INCREASED PASSENGER DENSITY IN A LONG-RANGE AIRCRAFT CABIN MOCK-UP AT MIXING VENTILATION

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Abstract

Increasing the seating density is a powerful tool to enhance the economic and ecologic performance of a passenger aircraft. To investigate changes in cabin ventilation, comfort and air quality, two increased seating densities (4-5-4 and 4-6-4) were compared with the 3-4-3 configuration well-known in long-range aircraft. As benchmark case, a generic mixing ventilation (MV) scenario, which is state-of-the-art in aircraft cabins, was investigated under static flight conditions in a full-scale twin aisle cabin mock-up at various flow rates. First results obtained at a constant airflow rate show a weak, but existing effect of the different seating configurations on the equivalent temperatures (determined for the individual body segments), i.e. the local thermal comfort for an aisle seat. Additional measurements were carried out with adjusted flow rates, which can be used to determine possible energy savings with the same level of comfort.

Keywords

Mixing ventilation, long-range aircraft cabin ventilation, thermal passenger comfort, passenger seating density

1. INTRODUCTION

Seating has remained largely unchanged since the early days of commercial aircraft. Even today, the seats look and feel familiar no matter what airline or plane. However, increasing the seat density is an effective tool to improve the economic and environmental performance of a passenger aircraft. Higher seating densities within a given aircraft geometry yield the potential of decreasing the costs per seat. Swan and Adler [1] state that an additional seat row may result in a 5% reduction of the seat costs per trip. Further, they found an almost linear correlation between the number of seats in a comparable aircraft design and the normalized trip costs for both single aisle and long-haul aircraft. They report on the fixed expenditure amounting to approximately 100 seats in short-haul design and twice the amount for long-haul designs used in long-haul operations. Adding additional seat rows, however, either means relying on new seat developments with thinner back-rests or reducing the legroom of the passengers. Other approaches increase the number of seats in one row. Examples are a 3-4-3 abreast configuration in a Boeing 777 or even a 3-5-3 abreast configuration on the lower deck of an Airbus 380, a design used in their first deliveries with one seat less abreast [2]. For a number of years, seat manufacturers have been concentrating on developing new concepts for aircraft seats which increase both capacity and passenger comfort. During this process they are also looking at revolutionary design besides the evolutional enhancement of classical seats. The Skyrider 2.0 is an example for an increase in seat density for low-cost tickets [3]. It places the passenger in a hybrid position between sitting and standing, with the seat slightly raised and tilted forward –an ergonomic design that is said to result in a 20 percent capacity increase and a 50 percent weight reduction of the aircraft seat, for details see [3]. In order to maximize the number of seats in the cabin, you have to reduce the space per passenger. Further, aircraft manufacturers aim to keep the mass of a seat as small as possible. This can also be achieved by attaching seats to a vertical pole [4]. When one of the seats is not in use, it can be folded up.

Besides the ergonomic challenges, an increased seat density also creates new challenges for the ventilation of the cabin in terms of maintaining comfort and air quality. Higher fresh air volume flow rates potentially combined with lower supply air temperatures are needed to remove the additional heat and to ensure acceptable indoor air quality. However, both higher flow rates and lower temperature will lead to draft and thus more uncomfortable conditions in the occupied zone.

In order to avoid high costs due to the time required for flight tests [5] and to enable more environmentally friendly and intelligent testing of ventilation concepts for future long-range aircraft, a 1:1 scale twin-aisle cabin model with thermodynamically realistic boundary conditions using temperature-controlled fuselage elements was developed at the German Aerospace Center (DLR) in Göttingen [6]. In addition to the state-of-the-art ventilation system, the modular design of the new system also offers the possibility to integrate new ventilation concepts and to install different cabin geometries. Further, various flight phases can be simulated with operationally relevant temperature and time scales. Previous studies performed in the new mock-up focused on the comparison of new ventilation systems with mixed ventilation used in aircraft cabins under stationary and dynamic conditions [7]-[11]. With a general trend of rising heat loads in modern passenger cabins, the interest of the aircraft industry in ventilation systems with the same or improved thermal passenger comfort is of high importance.

For this purpose, a high passenger density was experimentally examined in this study. As benchmark case, a generic mixing ventilation (MV) scenario was investigated under static flight conditions in the full-scale twin aisle cabin mock-up with high seating densities at various flow rates. Temperature-controlled thermal manikins were used in this

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cabin mock-up to simulate the heat release of the passengers. The measurement techniques and the test matrix were selected and designed in order to quantify and evaluate the following parameters: boundary conditions, cabin air temperatures, efficiency of the ventilation concept, local velocities as well as thermal comfort, i.e., equivalent temperatures. Two different cases of high seating density (4-5-4 and 4-6-4) were compared to the “normal” 3-4-3 case. The present work is of great importance to determine the impact of a high passenger density on the cabin climate as well as of adapted volume flows with regard to energy saving for future aircraft.

2. TEST EINVIRONMENT AND VENTILATION SYSTEM

The new modular cabin mock-up of DLR in Göttingen was developed, set up and chosen as a test platform for aircraft cabin research activities at ground level. It represents a full-size (1:1 scale) cabin section of modern wide-body airliners. The inner dimensions are: a total length of L = 9.96 m, a width of W = 6.25 m and a height of H = 2.7 m. The cabin interior is equipped with second-hand aircraft parts, see FIG 1. A twin-aisle economy seating class is realized, characterized by a 10-abreast seating configuration arranged in a 3-4-3 seating layout providing space for 100 passengers. Creating the typical flight scenario is of great importance for the evaluation of ventilation concepts under realistic thermodynamic boundary conditions with gap temperatures between the primary and secondary insulation of 10 °C for the “Cruise” case [5]. Based on these findings, the gap temperature was experimentally simulated with capillary tubes attached to aluminum sheets on the fuselage elements (Dado, side wall and ceiling panels, roof compartments and floor), through which a temperature-controlled water-glycol mixture flows. The front and back of the cabin are realized as adiabatic walls with a sufficiently thick insulation. For more details, see [6].

FIG 1. Interior of the cabin mock-up with thermal manikins.

Mixing Ventilation (MV), which is state-of-the-art in aircraft cabin ventilation, is characterized by a high degree of mixing of fresh air jets entering the cabin on both sides, see FIG 2. It should be noted that MV systems currently used in twin aircraft are often operated with an additional ceiling outlet. This additional outlet was not installed in our pure sidewall-based MV system. For optimal ventilation, four MV air inlets were installed in the cross section, two ceiling inlets above and two lateral air inlets below the luggage compartment. With nine inlets in longitudinal direction, overall 36 air inlets were installed in the mock-up. For this study, a volume flow rate split of 50%-50% between ceiling and lateral was chosen. Like in a real plane, the exhaust air openings are located in the lower part on both sides of the cabin (red arrows) close to the Dado panels. For more details, also on the air ducts out of the cabin mock-up, see [6].

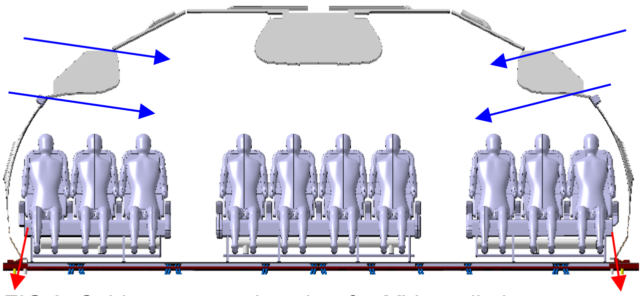


FIG 2. Cabin cross section view for MV ventilation concept in the cabin mock-up.

3. EXPERIMENTAL SETUP AND TEST CASES

This section provides an overview of the installed measurement techniques used to determine comfort-relevant quantities as well as key figures to analyze the energy efficiency of the ventilation system. For a realistic heat load and to simulate the dimensions of real people, thermal manikins (TMs) with a volume of 0.05 m^3 and a surface of 1.52 m^2 were used in the experimental investigations, see FIG 1 and [5]. The TMs consist of a foam core wrapped with a resistance wire, which provides realistic surface temperatures and buoyancy forces through a homogeneous heat flow density (slightly increased in the head area). An automatic control of the heating power enables the emission of sensible heat depending on the ambient temperature based on a railway standard [12]. For the current investigations, the TMs were operated with increased heat releasing rates to simulate the different seat configurations. That means, the heat release per row was adjusted from 820 W for a 10-abreast (3-4-3) configuration to 1066 W for a 13-abreast (4-5-4) configuration and to 1148 W for a 14-abreast (4-6-4) configuration. In addition to the 100 TMs, the cabin measuring system consists of more than 200 temperature and 40 velocity sensors as well as an infrared camera setup to analyze the surface temperature distribution on the TMs and on the interior paneling elements.

The resistance temperature detectors (RTDs) were installed at chest height in front of all TMs to capture the temperatures throughout the cabin. To investigate the temperature layers and to determine the mean cabin air temperature (T_{cab}), the RTDs were positioned at four different heights (ankle, knee, chest, head) in the vicinity of the TMs on 10 seats in row 4, see SR1 in FIG 3. Combined omnidirectional velocity and temperature probes (OVTP, SR2) were installed in a similar array in row 6. They were used to measure comfort-relevant air velocities and their distribution for different parts of the body with an accuracy of 0.2 K for the temperature and 0.02 m/s for the velocity (for details see [6]). The velocity and temperature measurement system was combined with a humidity measurement and an operative temperature probe to determine the thermal passenger comfort quantities, such as Predicted Mean Vote (PMV) and Predicted Percentage of Dissatisfied (PPD). To determine the surface temperatures inside the cabin, two infrared (IR) cameras with a resolution of 640 x 480 px and a sensitivity of 0.08 K were installed in the front part of the cabin in accordance with the fields of view depicted in FIG 3.

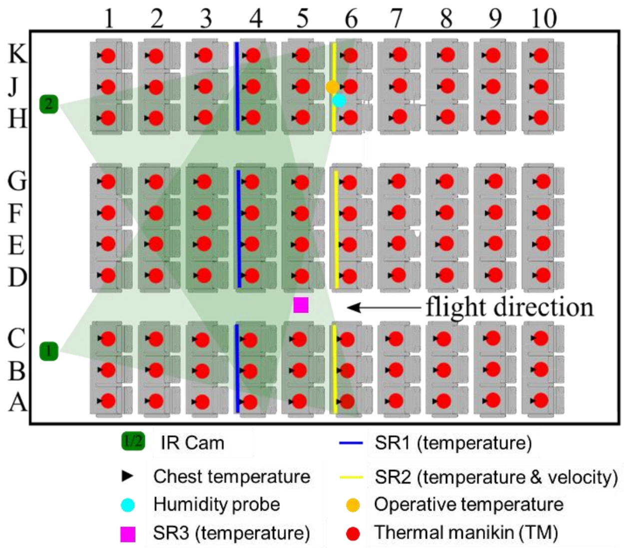


FIG 3. Cabin layout and measurement installation.

Finally, 16 so-called "Equites probes" based on the detection of local heat flows were mounted on a TM in the aisle area, see FIG 4. The system enables an objective comfort measurement – resolved for the individual body segments – in terms of local equivalent temperatures [13] and its interpretation on a five-level scale of sensation from too cold to neutral to too warm. The equivalent temperature is an integral quantity combining air temperature, air movement and radiation, for details see [14].

FIG 4. Manikin with 16 Equites comfort probes.

In addition to the 10-abreast standard seating configuration arranged in a 3-4-3 seating layout – the “norm case” for the long-range cabin mock-up – two increased passenger densities (4-5-4 / 4-6-4) were investigated. Since converting the mock-up from 3 to 4 (flight direction left and right) or 4 to 5/6 (middle row) seats entails an enormous amount of work, only the heating capacity of the individual TMs in the 3-4-3 seating arrangement was increased to simulate the 4-5-4 as well as 4-6-4 passenger density, as stated above. For the lower two seating configurations (4-5-4 / 4-6-4), also different volume flow rates were analyzed.

TAB 1. Investigated test cases with boundary conditions

	3-4-3			4-5-4			4-6-4
T_{cab} [°C]	23.0	23.1	23.1	23.1	23.2	23.1	23.1
T_{in} [°C]	16.3	17.6	19.3	15.0	16.8	17.8	16.4
T_{cab}-T_{in} [K]	6.7	5.1	3.8	8.1	6.4	5.3	6.7
T_{out} [°C]	20.5	20.8	21.1	20.4	20.8	21.0	20.7
TM-Power [kW]	8.2			10.7			11.5
PAX [-]	100			130			140
(Q_V) [m³/s]	0.6	0.8	1.0	0.8	1.0	1.2	1.0

All studied cases including the corresponding boundary conditions, such as flow rate (Q_V), manikin power as well as temperature for supplied (T_{in}), exhausted (T_{out}) and cabin (T_{cab}) air are summarized in TAB 1. It has to be noted that T_{cab} serves as a control temperature and was kept constant with a maximum deviation of 0.1 K during the steady state conditions, reflecting the high precision of the temperature control system in the new mock-up. To reach the setpoint and keep it constant, T_{in} was adjusted individually for each of the studied cases.

One possible evaluation criterion for the efficiency of the ventilation system is the temperature difference between the mean temperature in the cabin T_{cab} and the supply air temperature T_{in}. For a steady and comfortable value of T_{cab} = 23 °C, higher supply air temperatures lead to a smaller pre-cooling demand of the fresh air by the HVAC unit. TAB 1 shows that reducing the volume flow results in a lower T_{in}, which indicates a greater need for cooling. At the same time, however, a reduction of the volume flow rate reduced the energy demand of the HVAC system for the pre-conditioning of the air. Which of the two processes outbalances the other depends on many different parameters, e.g., pressure and temperature levels of the bleed air or the coefficient of performance of the HVAC sub-systems. However, this evaluation would go beyond the scope of this article.

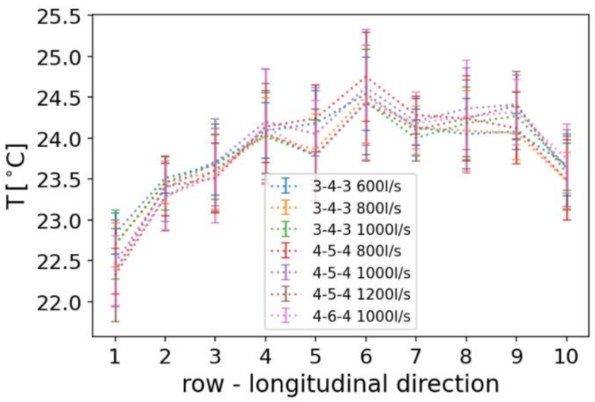
4. RESULTS

4.1. Fluid temperatures and velocities

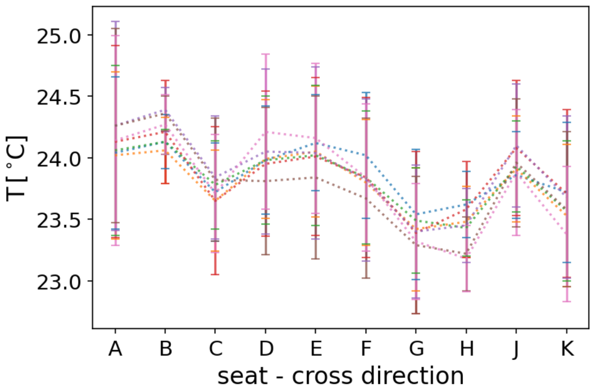
To evaluate the thermal comfort, TAB 2 summarizes the vertical and horizontal temperature stratifications. The vertical temperature layers are given as mean (ΔT_{ha}^{mean}) and maximum (ΔT_{ha}^{max}) differences between head and ankle in row 4. As described in the last section, the increased passenger density was generated by an increased heating power with the same number of TMs (3-4-3). Therefore, it should be noted that the results, in specific of parameter which are evaluated in the vicinity of the manikins, might slightly change when placing more seats in one row. For horizontal homogeneity, ΔT_{chest} shows the maximum difference at chest height for all TMs. No major differences of ΔT_{ha}^{mean} were found between the variants. All temperature stratifications are rated as good in accordance with the requirements defined in the standards. As expected, the values related to the temperature stratification between head and ankle increase for lower volume flows. At ΔT_{ha}^{max} the values increase by 0.9 K and are no longer classified as good in accordance with [12].

TAB 2. Results of investigated test cases

Q_V / PAX [l/s]	3-4-3			4-5-4			4-6-4
	6	8	10	6.2	7.7	9.2	7.1
ΔT_{ha}^{max} [K]	4.2	3.7	3.3	4.0	3.7	3.2	3.9
ΔT_{ha}^{mean} [K]	3.0	2.7	2.3	3.0	2.6	2.2	2.6
ΔT_{chest} [K]	2.9	3.0	3.4	3.9	4.1	4.0	3.9
U_{max}^{mean} [m/s]	0.30	0.26	0.30	0.28	0.29	0.35	0.29



(a)



(b)

FIG 5. Fluid temperatures at chest position of the TMs averaged over a) seat rows and b) seat columns for the investigated cases under "Cruise" conditions.

For the homogeneity in horizontal direction, an increase of ΔT_{chest} was observed with increasing volume flow and a simulated layout with a higher number of seats. Here, the higher flow rate of the standard seating layout results in bigger/more significant differences in the local temperatures when comparing all seats. At higher seating densities, the influence of the flow rate on the temperature distribution at chest level is negligible. This is possibly caused by the increased importance of the buoyancy forces.

For a detailed analysis, FIG 5 shows the temperatures at chest height averaged in cross (a) as well as in longitudinal direction (b). TAB 3 shows the associated temperature differences between maximum and minimum. The average temperatures per row do not show any major differences in longitudinal direction, see FIG 5 a). The largest temperature differences in the cross section ($T_{cr}^{max\text{-}min}$) of up to 2.4 K, mainly caused by row 1, can be found for the 4-5-4 configuration at a flow rate of 800 l/s. The lowest value of 1.7 K was observed for the 3-4-3 seating arrangement and a volume flow rate of 600 l/s. In general, it should be noted that the spatial temperature differences of 2.5 K or lower are all rated as good.

TAB 3. Results of mean values and temperature differences of the investigated test cases

Q_V / PAX [l/s]	3-4-3			4-5-4			4-6-4
	6	8	10	6.2	7.7	9.2	7.1
$\Delta T_{cr}^{max\text{-}min}$ [K]	1.7	1.8	1.7	2.4	2.2	2.1	2.1
$\Delta_{row}^{max\text{-}min}$ [K]	0.6	0.6	0.7	0.8	1.0	1.1	1.1
U_h^{mean} [m/s]	0.16	0.17	0.22	0.18	0.23	0.26	0.22
U_h^{std} [m/s]	0.05	0.06	0.07	0.06	0.07	0.08	0.07
$U_h^{max\text{-}min}$ [m/s]	0.20	0.12	0.17	0.14	0.13	0.20	0.13

The averaged values in longitudinal direction (FIG 5 b) reveal lower temperatures for window (A, K) and aisle (C, H) seats as compared to the middle seats (B, E, F, J) on both sides of the cabin for all configurations. The maximum temperature difference in the row ($T_{row}^{max\text{-}min}$) increases with increasing volume flow and with increasing seating density, see TAB 3. However, the differences between 0.6 K at 3-4-3 and 600 l/s and 1.1 K at 4-6-4 and 1000 l/s are rather small and all of them are evaluated as - uncritical.

In addition to the mean cabin temperatures, spatial temperature homogeneity and temperature stratification, (summarized in TAB 3), the local temperatures in the vicinity of the manikins are also highly relevant in terms of passenger comfort. Exemplarily, FIG 6 (a) shows the temperatures at head level. Firstly, it should be noted that the temperature distribution over the different seats and the average level of the temperatures on head level do both only slightly change for the different seat configurations or volume flow rates. Seat A is significantly warmer for all investigated parameter combinations compared to, e.g., seat G, which is the coldest for many cases. It should be noted that maximal differences between two seats for a given configuration are in the range between 0.7 K (3-4-3 at 800 l/s) and 1.7 K (4-6-4 at 1000 l/s). Accordingly, the spatial homogeneity of the local temperatures at head level can be evaluated as acceptable for all cases. The mean temperatures at head level deviate only by 0.35 K between all investigated configurations spanning a range from 23.36 °C (4-5-4 at 1200 l/s) to 23.71 °C (4-5-4 at 800 l/s). A comparison of the right and left row of seats (ABC vs. HJK) shows only minimal differences. However, a decrease in temperature from seat 6D to 6G was observed in all cases.

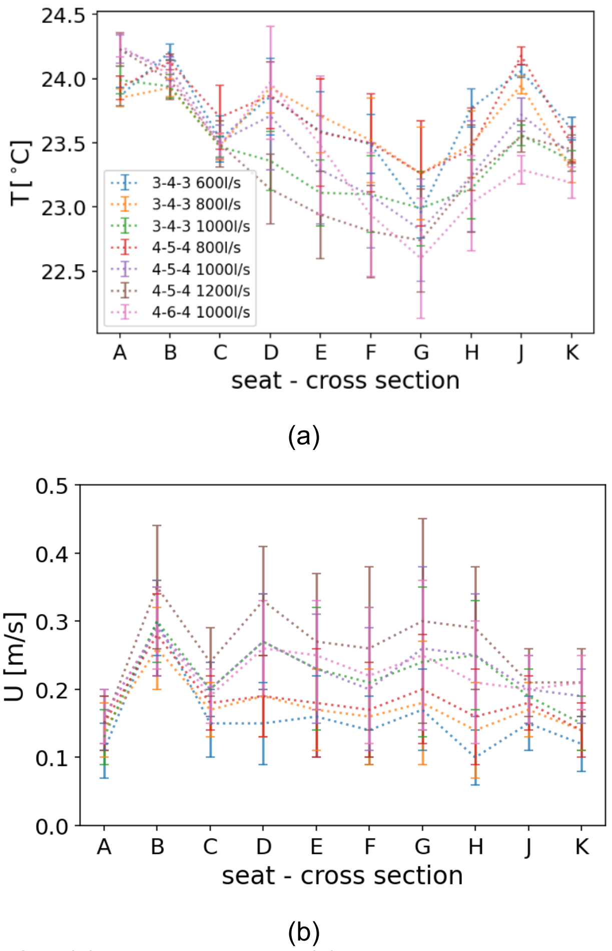


FIG 6. (a) Temperatures and (b) velocities at head level in cross section in row 6 measured with SR2.

FIG 6 (b) depicts the associated mean fluid velocities in row 6 at head level. Additionally, TAB 3 summarizes the associated mean values, standard deviations as well as the differences between maximum and minimum. The first thing to note is that, except for the 4-5-4 configuration at 1200 l/s, no high mean velocities greater than 0.31 m/s, outbalancing the maximum velocity as upper comfort threshold defined in [15], were found for any seat, seat density or volume flow rate. A general trend for all investigated cases reveals rather low velocities on seat A and high velocities on seat B. Except for these seats, the local air velocities at head level are almost constant on all other seats for a given configuration. Regarding the different configurations, as expected, lower velocities are found for lower airflow rates and higher velocities are found for higher airflow rates.

4.2. Surface temperatures

In the following, the influence of the seating layout on the surface temperatures will be discussed using infrared images of the inner surfaces recorded from the front left at a flow rate of 1000 l/s, see FIG 7. A homogeneous temperature distribution in longitudinal direction was found for all seating layouts. Despite increasing thermal heat load, no differences were found on the inner surfaces. The differences in the manikins' surface temperature reflect the higher seating density simulated by increased heating power.

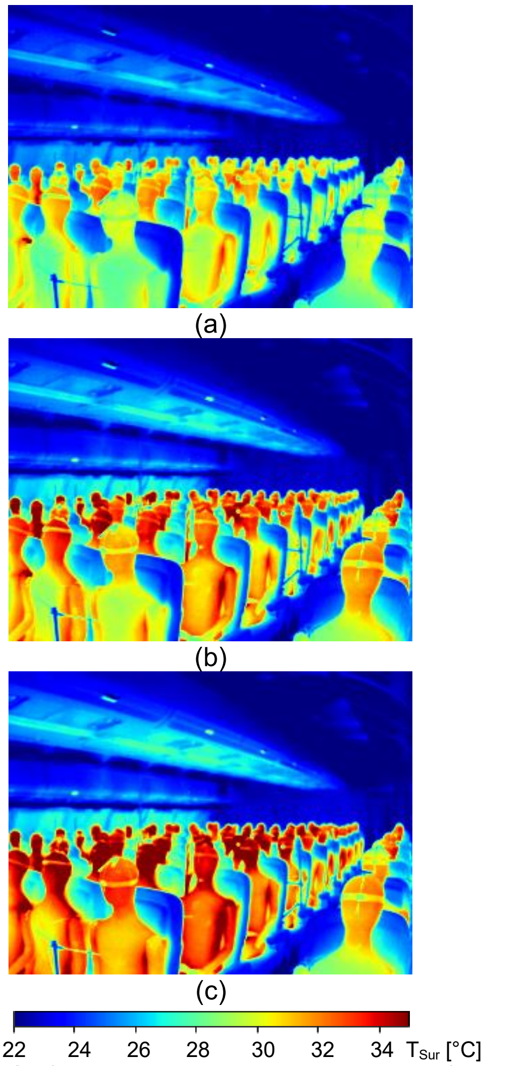


FIG 7. Surface temperatures recorded by infrared thermography in front of row 1 in flight direction left for (a) 3-4-3, (b) 4-5-4 and (c) 4-6-4 seating layout with a volume flow of 1000 l/s.

4.3. Comfort assessment

4.3.1. PMV and PPD on seat 6J

As already described, the Predicted Mean Vote (PMV) and the Predicted Percentage of Dissatisfied (PPD) were calculated using the OVTPs in combination with a humidity and an operative temperature probe in row 6. $|PMV| < 0.8$ corresponds to comfortable conditions, whereas $0.8 < |PMV| < 1.0$ represents slightly too cold or too warm conditions depending on the sign of the PMV [16].

FIG 8 shows values below -1 for all investigated cases and body positions. Apparently, the chosen T_{cab} of 23 °C seems to be too low according to this local comfort evaluation for seat 6J. The highest and lowest PMV values were found at knee and chest height, respectively, for all configurations. The values for the head are always close to the mean value, while the ankle PMV values are the second highest for all configurations except the 3-4-3 configuration at 600 l/s. For the 4-5-4 configuration, an additional trend of decreasing PMV with increasing airflow rate was found, which is caused by the higher flow velocities. These velocities increase from 0.18 to 0.26 m/s, see TAB 3. Surprisingly, this trend was not observed for the 3-4-3 configuration.

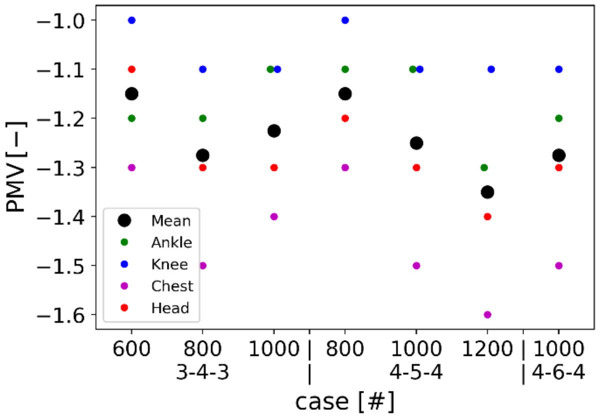


FIG 8. Thermal passenger comfort criteria shown as Predicted Mean Vote (PMV) at (a), ankle, (b) knee, (c) chest and (d) head level for all investigated cases.

FIG 9 shows the PPD values for the investigated configurations reflecting a high level of dissatisfaction of 32% - 45%, as expected based on the PMV values. The lowest PPD values were found for the configurations with the lowest flow rates (3-4-3 at 600 l/s and 4-5-4 at 800 l/s), leading to the conclusion that the local airflow is the main driver for these evaluations as the mean temperature in the cabin was maintained at 23 °C.

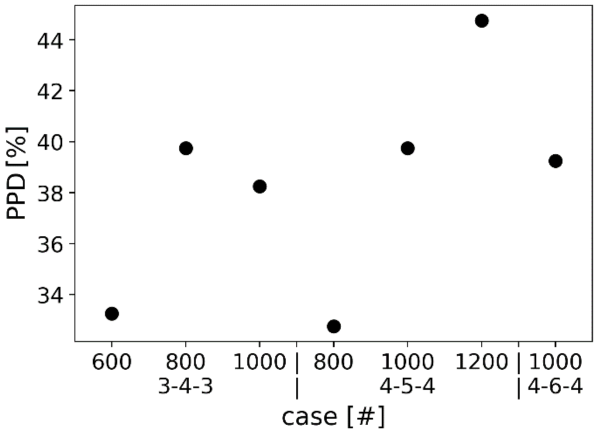


FIG 9. Thermal passenger comfort criteria shown as Predicted Percentage of Dissatisfied (PPD) evaluated as average value comprising the ankle, knee, chest and head level probes.

4.3.2. Equivalent temperature in the aisle

FIG 10 shows the equivalent temperatures – determined per body segment – evaluated for summer conditions according to [13]. FIG 10 (a) shows the impact of different flow rates for a fixed 3-4-3 seat configuration on the local equivalent temperatures. FIG 10 (b) presents the influence of the seating configuration at a constant volume flow rate of 1000 l/s. As described in section 3, the equivalent temperature was determined for 16 different body parts of a standing manikin in the aisle. This measurement position represents flight attendants or passengers who are standing or moving in the aisle during a long-range flight.

The first thing to note in FIG 10 (a) is that for all cases too low values were found at all body positions except the hands. However, a clear trend of decreasing local equivalent temperatures is found for increasing flow rates. That means in the present case of rather too low temperatures, the more comfortable conditions were found for lower flow rates. Despite different volume flows, similarly small fluctuations were found in almost all positions. FIG 10 (b) shows the comparison of the different seating layouts with at a constant volume flow rate of 1000 l/s. As in the previous figure (a), too cold temperatures were recorded except for the hands. Further, only minor effects in the range of 1 K of the seating configuration on the equivalent temperatures in the aisle were detected. No clear trend could be observed. Accordingly, we conclude that the airflow rate is the main influence parameter for the equivalent temperatures, i.e., the thermal comfort, for persons standing in the aisle. Different seat configurations, which are accompanied by different supply air temperatures (see TAB 1) at a constant volume flow rate, however, do not significantly influence the passenger comfort in the aisle.

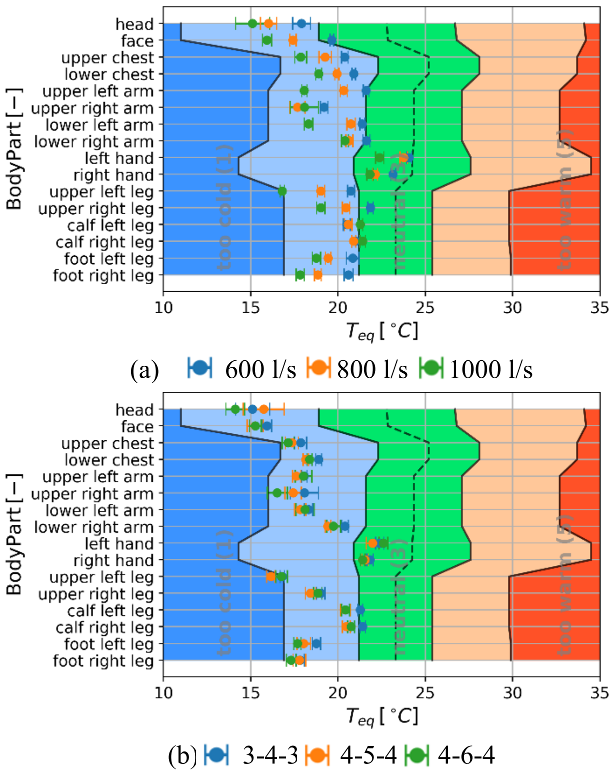


FIG 10. Comparison of equivalent temperatures for (a) three different volume flow rates at a fixed 3-4-3 seating configuration and (b) three different seating layouts at a constant flow rate of Q_V = 1000 l/s.

4.4. Assessment of energy-relevant parameters

Finally, **Fehler! Verweisquelle konnte nicht gefunden werden.** shows the resulting energy-relevant parameters of the investigated cases. A measure of the efficiency of the ventilation system is the so-called Heat Removal Efficiency, see (1):

$$(1) \quad HRE = \frac{1}{2} \cdot \frac{T_{out} - T_{in}}{T_{cab} - T_{in}}$$

Perfect mixing in the cabin, i.e., $T_{cab} = T_{out}$, yields an HRE of 0.5. Modern MV concepts achieve HRE values of around 0.4, see [5]. A higher HRE value of a ventilation system indicates a more efficient removal of heat from the cabin by the airflow. In single-aisle aircraft, new ventilation concepts, such as cabin displacement ventilation or a hybrid ventilation concept, show significantly higher HRE values compared to modern MVs reaching values of up to 0.9 [5]. In the present investigation, rather low HRE values in the order of 0.3 were found, which shows that the installed ventilation system tends to generate an undesirable short-circuit flow. This is underlined by the fact, that the exhaust air temperature is much lower than the mean temperature in the cabin, i.e., the air leaves the cabin before being heated significantly by the internal heat loads.

TAB 4. Results of energy-relevant parameters of the investigated test cases

Q_V / PAX [l/s]	3-4-3			4-5-4			4-6-4
	6	8	10	6.2	7.7	9.2	7.1
HRE [-]	0.31	0.29	0.24	0.33	0.31	0.30	0.32
H [W]	3050	3098	2178	5228	4840	4647	5204
H [%]	37	38	27	49	45	44	45
H / PAX [W]	30	31	22	40	37	36	37
P_{TM} [kW]	8.2			10.7			11.5

Finally, we evaluate the enthalpy flow of the airflow through the cabin, which is the product of the airflow rate, the specific heat capacity, the density and the temperature difference between exhaust and supply. It serves as a measure of the amount of heat that is removed from the cabin by the airflow. The difference between this quantity and the total internally released heat by the manikins P_{TM} must be transported through the wall, the floor and the ceiling, which are – as a reminder – operated at low temperatures to simulate flight conditions. In addition to the total H value, we also evaluate H per passenger (H/PAX) and the percentage amount of heat being removed by the ventilation system compared to the total internal heat release (H/P_{TM}), both summarized in TAB 4. The results are not completely unequivocal and further investigations and a more detailed analysis must be performed in the future. Nevertheless, there seems to be a trend that more heat is transported by the ventilation system with decreasing airflow rate. Furthermore, a higher heat load in the cabin also results in an increased fraction of heat transported by the ventilation system. In other words, the lower the seating density and the higher the airflow rate, the less (pro rata) heat is removed by the ventilation system to the exhaust air and the more heat is dissipated through the enclosing walls. On the one hand, this could lead to a reduced demand of energy of the HVAC system for pre-conditioning the air. On the other hand, strong temperature gradients with regard to the inner surfaces and increased volume flow rates will lead to comfort-critical conditions. Finally, it should be noted that a) a more detailed analysis is needed for a deeper understanding of these first findings, b) the local air quality was not assessed in this study which is also strongly dependent on airflow rates and occupancies and c) the thermal comfort was only evaluated on a single seat and thus might not be representative of the conditions in the whole cabin.

5. DISCUSSION AND CONCLUSION

This article describes the investigation of increased passenger density in a ground-based test facility at the German Aerospace Center (DLR) in Göttingen. The cabin mock-up features the typical geometric dimensions of a passenger cabin of a modern long-range aircraft on a 1:1 scale. The cabin is characterized by a two-aisle arrangement and can accommodate a total of 100 passengers distributed over 10 seats with normal 3-4-3 seating layout. Mixing ventilation (MV) – which is state-of-the-art for aircraft cabins – is used as ventilation system. A jacket heating/cooling system based on capillary tubes was implemented in the structure to generate realistic temperature boundary conditions of the flight case (cruise). Thermal manikins were positioned in the mock-up to simulate the heat emission and the dimensions of the passengers. Various measurement techniques were used to record and evaluate the following parameters: boundary conditions, cabin air temperature, efficiency of the ventilation concept, thermal comfort, flow velocities, surface and equivalent temperature.

Two seating configurations with a higher number of seats, i.e., 4-5-4 and 4-6-4, with partially adjusted volume flow rates were compared with the reference case 3-4-3 seating layout at QV = 1000 l/s. Additionally, reduced volume flow rates were analyzed for the reference seating layout. For reasons of comparability, the inflow temperature (T_{in}) was adjusted to the same average cabin temperature (T_{cab}) for each case.

All temperature stratifications in the vicinity of the seated thermal manikins are rated as good in accordance with the requirements defined in the standards. Furthermore, the spatial temperature distribution, averaged at chest level in cross as well as longitudinal direction, reveals differences of 2.5 K or lower, reflecting a good spatial homogeneity for all cases. Except for seats A and B, the local air velocities at head level are almost constant on all other seats for a given configuration. Regarding the different configurations, as expected, lower velocities are found for lower airflow rates and higher velocities are found for higher airflow rates.

A comparison of the results of the comfort evaluation in the aisle and in the seating area shows similar, slightly too cold areas. The PPD index shows a high level of dissatisfaction of 32% - 45% with the best values at the lowest flow rates. This leads to two conclusions: a) overall it is slightly too cold in the cabin and b) the lower the local air velocities (caused by lower airflow rates) at this rather low mean temperature, the better the comfort evaluation.

The calculated enthalpy flow of the airflow through the cabin shows a trend that more heat is transported by the ventilation system for decreasing airflow rates. Furthermore, with increasing heat loads in the cabin, the relative amount of heat transported by the ventilation system increases as well.

In general, rather poor HRE values, corresponding to a significant short-circuit flow, were measured for all configurations. The HRE was almost independent of the configuration at a level of approx. 0.3. Only the highest flow rate at the lowest seat density revealed an even lower HRE of 0.24. Further, we found that reducing the volume flow rate results in a lower T_{in}, which indicates a greater need for pre-cooling. Simultaneously, however, a reduction of the volume flow rate decreases the energy demand of the HVAC system for the pre-conditioning of the air.

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