise, during landing, and after landing.

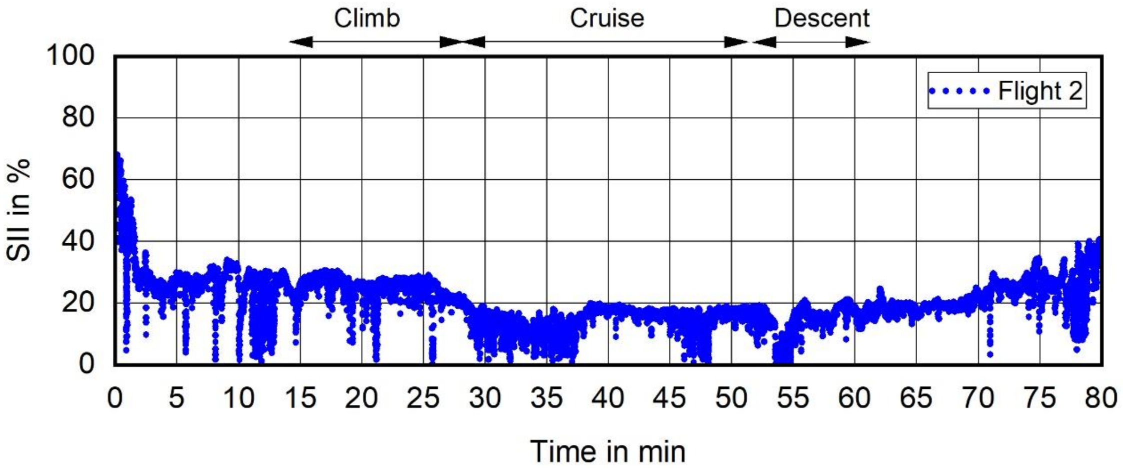

Figure 15: SII during the flight with raised speech level on Seats 9D/F

Table 2: SII values (average) during different time periods of the flight and with different speech levels.

	Normal	Raised	Loud	Shouting
Before takeoff	4	25	47	68
During takeoff	0	11	32	54
During cruise	0	18	40	62
At landing	1	19	41	63
After landing	11	34	56	75

3.8 Speech Interference Level

A Speech Interference Level (SIL) analysis (SIL-5, slow) was performed for the entire duration of the second flight (Figure 16). This shows a clear impairment of speech intelligibility due to the background noise of the turboprop.

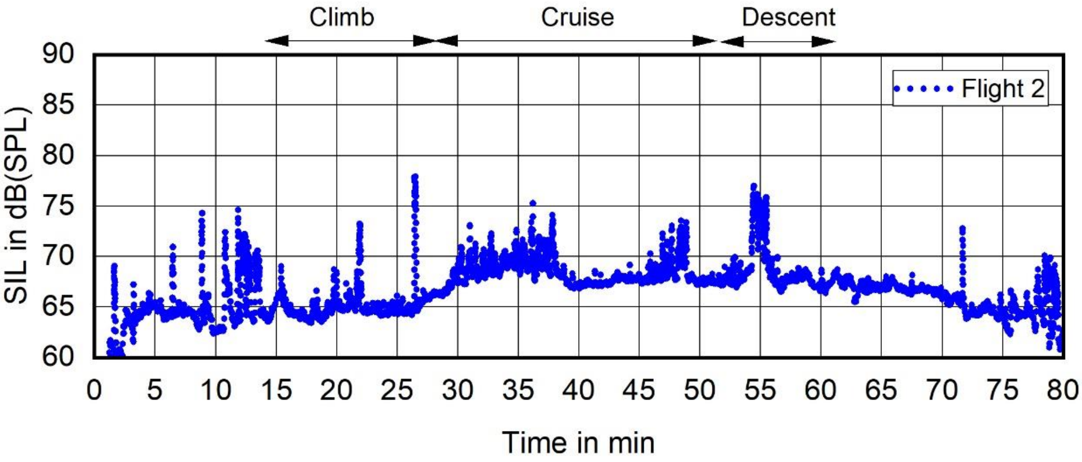

Figure 16: SIL analysis of the flight

3.9 Spot noise measurement – cabin length

In the first flight, spot measurements were taken during the cruise phase in each row along the aisle. A clear spatial distribution of the noise is visible with lower levels in rows 1-3 and then a steep increase from 77 dB(A) to 83 dB(A) in rows 7-10 (Figure 17). Towards the rear cabin, noise level gradually decreases to 78 dB(A) in the last row. Additionally, a measurement was performed in the rear galley. Here, the noise increases to 82 dB(A) again. A possible explanation is that the doors provide a passage for the exterior noise into the cabin and the crew working in the galley may have made noise.

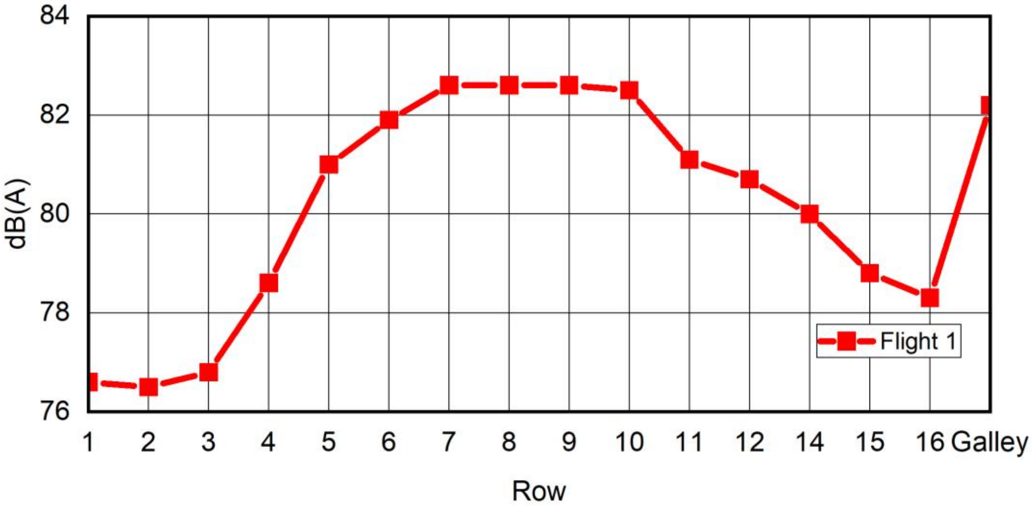

Figure 17: Cabin noise distribution, measured in the aisle

4. Conclusion

This campaign recorded the indoor environment in two realistic chartered flights of an ATR 72. The measurements show that cabin environmental conditions remain within limits set out by [1]. To summarize, the following results are found:

- The minimum cabin pressure recorded was 900 hPa

- Cold soak during the first flight led to colder flow, resulting in noticeable temperature stratification. Except this fact, the temperature control proved to be stable and temperatures were contained within comfortable ranges. No worrying low surface temperatures were consistently observed on large scale.
- The lowest cabin humidity recorded was 14% at end of cruise
- CO_2 concentrations during cruise were 1152 – 1339 ppm. During boarding, a short term CO_2 peak of 4000 ppm was observed before the ECS was started. Especially during pandemic times, such an operation should be avoided as – together with CO_2 – other contaminants or pathogens quickly build up in the cabin air.
- Estimated fresh air flow rates are 5.7 l/s and 6.2 l/s in cruise.
- Noise levels were measured around 81 dB(A) during cruise at seat 9D/F.
- Varying tonal components were detected in the spectrum during all flight phases.
- The Speech Intellegebility Index was below 0% during cruise with normal speech level at 1m distance.
- A clear longitudinal distribution of cabin noise ranging from 77 dB(A) to 83 dB(A) became obvious.

5. Way forward

The measurements conducted on this real flight will serve as baseline for an upcoming subject test campaign on 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. 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 be 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 1.

Figure 18: 3D printed model of the Passenger Cabin Ground Demonstrator

6. Acknowledgements

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CLEAN AVIATION

7. Copyright Statement

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