

Numerical Study on the Effects of Ventilation System on Hydrogen Dispersion in an Underground Garage with Smoke Barriers

Zhenming Xue^{1, a}, Xuhai Pan^{1, 2, b *}

¹ College of Safety Science and Engineering, Nanjing Tech University, Nanjing 211816, China;

² Nanjing Vocational University of Industry Technology, Nanjing, 210023, China.

^a xuezhenming@njtech.edu.cn, ^b xuhaipan@njtech.edu.cn

Abstract. The promotion of hydrogen fuel cell vehicles (HFCVs) has been hindered by hydrogen safety issues. In this paper, hydrogen leakage in an underground garage with smoke barriers is numerically simulated. Nine vents are arranged for the distribution of smoke barriers, and the effects of the ventilation mode and ventilation opening time on hydrogen dispersion and hydrogen removal efficiency are discussed. It is found that ventilation can effectively inhibit the formation of flammable hydrogen clouds. The hydrogen removal efficiency of mechanical ventilation is much higher than that of natural ventilation, and the effect becomes more significant as the ventilation time increases. Reducing the opening time of ventilation can improve the overall ventilation effect and the efficiency of removing high concentration hydrogen, while reducing the time required for hydrogen concentrations to drop below the safety limit.

Keywords: Hydrogen leakage and dispersion; Fuel cell vehicle; Underground garage; Mechanical ventilation; Smoke barrier.

1. Introduction

Hydrogen is considered to be one of the most promising alternative energy sources to traditional fossil fuels due to its many advantages, and HFCV is an important development direction for future hydrogen energy end-use applications. However, the promotion of HFCVs has been hindered by hydrogen safety issues. When hydrogen leakage occurs in an underground garage, if effective ventilation cannot be carried out in time, hydrogen is prone to accumulate and mix with air to form a flammable gas cloud, which may cause accidents such as fires and explosions. There is a need for a more comprehensive study of the dispersion characteristics of hydrogen in such confined spaces.

There have been some studies on hydrogen leakage and ventilation in garages. Pitts et al. [1] conducted helium leakage experiments in a downsized small residential garage and found that the use of two vents near the top and bottom of the garage allowed for better helium venting than a single large vent of equal size. Venetsanos et al. [2] investigated the hydrogen concentration distribution in a ventilated garage through numerical simulations, and the results showed a homogeneous distribution at low ventilation rates, while the hydrogen concentration is stratified at high ventilation rates. In addition, smoke barriers are often installed in existing large underground garages to limit the spread of smoke, but in the event of hydrogen leakage it can cause a localized increase in hydrogen concentration [3]. Li et al. [4] found that the volume ratio of the flammable region in a closed garage tends to increase as the beam height increases; after setting two symmetrical natural vents, the flammable volume ratio decreased by 50%. Merilo et al. [5] found that mechanical ventilation resulted in a significant reduction in hydrogen concentration and overpressure from deflagration.

At present, there are few studies on the mechanical ventilation system combined with smoke barrier distribution in underground garages. When hydrogen is gathered in the partition by the smoke barrier, the change of local hydrogen concentration after the ventilation system is turned on has an important reference value for the ventilation safety design of underground garages. In this paper, the hydrogen leakage and dispersion process in an underground garage with smoke barriers is numerically simulated by FLACS software, and the vents are arranged according to the smoke

barrier partition. The effects of different ventilation conditions on hydrogen dispersion and hydrogen removal efficiency are investigated by hydrogen concentration cloud diagrams and monitoring point data. This study can provide supportive data for the improvement of the ventilation system in underground garages.

2. Numerical Simulation

2.1 Simulation setup

As shown in Fig. 1, a model of an underground garage of 62 m length, 32 m width, and 2.9 m height is built, including an exit of 5 m width and 2.82 m height, and 32 columns with dimensions of 0.5 m \times 0.5 m. The vehicle model is 3.6 m long, 1.5 m wide and 1.5 m high. The underground garage has a total of 60 parking spaces, which are arranged in 3 rows in the Y-direction, represented by letters A, B and C, and in 21 columns in the X-direction, represented by numbers 1 to 21 respectively. A vehicle is parked in the corner parking space C21 away from the exit. The leakage port is a 33.8 mm diameter circle located at the undercarriage of the vehicle, 1.26 m from the rear of the vehicle. Smoke barriers of 0.5 m in height are installed at the ceiling, and nine vents, named V1 to V9, are arranged according to the smoke barrier partition. In addition, monitor points, named MV 1 to MV 9, are set 1 cm below each vent.

Hydrogen leaks vertically downward from the leakage port at a mass flow rate of 0.003 kg/s in order to simulate a continuous leakage due to piping breakage in the on-board hydrogen supply system. The system of control equations for the hydrogen leakage process is solved by FLACS software, and the standard k- ϵ model is used to simulate the turbulent flow of hydrogen. The ambient temperature is set to 20 °C and the ambient pressure is set to 100 kPa. NOZZLE boundary conditions are used for all leakage scenarios. According to the Chinese national standard JGJ 100–2015, the number of air changes in garages with mechanical ventilation systems is 6 times/h, which translates into an air velocity of 4.26 m/s for a single vent. Hydrogen sensors in parking garages can result in different ventilation opening time due to their arrangement location. The time at which the hydrogen concentration reached 0.4% at the MV 9 monitoring point closest to the leakage, 45 s, is used as the fastest ventilation opening time, and three other opening times are considered. In order to investigate the effect of ventilation mode and ventilation opening time, simulation schemes are designed as shown in Table 1. Case 1 is a scenario with no ventilation, and Case 2 is a natural ventilation scenario with open vents and 0 m/s fan speed. The total simulation time $t = 1000$ s.

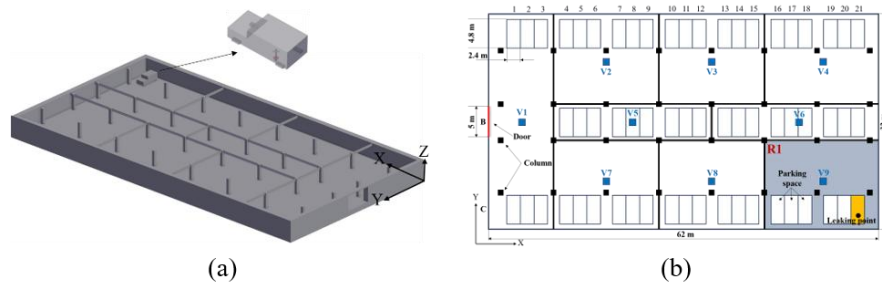


Fig. 1 (a) Geometric model of the garage and the vehicle; (b) Garage layout
Table 1. Simulation schemes

Number	Leakage time (s)	Mechanical ventilation time (s)	Fan speed (m/s)
Case 1	0–300	Without vents	
Case 2		/	0
Case 3		0–1000	4.26
Case 4		45–1000	4.26
Case 5		130–1000	4.26
Case 6		215–1000	4.26
Case 7		300–1000	4.26

2.2 Reliability verification

The size of the entire computational area is set to $69\text{ m} \times 34\text{ m} \times 7\text{ m}$. The grid near the leakage point and vents are locally refined. Three sets of grids with different sizes, 0.5 m, 0.4 m, and 0.3 m, are constructed, and the hydrogen concentration data from monitoring point MV6 are selected for grid independence analysis. As shown in Fig. 2 (a), the results obtained from the calculation of 0.3 m grid and 0.4 m grid are very close to each other, indicating that the grid accuracy no longer affects the calculation results. Therefore, a grid with a basic size of 0.4 m and a total number of 610,000 is selected.

Referring to the hydrogen leakage experiment conducted by Pitts et al.[6], the same model is developed for simulation in this paper to verify the reliability of the numerical method. The experiments were conducted in a garage 6.1 m long, 6.1 m wide, and 3.05 m high with two windows in the side wall for ventilation. Hydrogen was released at a mass flow rate of 83.3 g/min at the center floor of the garage. The hydrogen concentrations at two monitoring points in the experiment, named S1 and S2, with heights of 3.05 m and 1.52 m, are selected for model validation. As shown in Fig. 2 (b), the simulation results are in good agreement with the experimental results, indicating that the numerical method used in this paper to simulate hydrogen leakage and dispersion is reliable.

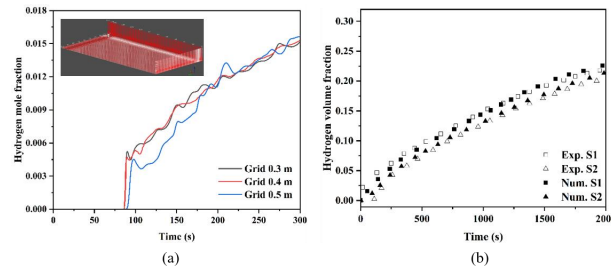


Fig. 2 (a) Grid independence analysis; (b) Model validation

3. Results and discussion

3.1 Effect of ventilation mode

The three-dimensional distribution of hydrogen concentration in the garage at $t = 300\text{ s}$ is shown in Fig. 3. It can be seen that compared with the unventilated leakage scenario in Case 1, the hydrogen concentration in the parking lot did not exceed the lower flammable limit of 4% in both the natural and mechanical ventilation scenarios, which proves that the ventilation can effectively inhibit the formation of a flammable hydrogen cloud. In Case 2, the leaked hydrogen spread around after impacting the ceiling above, and when it moves to the position of the vent, it is discharged upward due to buoyancy and concentration gradient, which prevent the hydrogen from accumulating in a short period of time, thus making it difficult for the combustible hydrogen cloud to form. In Case 3, the hydrogen in the vicinity of the vents is rapidly reduced by the suction effect of the fans, and the hydrogen concentration and distribution range in the parking lot were smaller than those in Case 2.

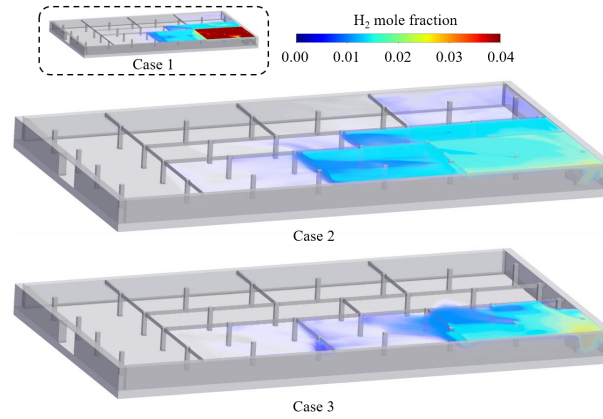


Fig. 3 Three-dimensional distribution of hydrogen concentration in the garage at $t = 300$ s

The safety limit for hydrogen concentration is set at 1% hydrogen mole fraction in many standards. Therefore, areas with concentrations exceeding 1% are defined as hazardous areas. The hydrogen concentration distribution at the ceiling for different ventilation modes is shown in Fig. 4. It can be seen that the hydrogen removal efficiency of mechanical ventilation is much higher than that of natural ventilation. After the leakage stopped at 300 s, the local hydrogen concentration in the underground garage under both ventilation methods exceeded 1%, in which the maximum lateral distance of the hazardous area is about 35 m in the case of natural ventilation, while it is only about 22 m in the case of mechanical ventilation, which is reduced by 37.1% compared with that of natural ventilation. At $t = 425$ s, the hydrogen concentration in the mechanically ventilated parking lot has been reduced to less than 1%, while the size of the hazardous area in the naturally ventilated scenario has not been significantly reduced.

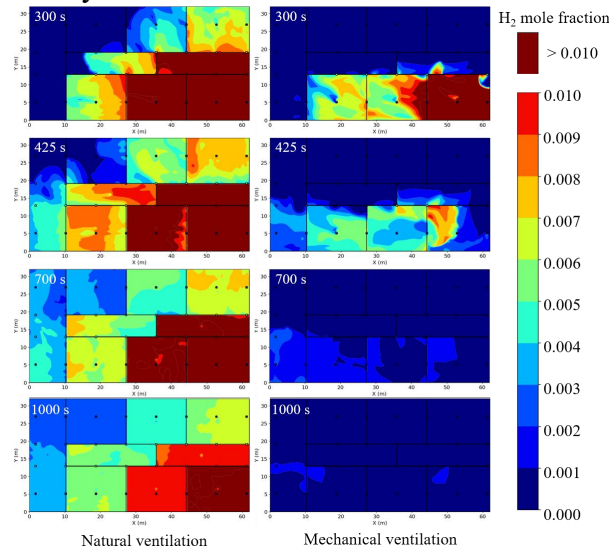


Fig. 4 Hydrogen concentration distribution at ceiling under different ventilation modes

The hydrogen removal efficiency of the two ventilation methods is analyzed by comparing the hydrogen concentration changes at three monitoring points MV 6, MV 8 and MV 9, which are closer to the leakage point. As shown in Fig. 5, mechanical ventilation can remove hydrogen from the parking lot to the outside more quickly than the natural ventilation method. During the hydrogen leakage phase, the concentration at each monitoring point is significantly reduced due to the opening of mechanical ventilation. At $t = 300$ s, the hydrogen concentration at monitoring point MV 9 under natural ventilation and mechanical ventilation is 1.67% and 0.51%, respectively, and the mechanical ventilation results in a relative reduction of 69.3% of the hydrogen concentration at MV 9 compared with the natural ventilation.

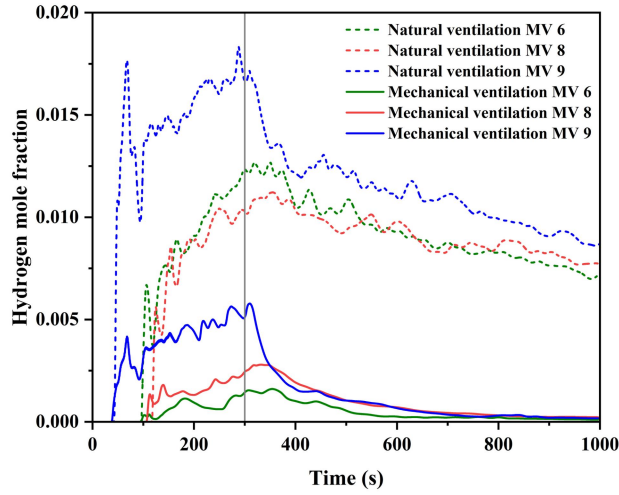


Fig. 5 Comparison of concentrations at monitoring points under different ventilation modes

3.2 Effect of ventilation opening time

A hydrogen mole fraction of 0.4% (10% of the lower flammable limit) is used to compare the effectiveness of ventilation due to the large scale of the garage resulting in a low hydrogen concentration in the space. The hydrogen concentration distribution at the ceiling for different ventilation opening times is shown in Fig. 6. In all four cases, areas of low concentration are evident at the vents. At $t = 400$ s, in Case 4 and Case 5, the distance of the highly concentrated area in the longitudinal direction is less than 16 m, mainly distributed in the lower half of the ceiling plane; in Case 6 and Case 7, due to the late ventilation opening time, the hydrogen has already dispersed to the upper half of the ceiling cross-section, where the maximum longitudinal distance of the highly concentrated area reaches 32 m in Case 7. Moreover, hydrogen is discharged faster in the case with earlier ventilation opening time. At $t = 550$ s, the hydrogen concentration in Case 4 is basically at below 0.4%, and the area of the high concentration region gradually increases with the delay of ventilation opening time.

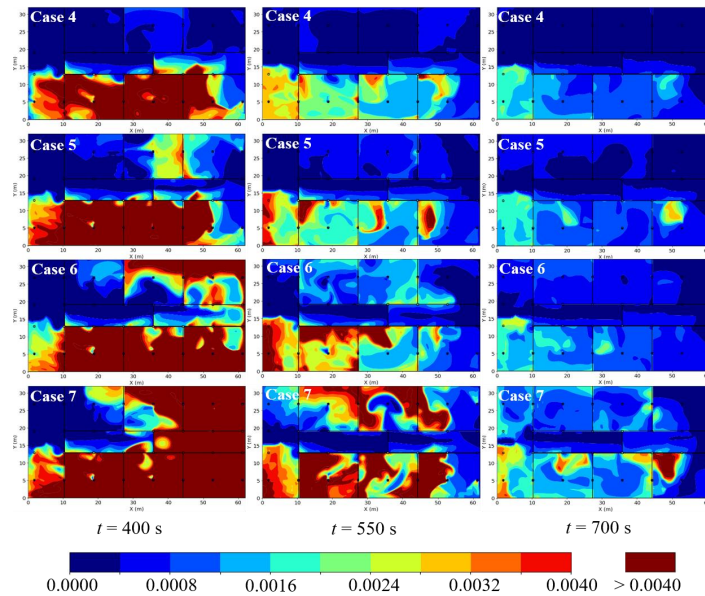


Fig. 6 Hydrogen concentration distribution at the ceiling for different ventilation opening times

A comparison of hydrogen concentrations at monitoring points MV 9 and MV 8 at different ventilation opening times is shown in Figure 7. The results show that turning on the ventilation earlier improves the overall ventilation effect. The hydrogen mole fraction at the monitoring point decreases rapidly after turning on the mechanical ventilation in all four cases. During the hydrogen leakage stage, the hydrogen concentration at MV 9 decreases with the shortening of the ventilation

opening time, while the hydrogen concentrations at MV 8 in Case 4–6 are closer, indicating that earlier ventilation opening can discharge the high concentration of hydrogen near the leakage point faster, but the ventilation opening time has less effect on the low concentration of hydrogen farther away from the leakage point. After the leakage stopped for 100 s, compared to the scenario where ventilation is turned on at 300 s, turning on ventilation at 45 s result in a relative reduction of 51.7% in hydrogen concentration at MV 9.

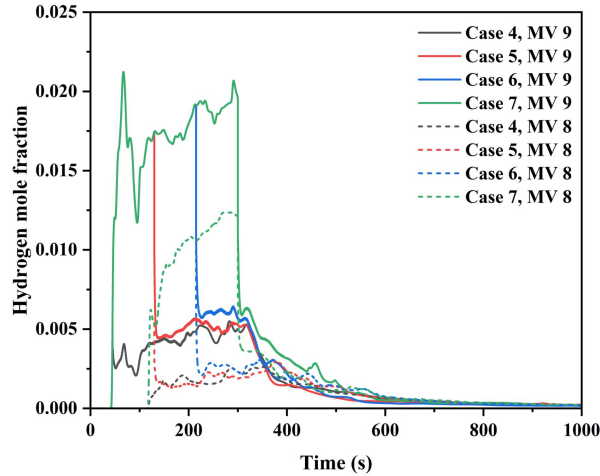


Fig. 7 Comparison of concentrations at monitoring points at different ventilation opening times

The concentration distribution of hydrogen concentration at different ventilation opening times when the hydrogen concentration reaches the safe state is shown in Fig. 8. As can be seen from the figure, the later the ventilation is turned on, the longer it takes for the hydrogen concentration to decrease below the safe limit. In Case 7, it takes 627 s to reduce the hydrogen concentration to the safe state, which is a relative increase of 28.7% compared to Case 4.

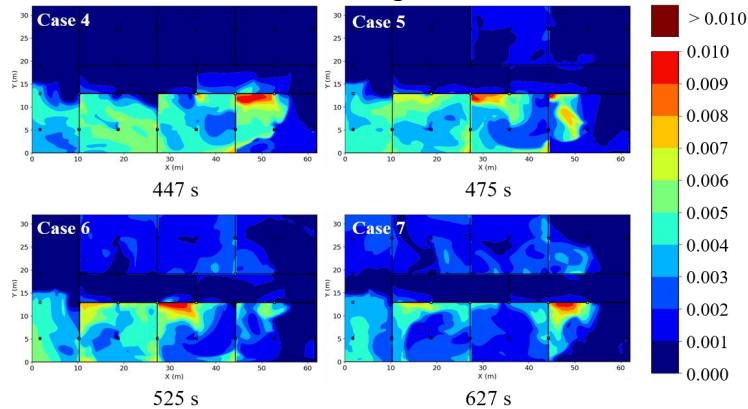


Fig. 8 Hydrogen concentration distribution at safe conditions for different ventilation opening times

4. Summary

In this paper, the scenario of ventilation after hydrogen leakage in an underground garage with the presence of a smoke barrier is numerically simulated, and the effects of ventilation conditions, such as the ventilation mode and the ventilation opening time, on the hydrogen dispersion and hydrogen removal efficiency are discussed. It is found that ventilation can be an effective safety solution to the increased localized hydrogen concentrations caused by smoke barriers. The hydrogen removal efficiency of mechanical ventilation is much higher than that of natural ventilation, and the effect becomes more significant as the ventilation time increases. Reducing the opening time of ventilation can improve the overall ventilation effect and the efficiency of removing high concentration hydrogen, while reducing the time required for hydrogen concentrations to drop below the safety limit.

References

- [1] Pitts WM, Yang JC, Fernandez MG. Helium dispersion following release in a 1/4-scale two-car residential garage. *Int J Hydrogen Energy* 2012;37:5286–98. <https://doi.org/10.1016/j.ijhydene.2011.12.008>.
- [2] Venetsanos AG, Papanikolaou E, Cariteau B, Adams P, Bengaouer A. Hydrogen permeation from CGH2 vehicles in garages: CFD dispersion calculations and experimental validation. *Int J Hydrogen Energy* 2010;35:3848–56. <https://doi.org/10.1016/j.ijhydene.2010.01.135>.
- [3] Xin J, Duan Q, Jin K, Sun J. A reduced-scale experimental study of dispersion characteristics of hydrogen leakage in an underground parking garage. *Int J Hydrogen Energy* 2023;48:16936–48. <https://doi.org/10.1016/j.ijhydene.2023.01.170>.
- [4] Li Y, Jiang J, Yu Y, Zhang Q. Numerical simulation of dispersion and distribution behaviors of hydrogen leakage in the garage with a crossbeam. *Simulation* 2019;95:1229–38. <https://doi.org/10.1177/0037549718825303>.
- [5] Merilo EG, Groethe MA, Colton JD, Chiba S. Experimental study of hydrogen release accidents in a vehicle garage. *Int J Hydrogen Energy* 2011;36:2436–44. <https://doi.org/10.1016/j.ijhydene.2010.04.056>.
- [6] Pitts WM, Yang JC, Blais M, Joyce A. Dispersion and burning behavior of hydrogen released in a full-scale residential garage in the presence and absence of conventional automobiles. *Int J Hydrogen Energy* 2012;37:17457–69. <https://doi.org/10.1016/j.ijhydene.2012.03.074>.