Study on the Influence of Garage Ventilation Conditions on Hydrogen Leakage and Diffusion

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Abstract. To investigate the effects of garage ventilation volume and ventilation area on hydrogen diffusion and concentration distribution after accidental hydrogen leakage in fuel cell vehicles, numerical simulation methods were used to study and analyze the hydrogen accumulation concentration and combustible hydrogen accumulation area under the garage roof. The results showed that with the increase of ventilation volume and ventilation area, the elimination effect of combustible hydrogen in the garage gradually became significant. There was a critical ACH of 10, beyond which the effect of eliminating combustible hydrogen was no longer significant; Similarly, there is a critical ventilation area of 2.25 m^2, which can completely eliminate combustible hydrogen in the garage. In addition, when the garage is ventilated, a vortex zone will be generated that causes the accumulation of flammable hydrogen, and it will move away from the ventilation opening as the ventilation volume increases. The research results of this article can provide guidance for the ventilation design of garages that can meet the parking needs of hydrogen fuel cell vehicles.

Keywords: Garage; Hydrogen leakage; Ventilation volume; Ventilation area;

1 Introduction

Since the goal of "peak carbon emissions and carbon neutrality" was proposed in the 14th Five Year Plan, China's energy structure has undergone rapid transformation. Hydrogen energy, as a zero pollution and environmentally friendly renewable clean fuel, is one of the main energy carriers in the future and has been widely used in recent years [1]. However, due to the wide range of hydrogen combustion (4%-75%), low ignition energy, and large diffusion coefficient, if hydrogen fuel cell vehicles are parked in relatively enclosed garages, there will be certain potential hazards when hydrogen leaks [2]. Therefore, in order to reduce the safety hazards caused by hydrogen leakage, further research is needed on the prevention and control capabilities of combustible hydrogen in garages.

Domestic and foreign scholars have conducted some research on the leakage and diffusion of hydrogen gas in confined spaces. Liu et al.[3] established a numerical analysis model for hydrogen leakage and diffusion inside fuel cell vehicles, and obtained

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the distribution of hazardous areas after hydrogen leakage and diffusion inside the vehicle. Li et al.[4] studied the effect of spacing between garage crossbeams on hydrogen diffusion and concentration distribution under natural ventilation conditions. Zhang et al.[5] conducted research on hydrogen leakage in multi obstacle garages and obtained the influence of leakage velocity on hydrogen diffusion behavior and concentration distribution characteristics. Zhang et al.[6] studied the effects of the aspect ratio and height of garage ventilation openings on the diffusion and distribution of hydrogen gas. He et al.[7] used numerical simulation methods to study the effects of different ventilation methods in garages on hydrogen leakage, diffusion, and concentration distribution. Xie et al.[8] studied the harmful effects of longitudinal wind speed in tunnels on combustion and explosion after hydrogen leakage. Choi et al.[9] used numerical simulation methods to study the effects of hydrogen leakage direction and flow rate on gas diffusion and combustible gas cloud distribution in a closed garage. Shentsov et al.[10] studied the influence of the diameter and angle of the hydrogen release valve in fuel cell vehicles on the distribution of combustible hydrogen gas clouds after hydrogen leakage, providing a theoretical basis for the design of hydrogen safety release devices. Hajji et al.[11] analyzed the influence of factors such as the position, shape, and area of garage ventilation openings on hydrogen leakage and diffusion. Pitts et al.[12] conducted experimental research on hydrogen leakage in a typical residential garage, and obtained the temporal variation patterns of hydrogen diffusion, concentration distribution, and flame combustion behavior after ignition. Chen et al.[13] used the principle of similarity to build a scaled down experimental platform to study hydrogen leakage and obtained the influence of different ventilation forms on hydrogen diffusion distribution in a closed garage.

Due to the serious safety issues caused by high-pressure hydrogen gas leakage in garages, and the current research on hydrogen gas leakage in garages mainly focuses on the influence of leakage conditions and ventilation forms on hydrogen diffusion distribution, there is little research on the influence of garage ventilation volume and area on the diffusion characteristics and concentration distribution of hydrogen gas after leakage. Therefore, based on existing research results, this article conducts numerical simulation and analysis of hydrogen leakage in fuel cell vehicles in garages, explores the influence of different ventilation volumes and areas on hydrogen diffusion and concentration distribution in garages, and provides guidance for ventilation design of garages that can meet the parking needs of hydrogen fuel cell vehicles.

2 Numerical Simulation Model

2.1 Geometric Model

This article establishes a garage model that is closer to the actual garage as the research object based on the "Code for Design of Garage Buildings" [14] (JGJ 100-2015) and the "Code for Fire Protection Design of Garage, Repair Garage, and Parking Lot" [15] (GB 50067-2014). The size of the garage is 25*20*3m, with a parking capacity of 20 vehicles. There is a 4m wide and 2.5m high entrance and exit on one side of the garage, and a square exhaust outlet on the other side. The size of the fuel cell vehicle parked in the garage adopts the standard passenger car size, with a specific value of 4.8*1.8*1.6m. The hydrogen leakage point is set at the bottom of the vehicle, and the leakage source uses a 5mm high-pressure pipeline leakage diameter, with the leakage direction vertically downward. The schematic diagram of the above model is shown in Figure 1.

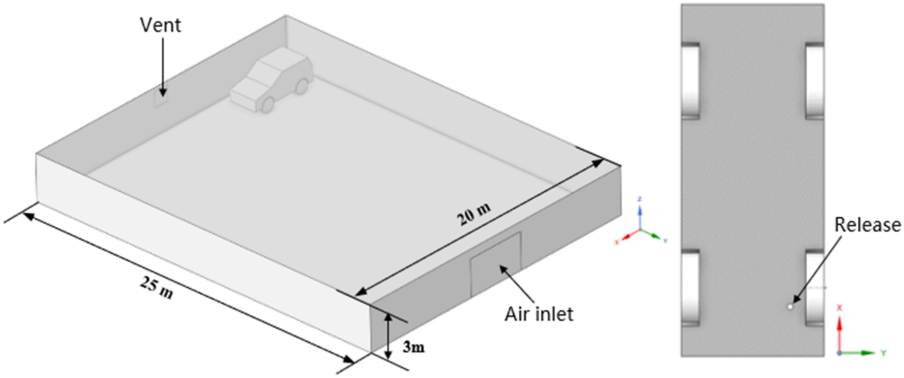

Fig. 1. Schematic diagram of garage model

The parking equivalent of the garage studied in this article is less than 50 vehicles, which belongs to the type of small garage. The ventilation mode of such garages is usually a combination of natural air intake and mechanical exhaust. The garage entrance and exit serve as fresh air inlets, and the exhaust outlet uses fans for mechanical exhaust. In order to clarify the impact of garage ventilation conditions on hydrogen diffusion and concentration distribution after hydrogen leakage in fuel cell vehicles, this article only placed a single fuel cell vehicle in the garage to eliminate the influence of obstacles on hydrogen leakage and diffusion. At the same time, considering the worst leakage situation, the vehicle was placed in a corner away from the garage air inlet and close to the exhaust wall to explore the influence of garage ventilation conditions on hydrogen leakage.

2.2 Grid Division

To improve the efficiency of grid division, hexahedral grid division is used in the core area of the calculation, and polyhedral grid division is used in the transition area and near the wall. The overall size of the grid is 0.05m, and the area near the leakage port is locally densified to a size of 1mm to improve grid quality and calculation accuracy. The final total number of grids is 5604263, and the cross-sectional grid of the computational domain is shown in Figure 2.

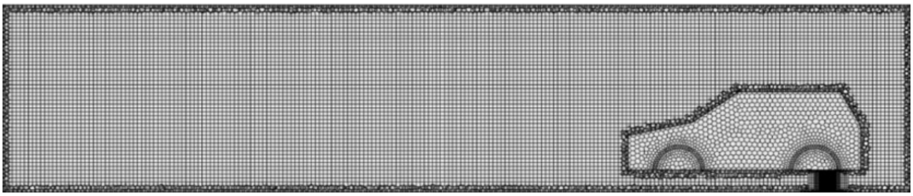

Fig. 2. Schematic diagram of cross-sectional mesh in computational domain

2.3 Boundary Condition

The leakage and diffusion process of hydrogen gas is actually the mixing process between the leaked hydrogen gas and the air in the space. Based on existing research and theory, the following assumptions are made:

1) Hydrogen, air, and their mixtures are all ideal gases that satisfy the equation of state for ideal gases;

2) Hydrogen does not undergo chemical reactions with the outside world during the leakage process;

3) The leakage process of hydrogen is continuous, and a constant leakage rate is maintained during the leakage process;

4) The inner wall of the computational domain is isothermal, adiabatic, and smooth.

Based on the above assumptions, this article adopts the Realizable k - ε turbulence model, which can better calculate circular hole jets by modifying the buoyancy term of the standard k - ε model. At the same time, using a component transport model, opening the energy equation, adopting the ideal gas law, and considering compressible flow to calculate the turbulence generated by high-pressure hydrogen gas leakage and the process of mixing and diffusion with air. In addition, during the calculation process, the PISO coupling algorithm is used to achieve complete pressure and velocity coupling, and the second-order upwind scheme is used to discretize the control equations.

The boundary of the hydrogen leakage port is set as the mass flow inlet, and the leakage rate is set to 0.08 kg/s. This flow rate meets the mass flow condition for fuel cell vehicles to quickly complete the leakage after the high-pressure pipeline breaks[16]. The entrance and exit of the garage, also known as the air inlet, are set as pressure inlets, with an inlet pressure of standard atmospheric pressure. The exhaust outlet is set as the boundary of the exhaust fan, and all walls are set as stationary and non slip walls. In order to make the simulation closer to the actual situation and increase its universality, the ambient temperature and ambient pressure are set to 300 K and 101325 Pa. Considering the influence of gravity similarly, the gravity acceleration is 9.8 m/s^2.

2.4 Model Validation

To verify the accuracy of the numerical calculation model and method in this article, the hydrogen leakage process was simulated based on the experimental conditions of hydrogen leakage and diffusion conducted by Pitts et al.[12]. In the experiment, there was a door (2.4m*2.1m) on the front wall of the garage (6.1m*6.1m*3.05m) and two square ventilation openings with a side length of 0.2m on the right side that are 2.3m above the ground. A steel gas box (0.305m*0.305m*0.15m) is placed in the center of the garage, and hydrogen gas is transported from outside the garage to the steel gas box. Within 1 hour, 5 kg of hydrogen gas is leaked at a uniform rate through the square opening on the upper part of the steel gas box in the test space. The experimental scenario and model are shown in Figure 3. A hydrogen concentration sensor is installed at a distance of 5.5m from the door and a height of 3.05m in the garage to monitor changes in the concentration of hydrogen gas accumulated at the top of the garage. This article uses the numerical calculation model described earlier to simulate and compare the hydrogen concentration change curve at the monitoring point with experimental data, as shown in Figure 4. The data obtained from numerical calculations is slightly larger than the experimental values, and the trend of their changes is consistent. The overall error between the two is around 5.6%, which is within an acceptable range.

Therefore, the verification results indicate that the numerical calculation model and method used in this paper have high accuracy and can accurately simulate the hydrogen diffusion and accumulation behavior of fuel cell vehicles in garages after hydrogen leakage.

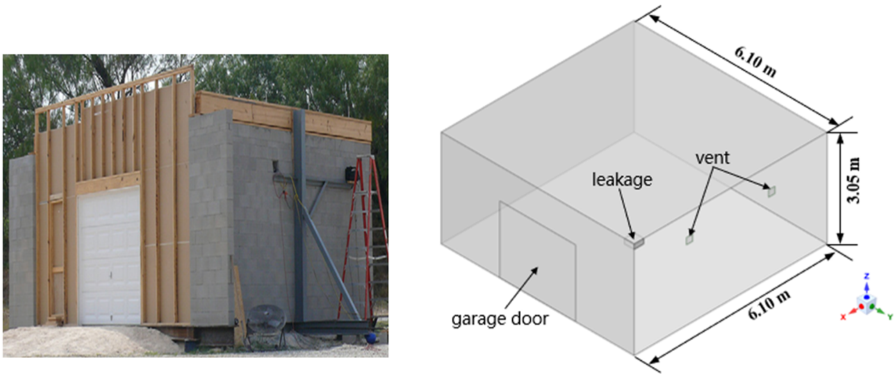

Fig. 3. Experimental Scene and Verification Model Diagram

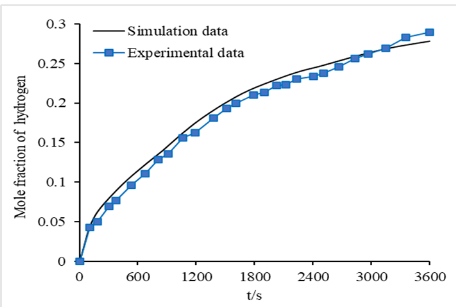

Fig. 4. Mole fraction of hydrogen at monitoring points

3 Analysis of Hydrogen Diffusion Process

The simulation lasted for a total of 40s. A hydrogen leak occurred in a fuel cell vehicle from 0 to 20s , and the hydrogen leak ended in 20 to 40s while maintaining ventilation. The impact of ventilation conditions on hydrogen diffusion and accumulation was observed. The diffusion cloud map of hydrogen gas on the cross-section of the vehicle after leakage under basic ventilation conditions (ACH=6, S=1m^2) is shown in Figure 5. The leakage and diffusion process can be divided into three stages:

The first stage is the collision diffusion stage (0-5s), during which the hydrogen jet is mainly controlled by momentum. The hydrogen jet hits the ground vertically and at high speed, and at this time, the hydrogen gas mixes unevenly with the surrounding air, quickly filling the vehicle chassis area.

The second stage is the upward diffusion stage (5-25s), during which the kinetic energy of hydrogen rapidly decays. Hydrogen continuously overflows from around the vehicle chassis and mixes well with the surrounding air. Due to the dominant control of buoyancy on the hydrogen jet at this time, hydrogen begins to float along the side of the vehicle and the wall, gradually accumulating at the top of the garage.

Finally, there is the accumulation stage (25-40s), during which the hydrogen leakage has ended. The hydrogen gas that first reached the top of the garage has completed its accumulation, and the lower hydrogen gas continues to rise and mix with the top hydrogen cloud cluster. At the same time, due to continuous ventilation driving the airflow in the garage, the hydrogen gas accumulated at the chassis of the vehicle overflows and rises to the top of the garage. The hydrogen gas accumulated at the top of the garage also begins to shift under the action of ventilation airflow and gradually forms a stable accumulation cloud cluster.

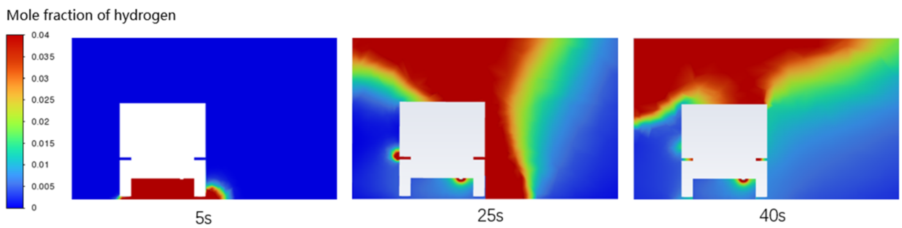

Fig. 5. Schematic diagram of hydrogen diffusion

4 Analysis of the Influence of Ventilation Volume on Hydrogen Diffusion

When mechanical exhaust is used in the garage design, the ventilation volume known as the exhaust volume is usually measured by the number of air changes per hour(ACH). This indicator emphasizes the number of air changes in confined spaces and it is not affected by the size and structural characteristics of the garage. Therefore, it is applicable to confined spaces of any volume and can provide guidance for ventilation design of various types of garages.

According to building design requirements[14], the minimum standard for the value of garage ACH is no less than 6. Therefore, in order to investigate the effect of garage ventilation on hydrogen leakage and diffusion, this paper sets ACH values of 6, 8, 10, and 12 to study the impact of different sizes of ventilation on hydrogen diffusion and accumulation.

4.1 Analysis of the Accumulation Area of Combustible Hydrogen on the Top of the Garage

Hydrogen overflows from the vehicle chassis and spreads upwards to the garage ceiling, forming an accumulation cloud. When the hydrogen concentration exceeds 4%, the accumulation cloud will develop into a combustible hydrogen gas cloud. If ignited, it will have a destructive accident impact on the entire garage. The variation curve of the accumulation area of combustible hydrogen gas clouds at the top of the garage is shown in Figure 6. From the curve in the figure, it can be seen that combustible gas clouds begin to form at the top of the garage around 6s. As the leakage continues, hydrogen gas continuously rises to the top of the garage and mixes with the combustible hydrogen gas cloud, causing the accumulation area of combustible hydrogen to continue to increase. At the 25s, the area of the accumulated combustible hydrogen gas cloud at the top of the garage began to decrease until it stabilized. This was due to ventilation creating a vortex zone inside the garage, where the combustible hydrogen cloud was influenced by the ventilation airflow and diffused to the vortex core area, forming a stable combustible hydrogen accumulation cloud.

Comparing the effects of four different ventilation volumes on the combustible hydrogen accumulation area at the top of the garage, it was found that when the ACH = 6, the peak and stable combustible hydrogen accumulation areas were 11.2 m^2 and 5.1 m^2, respectively. Based on this value, as the ventilation volume increases, the peak combustible hydrogen area decreases by 8.1%, 27.4%, and 29.5% respectively, and the stable combustible hydrogen area decreases by 15.7%, 41.2%, and 45.1% respectively. The increase in ventilation volume has no effect on the time for hydrogen to diffuse to the top of the garage, but it will reduce the peak and stable accumulation area of combustible hydrogen at the top of the garage. Moreover, combustible hydrogen in the garage cannot be completely eliminated under any ventilation conditions. Through comparison, it was found that when the ACH sets 10, the combustible hydrogen area at the top of the garage is significantly reduced, which has a significant effect on the elimination of hydrogen gas. When the ACH continues to increase to 12, the effect of eliminating the accumulation of flammable hydrogen is similar to that of the ACH sets10, and there is no significant improvement effect.

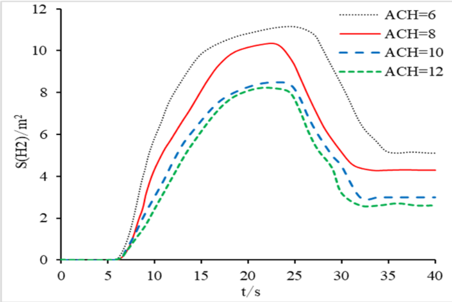

Fig. 6. Accumulation area of combustible hydrogen at the top of the garage

4.2 Comparative Analysis of Hydrogen Concentration at the Top of the Garage

Due to the characteristics of this type of garage ventilation mode, even if ventilation is maintained after the leak is over, it is still impossible to completely eliminate the combustible hydrogen inside the garage. This is because ventilation creates vortex areas of different sizes above the parking spaces on both sides of the garage, causing hydrogen gas to diffuse away from the ventilation openings and form a combustible hydrogen accumulation cloud in the vortex core area. After the stable diffusion and accumulation of hydrogen gas inside the garage at 35s, the position of the vortex area at the top of the garage and the hydrogen concentration cloud map at that location are shown in Figure 7. As shown in the figure, with the increase of ventilation volume, the vortex zone moves away from the exhaust outlet of the garage and closer to the entrance or air inlet of the garage. Hydrogen gradually surrounds the space on the side where hydrogen leakage occurs. Although the hydrogen concentration in most of the space is within 4%, the hydrogen accumulation concentration in the vortex core area exceeds the minimum explosive limit of hydrogen. After ACH exceeds 10, only the maximum hydrogen concentration in the vortex core area decreased, and the diffusion distribution characteristics of hydrogen gas remained basically unchanged.

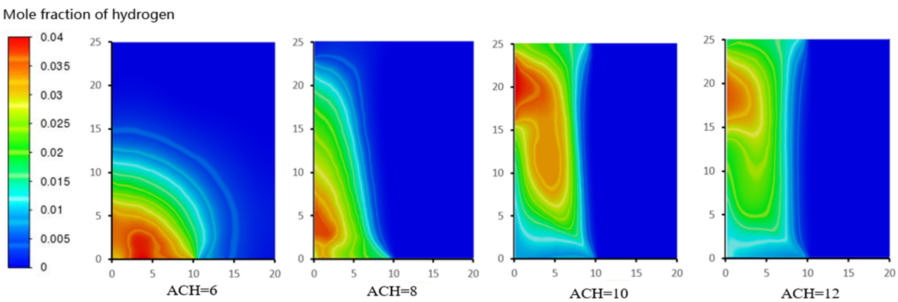

Fig. 7. Cloud map of hydrogen concentration at the top of the garage

5 Analysis of the Influence of Ventilation Area on Hydrogen Diffusion

In the design of ventilation area in a garage, it usually represents the total area of exhaust vents. Its value is usually determined based on the ventilation method of the garage. According to the requirements of building design fire protection standards[15], when the garage adopts a combination of natural air intake and mechanical exhaust ventilation mode, the exhaust vent area of any garage structure should not be less than 0.2 m^2. For the type of garage studied in this article, the ventilation area refers to the area of a single exhaust vent. Therefore, this study considers the effects of four ventilation areas on hydrogen diffusion and accumulation, with ventilation areas of 0.25m^2 (0.5m*0.5m), 1m^2 (1m*1m), 2.25m^2 (1.5m*1.5m), and 4m^2 (2m*2m).

5.1 Analysis of the Accumulation Area of Combustible Hydrogen on the Top of the Garage

The variation curve of the combustible hydrogen accumulation area at the top of the garage is shown in Figure 8. It can be seen from the figure that hydrogen gas begins to form a combustible gas cloud at the top of the garage around 6s, and the area of the combustible hydrogen gas cloud accumulated at the ceiling begins to decrease until it stabilizes at 25s. The change in ventilation area will not affect the time for combustible hydrogen to float and diffuse to the top of the garage, but it will affect the residual amount of combustible hydrogen after stable diffusion in the garage. The maximum combustible hydrogen cloud areas formed by the four ventilation areas are 12.1 m^2, 10.3 m^2, 8.1 m^2, and 6 m^2, respectively. The combustible hydrogen cloud areas after stable hydrogen diffusion inside the garage are 5.1 m^2, 4.3 m^2, 0 m^2, and 0 m^2, respectively. When the ventilation area increases to 2.25 m^2, the combustible hydrogen in the garage can be completely eliminated. Continuing to increase the ventilation area will accelerate the rate of complete hydrogen elimination.

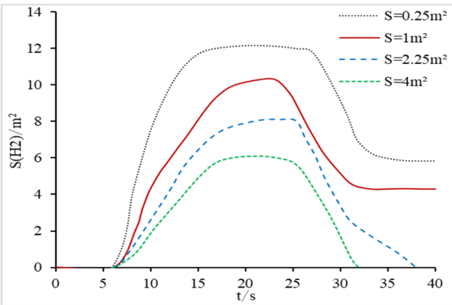

Fig. 8. Accumulation area of combustible hydrogen at the top of the garage

5.2 Comparative Analysis of Hydrogen Concentration at the Top of the Garage

Figure 9 shows the distribution cloud map of hydrogen concentration at the top of the garage at different times under four different ventilation areas. It can be seen from the figure that increasing the ventilation area is beneficial for reducing the accumulation concentration and range of hydrogen at the garage ceiling, and the core area of hydrogen accumulation always remains above the leaking vehicle, without significant displacement of the hydrogen accumulation position due to the increase in ventilation area. The increase in ventilation area will not affect the diffusion law of hydrogen, which is opposite to the law of how changes in ventilation volume affect hydrogen diffusion. In addition, the increase in ventilation area only affects the highest concentration of hydrogen accumulation in the core area. By increasing the ventilation area, the hydrogen concentration in the hydrogen vortex core area can be effectively reduced. When the ventilation area exceeds 1m2, the concentration of hydrogen diffused and stabilized inside the garage is below the minimum combustion limit of hydrogen, and there is no risk of explosion.

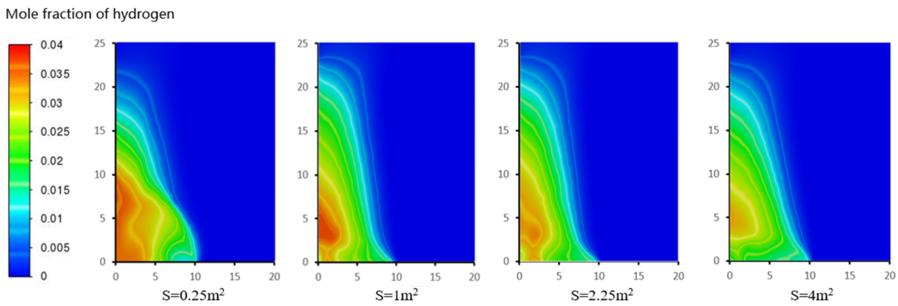

Fig. 9. Cloud map of hydrogen concentration at the top of the garage

6 Conclusion

This article uses Fluent to conduct numerical simulation research on hydrogen leakage in fuel cell vehicles in garages, and studies the effects of different ventilation volumes and ventilation areas on hydrogen concentration and diffusion distribution in garages. The following conclusions are drawn:

The diffusion process of hydrogen gas leakage can be divided into three stages: collision diffusion, upward diffusion, and accumulation diffusion. After the high-speed jet of hydrogen gas hits the ground, it quickly disperses and floats along the vehicle chassis and garage wall to the top of the garage, forming a stable accumulation cloud cluster. This process is mainly related to the characteristics of hydrogen gas, the direction of leakage, and the degree of spatial limitation.

Increasing ventilation volume can have a certain effect on eliminating hydrogen accumulation, but it cannot completely eliminate combustible hydrogen in the garage. When the ACH is set to 10, it can effectively eliminate the accumulation of flammable hydrogen in the garage. If the ventilation volume continues to increase, the effect of hydrogen elimination will no longer be significant.

The larger the ventilation area of the garage, the more significant the effect of eliminating hydrogen accumulation in the garage. When the ventilation area is set to 2.25 m^2, combustible hydrogen in the garage can be completely eliminated without increasing the ventilation volume. If the ventilation area continues to increase, only the elimination time of combustible hydrogen will be shortened.

Hydrogen leakage will accumulate at the top of the garage in the form of a vortex zone. An increase in ventilation volume will cause the vortex zone to shift away from the ventilation opening, while a change in ventilation area will not cause the vortex zone to shift. In order to maintain good ventilation in the garage, while increasing the ventilation volume, the ventilation area should be correspondingly increased to ensure the formation of through air inside the garage, suppress the formation of vortex zones, and eliminate safety hazards caused by the accumulation of flammable hydrogen.

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