Influence of air distribution modes in civil air defense basement on carbon dioxide concentration distribution in wartime

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Abstract. In order to protect the living environment and effectively control the harmful gas composition in the basement of civil air defense in wartime, this paper studies the pollutants of a civil air defense basement project in Jinan by CFD numerical simulation technology, and simulates the CO_2 concentration distribution under three different air distribution forms in civil air defense. The results show that when the second-class shelter reaches the high-density population environment, the air conditions under the distribution form of side air supply and upper air return of the building meet the living conditions of the shelter personnel. The average CO_2 concentration is 7200 ppm, but the central area forms a pollutant concentration area with an area of about 14.3%, and the highest concentration is 17000 ppm, which affects the physiological function of the shelter personnel. The CO_2 concentration distribution simulated by the air distribution modes of upper air supply, side air return and upper air supply, lower air return is more uniform, and the average pollutant concentration is 6000 ppm and 5500 ppm. The air distribution effect of upper air supply and lower air return is the best, where the CO_2 concentration is 23.6% lower than that of side air supply and upper air return scheme and 8.3% lower than that of upper air supply, side air return outlet scheme. The CO_2 concentration distribution is uniform and there is no pollutant aggregation point. Under the special conditions of wartime, the air distribution of upper air supply and lower air return with uniform air outlet layout is more conducive to pollutant control.

1 Introduction

Civil air defense basement is a key part of China's national defense construction and a long-term strategy of national security. In future wars, civil air defense basement can protect the lives and property of the people, and maintain the achievements of reform and opening-up and modernization (L Shi. [1-3]). To protect the level of protection, civil air defense basement airtightness is strong, air circulation is poor, and in the emergency, a high-density crowd is formed in the civil defense basement for a short period, and the respiratory effect of the sheltered personnel continuously releases carbon dioxide. Therefore, it is necessary to supplement fresh air in time to reduce the concentration of air pollutants and guarantee the quality of the human living environment in the human defense basement.

Analyzed the pollutant components in the underground civil air defense combined with peacetime and wartime, and determined that the main pollutant component in the underground air defense room before the war was CO (Song Renjiang et al. [4]). Analyzed and measured the main pollutants in the civil air defense underground room, the results show that CO_2 is the most harmful gas in the air defense command post (Wen

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Zhengjiang et al. [5]). The study details three types of ventilation in wartime civil air defense basement and calculates the amount of clean ventilation and filtration ventilation in combination with a case of a civil air defense basement project (Ma Wenke. [6]). A study was conducted to analyze the CO_2 concentration in the space and to control the CO_2 concentration in the space by installing more fans (Tham et al. [7]). Designed a CO_2 purification device for emergency space, and the result showed that the purification rate of this device increased by 40.3% compared with normal equipment (MAO Jinfeng. [8]). Many scholars have researched the pollutants of underground civil defense, but the condition of high-density populations living in wartime air environment research is less. This paper combines a civil air defense project in Jinan and the ventilation parameters of the second-class personnel shelter in "Code for The Design of Civil Air Defense Basements" (GB 50038-2005). And CO_2 is taken as the main air pollutant research object. CFD simulation technology was used to simulate the air environment of human habitation under clean ventilation condition in wartime, and air distribution optimization was carried out according to the results, providing a relevant experience for future civil air defense construction.

2 Method

2.1 Research Case

The research subject is located in Jinan, Shandong Province, which is belongs to the civil air defense underground project combining peacetime and wartime, and it is classified as the second-class personnel shelter. Civil air defense engineering has multiple protection zones, and the protection zone of the second-class personnel shelter and fire protection zone are divided into the same system. One of the protection zones is selected as the research object, and the area of civil air defense basement is 2000m^2.

2.2 Evaluation Indicators

The respiration of the crowd in the civil air defense basement will produce CO_2, and the high concentration will seriously affect the life and health of the shelter personnel in civil air defense. In this paper, CO_2 is mainly used as the evaluation index of human settlement environment in wartime civil air defense. The minimum evaluation standard is 2.5% CO_2 concentration limit of second-class personnel shelter stipulated in "Code for Design of Civil Air Defense Basements", and the advanced index is no physiological impact on the human body, that is, CO_2 concentration is less than 10,000 ppm. Evaluation indexes of different CO_2 concentrations in the civil air defense basement are shown in Table 1.

Table 1. Evaluation indexes of carbon dioxide concentrations.

CO_2 concentration (ppm)	Effects on the human body
0~10000	No harmful effects
10000~50000	Breathing is heavy and increased
＜25000	Normative limit value
⩾50000	Threat life and health

2.3 Calculation of clean ventilation volume

The population density in the civil air defense basement is large in wartime, and the concentration of air pollutants needs to be diluted by clean ventilation. It is stipulated in "Code for Design of Civil Air Defense Basements" (GB 50038-2005. [9]) that the fresh air volume in the clean ventilation mode of second-class personnel shelters should be greater than or equal to 5m^3/(p • h). In this study, a ventilation capacity of 5 m^3/(p-h) was selected. The total number of civil air defense basement is 2000m^2. Considering the anti-impact retaining wall for civil air defense projects in wartime, the personnel shelter area is 1200m^2. The number of wartime air defense shelter personnel in this project is 1200. So the fresh air volume of civil air defense is 6000m^3/h.

2.4 Calculation of personnel CO_2 release rate

The respiration of personnel in civil air defense in wartime is continuous, and the CO_2 release rate needs to be accurately calculated by establishing a mathematical model. The per capita CO_2 release rate is the product of respiration quotient and oxygen consumption rate per person (Rui Li. [10]), the CO_2 release rate g=0.0054 L/s for the sheltered personnel is calculated by substituting in Eq, as show in equation (1).

$$g = RQ\frac{0.00276A_D MC}{0.23RQ + 0.77} \quad (1)$$

Where, g is CO_2 release rate (L/S), RQ is respiratory quotient, MC is the metabolic rate of human body (Met), A_D is the body surface area (m^2).

3 CFD Simulation

3.1 Physical Model

The physical model is established based on the actual situation of a civil air defense basement project in Jinan, and the model needs to be simplified to guarantee the accuracy of the calculation. The size of the model is a rectangular body of 50m×40m×5m, the air inlet and the air return are located on the same side, and the air return is connected to the exhaust room through the return air duct. The actual emission source is 1200 sheltered personnel, and a block of 40m×30m×0.8m in the central area is set as the CO_2 pollution source. The model of the civil air defense basement is shown in Figure 1

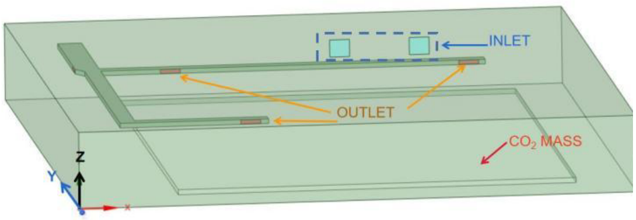

Fig. 1. Civil air defense basement mode.

3.2 Simulation parameters

The mesh numbers of 3102072, 5701784 and 6432734 were set to simulate the air concentration variations. Among the above three gridding schemes, the deviation is less than 0.15% when the number of meshes are 5701784. Assuming that the fluid mixture is incompressible, the inlet boundary is set to velocity inlet with a velocity parameter of 0.56m/s and the inlet CO_2 concentration parameter is set to 0.05%. The pollution source is set to mass flow inlet with a parameter of 0.013 kg/s. The outlet is set as mass flow outlet with a parameter of 2.15 kg/s. The remaining boundary is set to the adiabatic boundary (WALL). The model is solved using the SIMPLE solution method, The residual curve absolute criterion of the energy equation is set to $10e^{-6}$, the k-ε equation residual curve absolute criterion were set to $10e^{-3}$.

3.3 Air distribution modes

Firstly, the simulation is based on the actual project's side air supply and upper air return air distribution mode. In order to study the distribution of CO_2 concentration under different forms of air distribution, two different air distribution modes, Case B and C, were set up for comparison with the original project Case A, keep the fresh air volume and the number of people undercover unchanged and change the position of the air outlet, simulation to keep the fresh air volume and the number of people sheltered constant and change the position of the air outlet. The case of air distribution is shown in Table 2.

Figure 1 illustrates the location of the air outlet for Case A, with the supply air outlet located in the middle of the north wall of the building and the return air outlet located in the ventilation duct at the top of the building. For Case B, the air outlet location arrangement is opposite that of Case A. The air supply outlet of Case A is used as the air return outlet of Case B, and the air return outlet of Case A is utilized as the air supply outlet of Case B. Figure 1 details the air outlet location arrangement of Case B. The position of the air outlet in Case C is to change the return air outlet of Case B to the ground, and the position of the inlet air outlet remains unchanged.

Table 2. Air distribution modes.

Case	Air distribution modes	Inlet	Outlet
A	Side air-supply upper air-return	Middle of north wall	Basement top
B	Upper air-supply side air-return	Basement top	Middle of north wall
C	Upper air-supply lower air-return	Basement top	North wall floor

4 Results

4.1 Case A Analysis

Based on the case of a project in Jinan (side air supply and upper air return), the concentration distribution of CO_2 in the air defense basement is simulated under emergency conditions. The 1.5m section of the basement was selected as the study object, and the cloud map of CO_2 concentration distribution at Z=1.5m is shown in Figure 2. According to the calculation results, the average CO_2 concentration with a height of 1.5m in the basement is about 7200 ppm, meeting the limit of less than 2.5% CO_2 concentration in the code. However, a concentrated area of CO_2 concentration exists in the central region, with an area share of approximately 14.3% and a concentration range of 1.2% to 1.7%. It is worth noting that the air quality in this area is poor and affects the comfort of the shelter personnel.

The contaminant concentration area is located in the center of the shelter personnel, and the primary reason for the formation of the contaminated area is the poor air distribution mode in the central area due to the high density of shelter personnel. The simulation verifies that the clean ventilation method of this project can guarantee the survival environment of wartime shelter personnel. However, several areas have poor personnel comfort, and there is a potential for the optimization of the air distribution mode.

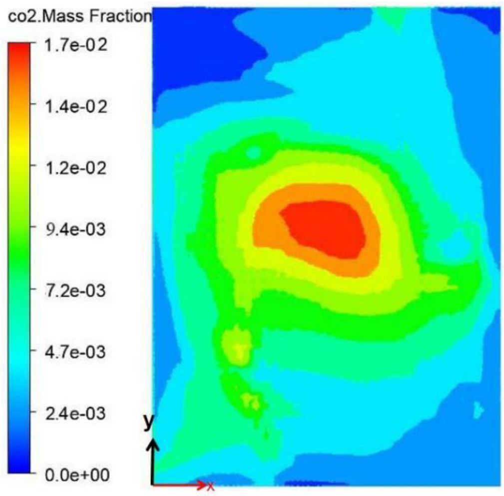

Fig. 2. Cloud map of CO_2 distribution at Z=1.5m for Case A.

4.2 Case B Analysis

The positions of the air supply and return air outlets of the project are switched with each other, and the airflow is organized as an upper air supply and side air return (Case B). Under this airflow organization, Figure 3 shows the cloud diagram of CO_2 concentration distribution in the civil air defense basement with a height of 1.5m section. According to the simulation results, the average CO_2 concentration with a height of 1.5m in the basement is calculated to be about 6000 ppm, which is 1000 ppm lower than Case A. In this case, it meets the requirement of CO_2 concentration being less than the 2.5% limit in the code. Meanwhile, the indoor CO_2 distribution is more even, showing three parts of the upper, middle, and lower regions, and the CO_2 is largely distributed on the upper and lower sides, with a total area of 46% and a CO_2 concentration range of 7000 to 10200 ppm. The CO_2 concentration in the middle region is relatively low, with a total area of 54% and a CO_2 concentration range of 2000 to 7000 ppm.

The return air outlet is located on the upper right side of the building, and the inlet air outlet is evenly distributed in the central area, forming the airflow from the central area to the upper right side. Therefore, at a height of 1.5m, the air stagnation area on the upper left side and the lower right side is formed, and the air circulation in the area is poor. The central location of the region forms a CO_2 concentration gathering point with an area of 0.6% and a concentration greater than 1000 ppm. This accelerates the breathing frequency of shelter personnel and makes them more uncomfortable. The air distribution mode of Case B can guarantee the survival environment of shelter personnel in wartime. Also the CO_2 concentration distribution is more uniform, the pollutant gathering point area is smaller, and the comfort of the human living environment is better.

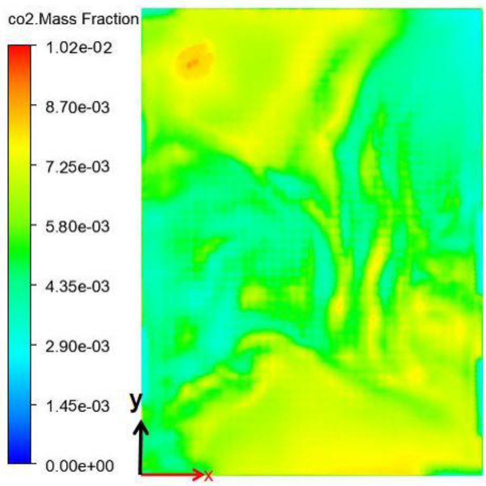

Fig. 3. Cloud map of CO_2 distribution at Z=1.5m for Case B.

4.3 Case C Analysis

Changing the air distribution mode of the project to upper air supply and lower air return yields simulation results with a height of 1.5m (Figure 4). According to the simulation results, the average CO_2 concentration at 1.5m inside the defense basement is calculated to be about 5500 ppm. The CO_2 concentration is lower than the first two air supply methods, with 23.6% lower concentration than Case A and 8.3% lower concentration than Case B, meeting the requirement of the CO_2 concentration limit being less than 2.5% in the code. The CO_2 concentration of Case C is more evenly distributed, and the CO_2 concentration in all locations at the civil air defense basement is located from 1000 to 8000 ppm, all of which are less than 10000 ppm. The concentration has no harmful effects on the shelter personnel, and the comfort level is high. In this case, the air distribution mode of upper air supply and lower air return can guarantee a high-quality survival environment for the shelter personnel in wartime.

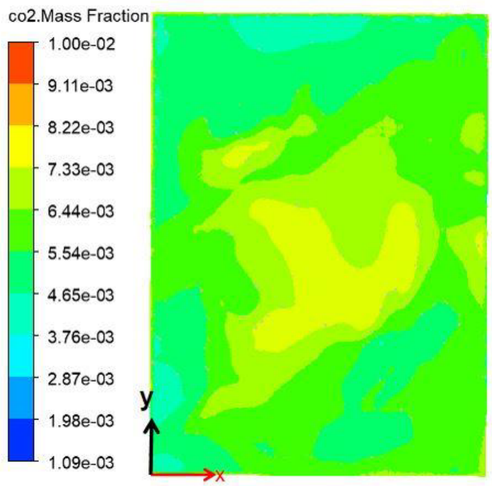

Fig. 4. Cloud map of CO_2 distribution at Z=1.5m for Case C.

4.4 Data Comparison

The simulation results of the three cases are compared with the data, as illustrated in Figure 5. The average CO_2 concentration varies less with different forms of airflow distribution: (a) Case A has the highest average CO_2 concentration of about 7200 ppm, (b) Case B has an average CO_2 concentration of about 6000 ppm, and (c) Case C has the lowest average CO_2 concentration of about 5500 ppm. The maximum CO_2 concentration varies widely, and the higher the maximum concentration, the more uneven the CO_2 distribution. Moreover, the maximum CO2 concentration of Case A is greater at about 17,000 ppm, while it is around 10,200 ppm for Case B and approximately 8,220 ppm for Case C. According to the data comparison chart, Case C has the lowest maximum CO_2 concentration and is more uniformly distributed, with the average concentration being about 8.3% lower than that of Case B and about 23.6% lower than that of Case A.

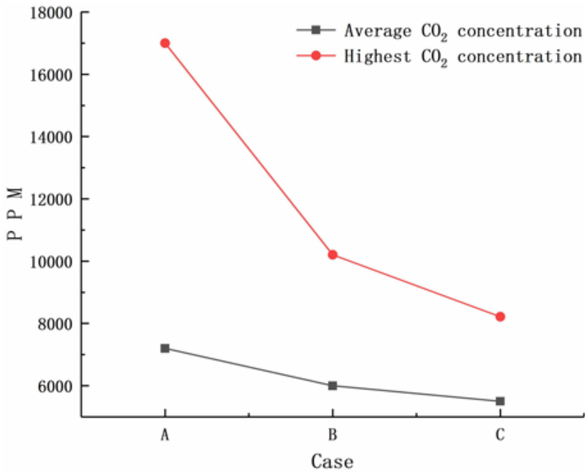

Fig. 5. Simulated data comparison chart.

5 Conclusion

CFD simulation is used to simulate the air environment of high-density shelter personnel. The new air volume is selected as the minimum limit value in the "Code for Design of Civil Air Defense Basements. The results demonstrate that the clean ventilation method of the project can guarantee the survival environment of the shelter personnel, but there is a concentrated area of CO2 pollutants in the central part of the crowd. With a total area of around 14.3%, the concentration in this area is excessively high, causing shortness of breath and poor comfort among the shelter personnel. Hence, the airflow distribution in the civil air defense basement should be optimized in order to enhance the pollutant control effect.

The results show that different modes of air distribution will affect the CO_2 distribution in the civil air defense basement, under the same fresh air volume, the Case B (upper air supply and side air return) and Case C (upper air supply and lower air return) are better than the Case A (side air supply and upper air return), and the CO_2 distribution is more uniform and lower in concentration. Concentration of about 6,000 ppm in the upper air supply and side air return mode, with only 0.6% of the area forming a pollutant concentration point. The concentration is about 5,500 ppm in the upper air supply and lower air return mode, and the CO_2 concentration is less than 10,000 ppm in all areas, with no contaminant concentration point, guarantee the survival environment of the shelter personnel while also having a certain degree of comfort. Therefore, the air distribution mode of upper air supply and lower air return is most suitable for the high-density crowd environment in the wartime civil air defense basement.

It is suggested that the civil air defense basement combined with the level of warfare should fully consider the use of the wartime state, the central area evenly arranged wind outlet location. Wartime shelter personnel fresh air volume selection as much as possible greater than the code requirements of $5m^3$ / (P • h), to protect the survival of the basic environment to give shelter personnel a certain degree of comfort. This study only addresses the high-density habitat of wartime civil air defense projects, and the wartime state almost does not occur, for the civilian air defense project combined with the civilian warfare has a certain special nature. Therefore, it is recommended to design two different air distribution modes in the civil defense basement combined with level and warfare, different ventilation ducts can be connected in the machine room in case of emergency to achieve better habitat.

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References

1. L. Shi, H. Zhang, Z. Li, X. Man, Y. Wu, C. Zheng, J. Liu. Research on passive humidity controlling in underground civil air defense work for command, Build Environ, **143**, 366-377 (2018)
2. W. Wu, J. Han, A. Malkawi, Simplified direct forcing approach for dynamic modeling of building natural ventilation, Build Environ, **188**, 1-9 (2021)
3. S. Hou, Q. Tan, Design of ventil ation and smoke exhaust for civil air defence works in the basement of a high-rise building, HV_2AC, **{4}(01)**, 45-47 (2001)
4. R. Song, S. Hu, G. Liu, K. Liu, H. Zhang, Y. Liu, Application of CFD simulation technology in the underground garage ventilation, Journal of Qingdao University of Technology, **37(03)**, 65-69 (2016)
5. Z. Wen, X. Han, Y. Liu, T. Lu, L. Zhang, Experimental research and source analysis of air pollutants of underground construction space, CC_2AC, **02**, 9-13 (2012)
6. W. Ma, Y. Du, Ventilation and air conditioning design for medical rescue station of a Chinese medical hospital, CC_2AC, **51(05)**, 98-102 (2021)
7. T. Wai, P. Kashinath, A. Prashant, C. Kok Wai, S. Chandra, Performance characteristics of a fan filter unit (FFU) in mitigating particulate matter levels in a naturally ventilated classroom during haze conditions, Indoor Air, **31(3)**, (2020)
8. J. Mao, L. Liu, S. Ji, F. Chen, Development and Performance Analysis of Carbon Dioxide Purification Device in Emergency Shelter Space, Building Energy $_2$ Environment, **37(02)**, 19-23 (2018)
9. Code for The Design of Civil Air Defense Basements(GB50038-2005), China Academy of Architecture and Design, 146 (2005)
10. D. Lv, Monitoring analysis and simulation of carbon dioxide concentration in college classrooms in Harbin, Harbin Institute of Technology, 16-17 (2005)
11. R. Li, CFD simulation-based optimization of airflow organization in a datacenter, Shandong University , 15-17 (2020)