Influence of the Airflow Concept on the Aerosol Spreading in a Generic Train Compartment

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Abstract. In our recent studies, we have applied a measurement system for aerosol spreading in the generic train laboratory Göttingen (GZG) for different source locations and various ventilation concepts. The latter comprised, among others, different exhaust positions either in the lateral ceiling or in the legroom. The measurements were carried out until a quasi-stationary local aerosol particle concentration was reached. The evaluation was performed in terms of the mean aerosol concentration load in the compartment and with regard to the number of seats revealing aerosol concentrations above certain thresholds. First results highlight the influence of the airflow concept on the aerosol spreading within the passenger compartment. In this context, the exhaust position caused only a minor change in the local aerosol particle concentrations, whereas larger differences were found for alternative, hybrid air-supply positions.

Keywords: passenger train · compartment ventilation · airflow management · aerosol spreading · HVAC system · local air quality

1 Introduction

The ventilation of passenger train compartments has to meet several standards, e.g. DIN EN 13129 [1] for long-distance trains, to guarantee thermal comfort for the passengers. At the same time, the energy demand of the HVAC system – which is the second largest consumer during a train journey [2] – and the local air quality must be considered. Balancing these three main pillars (thermal comfort, energy demand and air quality) is a challenging task in terms of ventilating passenger trains. Additional boundaries are defined by the geometrical constraints, i.e. available installation areas for air channels and openings as well as by specific operational conditions of the train such as different climate zones or fast changing conditions such as tunnel passages.

In previous studies, alternative ventilation concepts were evaluated regarding thermal comfort and energy demand, see e.g. [3]. These studies were performed in a generic train compartment with well-defined boundary conditions to ensure a) a high repeatability and b) a more general knowledge compared to highly specific solutions for selected train series. Therefore, thermal manikins were used to experimentally simulate the obstruction and heat release of seated passengers (see Fig. 1, left).

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Although the air quality in terms of a sufficient fresh air supply is already defined and has been established in standards for a long time, the Sars-CoV-2 pandemic draw additional attention to this topic. The newly raised questions are: How do exhaled aerosol particles spread in the compartment and in specific how "contaminated" are the other passenger seats?

2 Setup and Methods

2.1 Generic Train Compartment (GZG)

Fig. 1 The generic train compartment equipped with thermal manikins during a smoke visualization (left); with the aerosol-exhaling face and aerosol particle sensors (right) ©DLR.

The study was conducted in a generic laboratory, representing the lower cabin of the DLR's next generation train (NGT), see Fig. 1. The inner dimensions of the compartment are 6.0 x 2.88 x 1.95 m^3 (length x width x height) and it is equipped with 24 seats. Thermal manikins are used to simulate the blockage and the heat release of real passengers. Fresh air is supplied by an external HVAC system, which controls both the volume flow rate and the inflow temperature. The HVAC system is operated at 100% fresh air to solely investigate the effects of the interior airflow on the aerosol spreading, avoiding background contaminations caused by recirculated air.

2.2 Experimental Analysis of Aerosol Spreading

The experimental analysis of the aerosol spreading comprises three main points: the generation of the aerosol particles, the detection of the aerosol particles and the evaluation of the measured local aerosol particle concentrations (for details see [4]).

Generation of the Aerosol Particles. The aerosol generator consists of an airbrush pistol used to disperse a constant mist of artificial saliva (mixed in accordance with NRF 7.5, receipt see [4]). After the initial generation, the particles are guided through a settling chamber. The setup is designed in such way that the particles already have an age of more than one minute before being released into the cabin, i.e., all evaporation processes are expected to be finished, and pure dry particles are released. The particle size distribution of the generated particles shows that particles with diameters smaller than 2.5 µm are produced corresponding, e.g. to normal breathing.

Detection of the Aerosol Particles. For the spatially resolved acquisition of particle number densities within the cabin, 24 SPS30 low-cost particulate matter sensors are used and operated via the mobile measurement system of the DLR [6]. The sensors are mounted in the face area of all seated thermal manikins, and thus the local aerosol concentration can be recorded at a sample rate of approx. 0.9 Hz in our setup.

Evaluation of the Recorded Concentrations. To determine the amount of potentially 'inhaled' aerosols, the locally measured equilibrium-state particle concentrations [1/cm^3] are multiplied by the typical human tidal breathing volume and by the typical breathing frequency resulting in the number of measured 'inhaled' particles per minute ($\dot{N}_{seat}$). As our source produces more aerosol particles compared to a human, we calculate the 'inhalation fraction' $f_N = \dot{N}_{seat}/\dot{N}_{source}$, representing the amount of inhaled compared to the amount of exhaled aerosol particles.

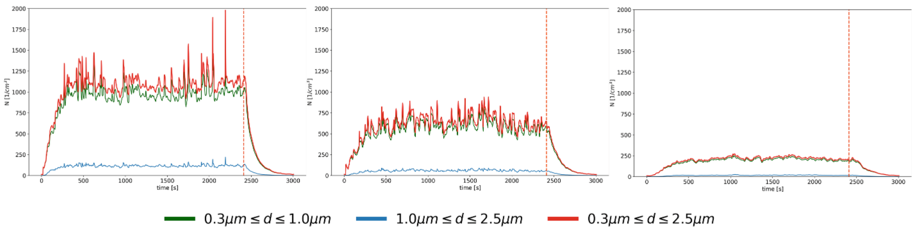

Fig. 2 Curve of the local aerosol concentrations over time; t = 0 s: start and t = 2400 s: stop of the aerosol exhalation. The source was positioned on an aisle seat. Concentrations recorded at the neighbouring window seat (left), the window seats one row behind (middle) and two rows behind the source (right). The data belongs to the MJV-CE case shown in Fig. 3. (left).

The measurements are performed until a quasi-stationary local aerosol particle concentration is reached. The average values for this quasi-stationary period, i.e. the 300 s before switching-off the aerosol source (see dashed lines in Fig. 2), are calculated for all seats. The evaluation is performed in terms of the mean aerosol concentration load in the compartment and with regard to the number of seats with aerosol concentrations above certain thresholds.

2.3 Investigated Ventilation Concepts and Boundary Conditions

In the present paper, the results of the aerosol spreading are compared for three different ventilation concepts, see Fig. 3. Microjet ventilation (MJV) with ceiling exhaust (CE) is characterized by an air supply via a trickle ceiling above the aisle and the air exhaust being installed in the lateral parts of the ceiling (Fig. 3., left). MJV with floor exhaust (FE) is operated with the same air supply system but the exhaust is realized at floor level in the lower side walls (Fig. 3. middle). The hybrid system also uses the ceiling exhaust openings. However, the fresh air is supplied by a combination of MJV and cabin displacement ventilation (CDV). The latter is installed using dense membranes which generate a low-momentum air supply below all seats. This hybrid MJV-CDV concept, shown in Fig. 3. (right), is investigated for three volume flow rate splits between MJV and CDV air supply.

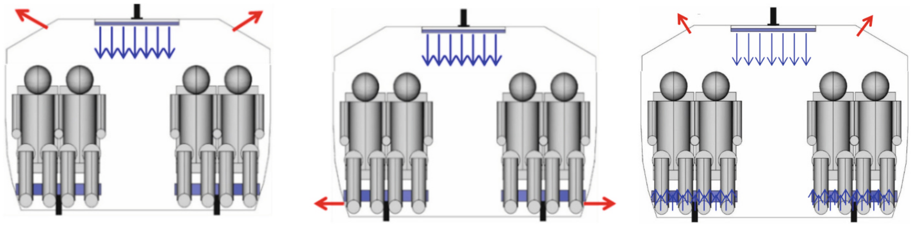

Fig. 3 Sketch of the investigated ventilation concepts. MJV-CE (left), MJV-FE (middle) and MJV + CDV (right). The latter was investigated for a 50%-50%, a 70%-30% and a 30%-70% volume flow rate split between MJV and CDV supply openings. ©DLR

3 Results

Figure 2 presents the curves of the concentration over time for three different seat locations (left: A02, middle: A03 and right A04), that is, with increasing distance from the aerosol source for the MJV-CE case. Furthermore, both the total number concentration (0.3 - 2.5 μm) and the curves of the individual particle size bins are shown. There are three main points to note: Firstly, the aerosol particle concentration decreases with increasing distance from the source. Secondly, the flow in the train compartment shows strong turbulent behavior, represented by the strong fluctuations of the local aerosol concentrations, especially in the vicinity of the source. The magnitude of the concentration fluctuations decreases with increasing distance from the source, as mixing with the cabin air dilutes the exhaled aerosol particle steam. Thirdly, the majority of the particles are smaller than 1.0 μm. Particles in the range of 1.0 - 2.5 μm have only a negligible impact on the local number concentrations. However, it should be noted that the impact on the transported fluid volume is different, since the volume of the larger particles increases with the third power of their diameter.

Figure 4 presents the time-averaged steady-state aerosol load in the compartment for the four configurations with the inhalation fraction indicated in different colors for the individual seats. The source remained on seat B02, marked as ‘S’. In general, we find the highest contamination in the vicinity of the source. Increasing distance from the source leads to a decreasing inhalation fraction. The comparison of the different exhaust positions for MJV – (a) and (b) – reveals only a minor impact, e.g. on the seat directly behind the source. The hybrid configurations (c) and (d) result in an increased spreading of the aerosol particles on the other side of the aisle, while slightly decreasing the forward and backward spreading. The hybrid configuration with a volume flow rate split of 30%-70% (MJV-CDV), see (e), stands out with significantly lower inhalation

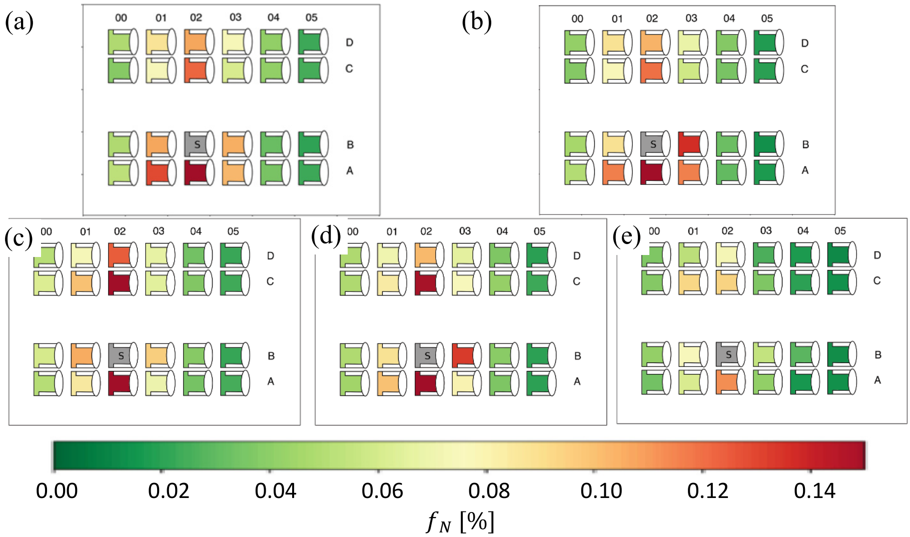

Fig. 4 Results of the aerosol spreading as heat map representation of the fraction of potentially inhaled aerosol particles within the compartment: MJV-CE (a), MJV-FE (b), MJV + CDV 50–50 (c), MJV + CDV 70–30 (d) and MJV + CDV 30–70 (e).

fractions. The increased fraction of floor-based air supply has clear advantages over the other concepts regarding the local inhalation fraction, as a more efficient removal of the exhaled particles towards the outlet is provided by the airflow.

Table 1. Summary of the average inhalation fraction on all seats as well as number of seats with a concentration above a certain threshold for all ventilation concepts. The volume flow rate amounted to $230 l/s$ for all cases.

Ventilation concept	$\langle f_N \rangle$ $\left[10^{-3}\%\right]$	Number of seats with $f_N > 0.05\%$	Number of seats with $f_N > 0.10\%$
MJV CE	68.5	12	7
MJV FE	64.8	12	6
MJV + CDV 50–50	68.7	15	4
MJV + CDV 70–30	66.4	11	4
MJV + CDV 30–70	43.3	8	1

Finally, the results of the local aerosol particle distributions are summarized in Table 1. for the comparison of the four analyzed configurations. In addition to the averaged local inhalation fraction $\langle f_N \rangle$, we evaluated the number of number of seats with a concentration above. The selected thresholds are arbitrary and not based on specific infection risk assumptions. The first thing to note is that in case of pure MJV supply, there is only a negligible effect of the exhaust position on both average particle load and number of seats with concentrations above the thresholds. That means that the change of the exhaust system, only changes the local distribution (Fig. 4) with a rather weak impact on the global values. In contrast, the combination of MJV with CDV reduces the number of highly contaminated seats and the volume flow rate split between ceiling and floor supply has a major impact. The 50%-50% and the 70%-30% configuration both result in a slightly reduced number of highly contaminated seats, while not changing the average load in the compartment. The 30%-70% configuration, i.e. most of the air is supplied at floor level, however, reveals significantly better values. For this configuration only one highly contaminated and only 8 intermediate contaminated seats were found and the mean load in the compartment was reduced by 36% compared to the MJV CE case.

Finally, it should be noted that all presented results are recorded for the source positioned on an aisle seat. The spreading behavior will be different for other source locations. Thus, a general evaluation of the concepts purely based on the given data is not recommended.

4 Summary and Conclusions

We presented results of an experimental investigation of the aerosol particle spreading originating from one selected source location in a generic train compartment for different airflow configurations. The results proved that the sole change of the exhaust air position from ceiling-based exhaust to floor-based exhaust has only a minor influence on the mean particle load in the breathing zone of the seated passengers.

In contrast, the integration of an additional floor-based air supply and thus a hybrid ceiling and floor-based air supply at a 30%-70% split ratio, with maintained total supply airflow rate, strongly reduces the local particle concentrations. The averaged particle load, evaluated in terms of inhalation fraction, was reduced by 36%, while the number of 'highly contaminated seats' was also minimized from seven to one.

It can be concluded that the airflow concept in the passenger zone of a train has a significant impact on the spreading behavior of locally induced aerosol particles, e.g. exhaled by a sick passenger.

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