energies

Review

Review on the Hydrogen Dispersion and the Burning Behavior of Fuel Cell Electric Vehicles

Hao Lan [1,*], Guiyun Wang [2], Kun Zhao [3], Yuntang He [1] and Tianlei Zheng [1,*]

[1] China Automotive Technology & Research Center Co., Ltd., Tianjin 300300, China
[2] Automotive Data of China Co., Ltd., Beijing 100000, China
[3] CATARC New Energy Vehicle Test Center (Tianjin) Co., Ltd., Tianjin 300300, China
* Correspondence: lanhao@catarc.ac.cn (H.L.); zhengtianlei@catarc.ac.cn (T.Z.); Tel.: +86-022-84379251 (H.L.)

Abstract: The development of a hydrogen energy-based society is becoming the solution for more and more countries. Fuel cell electric vehicles are the best carriers for developing a hydrogen energy-based society. The current research on hydrogen leakage and the diffusion of fuel cell electric vehicles has been sufficient. However, the study of hydrogen safety has not reduced the safety concerns for society and government management departments, concerning the large-scale promotion of fuel cell electric vehicles. Hydrogen safety is both a technical and psychological issue. This paper aims to provide a comprehensive overview of fuel cell electric vehicles' hydrogen dispersion and the burning behavior and introduce the relevant work of international standardization and global technical regulations. The CFD simulations in tunnels, underground car parks, and multistory car parks show that the hydrogen escape performance is excellent. At the same time, the research verifies that the flow, the direction of leakage, and the vehicle itself are the most critical factors affecting hydrogen distribution. The impact of the leakage location and leakage pore size is much smaller. The relevant studies also show that the risk is still controllable even if the hydrogen leakage rate is increased ten times the limit of GTR 13 to 1000 NL/min and then ignited. Multi-vehicle combustion tests of fuel cell electric vehicles showed that adjacent vehicles were not ignited by the hydrogen. This shows that as long as the appropriate measures are taken, the risk of a hydrogen leak or the combustion of fuel cell electric vehicles is controllable. The introduction of relevant standards and regulations also indirectly proves this point. This paper will provide product design guidelines for R&D personnel, offer the latest knowledge and guidance to the regulatory agencies, and increase the public's acceptance of fuel cell electric vehicles.

Keywords: fuel cell electric vehicle; hydrogen safety; hydrogen dispersion; hydrogen burn; standardization

Citation: Lan, H.; Wang, G.; Zhao, K.; He, Y.; Zheng, T. Review on the Hydrogen Dispersion and the Burning Behavior of Fuel Cell Electric Vehicles. *Energies* **2022**, *15*, 7295. https://doi.org/10.3390/en15197295

Academic Editor: Daniel T. Hallinan Jr.

Received: 6 September 2022
Accepted: 29 September 2022
Published: 4 October 2022

1. Introduction

It is well known that the use of fossil fuels causes energy consumption and environmental pollution on a global scale, so renewable and clean energy sources have also become a research hotspot [1]. The development of hydrogen energy is one of the technical solutions, and the ultimate goal is to achieve a zero-emission hydrogen energy-based society. The European Union, Japan, China, and South Korea have released hydrogen energy development roadmaps [2–5]. The main uses of hydrogen (pure or mixed hydrogen) at present, include refining (33%), ammonia production (27%), methanol production (11%), and steel production through the direct reduction of iron ore (3%). Now, 76% of the hydrogen consumed is produced by natural gas, and 23% is coal [6]. This shows that hydrogen has been widely used in industrial production; correspondingly, its physical properties and safety have also been thoroughly researched. Current research on hydrogen safety covers hydrogen characteristics [7,8], diffusion mechanisms [9–19], burning behaviors [7,13], and explosions [20]. Review articles have systematically summarized this research [21,22].

The best solution for building and developing a hydrogen energy-based society is to promote fuel cell electric vehicles. However, the current research on hydrogen safety has not been able to reduce the social and government management's safety concerns when fuel cell electric vehicles are promoted on a large scale. Hydrogen safety is both a technical and psychological issue [23]. There has been much research on fuel cell electric vehicles, and in-depth research has been conducted on the characteristics of hydrogen diffusion and the burning behavior of vehicles. This paper aims to provide a comprehensive overview of the fuel cell electric vehicles' hydrogen dispersion and burning behaviors and introduce the relevant work of international standardization and global technical regulations. It will also provide the latest knowledge and guidance for regulators and public officials and improve the public's acceptance of fuel cell electric vehicles.

This paper first introduces the concept and the evaluation model of the hydrogen safety of fuel cell electric vehicles. Then, it introduces and summarizes the research status of the fuel cell electric vehicles' hydrogen leakage, and the hydrogen burning behaviors and discusses the following research approach. Finally, it introduces the standards and regulations of fuel cell electric vehicles.

2. Hydrogen Safety Concept for Fuel Cell Electric Vehicles

Prior to discussing the safety of fuel cell electric vehicles, we need to distinguish three concepts: hazard, risk, and safety. A hazard is "a chemical or physical condition that may cause harm to people, property, and the environment"; risk is "a combination of the likelihood and the consequences that occur at a certain time"; safety is "the freedom from a risk that is not tolerable" [24].

Safety cannot be quantified, while risk can be qualified. Based on this, society can specify an acceptable level of risk. Therefore, the discussion of safety includes a risk analysis and an acceptance of risk. This means that safety is an abstract concept that cannot be separated from a risk analysis and an acceptance analysis. We aim to provide regulators and public officials with the latest knowledge and guidance and to increase public acceptance of fuel cell electric vehicles.

3. Hydrogen Leakage of Fuel Cell Electric Vehicles

This chapter will discuss the typical research results of hydrogen leakage in fuel cell electric vehicles, with the data obtained from simulations to actual vehicular research. In terms of the CFD simulations, Japan verified scenarios in tunnels, underground parking lots, and multistory parking lots, proving that hydrogen's excellent escape performance is excellent. A series of studies have proven that the flow and leak directions are the most critical factors affecting hydrogen distribution. The impact of the leakage location and the leakage pore size is much smaller. In order to verify the effect of obstacles on hydrogen diffusion, the United States conducted a hydrogen diffusion comparison test with or without vehicles in parking garages. For the parking garages, the obstacle is the vehicle itself. The results showed that although hydrogen has an excellent escape capability, obstacles still greatly influence the spatial distribution of hydrogen. As for the distribution of hydrogen in vehicles after a leak, Japanese research has shown that the impact of the leak direction is crucial. This has significant reference value for developing hydrogen leakage safety in fuel cell electric vehicles. I will cover the mentioned content in more detail.

3.1. Research Progress

It is of great significance to study the influence of different factors on the diffusion of hydrogen leakage in fuel cell electric vehicles in storage and application scenarios. There are relatively mature studies on the diffusion of hydrogen on a small scale, and the Reynolds number is a primary parameter at the microscopic scale. In fluid mechanics, the Reynolds number is the ratio of the inertial force of a fluid to the viscous force, and it is a dimensionless quantity. Inertial force and viscous force are calculated according to

Formulas (1) and (2). When the Reynolds number is small, the influence of the viscous force convection field is greater than that of the inertial force. The viscous force attenuates the flow rate's disturbance in the flow field, and the fluid flow is stable and laminar. Conversely, if the Reynolds number is large and the inertial force's influence on the flow field is greater than the viscous force, the fluid flow is more unstable. Small changes in the flow rate will develop a disordered and irregular turbulent flow field.

$$\text{inertial force} = \frac{\rho v}{L} \tag{1}$$

$$\text{viscous force} = \frac{\mu v}{L^2} \tag{2}$$

where ρ is the density of the fluid, kg/m^3; V is the flow speed, m/s; L is a characteristic linear dimension, m; μ is the dynamic viscosity of the fluid, kg/(m·s); and v is the kinematic viscosity of the fluid, m^2/s.

France's CEA (Atomic Energy and Alternative Energy Commission) analyzed the effects of hydrogen buoyancy and small leaks on the hydrogen diffusion in small flows [9]. The experimental results showed that the spatial and temporal variations in the volume fraction are entirely consistent with Worster and Huppert's theoretical rate [25], which proves that the study of hydrogen diffusion at the microscopic level is relatively mature.

However, a large flow leak is more dangerous. JARI (Japan Automotive Research Institute) conducted CFD (computational fluid dynamics) simulations of hydrogen leaks in tunnels, underground parking lots, and multistory parking lots [26]. The amount of leakage was 133 L/min. The simulation tests proved that the hydrogen escape performance is excellent. It was found that, even in the absence of gas exchange, the hydrogen concentration will exceed the limit only in the location of the gas leak. In a tunnel, the hydrogen concentration on top of the tunnel will be below the explosive limit after the hydrogen leaks. In an underground parking lot, if there is no ventilation device, the hydrogen concentration above the leak point will exceed the explosive limit. If there is a ventilation device, the hydrogen concentration can be reduced below the explosive limit. In a multistory parking lot scenario, the hydrogen concentration can also be controlled below the explosive limit because there is a ventilation device. The CFD simulations initially proved that hydrogen has a perfect escape performance.

In order to further verify the diffusion characteristics of hydrogen and the influencing factors, a test verification is required. The University of Orléans in France assessed the leak location (top, upside, lateral down) in an equivalence miniature scenario of 1/15 (0.47 m× 0.33 m × 0.20 m), with a leakage flow (5.4 Nm^3 h^{-1}, 1.8 Nm^{3}h^{-1}, 0. 1 Nm^3 h^{-1}), and a combination of obstacles [11]. The axis direction is shown in Figure 1.

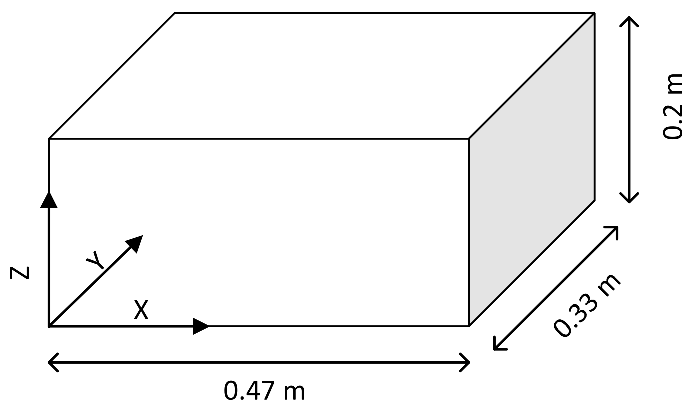

Figure 1. Experimental enclosure scheme of The University of Orléans.

The research parameter combination is shown in Table 1.

Table 1. Examples of hydrogen diffusion tests in confined spaces.

Release Traffic	**Case 1**			**Case 2**			**Case 3**		
Release Position	**Top**	**Upside**	**Lateral Down**	**Top**	**Upside**	**Lateral Down**	**Top**	**Upside**	**Lateral Down**
X-axis direction (m)	0.17	0	0	0.17	0	0	0.17	0	0
Y-axis direction (m)	0.165	0.165	0.165	0.165	0.165	0.165	0.165	0.165	0.165
Z-axis direction (m)	0.2	0.13	0.01	0.2	0.13	0.01	0.2	0.13	0.01
Release direction	−z	x	x	−z	x	x	−z	x	x
Flow rate ($Nm^3 h^{-1}$)	5.4			1.8			0.1		
Duration (s)	1			3			46		
Re	4500			1500			83		
Ri	1.27×10^{-6}			1.14×10^{-5}			3.70×10^{-3}		
l_s (m)	2.41			0.8			0.045		

The experimental results showed that the flow rate has the most significant influence on the hydrogen diffusion. When the Reynolds number is large, the momentum of the hydrogen occupies the dominant position. The layer thickness formed at the top is narrower than that when the Reynolds number is small. This is because the buoyancy is dominant when the Reynolds number is small. However, no matter how large the flow rate, as long as the amount of hydrogen injected is fixed, the concentration of the hydrogen in the enclosed space will be consistent. The effect of the position on the maximum hydrogen concentration, the mixing time, and the curve of the increase in the hydrogen concentration within 20 s is not apparent. However, it can be seen that the difference caused by the position, decreases as the flow increases. The influence of the obstacles on the diffusion of hydrogen has two aspects. On the one hand, the obstacle increases the hydrogen concentration gradient. On the other hand, the mixing time becomes longer, almost twice the original amount of time.

To assess the effect of the jet diameter on the diffusion of hydrogen, France's CEA (Atomic Energy and Alternative Energy Commission) studied the effect of the hydrogen volume (test 1 and test 2) and the injection port caliber (test 3 and test 4) [27] on the hydrogen concentration distribution. In order to evaluate the diffusion of the hydrogen concentration, a confined space was constructed with 30 sensor matrices; the experimental enclosure scheme is shown in Figure 2.

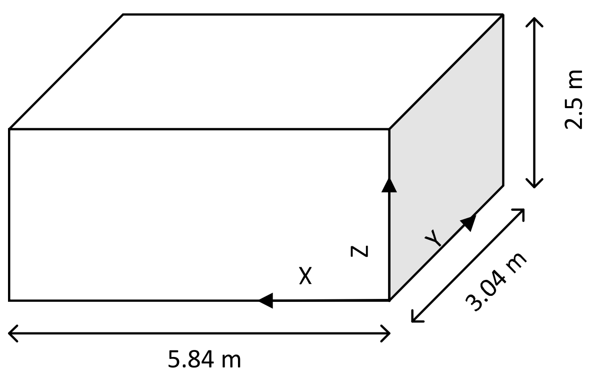

Figure 2. Experimental enclosure scheme of France's CEA.

The research parameter combinations are shown in Table 2.

Table 2. Effects of the different injection conditions on the hydrogen diffusion.

Subprojects	Test 1	Test 2	Test 3	Test 4
Volumetric flow rate (NL/min)	668	668	18	18
Mass flow rate (g/s)	1.99	1.99	0.05	0.05
x-axis direction (m)	2.88	2.88	2.88	2.88
y-axis direction (m)	1.48	1.48	1.48	1.48
z-axis direction (m)	0.22	0.22	0.22	0.22
Diameter (mm)	20.7	20.7	5	29.7
Garage temperature (°C)	20	20	20	20
Release speed (m/s)	35.5	35.5	16.4	0.5
Release direction	Vertically upwards	Vertically upwards	Vertically upwards	Vertically upwards
Release type	Uninterrupted release	Uninterrupted release	Uninterrupted release	Uninterrupted release
Release time (s)	121	500	3740	3740
Release hydrogen volume (Nm^3)	1.35	5.57	1.12	1.12
Release hydrogen mass (g)	240	994	200	200
Target concentration (%)	3.53%	14.6%	2.94%	2.94%
R_{e0} (20 °C)	6150	6150	686	115
R_{i0} (20 °C)	9.9×10^{-4}	9.9×10^{-4}	1.1×10^{-3}	8.3

The test results of test 1 and test 2 showed that, under the same conditions, the different leakage amounts will also affect the hydrogen diffusion. The leak time of test 2 was 500 s, while the leak time of test 1 was 121 s, but the hydrogen concentration of test 2 was not four times that of test 1, but only by about twice that. Over time, the hydrogen concentration in the top region gradually decreases, and the hydrogen concentration in the bottom area gradually increases. This will form a state of uniform mixing. It can be seen that the hydrogen layer formed in test 2 was thicker than that in test 1. Tests 3 and 4 compared the effects of the different leakage diameters on the hydrogen diffusion at the same flow rate, i.e., the impact of the different Reynolds numbers. The experimental results showed that the leakage diameter has little effect on the hydrogen diffusion.

France’s INES (National Institute of Industrial Environment and Risk) conducted a diffusion test, and the parameters included the flow rate and leakage diameter. The highlight of the test was designing a device that can accurately control the hydrogen flow. Using sensors, video, and other methods to trace the trajectory of hydrogen and helium, we can better understand the stratification of hydrogen in the air [28]. To further explore the influence of the pressure and air exchange law on the hydrogen leakage law, in Norway, a large-scale hydrogen leakage under different pressures, flow rates, leakage diameters, and ACHs (air exchange laws) was tested [29]. The combined parameters are shown in Table 3. The results of the study are consistent with those mentioned above, but more systematic.

Table 3. Hydrogen diffusion test parameter settings.

Serial Number	Nozzle Diameter (mm)	ACH Setpoint (1/h)	Outlet Pressure (bar)	Mass Flow (g/s)	Release Time (s)	Outlet Temperature (°C).
1	0.5	10	120	1.1	30	−1
2	0.5	10	120	0.8	60	−1
3	0.5	10	160	1.1	60	−1
4	0.5	6	160	1.0	60	−3
5	0.5	6	120	0.7	60	−3

6	0.5	6	60	0.4	60	−3
7	1.0	6	160	6.0	60	−3
8	1.0	10	160	6.0	60	−3
9	1.0	10	120	5.2	60	−3
10	1.0	10	120	4.2	60	−3
11	1.0	6	120	4.2	60	−1
12	1.0	6	60	2.2	60	−1
13	1.0	10	60	2.2	60	−1
14	1.0	10	140	5.3	1000	−1
15	0.5	10	700	7.9	1000	−5
16	0.5	6	700	7.8	1000	−3
17	0.5	6	360	4.2	1000	−4
18	0.5	6	207	2.5	1000	−2
19	0.5	10	360	4.2	1000	−3

The United States' NIST (National Institute of Standards and Technology) built a physical garage and conducted hydrogen aggregation tests. The test results showed that the hydrogen accumulation curve differs depending on whether the car is in the garage or not [13]. At the same time, the experiment showed a severe hazard at a concentration of 16% hydrogen, which was different from the results of a Japanese study [30]. In the garage without a car, using the sensor at 2.6 m as a benchmark, the test results showed that the hydrogen concentration sensor at the highest place detected hydrogen first each time. Then, the hydrogen concentration sensor in the lower place detected hydrogen. In contrast, over time, the rate of accumulation of the hydrogen concentration at the top gradually slowed down, compared to the concentration of hydrogen in lower places. In the garage with a car, the diffusion of hydrogen was different from the case without a car. The hydrogen concentration in the passenger compartment was lower than in other parts. The hydrogen concentration near the hood also increased rapidly, while the hydrogen concentration in other places was more uniform than when there was no car. In 2007, JARI conducted a real-vehicle hydrogen leakage test. The leakage location was below the front wheel axle, the middle position of the vehicle, and the bottom of the rear wheel axle. There were five measurement points in the engine compartment. The variables included the leakage flow, direction, location, and effect of the underbody skid plate on the hydrogen diffusion [30]. The results showed that the diffusion of hydrogen for the whole vehicle was in line with the above conclusions on the diffusion of hydrogen, in addition to the mentioned leakage flow, the leakage location, and the impact of the obstacles on the hydrogen diffusion in the vehicle test. It was found that the leakage direction had a significant effect on the accumulation of hydrogen in the engine compartment. The concentration of hydrogen after the downward hydrogen leakage was significantly lower than that in the upward direction. The main reason is that part of the gas escapes from the bottom of the car when the leakage direction is downward.

3.2. The Following Research Approach

Much of the research is focused on fuel cell electric vehicles' hydrogen leakage and diffusion. The influencing factors include the pressure, flow rate, leakage diameter, ACH, and obstacles, which have essential reference values for guiding product design. The following research approach should connect hydrogen leakage with specific scenarios, such as driving in a tunnel and ship transportation. However, the current research only focuses on the passenger car scenario. Commercial vehicles are the more common application scenarios for fuel cell electric vehicles. The amount of hydrogen carried and the layout of the onboard hydrogen storage system, are different for commercial vehicles, so conducting the relevant research on hydrogen leakage in the application scenarios for fuel cell electric vehicles will be necessary.

Another commonly used risk analysis model is the sequence diagram, which contains the accident source, the probability of the accident occurring, and the consequences after the accident [31], which align with the safety concept introduced in Chapter 2. Many researchers have adopted ESD (enhanced sequence diagram) models [32,33]. In the application of ESD models for the safety assessment, it is challenging to assess the possibility of an accident and the consequences after the accident. Many analyses using ESD models are unconvincing due to the lack of complete and accurate data. Therefore, the next step is to sort out the leakage scenario, the probability, and the consequence analysis of the fuel cell electric vehicles, and improve the database.

4. Burning Behavior of Fuel Cell Electric Vehicles

This chapter will discuss the typical research results on the hydrogen-burning behavior of fuel cell electric vehicles, by looking at the simulation research and the actual vehicular research. Normally, we think of the flammability limit of hydrogen as 4%, but in actual tests, it usually takes 8% to ignite. According to the GTR 13, the leakage rate of hydrogen after a collision cannot exceed 131 NL/min. Studies in Japan have shown that the risk of hydrogen being ignited at this leakage rate is low. In order to explore the safe boundaries of hydrogen leakage, Japan has further increased the hydrogen leakage rate by ten times, to 1000 NL/min, and then ignited it. The results show that the risk is still controllable. The hydrogen leakage rate was increased to 2000NL/min before an unacceptable hazard occurred, but the risk remained controllable if combined with a forced exhaust. At the same time, Japan conducted three fuel cell electric vehicle combustion test, and the results showed that the car was not ignited by hydrogen. I will cover the mentioned content in more detail.

4.1. Research Progress

The NIST research showed that although the accepted flammable limit for hydrogen concentrations is 4%, hydrogen was not ignited at 4% in the test but at 8% [13]. In 2001, Swain studied the burning behavior of hydrogen and gasoline. As a result, gasoline vehicles were severely damaged, while fuel cell vehicles were not damaged, and the maximum surface temperature (rear window position) of the fuel cell vehicles was 117° F (47.2 °C) [34]. The disadvantage of this research is that the ignition position of the hydrogen was above the vehicle. However, the gas cylinder installation position of the actual vehicle is under the vehicle.

In 2006, JARI's study compensated for the shortcomings of the Swain study by using hydrogen and methane for testing. The study showed that there was minimal harm with a leakage rate of 131 NL/min. The plastic parts in the front hatch did not melt, and the paper tissue in the front air grid did not burn [35]. JARI's research still has two deficiencies: first, it did not use a higher hydrogen flow rate for testing, that is, to study the upper limit of safety; second, an actual vehicle test was not used. This means that the TPRD was invalidated.

In 2007, JARI's research compensated for the first deficiency, by placing the ignition location in the middle of the vehicle chassis and the hydrogen leakage rates at 200 NL/min, 400 NL/min, 600 NL/min, and 1000 NL/min. The leakage duration was 600 s [30]. Ignition at 1000 NL/min caused the deformation of the front cover, resulting in a shape variable of up to 25 mm. A 15 kPa shock wave was observed on the side of the vehicle, with 1.1 kPa on the vehicle's front end. According to the research, 41 kPa will damage the eardrum, and 35kPa will cause a nose bleed. The sound intensity in this test exceeded 130 db at 1 m and 129.2 db at 5 m. The sound intensity of 130 db can cause discomfort, and 150 db can damage the eardrum. The temperature at the measuring point did not exceed 300 °C at a maximum. According to Eisenberg's study, people can feel the heat when a heat flow value of 14.2 kW/m^2 lasts more than 18 s [36]. However, the heat flow value in this test peaked at 14.2 kW/ m^2, and the duration was only 0.5 s.

In 2011, JARI's research made up for the second deficiency. A fuel cell electric vehicle and a gasoline vehicle were placed together, and the fuel cell vehicle was ignited. Then, multiple fuel cell vehicles were placed together, and one of them was ignited [37], as shown in Figures 3 and 4.

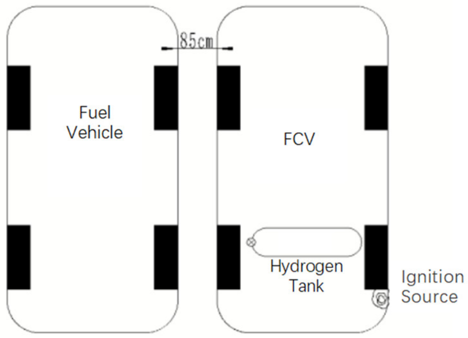

Figure 3. Fuel vehicle and hydrogen fuel cell vehicle stored side by side in a fire simulation.

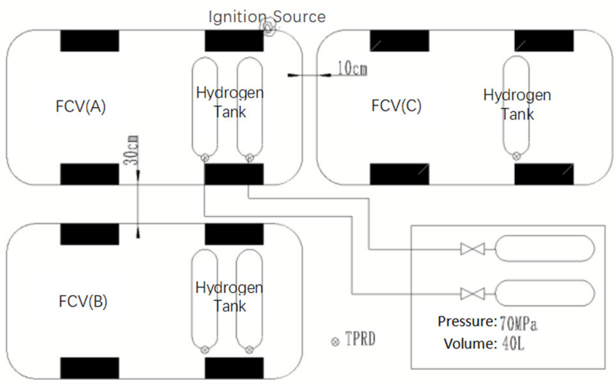

Figure 4. Multiple hydrogen fuel cell vehicles stored together in a centralized fire simulation test.

In the first case, the TPRD was placed downward. Once the flame activated the TPRD, the hydrogen gas was released, but at this time, it did not ignite the gasoline car next to it. The gasoline car was ignited nearly half an hour after the TPRD was activated. However, it was not ignited by the hydrogen, although the interior parts in the fuel cell vehicle were ignited. In the second case, the TPRD was 45 °C facing down, and eventually, all three vehicles' TPRDs were activated (except for the front TPRD of vehicle C). Therefore, in the transport scenario, the TPRD early detection before activation is essential. In the same study, the FCV-A's adjacent vehicle, FCV-B, caught fire first, and then FCV-C caught fire. This phenomenon was confirmed by the CFD Simulation Institute of Tongji University, and the vehicles parallel to the accident vehicle are more dangerous [38].

In 2014, JARI's research further explored the quantitative boundaries of hydrogen safety for vehicles that have already leaked. Even if the leakage reaches 2000 NL/min, the risk of the hydrogen burning behavior can be reduced by blowing up the front or side. If a wind speed of 10 m/s or higher is used, the hydrogen concentration can be reduced below the ignition point, which can greatly slow down the power of the shock wave even if ignited [39]. The simulation study by Tsinghua University further revealed that in the process of diluting hydrogen in the fan, only the concentration of the underside of the car could not be reduced to 4%. At the same time, in order to provide passengers with a safer escape space, it is recommended to place the fan in front of the vehicle [40].The United States also studied the effect of natural and mechanical ventilation on slowing down the burning behavior in a parking garage. Hydrogen was leaked at a fixed time and rate and ignited under natural and mechanical ventilation conditions. Mechanical ventilation significantly reduced the damage [41]. The test matrix is shown in Table 4.

Table 4. Hydrogen release test in a parking garage.

Serial Number	Garage Inside	Release Speed (kg/h)	Release Hydrogen Mass (g)	Theoretical Outlet Speed	Lm (m)	Fr	Release Time (min)	Ventilation Air Volume
1	Empty	9.22	3.07	668	18.7	667	20	Natural ventilation
2	There is a car	9.04	3.01	653	18.3	648	20	Natural ventilation
3	There is a car	0.88	0.44	63	1.8	62	30	Natural ventilation
4	Empty	3.3	2.2	240	6.7	238	40	0.12
5	Empty	3.33	2.22	247	6.9	245	40	0.19
6	Empty	3.27	2.18	241	6.8	240	40	0.42
7	Empty	6.70	4.47	502	14.1	499	40	0.1
8	Empty	1.65	1.10	124	3.5	123	40	0.1
9	Empty	1.52	1.01	113	3.2	112	40	0.2
10	Empty	1.55	1.03	116	3.2	115	40	0.38
11	Empty	4.92	3.28	367	10.3	365	40	0.1
12	Empty	4.98	3.32	361	10.1	359	40	0.19
13	Empty	4.92	3.28	360	10.1	357	40	0.38

If a fuel cell electric vehicle accident occurs in a semi-enclosed space, such as in a tunnel, it is possible to cause more significant harm to the human body. So far, there are no real car tests, and simulation studies have shown that the profiles of scaled impulse profiles are below the threshold at the elevation below 2 m (possible area for human beings) as the maximum overpressure decreases along the height. Meanwhile, the scaled impulse is still lower than the curve of 99% survival probability for the area above 2 m. Whatever the pressure wave will cause lung damage, severe damage to the ear drum, although is not lethal [42].

4.2. The Following Research Approach

The research on the burning behavior of fuel cell electric vehicles has become a hotspot. The research area includes the hydrogen burning behavior in a parking lot scenario and the chain reaction of the fuel cell electric vehicle burning behavior when the TPRD fails. However, the current research focuses on the passenger car scenario. Commercial vehicles are more commonly used in scenarios of fuel cell electric vehicles. The amount of hydrogen carried and arranged in the onboard hydrogen storage system of commercial vehicles is different from that of passenger cars, so the following approach is to conduct the relevant research on the burning behavior hazards of commercial fuel cell electric vehicles.

Unfortunately, there is a lack of data on the burning behavior of commercial fuel cell electric vehicles, including the risk sources, probabilities, and consequences. Therefore, it is now necessary to further improve the database. This situation is similar to the hydrogen leakage scenario of fuel cell electric vehicles mentioned in Chapter 3.2.

5. Standard and Regulations of the Fuel Cell Electric Vehicle Safety

5.1. Research Progress

In addition to basic research and application research, governments are also actively promoting the commercialization of fuel cell electric vehicles in standards and regulations on the safety requirements in hydrogen production, hydrogen storage, and transportation [23]. Benefiting from other hydrogen applications in the industrial field, we have a relatively complete standard framework. The usual standard is ISO/TR 15916:2015-Basic considerations for the safety of hydrogen systems [43]. The standard is currently being revised, and the guidelines are provided for the use of hydrogen in gaseous and liquid forms. It identifies the fundamental safety issues, hazards, and risks and describes the safety-related properties of hydrogen. The different international standards deal with the detailed safety requirements associated with the specific hydrogen applications.

The representative regulations in the field of fuel cell electric vehicles are UN R 134, the uniform provisions concerning the approval of motor vehicles and their components about the safety-related performance of hydrogen-fueled vehicles (HFCV) [44], and the GTR 13 Global Technical Regulation concerning hydrogen and fuel cell vehicles [45]. Both were developed under the framework of the United Nations. They stipulate the safety requirements for fuel cell electric vehicles and onboard hydrogen storage systems. The representative standard is SAE J2579 (Fuel Systems in Fuel Cell and Other Hydrogen Vehicles) [46]. It regulates the design, construction, operation, and maintenance requirements for the road vehicles' hydrogen fuel storage and handling systems. This standard also defines the performance-based requirements for validating the design prototypes and producing hydrogen storage and processing systems. Additional test protocols (for type approval or self-certification) are described to require the design (and/or production) to meet the specified performance requirements. Among the safety requirements of fuel cell electric vehicles, in China's national standard GB/T 24549, the fuel cell electric vehicle safety requirement [47], the confined space test requirements for fuel cell electric vehicles are stipulated. This standard is an exploration of hydrogen safety in actual use scenarios [48]. The test results show that if there is no leakage in the fuel cell electric vehicles, the primary hydrogen source is shut down and purging.

For the treatment after a disaster, the NFPA, in the United States, provides guidelines for firefighters and, in 2020, launched the second edition of the Hydrogen Energy Technical Guideline [43], which puts forward the requirements for buildings and equipment that use hydrogen.

5.2. The Following Research Approach

There has been in-depth research on the hydrogen safety of fuel cell electric vehicles. The next step should be to continue to explore the hydrogen safety of fuel cell electric vehicles interacting with a specific application scene and put forward more hydrogen safety requirements for fuel cell electric vehicles in related scenarios, such as in tunnels, ro-ro ships, parking lots, and transport vehicles. The aim is to provide the latest knowledge and guidance for regulators and public officials and to improve the public's acceptance of fuel cell electric vehicles.

6. Conclusions

Hydrogen safety is both a technical and psychological problem. Therefore, it is necessary to research the safety of fuel cell electric vehicles themselves. This paper summarizes the representative results of the hydrogen safety of fuel cell electric vehicles as the research object, covering the typical characteristics of the vehicles' hydrogen diffusion and burning behavior. The aim is to provide the latest knowledge and guidance for regulators and public officials and improve the public's acceptance of fuel cell electric vehicles.

There is much research on the hydrogen leakage and diffusion of fuel cell electric vehicles, and the influencing factors of the study include the pressure, flow rate, leakage diameter, ACH, and obstacles. The research on the burning behavior of fuel cell electric vehicles is also becoming a hotspot, such as the hydrogen-burning behavior in a parking lot scenario and the chain reaction of the burning behavior of a fuel cell electric vehicle following the failure of the TPRD. These are essential guides for product design.

It also shows that fuel cell electric vehicles have a high level of safety. CFD simulations in tunnels, underground car parks, and multistory car parks show that the hydrogen escape performance is excellent. At the same time, the test verifies that the flow, the direction of the leakage and the vehicle itself are the most important factors affecting the hydrogen distribution, and the impact of the leakage location and leakage pore size is much smaller. The results of the relevant tests also indicate that even if the hydrogen leakage rate is increased by 10 times to 1000 NL/min and then ignited, the risk is still controllable.

The hydrogen leakage rate was increased to 2000 NL/min before an unacceptable hazard occurred, but the risk remained manageable if combined with a forced exhaust. Multi-vehicle combustion tests of real fuel cell electric vehicles show that adjacent vehicles are not ignited by hydrogen. However, the current research focuses on the passenger car scenario. Commercial vehicles are more commonly used in scenarios of fuel cell electric vehicles. The amount of hydrogen carried and the layout of the onboard hydrogen storage system in commercial vehicles are different from those of passenger cars. Therefore, the next step is to conduct the relevant research on hydrogen leakage and burning behavior hazards in the application scenarios of commercial fuel cell electric vehicles.

The application of ISO/IEC GUIDE 51 for safety analysis is an essential method for quantitative analysis of safety; however, the difficulty lies in assessing the possibility of an accident and the consequences after the accident, and the current application cases are not convincing due to the lack of complete and accurate data. Therefore, in the next step, it is necessary to sort out the risk sources, probabilities, and consequences of fuel cell electric vehicle leakage and burning behavior scenarios and further improve the database.

Author Contributions: Conceptualization, H.L.; data curation, H.L.; formal analysis, H.L. and G.W.; investigation, K.Z., Y.H., and T.Z.; methodology, H.L.; project administration, T.Z.; resources, T.Z.; validation, K.Z.; visualization, Y.H.; writing—review and editing, H.L. and G.W. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Ministry of Science and Technology: 2021YFB4001000. The APC was funded by the Ministry of Science and Technology.

Conflicts of Interest: The authors declare no conflict of interest.{Matsuura, 2008 #148}

References

1. Jewell, J.; McCollum, D.; Emmerling, J.; Bertram, C.; Gernaat, D.E.H.J.; Krey, V.; Paroussos, L.; Berger, L.; Fragkiadakis, K.; Keppo, I.; et al. Limited emission reductions from fuel subsidy removal except in energy-exporting regions. *Nature* **2018**, *554*, 229–233. https://doi.org/10.1038/nature25467.
2. Hydrogen Roadmap Europe: A Sustainable Pathway for The European Energy Transition. Available online: https://www.fch.europa.eu/news/hydrogen-roadmap-europe-sustainable-pathway-european-energy-transition (accessed on 30 September 2022).
3. Hydrogen Supply Chain for the Realization of a Decarbonized Hydrogen Society. Available online: https://www.env.go.jp/seisaku/list/ondanka_saisei/lowcarbon-h2-sc/en/index.html (accessed on 30 September 2022).
4. Medium- and Long-Term Plan for the Development of Hydrogen Energy Industry (2021-2035). Available online: https://www.ndrc.gov.cn/xxgk/zcfb/ghwb/202203/t20220323_1320038.html?code=&state=123 (accessed on 30 September 2022).
5. South Korea' 's Hydrogen Industrial Strategy. Available online: https://www.csis.org/analysis/south-koreas-hydrogen-industrial-strategy (accessed on 30 September 2022).
6. IEA. The Future of Hydrogen. 2019. Available online: https://www.iea.org/reports/the-future-of-hydrogen (accessed on 30 September 2022).
7. Sánchez, A.L.; Williams, F.A. Recent advances in understanding of flammability characteristics of hydrogen. *Prog. Energy Combust. Sci.* **2014**, *41*, 1–55. https://doi.org/10.1016/j.pecs.2013.10.002.
8. Tarkowski, R. Underground hydrogen storage: Characteristics and prospects. *Renew. Sustain. Energy Rev.* **2019**, *105*, 86–94. https://doi.org/10.1016/j.rser.2019.01.051.
9. Cariteau, B.; Brinster, J.; Tkatschenko, I. Experiments on the distribution of concentration due to buoyant gas low flow rate release in an enclosure. *Int. J. Hydrogen Energy* **2011**, *36*, 2505–2512. https://doi.org/10.1016/j.ijhydene.2010.04.054.
10. Choi, J.; Hur, N.; Kang, S.; Lee, E.D.; Lee, K.-B. A CFD simulation of hydrogen dispersion for the hydrogen leakage from a fuel cell vehicle in an underground parking garage. *Int. J. Hydrogen Energy* **2013**, *38*, 8084–8091. https://doi.org/10.1016/j.ijhydene.2013.02.018.
11. De Stefano, M.; Rocourt, X.; Sochet, I.; Daudey, N. Hydrogen dispersion in a closed environment. *Int. J. Hydrogen Energy* **2018**, *44*, 9031–9040. https://doi.org/10.1016/j.ijhydene.2018.06.099.
12. Houf, W.; Evans, G.; Ekoto, I.; Merilo, E.; Groethe, M. Hydrogen fuel-cell forklift vehicle releases in enclosed spaces. *Int. J. Hydrogen Energy* **2012**, *38*, 8179–8189. https://doi.org/10.1016/j.ijhydene.2012.05.115.
13. Pitts, W.M.; Yang, J.C.; 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*, 17457–17469. https://doi.org/10.1016/j.ijhydene.2012.03.074.
14. Pitts, W.M.; Yang, J.C.; Fernandez, M.G. Helium dispersion following release in a 1/4-scale two-car residential garage. *Int. J. Hydrogen Energy* **2012**, *37*, 5286–5298.

15. Prasad, K. High-pressure release and dispersion of hydrogen in a partially enclosed compartment: Effect of natural and forced ventilation. *Int. J. Hydrogen Energy* **2014**, *39*, 6518–6532. https://doi.org/10.1016/j.ijhydene.2014.01.189.
16. Prasad, K.; Pitts, W.; Yang, J. Effect of wind and buoyancy on hydrogen release and dispersion in a compartment with vents at multiple levels. *Int. J. Hydrogen Energy* **2010**, *35*, 9218–9231. https://doi.org/10.1016/j.ijhydene.2010.06.001.
17. Prasad, K.; Pitts, W.M.; Fernández, M.; Yang, J.C. Natural and forced ventilation of buoyant gas released in a full-scale garage: Comparison of model predictions and experimental data. *Int. J. Hydrogen Energy* **2012**, *37*, 17436–17445. https://doi.org/10.1016/j.ijhydene.2012.04.148.
18. Matsuura, K.; Kanayamaa, H.; Tsukikawab, H.; Inouec M. Numerical simulation of leaking hydrogen dispersion behavior in a partially open space. *Int. J. Hydrogen Energy*, **2008**. *33*, 240–247.
19. Xie, H.; Li, X.; Christopher, D.M. Emergency blower ventilation to disperse hydrogen leaking from a hydrogen-fueled vehicle. *Int. J. Hydrogen Energy* **2015**, *40*, 8230–8238. https://doi.org/10.1016/j.ijhydene.2015.03.146.
20. Ng, H.D.; Lee, J.H. Comments on explosion problems for hydrogen safety. *J. Loss Prev. Process Ind.* **2008**, *21*, 136–146.
21. Hajji, Y.; Bouteraa, M.; Elcafsi, A.; Belghith, A.; Bournot, P.; Kallel, F. Natural ventilation of hydrogen during a leak in a residential garage. *Renew. Sustain. Energy Rev.* **2015**, *50*, 810–818. https://doi.org/10.1016/j.rser.2015.05.060.
22. Ricci, M.; Bellaby, P.; Flynn, R. What do we know about public perceptions and acceptance of hydrogen? A critical review and new case study evidence. *Int. J. Hydrogen Energy* **2008**, *33*, 5868–5880. https://doi.org/10.1016/j.ijhydene.2008.07.106.
23. Barilo, N.; Weiner, S.; James, C. Overview of the DOE hydrogen safety, codes and standards program part 2: Hydrogen and fuel cells: Emphasizing safety to enable commercialization. *Int. J. Hydrogen Energy* **2017**, *42*, 7625–7632. https://doi.org/10.1016/j.ijhydene.2016.04.070.
24. *ISO/IEC GUIDE 51:1999*; Safety Aspects—Guidelines for their Inclusion in Standards. ISO: Geneva, Switzerland, 1999.
25. Worster, M.G.; Huppert, H.E. Time-dependent density profiles in a filling box. *J. Fluid Mech.* **1983**, *132*, 457–466. https://doi.org/10.1017/s002211208300172x.
26. Mukai, S.; Suzuki, J.; Mitsuishi, H.; Oyakawa, K.; Watanabe, S. *CFD Simulation of Diffusion of Hydrogen Leakage Caused by Fuel Cell Vehicle Accident in Tunnel, Underground Parking Lot and Multistory Parking Garage*; Japan Automobile Research Institute: Tsukuba, Japan, 2005; p. 9.
27. Gupta, S.; Brinster, J.; Studer, E.; Tkatschenko, I. Hydrogen related risks within a private garage: Concentration measurements in a realistic full scale experimental facility. *Int. J. Hydrogen Energy* **2009**, *34*, 5902–5911. https://doi.org/10.1016/j.ijhydene.2009.03.026.
28. Lacome, J.; Jamois, D.; Perrette, L.; Proust, C. Large-scale hydrogen release in an isothermal confined area. *Int. J. Hydrogen Energy* **2011**, *36*, 2302–2312. https://doi.org/10.1016/j.ijhydene.2010.10.080.
29. Lach, A.; Gaathaug, A. Effect of Mechanical Ventilation on Accidental Hydrogen Releases—Large-Scale Experiments. *Energies* **2021**, *14*, 3008. https://doi.org/10.3390/en14113008.
30. Maeda, Y.; Itoi, H.; Tamura, Y.; Suzuki, J.; Watanabe, S. Diffusion and Ignition Behavior on the Assumption of Hydrogen Leakage from a Hydrogen-Fueled Vehicle. *SAE Trans.* **2007**, 2007-01-0428, 232–239. https://doi.org/10.4271/2007-01-0428.
31. Kaplan, S.; Garrick, B.J.; Apostolakis, G. Advances in Quantitative Risk Assessment--The Maturing of a Discipline. *IEEE Trans. Nucl. Sci.* **1981**, *28*, 944–946. https://doi.org/10.1109/TNS.1981.4331310.
32. Rodionov, A.; Wilkening, H.; Moretto, P. Risk assessment of hydrogen explosion for private car with hydrogen-driven engine. *Int. J. Hydrogen Energy* **2011**, *36*, 2398–2406.
33. Dadashzadeh, M.; Kashkarov, S.; Makarov, D.; Molkov, V. Risk assessment methodology for onboard hydrogen storage—*Int. J. Hydrogen Energy* **2018**, *43*, 6462–6475.
34. Swain, M.R. Fuel leak simulation. In Proceedings of the 2001 DOE Hydrogen Program Review, NREL/CP-570-30535, Baltimore, MA, USA, 17–19 April 2001.
35. Maeda, Y.; Takahashi, M.; Tamura, Y.; Suzuki, J.; Watanabe, S. Test of Vehicle Ignition Due to Hydrogen Gas Leakage. *SAE Trans.* **2006**, 2006-01-0126, 73–79. https://doi.org/10.4271/2006-01-0126.
36. Raj, P.K. A review of the criteria for people exposure to radiant heat flux from fires. *J. Hazard. Mater.* **2008**, *159*, 61–71. https://doi.org/10.1016/j.jhazmat.2007.09.120.
37. Tamura, Y.; Takabayashi, M.; Takeuchi, M. The spread of fire from adjoining vehicles to a hydrogen fuel cell vehicle. *Int. J. Hydrogen Energy* **2014**, *39*, 6169–6175. https://doi.org/10.1016/j.ijhydene.2014.01.140.
38. Shen, Y.; Zheng, T.; Lv, H.; Zhou, W.; Zhang, C. Numerical Simulation of Hydrogen Leakage from Fuel Cell Vehicle in an Outdoor Parking Garage. *World Electr. Veh. J.* **2021**, *12*, 118. https://doi.org/10.3390/wevj12030118.
39. Tamura, Y.; Takeuchi, M.; Sato, K. Effectiveness of a blower in reducing the hazard of hydrogen leaking from a hydrogen-fueled vehicle. *Int. J. Hydrogen Energy* **2014**, *39*, 20339–20349. https://doi.org/10.1016/j.ijhydene.2014.03.231.
40. Liu, W.; Christopher, D.M. Dispersion of hydrogen leaking from a hydrogen fuel cell vehicle. *Int. J. Hydrogen Energy* **2015**, *40*, 16673–16682. https://doi.org/10.1016/j.ijhydene.2015.10.026.
41. Merilo, E.; Groethe, M.; Colton, J.; Chiba, S. Experimental study of hydrogen release accidents in a vehicle garage. *Int. J. Hydrogen Energy* **2011**, *36*, 2436–2444. https://doi.org/10.1016/j.ijhydene.2010.04.056.
42. Li, Y.; Xiao, J.; Zhang, H.; Breitung, W.; Travis, J.; Kuznetsov, M.; Jordan, T. Numerical analysis of hydrogen release, dispersion and combustion in a tunnel with fuel cell vehicles using all-speed CFD code GASFLOW-MPI. *Int. J. Hydrogen Energy* **2020**, *46*, 12474–12486. https://doi.org/10.1016/j.ijhydene.2020.09.063.

43. NFPA 2 Hydrogen Technologies Code. Available online: https://www.nfpa.org/codes-and-standards/all-codes-and-standards/list-of-codes-and-standards/detail?code=2 (accessed on 30 September 2022).
44. European Union. *Regulation No 134 Uniform Provisions Concerning the Approval of Motor Vehicles and Their Components with Regard to the Safety-Related Performance of Hydrogen-Fuelled Vehicles (HFCV);* European Union: Luxembourg, Luxembourg, 2019.
45. UN GTR No. 13 Global Technical Regulation Concerning the Hydrogen and Fuel Cell Vehicles. Available online: https://www.interregs.com/catalogue/details/ece-gtr13/global-technical-regulation-no-13/hydrogen-and-fuel-cell-vehicles/ (accessed on 30 September 2022).
46. SAE J2579 Standard for Fuel Systems in Fuel Cell and Other Hydrogen Vehicles ;SAE International: Warrendale, PA, USA, 2018.
47. GB/T 24549——2020 Fuel cell electric vehicles -- Safety requirements; SAC: Beijing, China, 2020.
48. Hao, D.; Wang, X.; Zhang, Y.; Wang, R.; Chen, G.; Li, J. Experimental Study on Hydrogen Leakage and Emission of Fuel Cell Vehicles in Confined Spaces. *Automot. Innov.* **2020**, *3*, 111–122. https://doi.org/10.1007/s42154-020-00096-z.