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Numerical study of diffuser type effects on transport characteristics of contaminants in a high-speed train cabin

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Abstract

Due to fast development of high-speed rail (HSR) globally, the transport system around the world has been improved significantly with the introduction of high-speed train (HST). Recalling the previous global outbreaks of airborne diseases such as SARS and H1N1 spreading in public transportation cabins [5], the investigation of containments transport within the HST cabin is critical to examine the transmission of airborne disease. A series of numerical simulations in HST cabins with different applied diffusers were performed in this study. Numerical results in terms of contaminant transport characteristics were examined and compared. It can be concluded that the overall cabin airflow pattern and contaminant distribution are significantly affected by the types of diffusers. Also, it was found that the contaminant transport characteristics varies under the same ventilation scheme. This study provides a specific way to assist the assessment of ventilation schemes, which could be used as a supplement to existing industrial standards.

Introduction

In recent years, HSRs are rapidly developed in many counties owing to their convenience and high efficiency. However, due to the fact that HST indoor space is enclosed and occupant density in HST cabin is extremely high, the airborne disease transmission in HST cabin becomes a critical issue. For instance, pathogen-carrying saliva droplets released by an infected passenger are more likely to be inhaled by other passengers as compared to a scenario occurring in other indoor environment such as offices and dwelling houses.

In order to minimize the possibility of disease transmission while maintaining the ride comfort, optimizing the ventilation schemes is the most effective way raised by [16]. Research on ventilation schemes, especially diffusers, has been widely conducted both simulatively and experimentally. When investigating different ventilation scenarios of bus cabins, [3, 17] found that the types of diffuser and location can influence passengers' thermal comfort and airborne disease transmission. In order to control the carbon-dioxide level in crowded train cabins, [2] made the conclusion that the air diffusion terminals should be placed in the upper area of cabins. In regard to HST cabins, [15] found that the back-door-oriented design of exhaust outlet accompanied by the CRH3 model cabin inlet diffuser exerts strong ability in removing cough droplets. In addition, [13] found that CRH5 model has the best ventilation efficiency as compared to CRH1 and CRH2 models. [6] reported that the mixed application of air diffusers would exert best ventilation performance in some airliner cabins.

In summary, diffuser is one of the crucial components in cabin ventilation system, and well-designed ventilation diffusers can effectively control the contaminant transport. Therefore, this study is aimed to investigate the effects of types of diffusers on contaminant transport in HST cabins. Computational fluid dynamics (CFD) models for HST cabins were firstly developed and validated using experimental data yielded from a mock-up cabin. Four types of prevailing HST cabin diffusers were subsequently assessed in a typical HST cabin model. Also, different sizes of contaminants were investigated respectively.

Numerical Model

According to [17], airflow pattern in HST cabin is affected by several factors including ventilation parameter， cabin geometry, seat arrangement, types of diffusers, location of exhaust vents and seating arrangement of passengers. In order to maintain the comparability of types of diffusers, the other factors were assumed to be constant. A four rows CRH2 model cabin section with 3-2 seat arrangement was set up as the ventilation environment. In this cabin section, two translational periodicity boundaries were applied in the front and back plane. By applying periodic boundaries, the computational domain was largely trimmed down which could correspondingly increase the computational cost efficiently while maintaining the ventilation and contaminants transport features.

Four different types of diffusers were applied in above mentioned cabin section, respectively. These are the most common diffusers applied in HSTs. Details of these diffusers are explained in table 1.

	Case-1	Case-2	Case-3	Case-4
Diffuser oriented HST model	CRH2	CRH3	CRH5	Shinkansen
Diffuser location	On each side wall	On the roof with downward air supply	On the roof with air supply against each other	On each side wall
Diffuser geometry	Discrete line sharp	Line sharp	Line sharp	Truncated cone sharp

Table 1. Details of four type diffusers in this study

The ventilation process of HST cabin in this study was performed in the frame of the prevalent railway HVAC standards TB 1951-87, and UIC 553-1 [10, 12]. In this study, the HST was assumed to be operated in summer when the temperature was 35 ℃. According to UIC 553-1, inner temperature of the cabin should be set at 27 ℃ under this operation condition. Air was supplied by inlet diffusers and exhausted by the outlets located under seats. Fresh air supply rate at inlet diffusers was 20-25 m^3/h/person when temperature was 23.85℃. Also, due to solar radiation effects, heat was conducted through cabin roof, walls and windows with the rate of 688.5 [W/m^2]. Other solid walls including floor and seats were assumed to be adiabatic.

In the simulations, the cabin was assumed to be fully occupied with very fine 3D-scanned adult female manikin models. Considering passengers were in seating posture and wore normal clothing, manikin skin surface was applied as the convective heat load of 40W [9]. The mouth area of the manikin needed to be well identified because this would serve as the cough droplets exhaust boundary in simulation. In this study, droplets were assumed to be released from the mouth of one passenger, Passenger-S, who was on the seat at second row of second column. According to [11], 2000 droplets with velocity of 3 m/s has been proved to be valid in representing a single human cough. The distribution of droplet size of a single cough used in this study was attained from [4] and it is plotted in figure 1. Considering the computational cost, the simulation was taken in the steady state that the breath from all the passengers and the cough-induced air flow from Passenger-S have not been modelled.

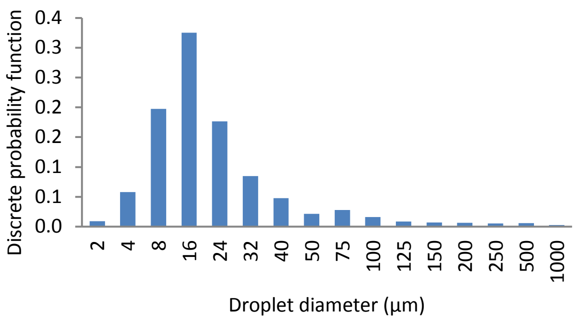

Figure 1. Droplet size distribution of a single cough model

In this study, the cabin airflow field was solved using the incompressible Navier-Stokes equations. Equation for air turbulent was obtained based on RNG k-epsilon model. Boussinesq approximation was employed to derive thermal buoyancy flow induced by human body heat. All governing equations were solved using the commercial CFD software ANSYS CFX 16.0.

Computations were conducted with droplets released from the mouth area of the Passenger-S sitting in the same position in the four cases, respectively. Cough droplets were regarded as particulate and tracked using the Lagrangian approach. For particles immersed in continuous air, important forces governing particle motions are the drag force F_D and buoyancy force F_B [8], thus,

$$m_p \frac{dU_p}{dt} = F_D + F_B \tag{1}$$

$$F_D = \frac{1}{2} C_D \rho_F A_F |U_S| U_S \tag{2}$$

$$F_B = \frac{\pi}{6} d_P^3 (\rho_P - \rho_F) g \tag{3}$$

Where m_p is the mass of particle, U_p is the particle velocity, C_D is the drag coefficient, ρ_F is the fluid density, A_F is the effective particle cross section, U_S is the velocity difference between fluid and particle, d_p is the particle diameter, g is the gravity vector. For turbulent tracking, the instantaneous fluid velocity U_f is decomposed into mean velocity $\overline{U}_f$ and fluctuating eddy velocity U'_f. Thus,

$$U_f = \overline{U_f} + U'_f \tag{4}$$

Considering the fact that most area of seats, cabin floor and passengers' clothes are fabric, all these surfaces were treated as the rough wall that droplets would stick into these surfaces after collisions. Therefore, the "Stick-to-Wall" model [1] was used in simulation, which counts these surfaces as a sink term of the particulate phase.

The cabin geometry model was discretised using unstructured mesh by ANSYS ICEM. In order to capture accurate cough flow pattern, meshes with high resolution were built around diffusers and manikins, especially in the vicinity of mouth area. Also, inflation layers with a grid expansion ration was applied around manikin surface. Prior to performing CFD simulations, grid independency study was conducted over five grid resolutions ranging from coarse to dense. The grid sensitivity study illustrates that once there are over 4.2 million mesh elements, air flow velocity at the reference location becomes stable.

Model Validation

Temperature and velocity along a vertical direction line, z coordinate, 20cm in front of Passenger-S obtained from simulation results were compared with the referred airflow measured in the mock cabin [7]. From comparison results (figure 2), velocity had slight big difference. This is caused by the measure precision, as the magnitude value is very small. In general, good agreements were found in velocity and temperature comparison. The validation results revealed that the proposed numerical model is valid when simulating the HST cabin ventilation.

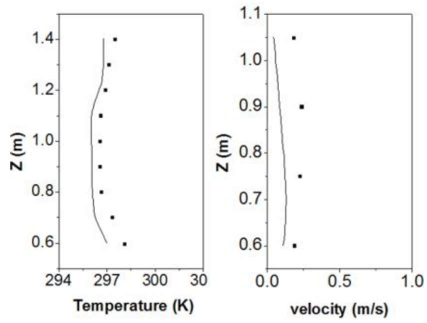

Figure 2. Comparison of temperature and velocity between experiment and simulation results

Results and Discussion

The planes crossing through the middle of the second-row passengers in the crosswise direction were compared to summarize the results of the ventilation performance, as shown in figure 3. The whole cabin section in Case-1 has a very good homogenous temperature field and velocity field, although the upper region has a relatively high velocity field. Passengers in all five columns experience similar temperature and low-speed stream, which is ideal for thermal comfort. In Case-2, the velocity in the middle-upper region is relatively high because of the fresh air coming downward from the inlet vents fitted on the cabin roof. However, due to passengers' heat flux effect, cool flow is reduced quickly so that the air flow velocity around those passengers is small. In Case-3, a strong flow of stream exists in the middle aisle, which comes from the joint fresh air in the roof area to the aisle floor area. This strong downwards airflow has an undesirable effect on the passengers in the third column as they may suffer from lower temperature and higher velocity flow compared with surrounding passengers. Different from other three cases, the lowest temperature found in Case-4 occurred around the passengers sitting near the cabin walls because fresh air blows down from the diffusers located right above them. Consequently, relatively high temperature appears around the passengers sitting near aisle. Case-4 has the overall smallest velocity field in this study, especially in the middle cabin region. Aside from the above analysis, figure 3 demonstrates that the temperature fields are mainly dependent on the velocity field.

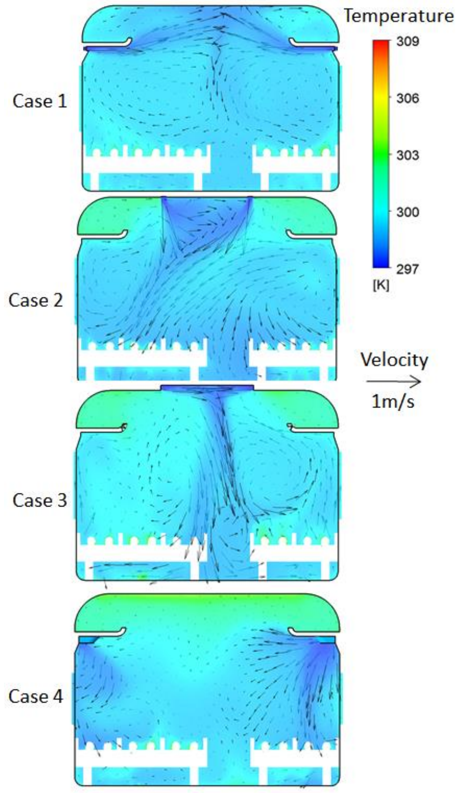

Figure 3. Temperature and velocity profiles at a selected plane

The transport and distribution characteristics of particles generated by coughs from Passenger-S were studied under the conditions of different diffusers. Individual computations as shown in figure 4 were conducted to simulate the tracks of particles. The trajectories of different particle sizes were also marked in this figure using different colours.

When comparing the distribution of particles with diameter larger than 5E-5m, it can be seen that trajectories of these particles are similar in all four cases. Particles sized between 5E-5m and 2E-4m fell into the leg and seat area of Passenger-S following parabola trajectories, immediately after leaving the mouth. The particles with size larger than 2E-4m has similar distribution trajectories as particles with size between 5E-5m and 2E-4m. However, these particles fell further to the shoes area or sunk into the back of front seat. Therefore, a conclusion can be made that the types of diffusers have small effect on the trajectory of particle transport if the diameter of particle is larger than 5E-5m.

However, for particles with diameter smaller than 5E-5m, the types of diffusers would significantly affect the trajectories of particles. In Case-1, these particles moved towards the right side along with the airflow after released by the Passenger-S, and then suddenly changed their direction backwards when they reached the large flow. These small particles would eventually spread over the whole cabin. During this process, many droplets would stick on the cabin wall beside Passenger-S and the roof area above Passenger-S. Case-2 model predicted that particles with sized smaller than 5E-5m would mainly join the bulk air above the source passenger, thus passengers around that area is considered to be at a relatively clean region. Then most of these droplets would travel through the area around the passenger in the third row of third column to the outlet vent beneath the seat. Similar to Case-2, these particles quickly concentrated into the bulk air flow to the back area of Passenger-S after leaving the release point. Then they would distribute into the back cabin section and ended by sinking into the cabin wall. In Case-4, these particles travelled only limited distance rather than spreading widely through the entire cabin section. The droplets largely ended around passengers sitting near Passenger-S, and the rest were taken away by the outlet vent under Passenger-S.

The main reason small droplets and large droplets travelled through significantly different trajectories can be explained by Lagrangian-method. In Lagrangian approach, small droplets were dominated by the drug force caused by air flow, while large droplets were dominated by the inertia force caused by self-weight. Overall, the simulation results revealed all these four types of diffusers could efficiently remove the particle contaminants within a certain time regardless of sizes, while small particles distribution processes vary.

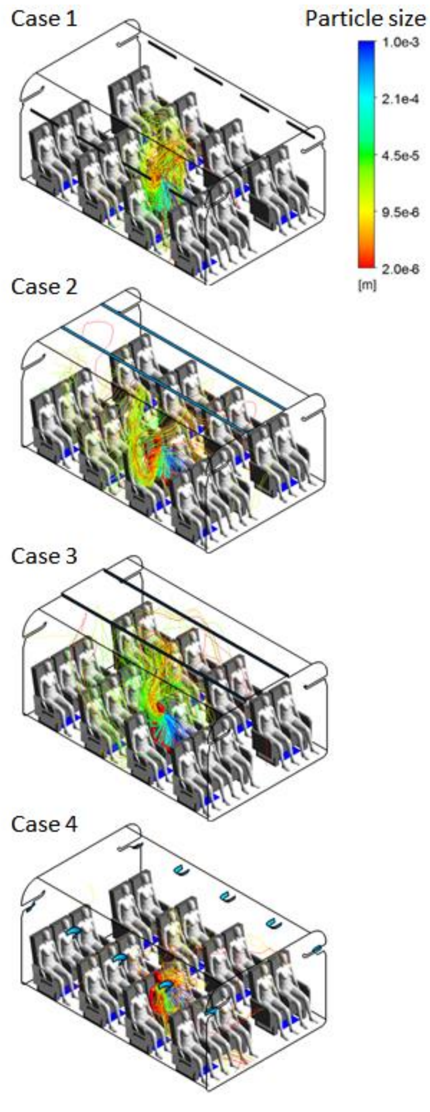

Figure 4. Size dependent droplets transport released by Passenger-S

Since the potential health risks caused by the contaminants transport would be critically relevant to the amount of contaminants inhaled by passengers [14], a quantitative exposure risk assessment of normalised droplet volume fractions at each passenger's breathing-zone were analysed and it is illustrated in figure 5. As Passenger-S was the source of droplets in this study, the droplets fraction at other passengers' breathing-zones largely depend on their seat positions. The predicted results of Case-1 in figure 5 showed the breathing-zone of the passenger next to Passenger-S in window side had the highest concentration of droplets. This can be illustrated from droplet transport trajectory in figure 4 that a strong airflow existed between them. Case-2 and Case-3 show similar situations that passengers at third row have a relatively higher concentration of droplets compared with those at other positions. This is caused by the backward airflow above Passenger-S. Passengers at both sides of Passenger-S in Case-4 suffered similarly high concentration of droplets in their breathing-zones because contaminants were highly concentrated around Passengers-S for a certain period. In summary, different types of diffusers will make contaminant distributions significantly different in every passenger's breathing-zone. However, all the passengers sitting under the condition of all four types of diffuser would experience contaminant concentration of only 5% of total released volume, which is an acceptable level.

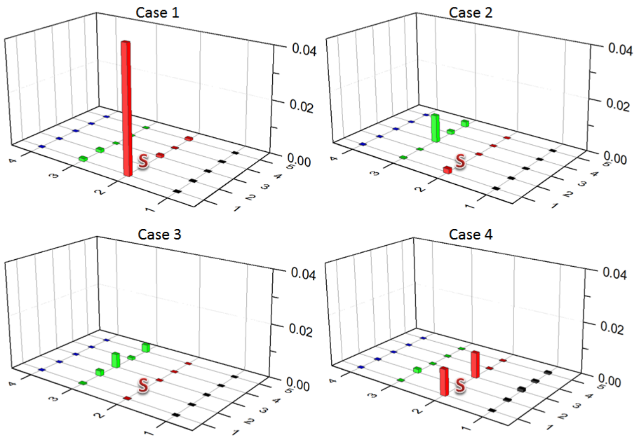

Figure 5. Normalised droplets concentrations at passengers' breathing-zones

Conclusions

Through performing the 3D numerical modelling of HST cabin section ventilation sceneries, the influence of diffuser type on contaminants transport was investigated. Simulation results indicate that the geometry and location of diffusers have significant effects on ventilation performance, contaminate transport, and passengers' breathing-zone concentration in HST cabins. Although in four cases containments dispersion processes vary, these four types of diffusers could efficiently remove the contaminants in a short period of time while keeping every passengers' breathing-zone in a relatively low pollutant concentration level. In addition, it was found that the difference in size of droplet also plays important roles in the containments dispersion inside HST cabin and it cannot be neglected for accurate pollutant dispersion prediction. This study demonstrates the importance of types of diffusers on transport characteristics of contaminants in HST cabin, and it could be used as a supplement to the current industrial standards.

Acknowledgments

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References

[1] ANSYS, I., ANSYS CFX-Solver Theory Guide, ANSYS, 2013.

[2] Chow, W.K., Ventilation of enclosed train compartments in Hong Kong, *Applied Energy*, **71**, 2002, 161-170.

[3] Daithankar, N., Udawant, K.D., & Karanth, N.V., Prediction of Thermal Comfort Inside a Midibus Passenger Cabin Using CFD and Its Experimental Validation, *SAE International*, **26**, 2015

[4] Duguid, J.P., The size and the duration of air-carriage of respiratory droplets and droplet-nuclei, *Journal of Hygiene*, **44**, 1946, 471-479.

[5] Gupta, J.K., Lin, C.H., & Chen, Q., Transport of expiratory droplets in an aircraft cabin, *Indoor Air*, **21**, 2011, 3-11.

[6] Li, F., Liu, J., Pei, J., Lin, C.H., & Chen, Q., Experimental study of gaseous and particulate contaminants distribution in an aircraft cabin, *Atmospheric Environment*, **85**, 2014, 223-233.

[7] Li, M., Zhao, B., Tu, J., & Yan, Y., Study on the carbon dioxide lockup phenomenon in aircraft cabin by computational fluid dynamics, *Building Simulation*, **8**, 2015, 431-441.

[8] Li, X., Inthavong, K., & Tu, J., Particle inhalation and deposition in a human nasal cavity from the external surrounding environment, *Building and Environment*, **47**, 2012, 32-39.

[9] Melikov, A.K., Human body micro-environment: The benefits of controlling airflow interaction, *Building and Environment*, **91**, 2015, 70-77.

[10] MRPRC, Ministry of Railways of the People's Republic of China Standard, Passenger Cabin Air Conditioning Design Parameters, Standard TB 1951-87

[11] Redrow, J., Mao, S., Celik, I., Posada, J.A., & Feng, Z.-g., Modeling the evaporation and dispersion of airborne sputum droplets expelled from a human cough, *Building and Environment*, **46**, 2011, 2042-2051.

[12] UIC, International Union of Railways Standard, Heating, Ventilation and Air Conditioning in Coaches, UIC 553-1, ed.

[13] Wang, H., Lin, M., & Chen, Y., Performance evaluation of air distribution systems in three different China railway high-speed train cabins using numerical simulation, *Building Simulation*, **7**, 2014, 629-638.

[14] Yan, Y., Li, X., Yang, L., & Tu, J., Evaluation of manikin simplification methods for CFD simulations in occupied indoor environments, *Energy and Buildings*, **127**, 2016, 611-626.

[15] Zhang, L. & Li, Y., Dispersion of coughed droplets in a fully-occupied high-speed rail cabin, *Building and Environment*, **47**, 2012, 58-66.

[16] Zhang, T.T., Lee, K., & Chen, Q.Y., A simplified approach to describe complex diffusers in displacement ventilation for CFD simulations, *Indoor Air*, **19**, 2009, 255-267.

[17] Zhu, S., Srebric, J., Spengler, J.D., & Demokritou, P., An advanced numerical model for the assessment of airborne transmission of influenza in bus microenvironments, *Building and Environment*, **47**, 2012, 67-75.