NOVEL VENTILATION CONCEPTS FOR LONG-RANGE AIRCRAFT CABINS – THERMAL COMFORT AND ENERGY EFFICIENCY

Daniel Schmeling[1], Andrey Shishkin[1], Tobias Dehne[1], Pascal Lange[1], Ingo Gores[2]
[1] German Aerospace Center (DLR), Institute of Aerodynamics
and Flow Technology, Göttingen, Germany.
[2]Airbus Operations GmbH, Ventilation Systems, Hamburg, Germany.

Abstract

In the present study, novel ventilation concepts for aircraft cabins comprising low-momentum and micro-jet based concepts integrated in the ceiling, floor or sidewall modules are analysed. The transient numerical simulations (URANS) are based on second-order finite volume schemes. In a post-processing tool chain, thermal comfort quantities, such as predicted percentage of dissatisfied (PPD) or predicted mean vote (PMV) are calculated. The test configuration is a slightly simplified Airbus A350 geometry with nine-abreast seating. We analyse and discuss temperature and velocity fields, streamline visualisations, heat removal efficiencies as well as the above-mentioned comfort indices for various ventilation configurations. First results prove the energetic advantages of displacement ventilation compared to state-of-the-art mixing ventilation. Further, different positions and dimensions of the micro-jet and trickle-ceiling air inlets result in locally different flow fields. Here, promising locations providing a good overall comfort with high horizontal temperature homogeneity are detected.

Keywords: aircraft ventilation, thermal comfort, ventilation efficiency, computational fluid dynamics

1 Introduction

A flexible cabin layout, high demands in terms of thermal comfort and energy efficiency as well as an industrial modular design are the main challenges for aircraft engineers when addressing the ventilation of the aircraft cabin. Nowadays, mixing ventilation systems are installed in all commercial aircraft, guaranteeing a high degree of mixing and therefore a robust and stable ventilation concept for the cabin (Kühn et al. 2009). However, complex and weight-intensive ducts are required. In addition, the system provides only limited heat removal efficiency, has a high capability of spreading of contaminants (Zhang and Chen, 2007) and high velocities are prone to draft on single seats (Bosbach et al. 2013). Addressing all these challenges, the ADVENT (Advanced ventilation techniques for modern long-range passenger aircraft) project is intended to investigate novel ventilation concepts to promote future energy management systems. One of the novel concepts is a ceiling-based micro jet ventilation system. This kind of air supply is well known from trains, especially from long-distance trains such as the German Inter City Express (ICE) (DB Systemtechnik, 2018).

2 Numerical Procedure

The numerical simulations are carried out on the high-performance computing (HPC) cluster of the Institute of Aerodynamics and Flow Technology in Göttingen. The commercial edition Engys of the open source CFD toolkit OpenFOAM is used to perform the calculations and for the pre- and post-processing operations. A detailed description of the numerical scheme and the post-processing tool chain can be found in Schmeling et al. (2020). However, it should be noted, that in this paper transient simulations are presented, whereas in Schmeling et al. (2020), steady-state simulations are discussed.

2.1 Computational Domain

The test configuration is a slightly simplified Airbus A350 geometry with nine-abreast seating, see Fig. 1 (left). The computational domain spans five rows with adiabatic, non-permeable boundary conditions in flight direction. The computational mesh has a maximum cell dimension of 3.4 cm, a sufficient grid refinement and in total approx. 25 million cells. Different patches are defined as cabin air outlets (see arrows in Fig. 1, left) and exhaust openings. For the implementation of micro jet cabin air outlets, small quadratic holes with a side length of 2.65 mm (c.f. 3 mm diameter holes) and a spacing of 25 mm are placed in the corresponding patches and the jet flows are simulated, see Fig. 1 (right).

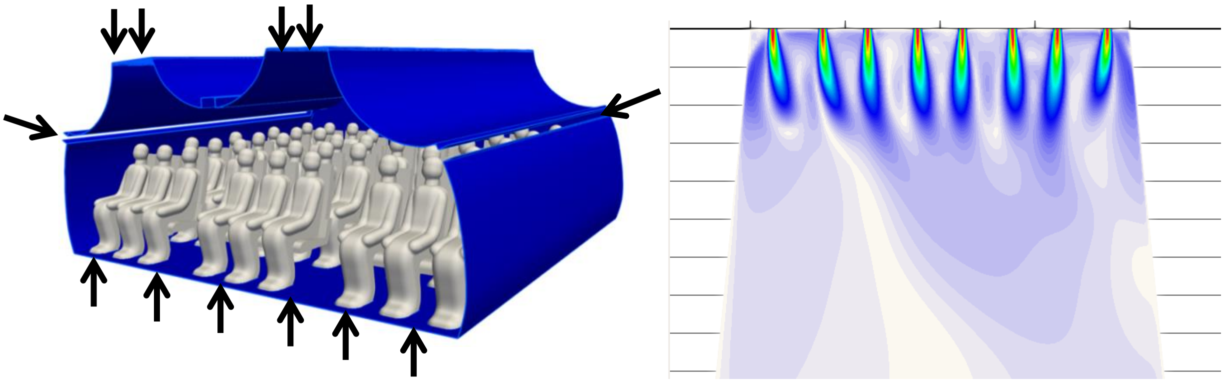

Figure 1: *CAD image of computational domain (left) and velocities of micro jet test simulations (right).*

2.2 Thermal Comfort

In a post-processing tool chain, thermal comfort quantities, such as predicted percentage of dissatisfied (PPD) and predicted mean vote (PMV) are calculated. Again, detailed descriptions can be found in Schmeling et al. (2020). The comfort quantities are averaged within the "sitting zone", see Fig. 2.

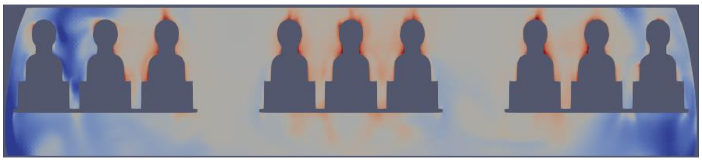

Figure 2*. Evaluation area for comfort indices (sitting zone),* $0.1\ \mathrm{m} < h < 1.3\ \mathrm{m}$.

2.3 Heat Removal Efficiency

The heat removal efficiency serves as a measure to evaluate the capability of the ventilation concept to remove heat from the cabin. It is defined as $HRE = 0.5 \cdot (T_{exhaust} - T_{supply})/(T_{cabin} - T_{supply})$ using the temperature of the supply air T_{supply}, the temperature of the exhaust air $T_{exhaust}$ and the mean cabin temperature T_{cabin}, calculated as average fluid temperature in the whole cabin. In accordance with this definition, a ventilation concept with perfect mixing of the cabin air, that is $T_{exhaust} = T_{cabin}$, has a heat removal efficiency of 0.5. However, state-of-the-art mixing ventilation, which is typically installed in passenger cabins of commercial aircraft, provides lower values of about 0.4 (Bosbach et al. 2013).

3 Results

The investigated ventilation concepts including the input parameters volume flow rate and supply air temperature are summarised in Tab. 1. Due to the sake of brevity, only exemplary results for the surface temperature distribution and the velocity fields are presented in Fig. 3.

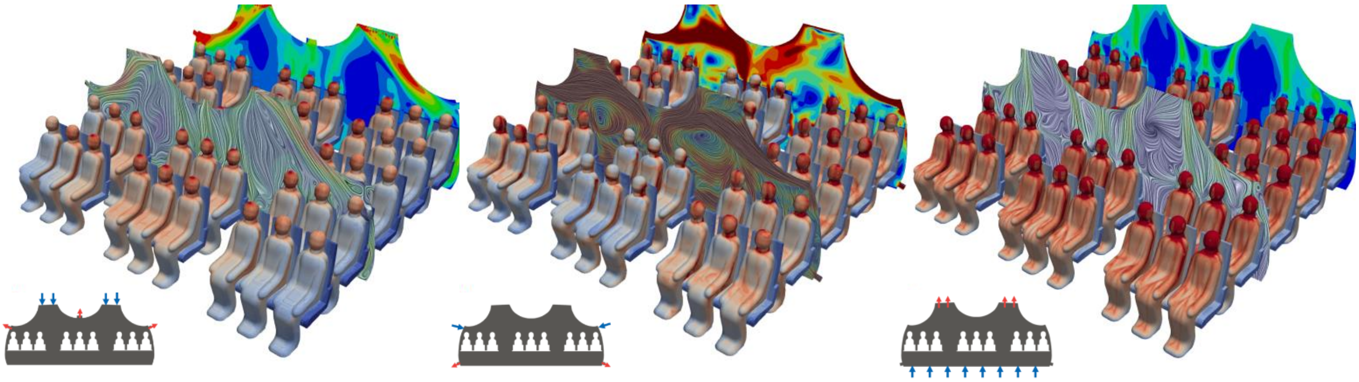

Figure 3: *Combined streamline, velocity and surface temperature visualization for* cases CV-1 *(left) LV-1 (middle) and FV-1 (right).*

Looking at Figure 3, three completely different flow patterns are found: For ceiling-based ventilation CV-1 (Fig. 3, left) the main air flow direction is downward following the contours of the lateral overhead bins. When reaching the sidewalls, a part of the air leaves the cabin through the lateral exhaust openings, while the other part recirculates towards the central exhaust and upwards following the central overhead bin. As a consequence, the lowest temperatures are measured at the window seats and the highest temperatures at the central seats. Overall, the flow velocities in the occupied zone are rather low, see also draft rate of only 9.1% (Tab. 1). For the sidewall-based concept LV-1 (Fig. 3, middle) high flow velocities are found about $0.2 - 0.4$ m above the heads spanning the full width of the cabin. These high-momentum jets transport the fresh air towards the center of the cabin, resulting in the lowest temperatures on the central seats. Compared to the other concepts, the higher draft rates are caused by the high-momentum supply air jets. However, the averaged PMV and PPD values (Tab. 1) are also very good for the sidewall-based concept. For the floor-based concept (FV-1) with low-momentum air supply on floor level, only low velocities are observed, see Fig. 3 (right). Here, the main physical driving mechanism of the flow is thermal convection induced by the warm thermal manikins. This results in a good PMV evaluation in combination with a very low draft rate (Tab. 1) for this concept. However, the pure floor-based ventilation bears the risk of colder feet and a head region that is too warm – also depicted in Fig. 3 (right) and summarised as vertical temperature difference $\Delta T_v = \langle T_{head} \rangle - \langle T_{ankle} \rangle$ in Tab. 1. The calculated value of $\Delta T_v = 1.5$ K is still in the comfortable range, but much higher than compared to all other concepts, even though this concept has the highest volume flow rate.

Regarding the HRE, the first main finding is that all novel concepts are better than or comparable to state-of-the-art mixing ventilation, which typically has an HRE of 0.4 (Bosbach et al., 2013). Here, the floor-based concept stands out with an HRE of more than 1.1. The second best concept in terms of the HRE is the sidewall-based ventilation LV-1 followed by the ceiling-based concepts CV-1 and CV-2. Further, we found, that for the ceiling-based concepts, the HRE rises with increasing height of the exhaust positions, i.e. from CV-4 to CV-1.

Table 1*: Parameters and integral results of investigated concepts.*

Con-cept	*Supply*	*Exhaust*	T_{supply} [°C]	$\dot{V}$ [l/s /PAX]	$\langle T_{cab} \rangle$ [°C]	*HRE [-]*	ΔT_v [K]	*PMV [-]*	*PPD [%]*	*DR [%]*
CV-1	ceiling	central + lateral (1:2)	18.5	13.3	22.8	0.50	0.3	0.10	5.2	8.1
CV-2	ceiling	central + dado (2:1)	18.5	13.3	23.1	0.47	0.1	0.20	5.8	7.6
CV-3	ceiling	lateral + dado (2:1)	17.5	13.3	22.7	0.42	0.4	0.01	5.0	7.7
CV-4	ceiling	Dado	17.5	13.3	22.9	0.42	0.3	-0.10	5.2	7.4
LV-1	lateral	Dado	17.5	10.0	23.0	0.54	-0.2	-0.18	5.7	13.4
FV-1	floor	ceiling	21.5	16.7	22.8	1.13	1.5	0.24	6.2	4.7

4 Conclusion

Transient numerical simulations were performed to investigate promising ventilation concepts in a simplified A350 geometry with nine-abreast seating. In a post-processing tool chain, thermal comfort quantities, such as predicted percentage of dissatisfied (PPD) and predicted mean vote (PMV) were calculated. In total, six different combinations of supply and exhaust locations were studied.

The first main finding is that all analysed novel ventilation concepts reveal an HRE better than or comparable to state-of-the-art mixing ventilation. The floor-based concept stands out with a value above 1. However, a much stronger vertical temperature stratification compared to all other concepts is observed, even though this concept has the highest volume flow rate. For the ceiling-based concepts the HRE decreases with the following order of exhausts: central + lateral, dado + central, dado + lateral to solely dado exhaust. This leads to the conclusion that the downward trend of the HRE correlates with the decreasing height of the exhaust for the ceiling-based concepts. It should also be noted that the sidewall-based concept LV-1 was operated at the lowest volume flow rate, which means that there is still a considerable energy-saving potential.

The second main finding is that the analysed spatially averaged mean PMV values are all within the very good range of $|PMV| < 0.25$ resulting in PPD values below 7% for all concepts. Further, the draft rate is also below 9% for all concepts except for LV-1, where 13.4% were measured. However, a detailed analysis for single seats or even single body parts is required for more reliable statements. For the sake of brevity, these are not discussed in this paper, but will be presented at the conference.

Within the framework of the ADVENT project, we are going to install different novel ventilation concepts in the new cabin mock-up starting with ceiling-based concepts. These concepts are going to be analysed both experimentally and numerically and detailed solutions regarding orientation and technical realisation are going to be developed. Subsequently, further novel concepts are going to be analysed solely and in combination with other comfort-enhancing techniques.

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