Research on Pollutant Diffusion Law in Confined Space

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Abstract. Pollutant diffusion law in typical confined space is special. This paper studied an air conditioned carriage with crowded passengers. The law of CO2 diffusion was studied by CFD simulation method. The result shows that at the 1.7m height from the floor, CO2 concentration in the region away from return air inlet and near the end of carriage is significantly lower than that in the region near return air inlet and inner end of carriage. The pollutant CO2 concentration in the region near return air inlet and at the 1.1m height of the passengers’ seats of both sides in the carriage is overall higher than that in the region away from return air inlet and at the 1.1m height of the passengers’ seats of both sides in the carriage. The research provides the theoretical base for arranging measurement points to monitor contamination content and improving airflow in the confined space.

1. Introduction
Typical airtight spaces include cabins, subway carriages, aircraft cabins, train carriages, etc. [1]. Due to the limited volume of the confined space and poor natural ventilation, the spread of pollutants has its own special laws. It is important to understand indoor pollutant diffusion rules for ventilation system design and air quality control.

In this paper, an air-conditioned carriage with high density of personnel is taken as the research object. In the carriage, the pollutants emitted by the passenger’s own metabolism are the main pollutants in the space. The main pollutant of human metabolism is CO2[2-3]. Therefore, this paper takes CO2 as an example to study its diffusion law. At present, the detection of air quality in air-conditioned vehicles is generally carried out by setting a monitoring point 1.5 m from the ground and 1 m from the vehicle wall in the middle and both ends of the carriage[4]. The setting of the three measuring points cannot understand the distribution of CO2 in the whole carriage as a whole, and the air quality of the carriage cannot be more accurately evaluated. In order to understand the diffusion law of the pollutant CO2 in the carriage as a whole, this paper attempts to use the numerical simulation method to study the diffusion law of CO2 in the air-conditioned carriage.

2. Physical model
Since the air-conditioned car is basically symmetrical along the length direction, and the sending and returning air systems are also relatively symmetrical along the length of the car, considering the saving of computing resources and improving the calculation efficiency, this article adopts a quarter-car length for simulation analysis. The total length of each car is 20000mm, the width is 2600mm, and the height is 2200mm. The physical model of empty carriage is shown in Figure 1. In the figure, 1 is the grille air supply outlet, 2 is the air return outlet, 3 is the exhaust outlet, and 4 is the seat.
According to relevant literature [5], the standing area of the carriage is the passenger room area excluding seats and leading edge 100mm, and the rated number of standing seats is determined by 6 people/m². Referring to literature [6], the human model is simplified. The physical model when the carriage is full of passengers is shown in Figure 2.

3. Mathematical model

A standard $k-\varepsilon$ model is used to simulate the turbulence, and a standard wall function method is used to deal with the turbulence near the wall. The governing equations are discretized by the finite volume method and the second order upwind scheme. The coupling of pressure and speed is SIMPLE algorithm.

4. Boundary conditions and physical parameters

Send air volume of the whole car is 9000m³/h, exhaust air volume is 2800m³/h, air supply temperature is set to 16°C, the comfort temperature in the car is set to 27°C, and the outside temperature is 35°C. The heat transfer coefficient of the car wall is 2.4 W / ( k • m² ), the passenger body surface is set to a constant temperature.

The air goes through air supply grille on the roof of the car at a speed of 2.5m/s. Air reaches passenger area, carrying the passenger's heat dissipation, moisture and pollutants such as CO₂ discharged by metabolism, and then discharged through the return air outlet.

The amount of CO₂ emitted by the human body is 35 g/h. CO₂ content in the air supply is 0.03%.

The floor, inner and outer ends of the car are treated as adiabatic boundary conditions. Air flow at the gas-solid interface meets no slip conditions.

Boundary conditions and physical parameters are shown in Table 1.

| Item                                | Numerical value |
|-------------------------------------|-----------------|
| Air supply speed (m/s)              | 2.5             |
| Supply air temperature (°C)         | 16              |
| CO₂ content in air supply (%)       | 0.03            |
| Human body CO₂ emission (g/h)       | 35              |
5. Simulation results and analysis

In order to check the diffusion law of CO$_2$ in the carriage, 122 measuring points are set at the height of 1.1m and 1.7m from the floor of the carriage. The arrangement position of the measuring points in the carriage is shown in Figure 3. Since the passengers in this carriage are mainly in a standing state with few seat Settings, that is, the number of passengers that can sit is relatively small. Therefore, this study will mainly investigate the diffusion law of pollutant CO$_2$ at the breathing height of passengers standing in the carriage (Y=1.7m). In order to comprehensively grasp the situation of CO$_2$ diffusion in the compartment, a total of 92 measuring points (X1, X2, X3, X4) are set in the middle of the compartment along the Z direction of the width of the compartment and at the height of Y=1.7m. 30 measuring points (X1’and X4’) in two columns are set on the height Y=1.1m of the breathing height near the sitting passengers on both sides of the carriage. Considering the comfort and health of passengers, it is required to control the CO$_2$ volume content in air-conditioned carriages below 0.15% [9], which should be less than 0.23% when converted into mass fraction.

Figure 3. Measuring point layout

5.1. The diffusion law of CO$_2$ at the breathing height of standing passenger

Figure 4 shows the change of CO$_2$ concentration in the compartment at the height of Y=1.7m, which is the breathing height of passengers when standing. X axis represents the direction measurement point of carriage length. Y axis is the mass fraction of CO$_2$.

Figure 4. Change of CO2 mass fraction at the height of Y=1.7m in the carriage

It can be seen from Figure 4 that in the air supply mode of the current top air supply and the top return air on both sides, in the cross section of the height of Y=1.7 m, away from the return air outlet and the area close to the outer end surface of the compartment (this area is It mainly consists of measuring points 13-23. The concentration of pollutant CO$_2$ is significantly lower than the concentration of pollutant CO$_2$ near the return air inlet and the inner end surface area (this area is including measuring points 1-10 and measuring points 11-12). The CO$_2$ mass fraction of measuring points 13-23 of the X1, X2, X3 and X4 columns far away from the return air passage area mainly
fluctuates around 0.3%, which basically satisfies the requirements of passengers’ comfort and health. The CO₂ mass fraction in points 1-10 on the X1 and X4 rows on both sides of the compartment fluctuates mainly at 0.6%, which is 2.6 times the CO₂ mass fraction limit required in the air-conditioned compartment (should be less than 0.23%).

The top of the measuring point 11-12 belongs to the position of the air duct distribution box. There is no air supply outlet in this section. As a result, the CO₂ mass fraction at measuring points 11-12 on both sides of X1 and X4 columns of the compartment is significantly higher than that at measuring points 1-10 and 13-23 on both sides of X1 and X4 columns. The CO₂ mass fraction at measuring points 11-12 in X2 and X3 in the middle of the carriage is generally higher than that at measuring points 1-11 and 13-23.

5.2. The diffusion law of CO₂ at the breathing height of sitting passengers
Figure 5 shows the change of CO₂ concentration in the carriage at the height of Y=1.1m, which is the breathing height of passengers when they sit. X axis represents the direction measurement point of carriage length. Y axis is the mass fraction of CO₂.

It can be seen from Figure 6 that the mass fraction of pollutant CO₂ on the seated breathing height of the passenger compartments on both sides of the compartment near the return air outlet is generally higher than the mass fraction of the pollutant CO₂ on the passenger seated breathing height on both sides of the compartment far from the return air outlet. The reason for this phenomenon is mainly due to the influence of return air attraction, which makes it difficult to send air near the return air inlet to the lower part of the carriage, while the area far away from the return air inlet has a relatively longer range to the air supply on both sides of the carriage.

6. Conclusion
In order to understand the law of the spread of pollutants in the air-conditioned confined carriage in the case of full passengers, the numerical simulation method is used to determine the diffusion of pollutant CO₂ in the breathing height of the passengers in the standing space area (1.7m above the floor) and the sitting height of the passengers on both sides (1.1m above the floor). The conclusions are as follows:
- On the cross-section 1.7m above the floor, the concentration of pollutant CO₂ in the area far away from the air inlet and close to the outside end of the carriage is significantly lower than that in the area close to the air inlet and the inside end. The mass fraction of CO₂, which is far away from the return air inlet and close to the outer end surface of the car, mainly fluctuates around 0.3%, which basically meets the passenger’s comfortable and healthy requirements. The mass fraction of pollutant CO₂ on both sides of the carriage near the return air inlet and the area on the inner end of the carriage fluctuates around 0.6%, reaching about 2.6 times of the limit value of the mass fraction of CO₂ required in the air-conditioned carriage. The concentration of CO₂ in the middle of carriage is basically higher than that on both sides of the carriage.
There is a 460mm space between the air inlet and the outside end of the carriage, which belongs to the position of the distribution box of the air duct. There is no air supply outlet in this section. Affected by this, the mass fraction of pollutant CO$_2$ on both sides of the compartment in this section is significantly higher than that in other regions of the compartment. However, the mass fraction of the pollutant CO$_2$ in the middle part of this section is generally higher than that of the pollutant CO$_2$ in the middle part far away from the air inlet and close to the outer end of the carriage.

On the cross-section 1.1m above the floor, the mass fraction of pollutant CO2 in the sitting and breathing height of passengers near the return air inlet was higher than that in the sitting and breathing height of passengers far from the return air inlet.

Through the numerical simulation and analysis of the pollutant diffusion rule in the confined space, the pollutant diffusion rule in the confined space and the existing problems in the air conditioning design can be revealed. Therefore, the design can be corrected in a targeted manner. The predicted results of this method have certain engineering application value, so as to reduce the number of related test verification, improve the development efficiency and save the cost.

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