

Numerical Simulation Analysis of Hydrogen Leakage and Diffusion in Tunnel

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Abstract. In order to study the actual situation of accidental hydrogen leakage of fuel cell buses in tunnels, and to provide certain safety countermeasures when hydrogen leakage occurs in tunnels, a tunnel in Nanjing was taken as the research object by using the fluid simulation software Fluent, and the influence of external factors on hydrogen leakage and diffusion was explored from the angle of leakage rate. The simulation results show that after hydrogen leaks for a period of time, the distribution of hydrogen concentration will form an obvious layered structure with the increase of time. The higher the leakage rate, the higher the rate of hydrogen concentration rise in space, and the smaller the leakage rate, the smaller the area of explosion danger in space.

Key words: hydrogen fuel cell bus; Fluent; Leakage; numerical analysis

1. Introduction

Hydrogen is a dangerous flammable gas, which is easy to cause an explosion accident. Tunnel is a common restricted space in the city. When the tunnel is congested, once the hydrogen storage system of fuel cell bus leaks, and is not found in time, it is easy to happen fire, explosion and other accidents. Therefore, it is of great significance to study the mechanism and law of leakage and diffusion of high-pressure hydrogen in confined space. In this paper, the scenario of hydrogen leakage of hydrogen fuel cell bus in the tunnel is modeled and numerically simulated, and the influence of leakage rate on the diffusion of hydrogen leakage in the tunnel is explored, so as to provide certain safety measures for the occurrence of hydrogen leakage accidents in the tunnel.

2. Pretreatment

2.1 3D modeling

In this paper, the XML6809 hydrogen fuel cell city bus [1] was selected to simulate the hydrogen leakage in a tunnel in Nanjing. See Table 1 for its specification parameters.

In this paper, the hydrogen leakage of XML6809 hydrogen fuel cell city bus [1] in a tunnel in Nanjing was selected for numerical simulation. The medium used in this simulation is compressed gaseous hydrogen, the working pressure is 35MPa, the type of hydrogen storage vessel is type III, and the hydrogen is used by the self-supply gas pipe after decompression to the fuel cell, and the nominal water volume is less than 450 L [2].

2.2 leakage model

2.2.1 Ideal gas leakage model

Assuming that the hydrogen studied in this paper is an ideal gas, according to the ratio of the internal pressure of the hydrogen storage container to the external pressure, it can be determined whether the hydrogen is in supersonic flow or subsonic flow at the leakage outlet [3]. According to the above judgment, the leakage amount of hydrogen can be calculated, and judging the leakage amount is important for evaluating the gas safety in a confined space [4].

2.2.2 Abel-Nobel gas equation of state

Generally, the ideal gas leakage equation can describe the real gas in non-extreme cases. With the deepening of the research on the leakage of high-pressure hydrogen, some scholars have pointed

out that Abel-Noble equation of state can better describe the leakage behavior of high-pressure hydrogen [5].

2.3 grid division

When the number of grids is about 500,000 after many trials, the grid quality is high and the calculation speed is fast. 3 Calculation Settings and Boundary Conditions.

3. Calculation settings and boundary conditions

3.1 Setting of calculation conditions

(1) turn on the acceleration of gravity, the solver type is pressure base, and check the transient in the Time option;

(2) Activate the energy equation and choose the Realizable $k - \epsilon$ model.

(3) Select the SIMPLE algorithm and retain the default values for other options.

(4) Initial setting, in which hydrogen with low density is set as the main phase, and at the beginning of calculation, all the hydrogen in the calculation domain, that is, the volume fraction of the main phase is 0;

(5) Analyze the process of hydrogen leakage and diffusion in 60 s, with a single time step of 0.1 s and the maximum number of iterations of 20.

3.2 Setting of boundary conditions

The ambient temperature of this simulation is 288 K; The entrance of the selected tunnel section is the speed entrance, 0 m/s; The outlet is the pressure outlet; The leakage outlet is the mass inflow port (0.1kg /s). According to equation , the temperature at the leakage outlet is 235K. Set as Wall condition, ignore the influence of material and surface roughness, adopt standard wall function.

4. Analysis of influence of leakage rate on leakage and diffusion of high-pressure hydrogen

For the high-pressure hydrogen leakage involved in this paper, circular leakage ports with diameters of 1 mm, 5 mm and 10 mm are intended to be selected. Figure 1 and 2 reflect the concentration distribution of hydrogen leaking through leakage holes with diameters of 1mm, 5mm and 10mm at different leakage times.

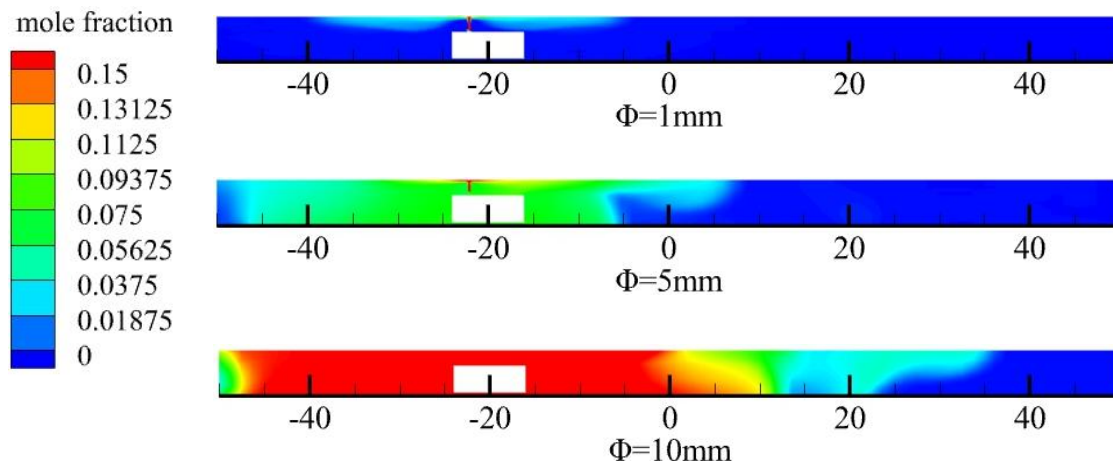


Figure 1 Contour of hydrogen mole fraction at 30 s under different leakage rate

It can be seen from the figure 1 that after the hydrogen touches the wall, the hydrogen jet can't continue to move upwards, and it begins to spread around. At this time, the concentration of

hydrogen is higher in the horizontal direction, and the higher the leakage rate, the faster the hydrogen will spread around.

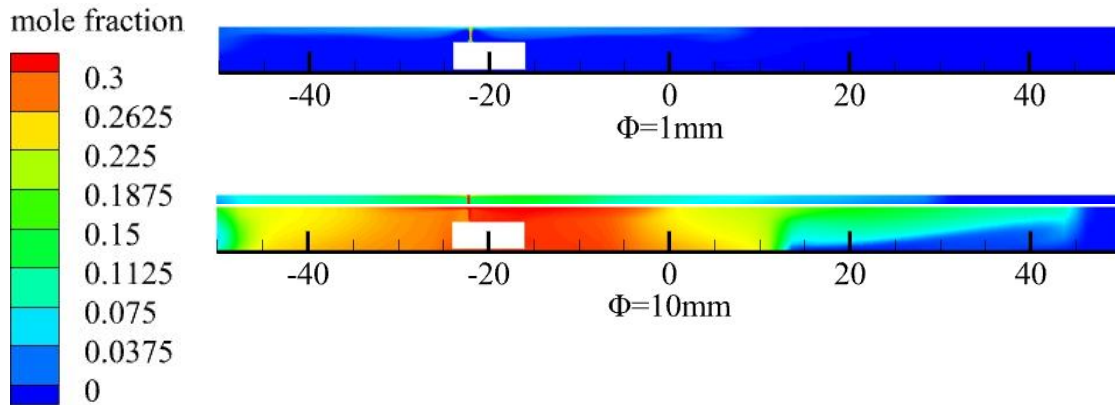
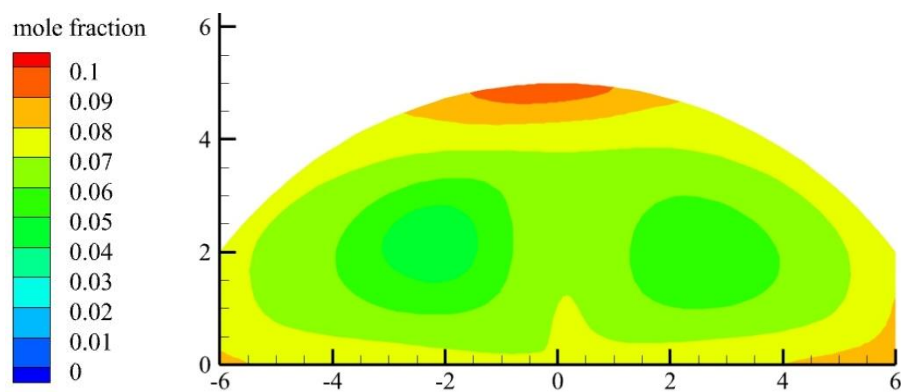


Figure 2 Contour of hydrogen mole fraction at 60 s under different leakage rate

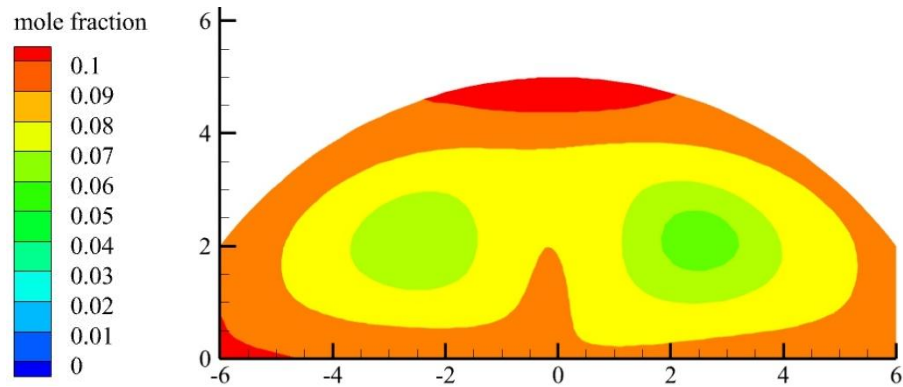
It can be seen from the figure 2 that at the same time, the larger the diameter of the leakage hole, the leakage rate will be correspondingly accelerated, and the corresponding volume of flammable hydrogen cloud will also increase. With the increase of leakage rate, the time for hydrogen to reach the explosion limit is shorter, and the diffusion range of flammable hydrogen cloud is wider.

For a period of time after the leakage accident, the distribution of hydrogen went through the following two stages: First, because the hydrogen that leaked first was pushed by the hydrogen that leaked later, it diffused in the horizontal direction; Second, the leaked hydrogen began to diffuse downward after a period of time in the horizontal direction, forming an obvious concentration stratification structure, and the concentration of the lower layer was lower than that of the upper layer. The hydrogen concentration gradient between the upper and lower walls of the tunnel increased with the increase of the leakage rate.

Figure 1-4 shows the molar concentration distribution of hydrogen leaking from two different calibers at different leakage rates at $x=-12.075$ m cross section 10 m away from the leakage outlet after 30 s.



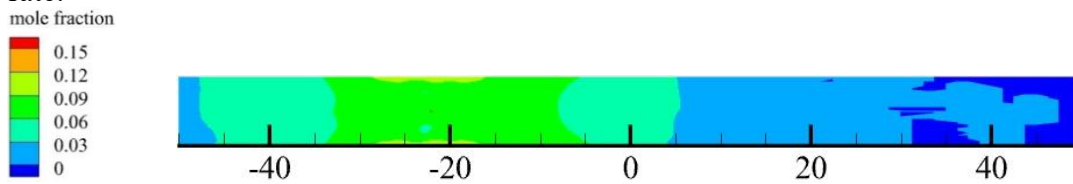
(a) Hydrogen stratification at the tunnel cross section when the leakage rate is 0.382 kg/s



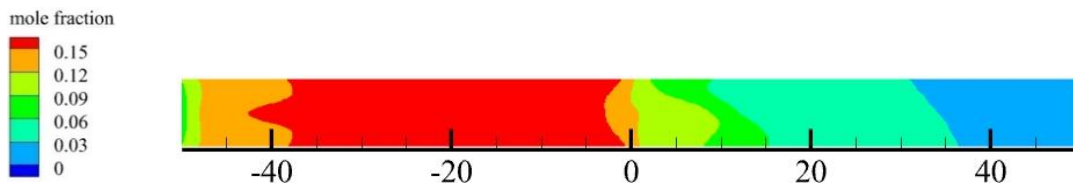
(b) Hydrogen stratification at tunnel cross section when the leakage rate is 1.528 kg/s

Figure 3 Structure of hydrogen stratification at two leakage rates

As can be seen from the figure, the concentration distribution of hydrogen at the position 10 m away from the leakage position also shows an obvious stratification phenomenon. At the top of the tunnel, there is a layer of hydrogen cloud with higher concentration, and the concentration of hydrogen cloud shows a decreasing trend from the top to the bottom. When the leakage rate is 0.382 kg/s 30 s after the leakage, hydrogen is divided into three layers at the top of the tunnel, and the molar fraction of hydrogen at the highest point is about 0.09. When the leakage rate is 1.527 kg/s, the hydrogen is divided into two layers at the top of the tunnel. The molar fraction of hydrogen at the highest point is above 0.1, and the thickness of the single layer is larger than that of the lower leakage rate.



(a) When the leakage rate is 0.382 kg/s, the hydrogen concentration distribution at the cross section of $Z = 4$ m.



(b) When the leakage rate is 1.527 kg/s, the hydrogen concentration distribution at the cross section of $Z = 4$ m.

Figure 4 Mole fraction of hydrogen at the same height under different leakage rates

It can be seen from the figure that the rate of hydrogen leakage will also affect the concentration distribution on the single-layer hydrogen cloud. That is, the higher the hydrogen leakage rate, the higher the concentration of hydrogen clouds at the same height. At the same time, it can be seen that the concentration distribution of hydrogen at the same height after leakage is quite uniform, and the molar fraction of hydrogen at the leakage outlet is relatively high. As hydrogen begins to diffuse to both sides, the molar fraction of hydrogen at both sides of the leakage area shows a decreasing trend from the leakage center to both sides.

Figure 1-5 shows the concentration change curves of hydrogen leaking at different rates at the 25 m monitoring point at the top of the tunnel. As can be seen from the figure, when the aperture of the leakage port is 1 mm, that is, when the leakage rate is 0.015 kg/s, the hydrogen concentration rises slowly and is always below the explosion limit within 60 s. When the aperture of the leakage port is 5 mm, that is, when the leakage rate is 0.382 kg/s, the hydrogen concentration reaches the explosion limit 11 s after the leakage begins. When the leakage port aperture is 10 mm, that is, when the leakage rate is 1.527 kg/s, hydrogen reaches the explosion limit 3 s after the leakage start, that is,

when the leakage hole increases from 5 mm to 10 mm, the time for hydrogen air mixture to reach the explosion limit is shortened by 3.7 times. From the point of view of subsequent development, the greater the leakage rate of hydrogen, the faster the mole fraction in the tunnel will increase.

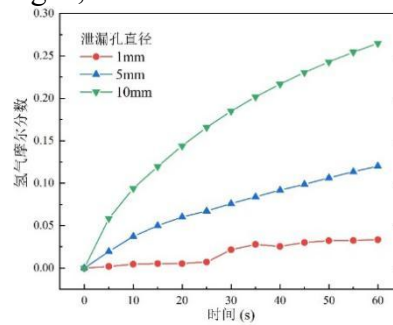


Figure 5 Curve of hydrogen concentration corresponding to different leakage rates at 25 m monitoring point

After the hydrogen leakage accident in the tunnel, with the increase of the leakage rate, the volume of the hydrogen-air combustible mixed gas cloud will be larger, and the consequences of explosion will be more serious after being ignited. If the hydrogen cloud concentration is not reduced to the lower explosive limit in time and effectively, the subsequent rescue work will also face many difficulties.

5. Emergency response of hydrogen leakage accident in tunnel

Since the tunnel is a restricted space, hydrogen is prone to gather and produce flammable gas clouds after a hydrogen leakage accident. According to the above analysis, for the emergency disposal work after a hydrogen leakage accident occurs in the tunnel, it is suggested that the leaked hydrogen will not reach the lower explosive limit in a short time under the condition that the leakage port is small. The personnel on the car can plug the leak mainly. It should be noted that the temperature of the leaking hydrogen is low, and anti-freezing measures should be taken when plugging the leak. If the leak is large, the tunnel will be filled with a lot of combustible gas in a very short time, and the evacuation should be mainly carried out at this time. In the design of fuel cell bus, attention should also be paid to the installation of hydrogen leakage alarm device, so as to facilitate the timely response of the vehicle personnel.

6. Conclusion

In this paper, a three-dimensional model of the accidental leakage accident of the hydrogen storage system of the fuel cell bus in the tunnel is established, and the influence of the leakage rate on the hydrogen leakage and diffusion in the fuel cell bus tunnel is numerically simulated by using Fluent software. The results show that after a period of leakage, hydrogen will first accumulate in the upper part of the space and diffuse horizontally, and the distribution of hydrogen concentration will form an obvious layered structure with the increase of time. The higher the leakage rate, the higher the rising rate of hydrogen concentration in the space, the larger the size of combustible gas cloud in the space, and the greater the gradient of hydrogen concentration between the upper wall and the lower wall of the tunnel. The smaller the leakage rate is, the less the area of explosion danger in the space will be, and more hydrogen will gather in the enrichment layer near the upper wall of the tunnel.

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