



Mixing ventilation by in-seat air outlets for single-aisle aircraft

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Abstract

In recent years, alternative ventilation systems for aircraft cabins have attracted the attention of scientists and aircraft manufacturers due to their potential to save energy and increase thermal comfort. The aim of this study was to investigate whether comfortable thermal conditions for the passengers can be achieved by a floor-based cabin displacement ventilation (CDV) in combination with an in-seat ventilation (ISV). The two alternative ventilation systems were therefore investigated in the Dornier 728 test facility of the German Aerospace Center in Göttingen. Firstly, ISV, where fresh air flows vertically into the cabin in the immediate vicinity of the passengers through air outlets attached to the back of the seats, and secondly, CDV, which is based on low supply air velocities through dense membranes under the seats. Furthermore, the potential of combining the two ventilation technologies to create a hybrid ventilation system in the single-aisle cabin was investigated. The measurement techniques were selected and designed to quantify and evaluate the following parameters: boundary conditions, cabin air temperature, efficiency of the ventilation concept, flow velocities, 3D flow measurements and thermal comfort. The results showed that neither CDV nor ISV alone meets the comfort requirements. However, combining the ventilation systems produced good results for the ventilation of a single-aisle aircraft. Despite the high inflow velocities associated with ISV, no threshold values were exceeded near the passengers. Furthermore, ISV reduced the uncomfortable temperature stratification in CDV. Combining the systems resulted in equivalent temperatures that were neither too warm nor too cold for all body parts.

Keywords Aircraft cabin · In-seat ventilation · Cabin displacement ventilation · Passenger thermal comfort · Equivalent temperature · 3D flow fields

Abbreviations

AoA	Angle of air	HRE	Heat removal efficiency
CDV	Cabin displacement ventilation	HVAC	Heating, ventilation and air-conditioning
CFD	Computational fluid dynamics	ISV	In-Seat ventilation
Clo	Clothing insulation	Met	Metabolic rate
ΔT_{HA}	Temperature difference between head and ankle	MV	Mixing ventilation
DLR	German aerospace center	PMV	Predicted mean vote
DR	Draft rate	PPD	Predicted percent of dissatisfied
FDL	Flight direction left	PV	Personalized ventilation
FDR	Flight direction right	RTD	Resistance temperature sensors
		T	Local temperature
		T_{cab}	Cabin air temperature
		T_{eq}	Equivalent temperature
		T_{in}	Supply air Temperature
		T_{out}	Exhaust air temperature
		TPD	Thermal passenger dummy
		Tu	Turbulence intensity
		u	Velocity

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1 Introduction

Mixing ventilation (MV) – as state-of-the-art ventilation concept for passenger aircraft – comprises many advantages such as low temperature stratification and high robustness against changes of the boundary conditions [1, 2]. However, its heat removal efficiency is limited and high air flow velocities may cause negative draft. Moreover, its installation in the manufacturing process is time-consuming. Other studies proposed cabin displacement ventilation (CDV) [1] or personalized ventilation systems (PV) [3]; all of them revealing advantages and new challenges. In case of CDV, the fresh air is supplied through the floor with very low momentum. It then rises near the heat loads due to buoyancy and leaves the cabin in the ceiling area. This results in a high heat and aerosol removal efficiency. However, CDV causes unpleasant temperature stratifications, as demonstrated by the results of numerical simulations and experimental studies in ground-based facilities and even under flight conditions, see e.g., [4–7]. The use of personalized displacement ventilation to improve the cabin climate was investigated numerically and experimentally in a fully occupied single-aisle cabin [8]. Although the diffusers in the proposed system were located close to the passengers' legs, the air velocity in the lower part of the cabin and in the leg area remained acceptable. The proposed system maintained an acceptable thermal climate in the cabin. Another version of PV, directed conditioned fresh air directly into the passengers' breathing zone via the air outlets integrated into the seat armrests [3]. At the same time, a mixture of fresh and recirculated air was supplied through perforated under-aisle panels. Contaminated air was extracted through ventilation slots in the ceiling. Despite vertical temperature stratification, the system performed acceptably in terms of the percentage of dissatisfied people due to drafts. Another study investigated six innovative PV systems using CFD simulations in a twin-aisle cabin [9]. By comparing relative humidity, velocity, temperature, predicted mean vote (PMV), predicted percent of dissatisfied (PPD), and air of age (AoA), an acceptable thermal cabin climate was determined. It was found that a configuration of personal air vents at the passenger heads was the most effective solution. The performance of a PV system with headrest-mounted air supply devices was measured using a thermal breathing manikin and subsequently compared with subject tests [10]. The results indicated a significant improvement in the breathing air quality. Subjects rated the air movement and cooling as acceptable. No drafts were reported.

For the experimental analysis of ventilation systems in long-range aircraft, a modern two-aisle cabin model was developed at the German Aerospace Center (DLR) in Göttingen using original interior parts [11]. MV was compared

to alternative ventilation systems with regard to passenger thermal comfort and energy efficiency [11, 12], highlighting the advantages and disadvantages of the different ventilation concepts. Furthermore, a combination of CDV and an alternative in-seat ventilation (ISV) system, installed entirely in the floor area, was integrated and investigated. The idea behind ISV is to establish a concept that is a) fully floor-module integrated and b) based on a mixing-ventilation principle, i.e., high-momentum air supply enhancing the robustness of the flow field due to a high degree of forced flow. Another benefit of this concept is to bring in the fresh air close to the passengers to ensure an optimal supply of fresh air. The fresh air flows vertically into the cabin in the immediate vicinity of the passengers through air outlets on the backseats. The key advantages of this system include potential weight savings due to the elimination of air ducts in the ceiling area and integration into a row of seats, which also offers significant structural advantages. The concept has demonstrated its advantages and design challenges and has already been patented [13].

Another test facility of the DLR in Göttingen is the short-range aircraft Dornier Do 728, see Fig. 1a, b, which allows for measurements to be conducted in a real aircraft without the need for certification. In addition to MV, various studies have investigated novel ventilation systems in terms of passenger thermal comfort, efficiency, and the impact of unoccupied seats [1, 14].

The aim of the present study is to design an energy-efficient ventilation system that meets thermal comfort requirements and offers manufacturing advantages by being integrated into the seat bench. Therefore, the ISV system described in [13] was incorporated into the Do 728 test facility to evaluate its performance in a short-range aircraft. The additional air outlets were installed in three rows on the backrests of the seats, oriented towards the ceiling. A control system enabled the ISV and the CDV system to be operated independently or in combination at specific air flow rate distributions. The measurement area of the cabin was equipped with 35 thermal passenger dummies (TPDs) to ensure realistic, passenger-simulating thermal loads. Various measurement techniques were used including local velocity and temperature measurements (Dantec, Comfort Sense), body-segment-wise equivalent temperatures [15] as stipulated in [16] and 3D velocity fields using an optically tracked three-component ultrasonic anemometer (Streamwise, Procap).

Pure CDV, pure ISV as well as many combinations with varying flow rate splits were investigated.

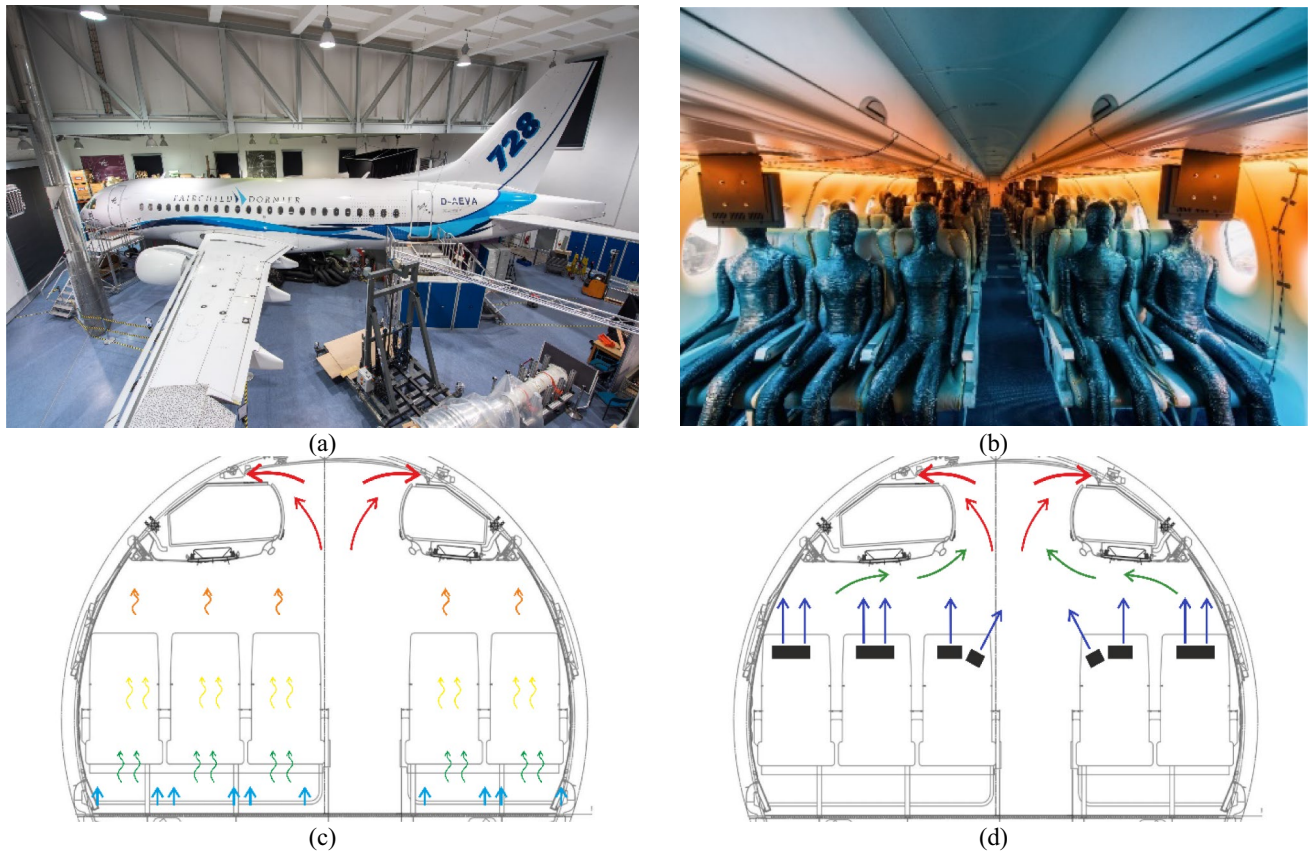


Fig. 1 **a** Image of the Do 728 and **b** its interior as well as the used ventilation systems, **c** cabin displacement ventilation (CDV) and **d** in-seat ventilation (ISV)

2 Materials and methods

2.1 Test environment and ventilation systems

As test environment, the Do 728 test facility of the German Aerospace Center in Göttingen was used, see Fig. 1a, b. It provides a realistic cabin structure of a short-range aircraft cabin which has a total length of 16.9 m, a width of 3.25 m and a height of 2.14 m. The free air volume within the cabin, i.e., inner volume without seats and thermal manikins, amounts to approx. 54 m³. An external heating, ventilation and air-conditioning (HVAC) system provides fresh air at a nominal volume flow rate of $QV = 9 \text{ l/s/PAX}$ at atmospheric pressure. As the research aircraft was designed with a 2–3 seating arrangement, see Fig. 1b, the air supply to the passengers was split: 40% from the left and 60% from the right. Please note: orientations such as “left” and “right” refer to the direction of flight, whereas the images and sketches in Fig. 1b–d face the rear of the cabin. In case of CDV, the fresh air – introduced with low momentum through dense air distribution membranes under the seats [1] – rises due to buoyancy near the heat loads and leaves the cabin in the crown area through the inversely operated ceiling outlets above

the overhead luggage compartments, see Fig. 1c. CDV has been shown to offer a significantly higher heat removal efficiency at very low flow velocities compared to state-of-the-art MV. A high proportion of CDV leads to uncomfortable temperature layers [1]. A further novel ventilation system investigated in this study is the so-called in-seat ventilation (ISV), see Fig. 1d and [13]. The idea is to establish a concept, which is a) fully floor-module integrated and b) based on a mixing-ventilation principle, i.e., high-momentum air supply enhancing the robustness of the flow field due to a high degree of forced airflow. The fresh air flows vertically into the cabin in the immediate vicinity of the passengers through air outlets on the backseats. In order to ensure a good ventilation for cabin occupants and people standing in the aisle area, the outlets for the aisle seats were separated. One part was directed at an angle of 45 degree into the aisle, while the other part was aligned horizontally. The total outflow area of the two aisle seat outlets and the larger air outlets at the middle and window seats is equal. As high inflow velocities are expected due to the small exit surface of the outlets [1] the system was combined with CDV for five additional cases. An air supply at floor level is of great importance in the planning of future aircraft in order to save

air ducts to the ceiling area. In addition to reducing material costs, weight and thus a considerable proportion of kerosene can potentially be saved. Furthermore, the entire air supply system can be integrated into the seat or pre-compiled floor modules for this system, simplifying the manufacturing process.

2.2 Measurement techniques and test cases

This section briefly describes the measurement techniques used to evaluate the different supply air conditions. To control the supply and exhaust air temperatures, resistance temperature sensors (RTDs) of type Pt100 (1/3 DIN B) with a calibration accuracy of 0.15 K were used in the CDV air distribution membranes, the in-seat ventilation outlets and in the exhaust air openings in the ceiling area.

2.2.1 Thermal passenger dummies

In order to achieve a realistic heat load and realistic dimensions, 35 thermal passenger dummies (TPDs) were used to simulate the passengers during the experimental investigations, see Fig. 1b and [1]. The TPDs consist of a foam core wrapped in resistance wire with a volume of 0.05 m³ and a surface of 1.52 m². A 75 W external power supply enables constant sensible heat dissipation. Realistic surface temperatures and buoyancy forces were achieved through a very homogeneous distribution of the heat flow density, slightly increased in the head area.

2.2.2 Combined velocity and temperature acquisition

The flow velocity in the cabin was measured on five seats at five different height levels (ankle, knee, chest, head, overhead) at a distance of 5 cm from the TPDs' surface using

the Thermal Comfort Measurement Solution System from Dantec Dynamics, see Fig. 2a, b. In addition, the fluid temperatures were measured with the probes mounted in row nine to determine the cabin air temperature (T_{cab}). They provide an accuracy of ± 0.02 m/s for the velocity and ± 0.2 K for the temperature with a frequency response of at least 2 Hz, for details see [17]. In total, 25 combined velocity and temperature probes were installed in the Do728. With the help of these probes, the comfort-relevant air velocities and their distribution were recorded for different body parts. In addition, the velocity and temperature measurement system was combined with two humidity and operating temperature probes with an accuracy of $\pm 1.5\%$ for the humidity and ± 0.2 K for the operating temperature. This allowed for the calculation of passenger thermal comfort criteria, such as the predicted mean vote (PMV) and the resulting predicted percentage dissatisfaction (PPD). The PPD index is the predicted percentage of people who perceive a thermal environment as uncomfortable. The calculation of the indices is presented in Sect. 2.3.

2.2.3 Flow field acquisition

The velocity field generated by the in-seat air supply was measured using an optically tracked three-component ultrasonic anemometer (Streamwise Procap). This measurement system allowed for a non-time-resolved acquisition of all three velocity components and the fluid temperature in a pre-defined three-dimensional measurement volume. The spatial resolution was set to 2 cm and the accuracy of the velocity probes is given as 0.1 m/s with a resolution of 0.01 m/s and an acquisition rate of 40 Hz. In the current study, the measurement volume was represented by a cubical box with a side length of 1000 mm reaching from the air inlets to the next TPD.

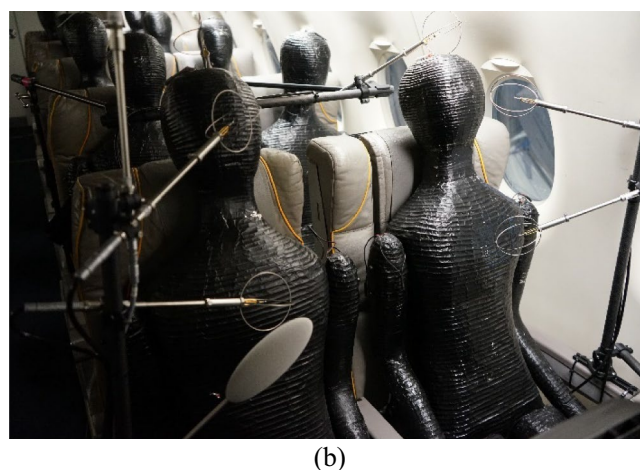
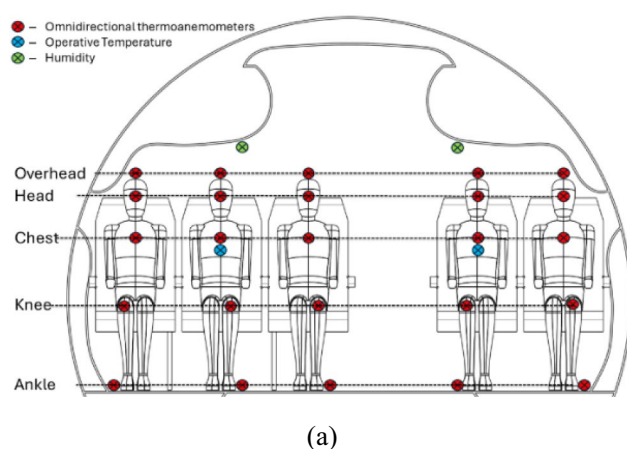


Fig. 2 a Humidity, operative temperature and combined omnidirectional velocity and temperature sensor arrangement in the vicinity of the TPDs and b photo of the measurement installation

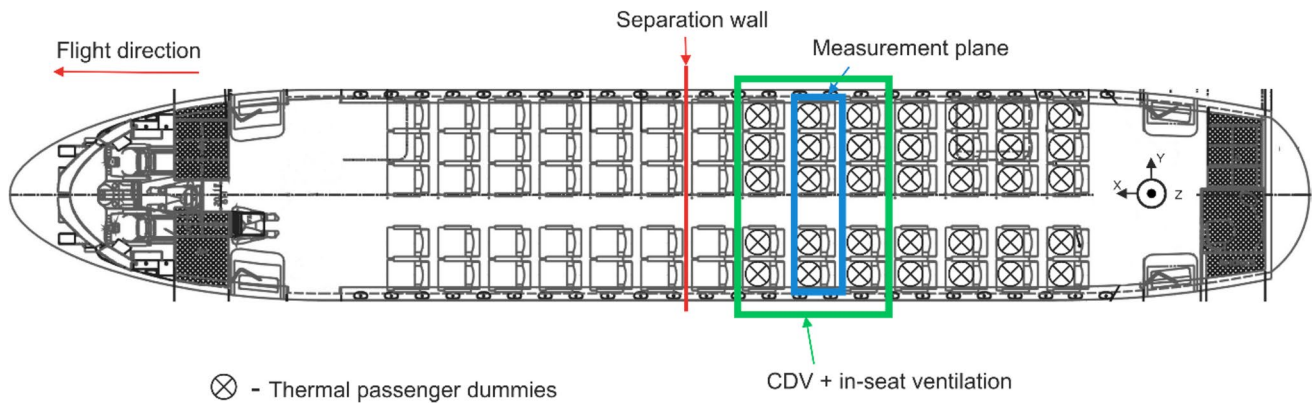


Fig. 3 Cabin layout of the Do 728 measurement installation

Table 1 Investigated test cases with percentage and absolute volume flow distribution per TPD

Case [#]	CDV [%]	ISV [%]	CDV [l/s/PAX]	ISV [l/s/PAX]
0	100	0	9.0	0
1	50	50	4.5	4.5
2	40	60	3.6	5.4
3	30	70	2.7	6.3
4	20	80	1.8	7.2
5	10	90	0.9	8.1
6	0	100	0	9.0

2.2.4 Equivalent temperature acquisition

The thermal comfort of individual body segments was recorded and evaluated using a 16-probe sensor system (Comlogo, Equites System [15]) in accordance with the defined equivalent temperature [16] on seat 9D. This enabled objective thermal comfort to be recorded and evaluated in accordance with the stipulations of international standards and recognized comfort levels ranging from too cold to too warm via neutral. The system enables objective comfort measurement in the form of local T_{eq} with an accuracy of ± 0.5 K at a recording frequency of 1 Hz. The comfort assessment in this study was conducted using the summer evaluation scheme, see [16].

2.2.5 Cabin layout and test cases

The TPDs described in Sect. 2.2.1 were positioned in the rear part of the Do728, see Fig. 3. To minimize boundary effects in longitudinal direction, the measurement section was separated by a Styrofoam partition wall with a thickness of 0.1 m. The CDV-ISV system was only installed in row 8–10 for structural reasons. In row 7 and 11–14, the fresh air supply was regulated by 100% CDV. The investigated parameter configurations in the measurement rows are summarized in Table 1. Both systems, CDV (#0) and ISV (#6) were measured individually. Additionally, the volume

flow rate was investigated in steps of 10%, ranging from 50% CDV and 50% ISV (#1) to 10% CDV and 90% ISV (#5).

2.3 Thermal comfort indices and heat removal efficiency

As previously described in Sect. 2.2.2, the PMV and the resulting PPD index were calculated using the Dantec Comfort Sense system. The PPD index is calculated based on the PMV index in accordance with [18] as follows:

$$PPD = 100 - 95^{(-0.03353 \cdot PMV^4 - 0.2179 \cdot PMV^2)} \quad (1)$$

The PMV index is an integral thermal comfort parameter that combines the air temperature, the radiation temperature as well as the air velocity and air humidity. The PMV-PPD model considers clothing insulation (Clo) and metabolic rate (Met), both of which influence thermal comfort. For the presented results, the clothing insulation was fixed at 1 Clo and the metabolic rate at 1.38. A clothing insulation level of Clo = 1 corresponds to a person wearing a shirt, trousers, a jacket, socks and shoes, with MET = 1.38 being set for very light sitting activities.

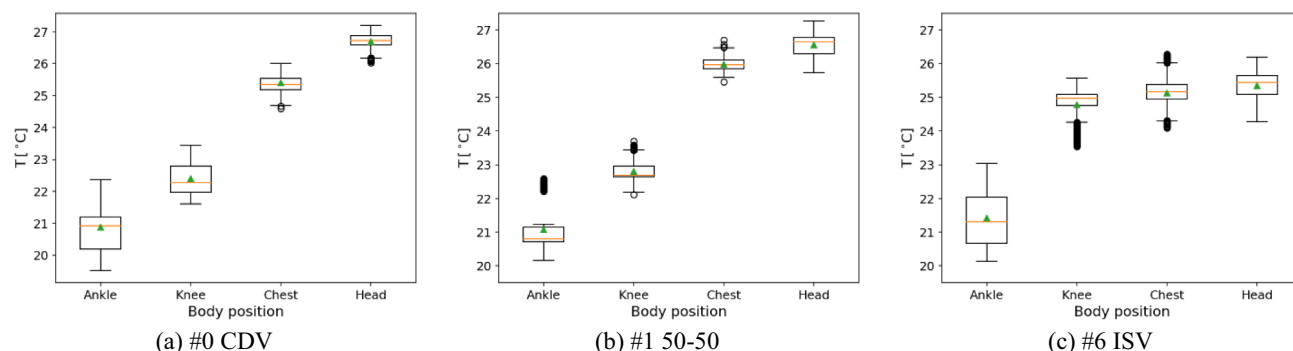
The calculated draft rate (DR) indicates the probability of passengers complaining about unpleasant drafts. This was also determined based on the combined velocity and temperature probes in accordance with Eq. (2), taking into account the local temperature (T), the velocity (u) and the turbulence intensity (Tu).

$$DR = ([34 - T] \cdot [u - 10]^{0.62}) \cdot (0.37 \cdot u \cdot Tu + 3.14) \quad (2)$$

The third calculated quantity is the heat removal efficiency (HRE) as defined by Equ. (3). The HRE definition considers that efficient removal of the heat loads requires, firstly, low local air temperatures and, secondly, that the air absorbs as much thermal energy as possible before leaving the cabin. It

Table 2 Investigated boundary conditions with T_{in} , T_{cab} , T_{out} , ΔT_{HA} and HRE and the velocities (u / σ_u) for all investigated cases

Case [#]	T_{in} [°C]	T_{cab} [°C]	T_{out} [°C]	ΔT_{HA} [K]	HRE [-]	u [m/s]	σ_u [m/s]
0	19.1	23.8	27.4	5.8	0.88	0.08	0.02
1	20.0	24.1	26.6	5.5	0.80	0.10	0.03
2	20.3	24.1	26.4	5.2	0.80	0.11	0.02
3	20.0	24.3	26.6	4.8	0.77	0.11	0.03
4	19.7	24.2	26.4	4.3	0.74	0.14	0.04
5	19.9	24.1	25.9	4.1	0.71	0.16	0.04
6	19.9	24.2	25.8	3.9	0.69	0.18	0.05

**Fig. 4** Boxplots of fluid temperatures in the vicinity of five TPDs in cross-section in row 9 at four height levels of **a** #0 CDV, **b** #1 50–50 and **c** #6 ISV

is calculated using the supply (T_{in}), exhaust (T_{out}) and mean cabin (T_{cab}) air temperature as follows:

$$HRE = \frac{1}{2} \cdot \frac{T_{out} - T_{in}}{T_{cab} - T_{in}} \quad (3)$$

3 Results

After this brief general description of the measurement techniques, the following sections contain the detailed discussion of the results: Sect. 3.1 describes the results for the fluid temperatures and for the heat removal efficiency (HRE). The subsequent section deals with the fluid velocities determined using the combined velocity and temperature probes as well as the optically tracked three-component ultrasonic anemometer. Finally, Sect. 3.3 shows the differences when it comes to thermal comfort:

Before briefly discussing the results in terms of the different ventilation concepts, it should be noted that throughout all tests, the incoming air temperature (T_{in}) of the HVAC was kept constant at 16 °C, resulting in slightly different incoming air temperatures at the outlets due to the supply air distribution between CDV and ISV. T_{in} was averaged as a percentage, depending on the case indicated in Table 1, using the RTDs in the CDV as well as in the ISV supply air outlets in row 9. However, as Table 2 shows, maximum differences of ± 0.3 K were found around 20 °C. Furthermore, no major differences were found in the cabin air temperature

(T_{cab}), averaged over four height levels (ankle, knee, chest, head) at five seats in cross-section in row 9. As further boundary conditions, Table 2 shows the exhaust temperature (T_{out}) averaged over one sensor each in flight direction left (FDL) and right (FDR) in the ceiling outlet above the measuring plane. The other values from Table 2 will be discussed in the following sections.

3.1 Fluid temperatures

In this section, the fluid temperatures for all investigated flow distributions under CDV and ISV conditions will be discussed.

Figure 4 shows a comparison of the cases #0, #1 and #6 as boxplots for four height levels (ankle, knee, chest, head). The rectangle with the orange median shows 50% of all measured values. The mean of all data is indicated by the green triangle. Furthermore, the whiskers represent a maximum of 1.5 times the interquartile range. They do not have to end exactly at this length, but rather at the value from the data that still lies within this limit. Therefore, the two sides do not have to be the same length. Outliers, marked by circles, show all values above/below the whiskers. The results were averaged temporally over 1800s and spatially over five seating positions in cross-section in row 9. The averaging period of 1,800 s at steady-state conditions covers around 20 nominal air exchange rates. Therefore, it is reasonable to assume that both the large-scale flow dynamics and the faster small-scale fluctuations were captured. The

mean temperature differences between head and ankle are also shown in Table 2.

Figure 4a shows the temperature stratification for CDV from the ankle to the knee, across the chest to the head. The average difference between the head and the ankle was found to be 5.8 K, with a maximum difference of 7.7 K. Both values can be reduced by the equal percentage distribution in (b), but #1 also shows a considerable stratification. For ISV, differences of 0.5 K were observed in the mean values between the knee and the head, see Fig. 4c. Furthermore, the average temperature difference between the head and the ankle can be reduced to 3.9 K. The combination of CDV and ISV generates the smallest 50% boxes and whiskers for all heights. Especially in the ankle area, both individually operated systems show a larger spread of values. Outliers were found for all ventilation variants.

An important quantity in terms of passenger thermal comfort is the spatial and temporal averaged temperature difference between head and ankle level, ΔT_{HA} , shown in Fig. 5. Clearly, this value should not be too high. Although there are other means to control this quantity, such as using a higher volume/mass flow rate, reveals how the additional volume flow rate from the ISV outlets in the hybrid scenarios helps to reduce the vertical temperature stratification. Compared to CDV #0, the stratification with pure ISV #6 can be reduced by 1.9 K, see Table 2.

Further, T_{cab} is plotted relative to T_{in} as a function of the ventilation scenario. No clear trend could be found. However, $\langle T_{cab} - T_{in} \rangle$ starts at 4.7 K for CDV and decreases to a minimum value of 3.8 K for #2 when using ISV. This plot shows that in order to keep T_{cab} at a constant value, the required inflow temperatures for ISV do not need to be cooled any further than with state-of-the-art MV [1]. As the cabin is usually pressurized with bleed air nowadays—which has to be cooled down from about 300 °C—higher

inflow temperature levels can be considered to save energy in the environmental control system.

The third depicted quantity is the HRE as defined by (3). For state-of-the-art MV there is a theoretical upper limit of 0.5, which corresponds to a perfectly mixed fluid ($T_{out} = T_{cab}$). As known from previous studies, a high HRE of 0.88 for CDV was found here as well [1]. The use of ISV and the resulting forced convection reduces the HRE. However, even in case #6 with pure ISV, a value of 0.69 was calculated, see Table 2. Thus, this value is significantly higher than the theoretically possible value (0.5) and the value known from previous studies (0.4) for MV [1].

3.2 Fluid velocities

In addition to the fluid temperatures, the flow velocities in the cabin are important for two reasons: First, the velocity should be low enough to prevent draft. Second, the large-scale flow patterns and the small-scale turbulence structure of the cabin flow govern mixing and heat exchange, thus determining macroscopic quantities, such as heat removal efficiency, temperature homogeneity and temperature stratifications.

Figure 6a depicts the velocities including standard deviation for all investigated cases measured with the combined velocity and temperature probes described in Sect. 3.2. The results were averaged temporally over 1800s and spatially over four heights (ankle, knee, chest, head) and five seating positions in cross-section in row 9. The mean values and standard deviations are summarized in Table 2. As expected, the lowest values were found for CDV, where a velocity of 0.1 m/s is not exceeded. Increasing the ISV part of the ventilation significantly increases the velocities. Satisfactory results were observed for all cases, with a maximum velocity of 0.31 m/s stipulated in [19], as the upper limit. To examine the velocities in more detail, Fig. 6b shows the time-averaged values at four height levels with the corresponding standard deviation in the vicinity of the TPDs for the cases #0, #1 and #6. Across all body regions, CDV shows the lowest mean velocities and standard deviations. A comparison with #1 shows only slightly increased mean values, while the standard deviations are almost identical. The highest values were found for ISV. However, no body region showed a value above the upper limit of 0.31 m/s specified in [19] for an air temperature of 24 °C. Maximum standard deviations of 0.13 m/s for the head area also indicate a good evaluation of the system. Although air is only supplied vertically at the seat backs, under pure ISV conditions (#6), higher velocities occur in the ankle area as compared to pure CDV (#0). For all other cases, not listed here for the sake of brevity, increasing velocities were found with

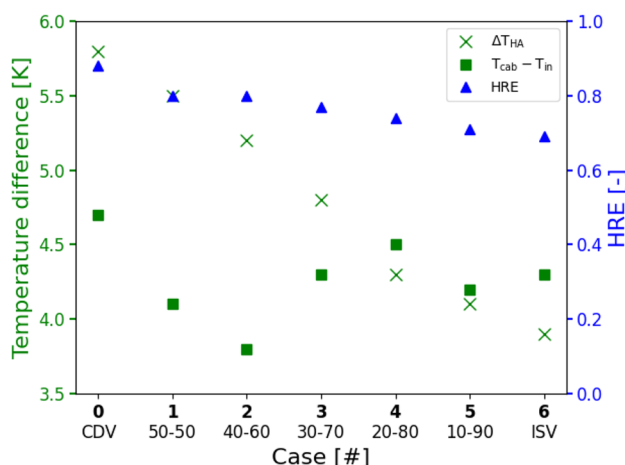


Fig. 5 Temperature differences between head and ankle (ΔT_{HA}) as well as $T_{cab} - T_{in}$ compared to the heat removal efficiency (HRE)

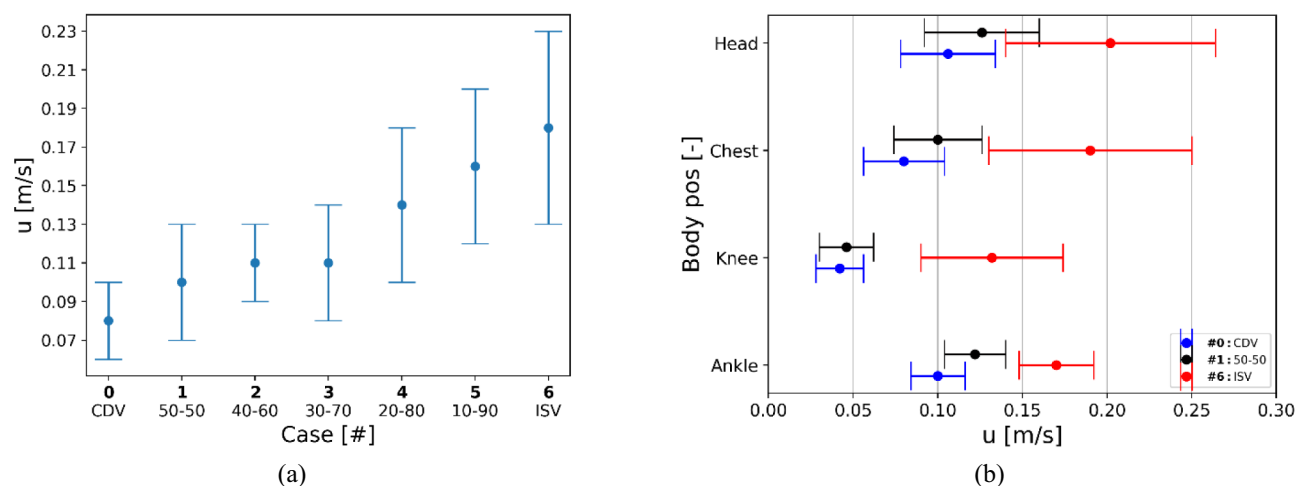


Fig. 6 **a** Spatially and temporally averaged velocities with standard deviations for all investigated cases and **b** time-averaged velocities at four height levels with corresponding standard deviation for cases #0, #1 and #6. Temperature

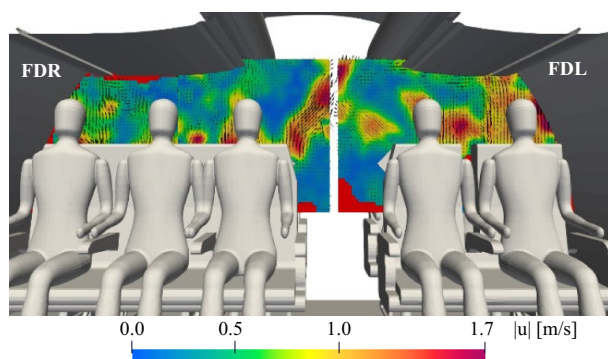


Fig. 7 Velocity fields in the cross-section of the complete cabin with ISV #6

an increasing ISV share. The lowest values were recorded at the measurement position near the knees.

The resulting velocity field of the complete cross section above the ISV outlets, measured using the optically tracked three-component ultrasonic anemometer (see Sect. 2.2.3), is shown in Fig. 7 for case #6. Limited by the measuring volume of $1 \times 1 \times 1 \text{ m}^3$ for single acquisition runs, four measurements were carried out and combined into one large dataset during post-processing. Increased vertical velocities

were found directly behind the heads of the TPDs, with higher values in FDL at seat 9A than in FDR at seat 9E. The diagonally mounted ISV outlets for the ventilation of the aisle area are clearly visible. In order to investigate possible effects of the supply air on the passengers in the front seats, the Table 3 shows the mean velocities for ISV as well as the maximum values for all cases over the head measured with the probes described in Sect. 2.2.2. Comparing the velocity fields with the mean values occurring above the head (the first row of the table—Mean #6) shows no major influence. Although Fig. 7 contains significantly higher velocities in FDL, the table indicates that higher values were found above the head in FDR. However, no seat shows a value above the specified upper limit of 0.31 m/s (see [19]). Regarding the maximum values, however, this limit is exceeded on several seats, as the following lines show for cases #6, #5 and #4. For configurations with a CDV share of 30% (case #3) or larger, no values above 0.31 m/s were found.

As the DR does not take clothing insulation or metabolic rate into account, it reflects people's dissatisfaction with the airflow over their bare skin. For CDV, the mean DR (blue dots in Fig. 9) shows a low value of 5%, which increases to 13% at a flow rate distribution of 10–90. For pure ISV, the

Table 3 Mean and maximum velocities from the overhead probe, all values given in m/s

FDR			Direction		FDL	
9E	9D	9C	Seat		9B	9A
0.21	0.12	0.24	$\langle U \rangle$ [m/s] #6 ISV		0.14	0.1
0.42	0.41	0.46	U_{max} [m/s]	#6 ISV	0.37	0.32
0.36	0.39	0.38		#5 10–90	0.35	0.28
0.29	0.40	0.33		#4 20–80	0.32	0.26
0.23	0.25	0.29		#3 30–70	0.20	0.21
0.22	0.24	0.29		#2 40–60	0.18	0.24
0.15	0.24	0.23		#1 50–50	0.23	0.19
0.05	0.18	0.33		#0 CDV	0.18	0.23

mean DR reached a value of 15%, which, according to [18], is already critical. For all cases with an ISV contribution of less than 90%, i.e. for case #0 (CDV) to case #4 (20–80), a mean $DR \leq 10\%$ was found. However, the maximum DR values (blue crosses) at single probe positions are already as high as 19% for CDV and rise to 30% for ISV. In addition to the mean DR values, we included the DR values at the head level “DR face” (green marker), as this body part is highly sensitive to draft. The results reveal that without significant forced convection—that is, up to 70% ISV—the values are comparable to the mean DR values and also to the PPDs values. With a higher ISV fraction, the peak values on the face DR increase faster than those of the mean DR. This effect can be explained by the higher flow velocities in the upper part of the cabin, and thus also around the face and the head, for higher ISV fractions, see also Fig. 6 and Table 3.

For a further analysis of the velocity fields, Fig. 8 shows a comparison of the window and aisle seats in FDL for the cases 50–50 in (a) and (b) as well as for ISV in (c) and (d), each in longitudinal direction. For an equal distribution between CDV and ISV, velocities of 0.6 m/s were found at the outlet, see (a) and (b). There are no higher values in the upper area of the cabin. Through the luggage compartment (a), fresh air flows forwards and backwards. At the aisle seat (b), fresh air flows into the ceiling area, outside the measuring plane. A different flow distribution was observed for pure ISV in case #6 in (c) and (d). While the outflow velocities

at the ISV outlet are very similar for both seats, the window seat in (c) shows increased values above the heads because the outflowing air hits the luggage compartment.

3.3 Thermal comfort

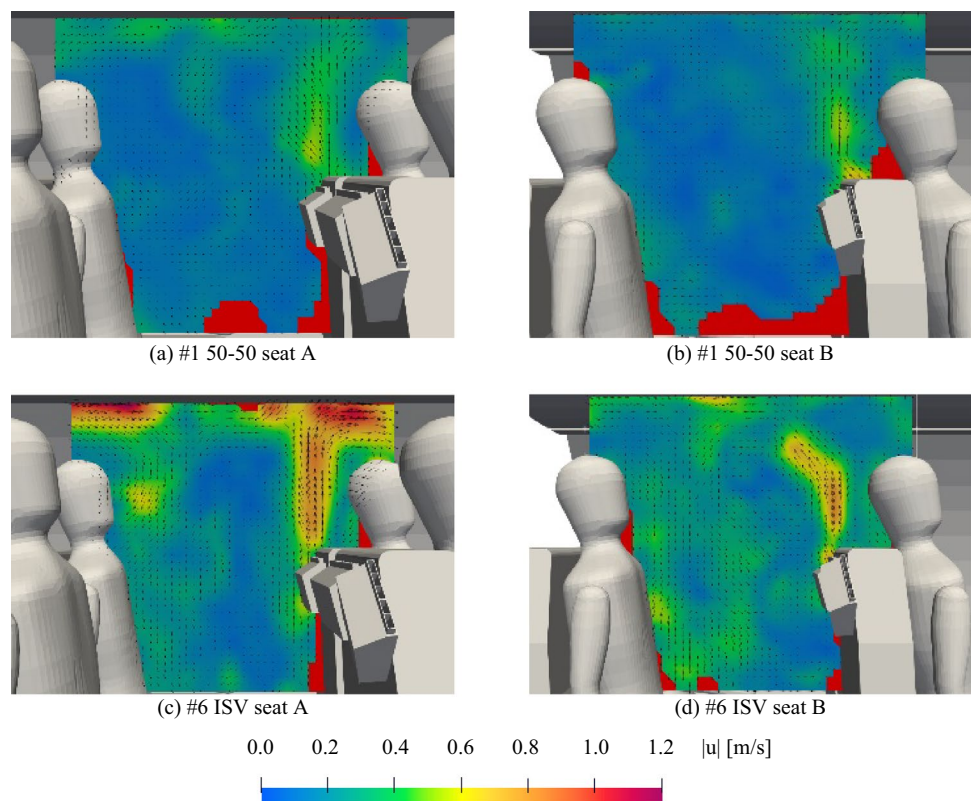
An evaluation of the thermal comfort near the TPDs in row 9 was performed based on the PPD index and the Draft Rate (DR) using the Comfort Sense System (Sect. 2.2.2). Figure 9 shows the values averaged temporally over 1800s and spatially over five seats in cross-section and over four height levels in row 9. The applied equation for the DR (2) and [18] is based on an empirical relationship developed to assess draft sensation—primarily in the neck and head areas—in mechanically ventilated indoor spaces. However, the head level was represented separately.

Further, the measured maximum values are shown. The results were calculated using Eqs. (1) and (2) described in Sect. 2.3.

For all shown quantities, including mean PPD, mean DR and face DR, we observed moderate, mostly linear increases with increasing ISV contribution from pure CDV (case #0) to 30–70 (case #4). For higher ISV, we again observed a mostly linear increasing trend, however, with much higher gradients.

Although both the DR and the PPD indicate dissatisfaction as a percentage, differences are shown by the clothing

Fig. 8 Velocity fields in longitudinal direction for case #1: 50–50 window seat 9A in (a) and aisle seat 9B in (b). Case #6 ISV window seat 9A in (c) and aisle seat 9B in (d)



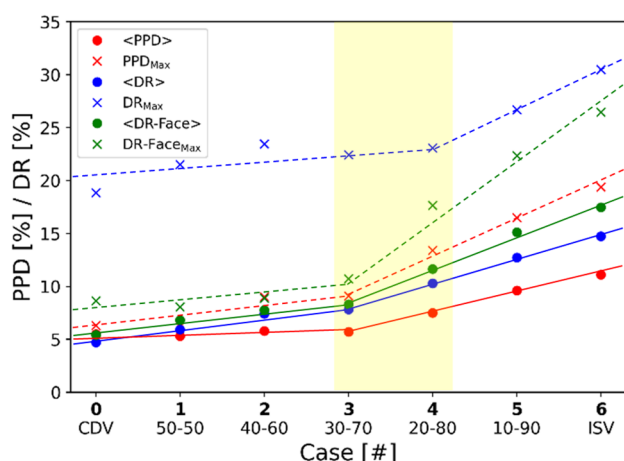


Fig. 9 Thermal passenger comfort criteria shown as Predicted Percentage of Dissatisfied (PPD) as well as Draft Rate (DR) evaluated as average value comprising the ankle, knee, chest and head level probes as well as the DR for the head level probe at five seat positions in row 9. Trend lines included as a guide to the eye. Solid lines for mean values and dashed lines for maximal values. Yellow highlighted area marks the cases where the slope changes

factor and the metabolism rate. However, the same trend emerges with increasing values from CDV to the combined cases to ISV. As Eq. (2) cannot produce values below 5%, excellent results were found for PPD from case #0 to #3 with values below 6%. With a maximum value of 11%, the other cases also show a moderate level of dissatisfaction. While the mean PPD and DR remain still relatively close, larger differences were observed in the maximum values. Dissatisfaction rates for configurations with an ISV part up to 70% were found to be below 10%. Even at the higher inflow velocities of ISV, the PPD index remains below 20%.

Figure 10 shows the equivalent temperatures (T_{eq})—determined per body segment—evaluated for summer conditions in accordance with [16] measured with the Equites system (Sect. 2.2.4). As we primarily focused on case #0,

#1 and #6 in the previous sections, Fig. 10a illustrates the comparison of these systems. The other configurations are shown in Fig. 10b. As described in Sect. 2.2.4, the equivalent temperatures were determined for 16 different body parts for a manikin positioned in seat 9D.

The first thing to note in Fig. 10a is that Case #0 shows the temperature stratification already described in Sect. 3.1 with too cold areas on the legs and feet and too warm temperatures in the head area. In contrast, the higher velocities at 100% ISV result in a T_{eq} that is too cool from the upper legs to the face. The 50–50 combination of the systems (#1) delivers values mainly in the neutral, i.e., comfortable, range. However, some body regions are still slightly too cold (calf—left) or slightly too warm (upper leg—right).

The more detailed analysis of the hybrid configurations with various volume flow rate splits (shown in (b)) reveals that neutral, i.e., comfortable, equivalent temperatures can be achieved for cases #2–#5. This means that the supply air distribution can be varied within this range with only minor impact on the thermal comfort. Thus, the system is rather robust as desired and fluctuations do not have a significant impact on the well-being of the passengers. Furthermore, despite higher velocities with increased ISV share, all cases show very small standard deviations. The influence of a higher proportion of CDV (#2) becomes evident in the cooler values recorded at the feet and calves. In contrast, a higher proportion of ISV (#5) resulted in lower T_{eq} values from the upper legs to the face.

3.4 Discussion and practical implementation

The results showed that the occurring flow field and thus the temperature stratification and the thermal comfort parameter on the passenger seats, generated by the combined ISV-CDV system, is suitable for single aisle passenger cabins. Each system alone revealed drawbacks, such as local air

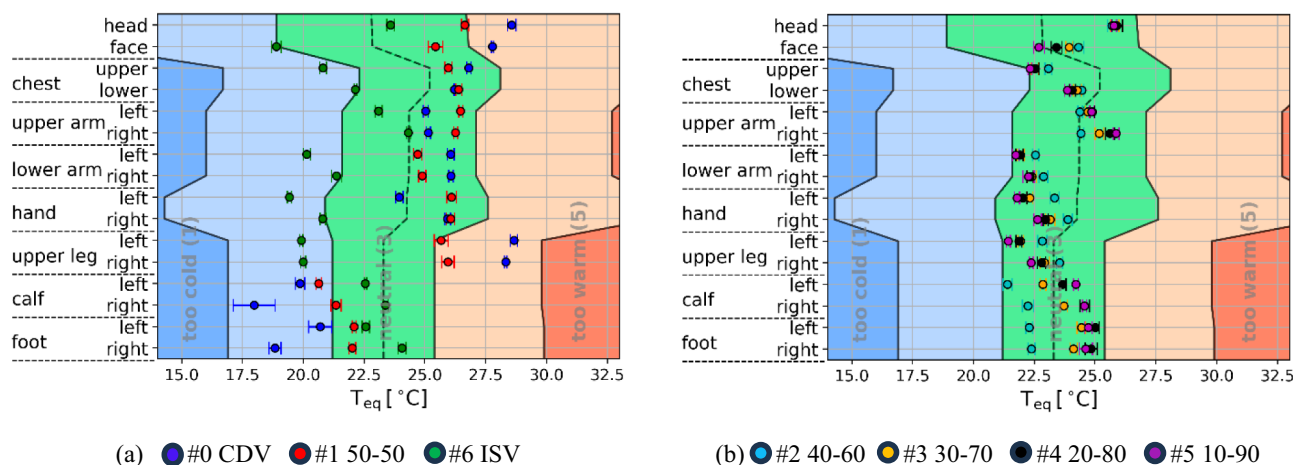


Fig. 10 Comparison of the equivalent temperature of **a** #0 CDV, #1 50–50 and #6 ISV and **b** cases #2–#5 at seat position 9D

velocities leading to negative draft, or uncomfortable temperature stratifications. However, combining the systems—in a rather broad airflow rate split distribution—eliminated these issues. The practical implementation of these findings means that the next steps in terms of research and development of these systems can be taken—a negative result would have ruled out this concept entirely. Furthermore, they demonstrate that suitable mixing ventilation can be generated in the passenger aircraft cabin without the need for lateral or ceiling-based air supply, i.e. without riser ducts or air distribution systems in the aircraft's crown. The entire air supply system can be integrated into the floor module, which could reduce the weight of this subsystem, but will mainly enhance the potential for industrial pre-manufacturing of the cabin modules. This reduces the time needed to install the air-distribution system in the aircraft, saving time and money in the manufacturing process. Another positive effect of the seat-integrated ventilation system is that it enhances customization capabilities. Different seat layouts will automatically adjust the ventilation system as required and no time-consuming adaptation of the air distribution, e.g., by integration of orifices has to be performed.

The next steps in transferring this technology from generic scientific studies to real-world application in the aircraft are as follows: ongoing analysis of the required airflow characteristics of the supply air openings in the seats and the resulting flow fields for different seat pitches as well as different geometries of the overhead storage bins. CAD-based analysis of the integration possibilities of the air supply systems into the seat structure, e.g., by using the aluminum tubes for the airflow. A connection system for the supply air between floor and seat-bench has to be developed, and finally, a weight-cost-benefit analysis has to be performed to investigate the economic aspects of this ventilation concept.

4 Conclusion

This paper presents the results of experimental investigations focusing on mixing ventilation based on seat-integrated air outlets. The experiments were conducted in the Dornier 728 aircraft cabin test facility of the German Aerospace Center in Göttingen. Three ventilation systems were investigated: first, cabin displacement ventilation (CDV) with low inflow velocities at floor level. Second, in-seat ventilation (ISV) with air outlets at the backrests of the seats, oriented towards the ceiling and producing a highly mixed airflow in the passenger cabin. Third, CDV and ISV were combined to form a hybrid ventilation system. To simulate realistic dimensions and heat emissions of the passengers, 35 thermal passenger dummies were used in the measurement plane in the rear part of the aircraft. Various measurement techniques were

employed to record and evaluate the following parameters: boundary conditions, cabin air temperature, efficiency of the ventilation concept, flow velocities and thermal comfort.

When comparing the results of the experiments in the single-aisle aircraft with seven different ventilation conditions, the most important findings are as follows:

- CDV causes uncomfortable temperature stratification which can be reduced by ISV.
- ISV offers advantages in terms of energy consumption due to higher inlet temperatures compared to state-of-the-art MV (known from previous studies).
- The heat removal efficiency for ISV is 38% higher than the theoretically possible value for MV.
- Despite high vertical inflow velocities near the passengers, the maximum values did not exceed the upper limit stipulated in [19].
- Draft rate and PPD index show an average dissatisfaction of less than 15% for all cases examined.
- For the combination of the systems, satisfactory equivalent temperatures were found for all body parts.
- For all volume flow ratios between 40–60 and between 10–90, comfortable conditions were achieved highlighting the robustness of the combined system.

For the current configuration in the single aisle aircraft, a volume flow ratio of 30–70 is recommended as setpoint value. This results in the best combination of equivalent temperatures, low DR and PPD as well as acceptable temperature stratification and high HRE.

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Author contributions T.D. and M.S. carried out the measurements, evaluated the data, prepared the figures and wrote the original draft. D.S. supervised and was involved in the evaluation of data as well as writing the article. All authors reviewed the manuscript.

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Data availability No datasets were generated or analysed during the current study.

Declarations

Conflict of interest The authors declare no conflict of interest.

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