

Analysis of Unintended Hydrogen Releases from a Fuel Cell Tram

BIN LIU, LEI ZHANG and FENG WANG

Abstract:

Hydrogen is a promising alternative energy carrier, and its application in the industrial field, especially in the transportation sector, is increasing through fuel cells to power vehicles. Hydrogen fuel cell vehicles are typically equipped with high-pressure on-board storage tanks. Due to the low volumetric energy density of hydrogen, these tanks are relatively large to provide a comparable range to current fossil fuel vehicles. Therefore, hydrogen is also suitable for large and heavy vehicles, as they have more space than passenger cars. However, accidental hydrogen leakage from high-pressure containers can have serious consequences. Therefore, in-depth research on hydrogen safety issues is necessary to promote the popularization and commercialization of hydrogen energy. CRRC plans to use hydrogen to power urban rail transit systems to reduce the demand for urban electricity supply. This study modeled hydrogen leakage and diffusion in the scenario where the on-board storage tank of a fuel cell tram is placed inside the carriage, including both stationary and moving scenarios. The results show that upward leakage will form a flammable cloud above the tram roof, and when hydrogen diffuses inside the carriage, the hydrogen concentration in the front part of the carriage is higher than that in the rear part. Compared to the stationary situation, vehicle movement will accelerate the diffusion of hydrogen from inside to outside the carriage and significantly reduce the mass of the flammable cloud formed. Additionally, the volume of the flammable cloud will decrease as the vehicle speed increases. This work provides guidance for the placement of hydrogen storage tanks and the structural design of fuel cell trams.

Keywords: Hydrogen safety, fuel cell tram, hydrogen releases and dispersion, moving tram

1 Introduction

With the increasing maturity of hydrogen production and storage technologies, the cost of hydrogen is getting lower and lower, and hydrogen energy technology is gradually moving from the aerospace and military fields to the civilian field. Hydrogen fuel cells, with their advantages of high efficiency, no noise and zero pollution, are in line with the energy development trend. However, for a new energy system to be promoted and applied, its safety must be the first concern. The various inherent characteristics of hydrogen, such as flammability, high diffusion coefficient and low density, determine that vehicles powered by hydrogen fuel cells have different dangerous features from conventional energy vehicles, such as leakage and combustion of on-board hydrogen fuel. Therefore, it is particularly necessary to study and analyze the hydrogen safety of fuel cell vehicles.

2 Numerical Calculation Model

2.1 Control Equations

To simulate the hydrogen leakage and diffusion behavior of the hydrogen storage system when it is arranged inside a vehicle, the CFD method is used for numerical simulation. The leakage and diffusion of hydrogen in the air follow the basic control equations of fluid mechanics, including the continuity equation, momentum equation, and energy equation.

Fluid continuity equation:

$$\frac{\partial \rho}{\partial t} + \frac{\partial(\rho u)}{\partial x} + \frac{\partial(\rho v)}{\partial y} + \frac{\partial(\rho w)}{\partial z} = 0 \quad (1)$$

Here, ρ represents density, t stands for time, and u , v , and w are the components of the velocity vector in the x , y , and z directions, respectively.

Momentum equation:

$$\begin{aligned} \frac{\partial(\rho u)}{\partial t} + \nabla \cdot (uu) &= -\frac{\partial p}{\partial x} + \frac{\partial \tau_{xx}}{\partial x} + \frac{\partial \tau_{yx}}{\partial y} + \frac{\partial \tau_{zx}}{\partial z} + F_x \\ \frac{\partial(\rho v)}{\partial t} + \nabla \cdot (vu) &= -\frac{\partial p}{\partial y} + \frac{\partial \tau_{xy}}{\partial x} + \frac{\partial \tau_{yy}}{\partial y} + \frac{\partial \tau_{zy}}{\partial z} + F_y \\ \frac{\partial(\rho w)}{\partial t} + \nabla \cdot (wu) &= -\frac{\partial p}{\partial z} + \frac{\partial \tau_{xz}}{\partial x} + \frac{\partial \tau_{yz}}{\partial y} + \frac{\partial \tau_{zz}}{\partial z} + F_z \end{aligned} \quad (2)$$

Here, p represents pressure, τ represents viscous stress, F represents body force, and u represents velocity vector.

Energy equation:

$$\frac{\partial(\rho T)}{\partial t} + \nabla \cdot (\rho u T) = \frac{\partial}{\partial x} \left(\frac{k}{c_p} \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y} \left(\frac{k}{c_p} \frac{\partial T}{\partial y} \right) + \frac{\partial}{\partial z} \left(\frac{k}{c_p} \frac{\partial T}{\partial z} \right) + \Phi + S_h \quad (3)$$

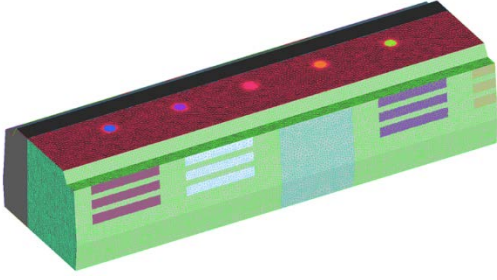


Figure 1. Grid of the carriage wall surface and doors and windows



Figure 2. Cross-sectional mesh at the leakage port

Among them, c_p represents the specific heat at constant pressure, T is the temperature, k is the thermal conductivity, Φ is the dissipation function, and Sh is the internal heat source in the fluid.

During the diffusion process of hydrogen, there exists a multi-component transport problem of air and hydrogen in the fluid domain. Therefore, the component transport equation is required:

$$\frac{\partial(\rho c_s)}{\partial t} + \nabla \cdot (\rho c_s \mathbf{u}) = \frac{\partial}{\partial x} \left(D_s \frac{\partial(\rho c_s)}{\partial x} \right) + \frac{\partial}{\partial y} \left(D_s \frac{\partial(\rho c_s)}{\partial y} \right) + \frac{\partial}{\partial z} \left(D_s \frac{\partial(\rho c_s)}{\partial z} \right) \quad (4)$$

Here, c_s represents the volume fraction of component s , and D_s is the diffusion coefficient of component s .

2.2 Computational Model

The interior model of the carriage is meshed with unstructured grids, with a total of 1.25 million grid cells, as shown in Figure 1.

This grid adopts the grid generation method of inserting hexa-core in unstructured grids, generating several layers of tetrahedral grids near the boundaries of the geometric structure, and hexahedral grids inside. This method can effectively reduce the number of grids, but the growth rate of the grids near the wall is difficult to adjust. If the growth rate of the grids at the leakage port is too large, it will cause the calculation to diverge. Therefore, a separate body is divided at the leakage port for grid refinement. The grid of the cross-section at the leakage port is shown in Figure 2.

3 Analysis Results

3.1 When the vehicle is stationary

When the vehicle is stationary, 100% leakage refers to the complete rupture of the hydrogen transmission pipeline within the hydrogen storage system. When the hydrogen storage system in a stationary vehicle leaks upwards, the hydrogen jet develops inside the vehicle under the combined effect of the initial velocity, buoyancy, and the fan. Constrained by the vehicle walls, hydrogen accumulates inside the vehicle under this condition, thereby affecting the people and equipment inside. After hydrogen leaks inside the vehicle, due to the pressure difference between the inside and outside,

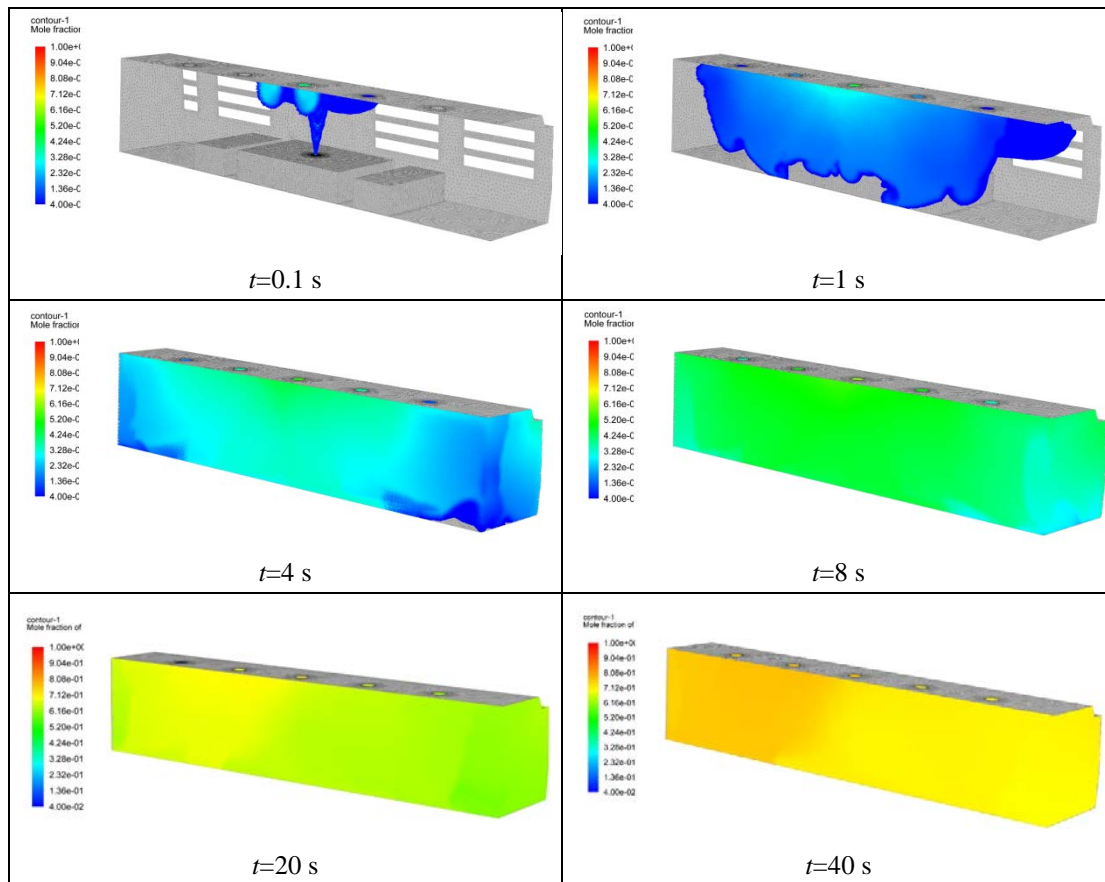


Figure 3. The range of hydrogen mole concentration greater than 4% at different moments when the stationary vehicle leaks upward by 100%

the leaked hydrogen diffuses outside through the windows and the fan opening on the roof, which may affect people and equipment outside the vehicle.

3.1.1 In-vehicle Hydrogen Leakage and Diffusion

When the hydrogen storage system leaks upwards, the hydrogen diffusion process inside the vehicle is shown in Figure 3. After the hydrogen is ejected from the leakage point, it impacts the top wall of the vehicle compartment. The top of the vehicle compartment is equipped with fan openings. However, the leakage rate of hydrogen is greater than the rate at which hydrogen is expelled from the vehicle. Therefore, under the combined effect of momentum and buoyancy, hydrogen accumulates inside the vehicle. As the leakage continues, hydrogen gradually diffuses to all areas of the vehicle compartment, and the concentration distribution tends to be uniform.

3.1.2 Calculation of the External Flow Field

When the intercity train is stationary, after hydrogen leakage occurs inside the car, due to the influence of the pressure difference between the inside and outside, the leaked hydrogen inside the car diffuses outward through the windows and the fan outlets on the roof, eventually forming a stable combustible area as shown in Figure 4. When the

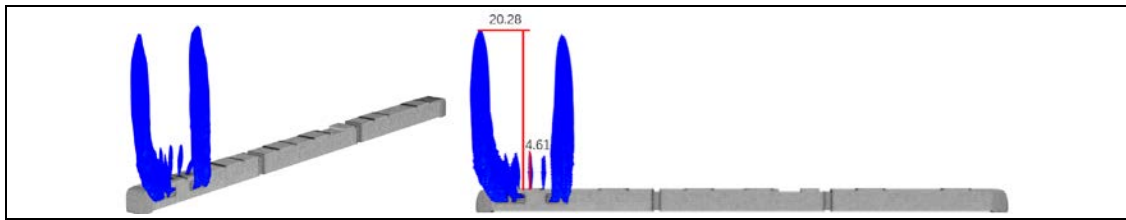


Figure 4. The range where the mole concentration of hydrogen leaked from a stationary vehicle exceeds 4% outside the vehicle at 100% upward leakage.

vehicle is stationary, the height of the combustible area formed at the fan outlets outside the vehicle is up to 4.61 m; the height of the combustible area formed at the windows is up to 20.28 m, and the final stable combustible area formed outside the vehicle has a volume of 194.51 m³.

3.2 Vehicle running at 140 km/h speed

When the hydrogen storage system in a moving vehicle leaks upwards, hydrogen will accumulate inside the vehicle, thereby affecting the people and equipment inside. After hydrogen leaks inside the vehicle, due to the influence of the pressure difference between the inside and outside, the leaked hydrogen inside the vehicle will diffuse to the outside through the windows and the fan outlets on the roof, which will affect the people and equipment outside the vehicle.

3.2.1 Initial external flow field calculation

When hydrogen leaks 100% upwards inside a moving vehicle, the diffusion process inside the vehicle is different from that when the vehicle is stationary, under the combined effect of inertial force, buoyancy and air resistance. During the vehicle's forward movement, the outlet conditions at the windows and fan outlets are calculated through iteration. When the intercity train runs at a speed of 140 km/h, the external flow field outside the windows is shown in Figure 5. The external flow field pressure at the front of the intercity train is less than that at the rear, and the pressure at the front windows is lower than that at the rear windows, with the pressure value being negative.

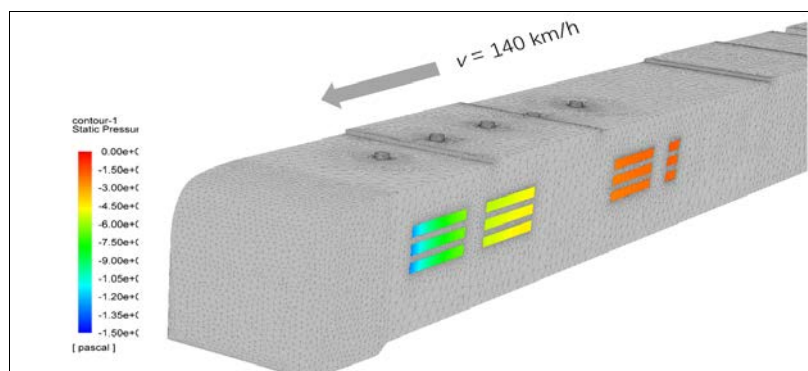


Figure 5. Pressure values on vehicle windows in the external flow field at a speed of 140 km/h

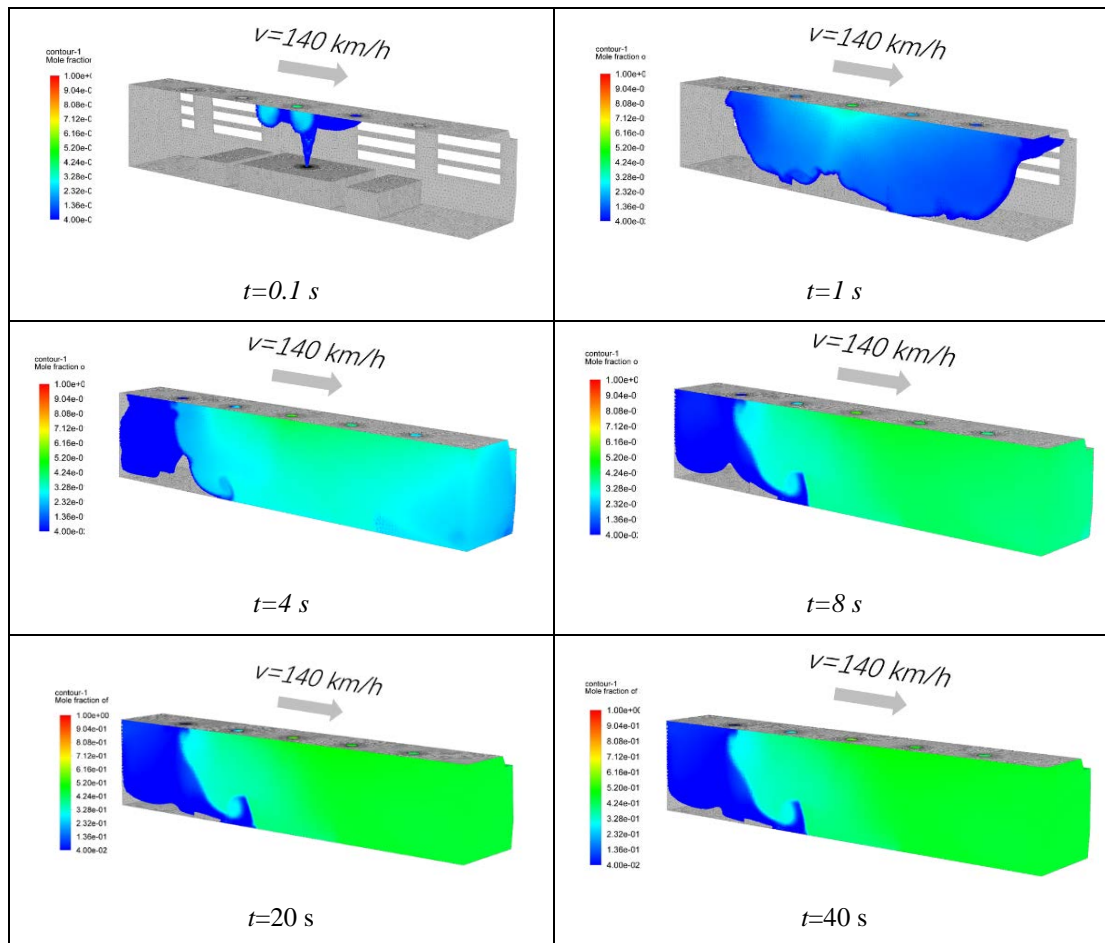


Figure 6. The range of hydrogen mole concentration greater than 4% at different moments inside the vehicle when it is running at a speed of 140 km/h with 100% upward leakage.

3.2.2 Hydrogen Leakage and Diffusion Inside the Vehicle

The hydrogen diffusion process inside the vehicle when the hydrogen storage system leaks upwards is shown in Figure 6. After hydrogen is ejected from the leakage point, it impacts the top wall of the vehicle compartment. The top of the vehicle compartment is equipped with fan openings. However, the leakage rate of hydrogen is greater than the rate at which hydrogen is expelled from the vehicle compartment. Therefore, under the combined effect of momentum and buoyancy, hydrogen accumulates inside the vehicle compartment. As the leakage continues, hydrogen gradually diffuses to all areas within the vehicle compartment. Due to the pressure value at the front window being lower than that at the rear window during the movement of the intercity train, the hydrogen concentration in the front part of the vehicle compartment is higher than that in the rear part during the hydrogen diffusion process inside the vehicle.

4 Conclusion

For hydrogen fuel cell rail vehicles, the computational fluid dynamics method was employed to study the diffusion and accumulation of hydrogen after an unexpected leakage in the on-board fuel cell system, and to conduct research on the risk assessment

technology of the fuel cell system. Simulations and analyses were carried out for hydrogen leakage accidents under the scenarios of the vehicle being stationary and running at 140 km/h, with the hydrogen storage unit placed inside the vehicle. The influence of hydrogen diffusion and accumulation behavior was clarified, thereby analyzing its safety.

5 Optimization Design Suggestions

Once hydrogen leaks, it will form a certain volume of flammable cloud, posing certain risks to the interior and surroundings of the vehicle. Therefore, in subsequent designs, hydrogen sensors should be installed around the hydrogen storage unit. Once hydrogen leakage and accumulation occur, they can be detected promptly, reducing the response time and enabling timely emergency handling. Additionally, the exhaust volume of the ceiling fans in the carriages should be increased, and the ventilation area of the windows should be enlarged. After a hydrogen leakage from the hydrogen storage unit inside the carriage, hydrogen can be promptly discharged to the outside through the ceiling fans and windows, reducing the probability of hydrogen ignition inside the carriage. However, when the hydrogen storage unit is installed inside the carriage, due to the presence of numerous devices inside the vehicle, hydrogen cannot diffuse rapidly, and hydrogen leakage will accumulate inside the vehicle to form a flammable cloud, enveloping the fuel cell box, fans, and other electrical equipment inside the carriage within the flammable area, resulting in a high risk of fire and directly threatening the safety of the vehicle. Therefore, the hydrogen storage system and fuel cell system should be avoided from being installed in the passenger compartment, luggage compartment, or other poorly ventilated enclosed or semi-enclosed spaces.

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