Research on Hydrogen Fuel Cell Safety Detection Analysis Based on Leakage Quality Limit Detection Method

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Abstract: As the state has increased its support for hydrogen fuel cell electric vehicles, many domestic companies and scientific research institutions have carried out the research and development of fuel cell vehicles, and many models have also received national announcements. However, due to the lack of standards related to the hydrogen safety detection of fuel cell electric vehicles after collision in the current international standard systems, various companies formulate their own testing plans and technical requirements when conducting collision tests, and there are standards inconsistencies. After comparative analysis of foreign standards on the hydrogen safety detection methods and requirements of fuel cell electric vehicles after collision, relevant suggestions are given to the collision plan, which provides a reference for the domestic development of fuel cell vehicle collision research.

1. Introduction
As a clean energy with strategic significance in the future, hydrogen energy is getting more and more attention. From the national strategic level, Japan and South Korea successively released new hydrogen energy industry policies in 2019 [1]. In September 2020, Ministry of Finance and other five departments jointly issued the "Notice on Carrying Out the Demonstration Application of Fuel Cell Vehicles", proposing the policy of "reward for subsidies" and vigorously supporting fuel cell vehicles mainly commercial vehicles [2]. At present, there are already many fuel cell commercial vehicles running on the road, and fuel cell passenger vehicles demonstration operations are underway. Due to the flammable and explosive characteristics of hydrogen [3], the safety requirements of fuel cell vehicles are particularly important.

2. Progress Of Domestic Fuel Cell Vehicles Safety Requirements Standards
At this stage, the national standard system has specific standards for the safety requirements and testing of fuel cell vehicles, including whole vehicle, fuel cell system, hydrogen storage system, and hydrogen refueling ports [4-5]. Table 1 lists the current standards related to fuel cell vehicle safety.

GB/T24549-2020 [6] and GB18384-2020 [7] specify the hydrogen safety requirements and electrical safety requirements that fuel cell vehicles need to meet during normal driving and parking. GB/T24554-2009 specifies the airtightness, insulation and detection methods of the fuel cell system during emergency shutdown [8]. GB/T26779-2011 specifies the safety requirements and detection methods of the hydrogen refueling port. GB/T26779-2012 specifies the safety requirements and detection methods of the on-board hydrogen storage system during normal driving and parking. GB11551-2014 and GB20071-2006 respectively specify the safety requirements of the entire vehicle structure during a frontal and side collision [12,13].
GB/T31498-2015 specifies the electrical safety requirements to be met after collision with a Class B voltage car \cite{14}. At present, the safety requirements of fuel cell vehicles during and after collisions can only refer to the standards of fuel vehicles and electric vehicles. Especially for the hydrogen safety detection methods and technical requirements after collisions, there are no specific standards. Therefore, when carrying out a fuel cell vehicle crash test, we can refer to international standards for testing \cite{15_16}, including how to detect the amount of hydrogen leakage after a collision \cite{17}, what is the maximum limit of hydrogen leakage and how to detect the hydrogen concentration and limit requirements in a confined space after hydrogen leakage occurs.

| Classification          | Standard contents                                      | Standard number   | Standard name                                   |
|-------------------------|--------------------------------------------------------|-------------------|------------------------------------------------|
| Whole vehicle           | Hydrogen safety requirements in non-collision          | GB/T24549—2020    | Fuel cell electric vehicle safety requirements |
|                         | Electrical safety requirements for non-collision       | GB18384—2020      | Electric vehicle safety requirements            |
| Fuel cell system        | Fuel cell engine performance                           | GB/T24554—2009    | Fuel cell engine performance test method        |
| Hydrogen supply system  | Safety requirements and testing methods for hydrogenation ports | GB/T26779—2011    | Fuel cell electric vehicle hydrogenation port   |
|                         | Safety requirements and testing methods for on-board hydrogen storage systems | GB/T26930—2011    | Technical requirements for on-board hydrogen system of fuel cell electric vehicles; Amendment No. 1 |
|                         |                                                        | GB/T29126—2012    | Fuel cell electric vehicle on-board hydrogen system test method; Amendment No. 1 |
| Collision               | Body structure safety requirements                     | GB11551—2014      | Passenger protection in frontal collision of car |
|                         | Electrical safety requirements after collision         | GB/T31498—2015    | Safety requirements for electric vehicles after collision |

3. Research And Analysis Of Gas Leakage Limits And Test Methods
Internationally, SAEJ2578-2014 "General Safety Recommendations for Fuel Cell Vehicles" and GTR13 "Global Technical Regulations for Hydrogen Fuel Cell Vehicles" introduce the gas leakage detection methods after fuel cell vehicle collision.

3.1. SAEJ2578-2014 Detection Methods
SAEJ2578-2014 "General Safety Recommendations for Fuel Cell Vehicles" describes in detail how to detect gas leakage after a crash test. This regulation introduces three methods for testing gas leakage after collision. Hydrogen leakage detection method for hydrogen storage cylinders at nominal working pressure, helium leakage detection method for hydrogen storage cylinders at nominal working pressure, hydrogen leakage detection method for hydrogen storage cylinders at lower pressure due to the risk of hydrogen leakage, the current domestic hydrogen fuel cell vehicle crash test does not use hydrogen, but inert gas instead. Among the inert gases, the molecular weight of helium is the closest to that of hydrogen, so we can refer to the second detection method.

3.1.1 Determination Of Helium Leakage Mass Limit
According to the regulation, the allowable leakage of liquid fuel within 60 minutes after collision is 1.7kg, and the average low calorific value of gasoline and diesel is 42.7MJ/kg, thus the allowable leakage energy is 72590kj. The maximum leakage energy of a hydrogen fuel cell vehicle within 60 minutes after a collision should also be calculated according to the low calorific value of hydrogen.
The allowable leakage hydrogen mass is 606g, and the volume when converted to an atmospheric pressure of 15°C is 7107L. Therefore, the maximum leakage rate of hydrogen is 118L/min.

A small hole with a mass of 606 g of hydrogen that can leak in 60 minutes is used to simulate the mass of helium that can leak through the hole in 60 minutes. Through the simulation data, it is found that the leakage quality decreases as the volume of the hydrogen storage cylinders increases, but it has a very small relationship with the nominal working pressure of the hydrogen storage cylinders, and the influence of the nominal working pressure can be ignored. Fitting to obtain the helium leakage mass limit formula under different hydrogen storage cylinders volumes, as shown in formula (1):

$$HeW = \frac{4270}{Vol} + 904$$  \hspace{1cm} (1)

In the formula 1, HeW is the limit of helium leakage mass within 60 minutes; Vol is the volume of the hydrogen storage cylinders. Taking the volume of a hydrogen storage bottle of 200L as an example, the mass of helium gas allowed to leak within 60 minutes is 925g.

### 3.1.2 Correction Coefficient For Helium Leakage Mass Limit

During the period which gas leakage is detected after the collision test, factors such as the initial hydrogen storage cylinders gas pressure, the initial gas temperature, the gas temperature at the end of the test, and the test time will affect the helium leakage mass limit. Therefore, it is necessary to consider the correction coefficient of these factors to the limit value.

SAEJ2578-2014 studied the relationship between the test time and the mass of the leaked gas, the relationship between the initial gas pressure, temperature and the mass of the leaked gas, and obtained the helium leak mass limit formula with correction coefficient.

$$AML = \left( \frac{4270}{Vol} + 904 \right) \times \frac{LT}{60} \times \frac{Ps}{NWP} \times \sqrt{\frac{288 \times T_{avg}}{Ts}}$$  \hspace{1cm} (2)

In the formula 2, AML is the allowable helium leakage mass; LT is the test time; Ps is the initial hydrogen storage cylinder gas pressure; NWP is the nominal working pressure; Ts is the initial hydrogen storage cylinder gas temperature; Tavg is the average gas temperature.

The average gas temperature Tavg is obtained by averaging multiple measurements. It’s measured at the moment before the collision, and then measured every 15 minutes. The test time is determined according to the measurement accuracy requirements. The following will introduce the relationship between the two and how to make the test time.

### 3.1.3 Make The Test Time According To The Measurement Accuracy Requirements

In the collision test, the inspector calculates the gas leakage mass by reading the pressure change of the hydrogen storage cylinder before and after the collision. According to the requirements of this regulation, the total test error should not exceed 10% of the test value. At present, the measurement errors generated during the test include sensor errors, zero-point drift errors, thermal conductivity sensitivity errors, and errors in the conversion of analog signals to digital signals. For a pressure sensor with a measuring range of 70MPa, the measurement error can reach 0.5% when the above-mentioned errors are added. Therefore, in order to ensure high measurement accuracy, the gas pressure change before and after the collision must be greater than 5% of the pressure sensor range.

Under the precondition of the same initial pressure of hydrogen storage cylinder, if a gas leak occurs, the gas pressure drop within 60 minutes will decrease as the volume of the hydrogen storage cylinder increases. Figure 1 describes whether the pressure drop in the hydrogen storage cylinder meets the measurement accuracy requirements after 60 minutes of gas leakage under different nominal working pressures and different volumes. The 5% line represents the pressure value corresponding to 5% of the
pressure sensor range under different nominal working pressures. When the initial pressure of the hydrogen storage cylinder is 70MPa, if the volume of the hydrogen storage cylinder is 200L, the pressure drop within 60 minutes of gas leakage is greater than 5% of the pressure sensor range, which meets the test accuracy requirements. If the volume of the hydrogen storage cylinder is greater than 200L, the pressure drop in the cylinder is less than 5% of the pressure sensor range, so the test time needs to be increased.

Figure 1 Helium pressure drop within 60 minutes under different hydrogen storage cylinder volumes

Figure 2 The time required for the pressure of hydrogen storage cylinders of different volumes to drop by 5%

Through simulation, the time required for hydrogen storage cylinders of different volumes to drop to 5% after gas leakage under different initial pressures is obtained, as shown in Figure 2.

It can be seen that if the initial pressure is the same, the larger the volume of the hydrogen storage cylinder, the longer the required time. For a hydrogen storage cylinder of 70MPa, it only takes 26 minutes when the volume is 100L, and when the volume is 200L, according to the simulation curve, the relationship between the volume of the hydrogen storage cylinder at 70MPa and the time required for the pressure to drop by 5% can be obtained, as in formula 3:

$$
Time_{-5\%} = \frac{Vol \times NWP}{1000} \times \\
\left( (-0.028 \times NWP + 5.5) \times \frac{SR}{NWP} - 0.3 \right) - 2.6 \times \frac{SR}{NWP}
$$

(3)

In the formula, SR is the pressure sensor range; when the calculated time is less than 60min, the
measurement time needs to be set as 60min. For commercial vehicles, the vehicle is equipped with 4-10 hydrogen storage cylinders and the total volume of the hydrogen storage cylinders can reach 400-1200L. In order to detect the mass of the leaking gas more accurately, it takes longer to detect the gas leak after a collision.

3.1.4 Helium Leak Detection Method

Measure the initial pressure in the storage cylinder before and after the collision. After the measurement time specified above, measure the pressure in the storage cylinder again. The gas density in the cylinder before and after the collision is calculated using the two pressure values to obtain the actual leaked helium gas mass. The calculation formulas are as follows: (4) and (5):

\[
P_{s_{15}} = P_s \times \frac{288}{T_s}
\]

(4)

\[
P_{e_{15}} = P_e \times \frac{288}{T_e}
\]

(5)

In formula 4 and 5, convert the measured pressure to pressure at 15°C under an atmospheric pressure. \(P_{s_{15}}\) is the gas pressure before collision at 15°C, \(P_s\) is the gas pressure in the cylinder before collision, \(T_s\) is the gas temperature in the cylinder before collision, \(P_{e_{15}}\) is the gas pressure after collision at 15°C, \(P_e\) is the gas pressure in the cylinder after collision, \(T_e\) is the gas temperature in the cylinder after collision.

Calculate the density of helium gas according to the pressure values, as shown in formula (6) and formula (7):

\[
D_s = -0.0043 \times \left( P_{s_{15}} \right)^2 + 1.53 \times P_{s_{15}} + 1.49
\]

(6)

\[
D_e = -0.0043 \times \left( P_{e_{15}} \right)^2 + 1.53 \times P_{e_{15}} + 1.49
\]

(7)

In formula 6 and 7, \(D_s\) is the density of helium before collision, \(D_e\) is the density of helium after collision.

Calculate the actual leaked helium mass, as shown in formula (8), \(ML\) is the mass of leaked helium and \(Vol\) is the volume of the hydrogen storage cylinder.

\[
ML = (D_s - D_e) \times Vol
\]

(8)

Therefore, the gas leak detection after collision using helium gas is shown in Figure 3.
Figure 3 Helium leak detection 3.2 GTR13 method after collision

There are two methods on how to detect gas leakage after collision in GTR13: (1) Use hydrogen for
detection; (2) Use helium for detection. There is no mention of hydrogen detection methods for hydrogen storage cylinders at lower pressures. The overall idea of two test methods of GTR13 is the same as SAEJ2578-2014, but there are several differences, which are summarized as follows:

In the hydrogen leakage test method, the measurement time and gas density calculation formula are slightly different from SAEJ2578-2014, but the effect is not significant. Since helium is basically used for post-collision gas leakage detection tests in China, the method will not be introduced here.

GTR13 specifies that the maximum hydrogen leakage volume flow is 118L/min and the influence of temperature on the leakage rate during the entire test process is not considered. When SAEJ2578-2014 formulated the hydrogen leakage mass limit, it considered the correction coefficient of the temperature change during the test process.

For the compliance judgment of gas leakage, GTR13 judges whether the actual gas leakage volume flow is less than the gas leakage volume flow limit, and SAEJ2578-2014 judges whether the actual gas leakage mass is less than the gas leakage mass limit. GTR13 proposed the relationship between the average volume flow rate of hydrogen leakage and the average volume flow rate of helium leakage based on calculations. If the gas temperature is 15°C and the average volume flow rate of hydrogen leakage is 118L/min, then the average volume flow of helium leakage rate should be 88.5L/min.

According to the above comparative analysis, SAEJ2578 considers more comprehensive factors when performing post-collision gas leakage detection. It clearly proposes that the gas leakage detection time required for hydrogen storage cylinders at different nominal working pressures and different volumes is different. When the pressure is the same, the larger the volume of the hydrogen storage cylinder is, the longer the detection time is required. When the volume of the hydrogen storage cylinder is the same, the greater the pressure is, the longer the detection time is required.

4. Gas Concentration Limits And Test Methods In Confined Space After Collision

For the test of gas concentration in confined space after collision, only GTR13 introduces the test method and specifies the gas concentration limit.

4.1. Gas Concentration Measurement Method

4.1.1 Technical Requirements Of Concentration Sensor

If the volume concentration of hydrogen is 4% and the volume concentration of helium is 3%, the measurement accuracy of the sensor should reach 5%. The sensor range should be higher than 25% of the target test concentration, that is, if we want to monitor a 10% concentration, the sensor range should be at least 12.5% volume concentration. When the gas concentration changes greatly, the sensor should have at least 90% probability to respond within 10s.

4.1.2 Sensor Placement Location

- Before the crash test, the concentration sensor should be installed in 3 positions:
  - 250mm above the driver’s seat or in the middle of the top of the passenger compartment;
  - On the floor 250mm in front of the rear seats of the passenger compartment;
  - 100mm from the top of the luggage compartment and cargo compartment.

4.1.3 Test Site

Carry out in a windless outdoor or empty indoor.

4.1.4 Data Collection Requirements

Sensor data can be collected by data collection device fixed in the car, or collected by remote transmission. Data collection starts after a vehicle collision occurs, and the data collection frequency is at least once every 5s and lasts for at least 60 minutes.

For fuel cell vehicles with different hydrogen storage cylinder volumes and different nominal working pressures, the test time for gas concentration in a confined space can also be corrected with
reference to the above-mentioned SAEJ2578 on the gas leakage detection time.

4.2. Gas Concentration Limit
At any time within at least 60 minutes after the collision, if hydrogen is used as the test gas, the concentration should be less than 3% ± 1%, and if helium is used as the test gas, the concentration should be less than 2.25% ± 0.75%. The helium concentration limit is 75% of the hydrogen concentration limit because the volume flow rate of helium leakage is 75% of hydrogen.

At present, for hydrogen fuel cell buses, in order to avoid potential safety hazards in the use of buses, relevant departments require safety measures for the on-board hydrogen supply system. The manufacturing department has conducted research to provide them with overvoltage protection, overcurrent protection, over-temperature protection, low-pressure alarm and other functions, and also have the detection and control of hydrogen leakage. However, there is a risk of fire when a fuel cell bus collides, so the fuel cell bus must also have an on-board hydrogen collision safety system. Among them, the collision sensor is the "nervous end" of the on-board hydrogen collision safety protection system. It mainly detects and judges the impact signal when the car collides, and inputs the signal to the vehicle and the hydrogen system controller so that they can start a series of safety protection measures in time. Hydrogen fuel cell vehicles are gradually beginning to trend. It is believed that in the future, fuel cell hydrogen safety collision protection systems with collision sensors as the core will be widely used. In this way, it can effectively reduce gas leakage and fire risk in hydrogen fuel cell collisions and provide protection for the wide application of hydrogen fuel cell vehicles.

5. Conclusion And Suggestions
Based on the above analysis of domestic and international standards, the collision scheme of fuel cell electric vehicles is summarized and some suggestions are given:

- After a fuel cell electric vehicle collision, the following should be detected: measuring the actual gas leakage mass at least 60 minutes after the collision; measuring the gas concentration change in the confined space at least 60 minutes after the collision.
- It is necessary to first calculate the appropriate gas leak detection time according to the volume of the hydrogen storage cylinder, and it cannot take 60 minutes at all. Commercial vehicles use large-volume hydrogen storage cylinders, which require more test time to ensure measurement accuracy.
- If the collision test gas is helium, the allowable leakage rate is 88.5L/min, which is smaller than the allowable leakage rate of hydrogen. The allowable concentration limit of helium in confined space after collision is 2.25%±0.75%, which is also smaller than the allowable hydrogen concentration limit.

The related departments should formulate and publish hydrogen safety related standards after the collision of hydrogen fuel cell electric vehicles as soon as possible, and implement unified testing standards and unified technical requirements when car companies or R&D institutions carry out crash tests, so as to point out the direction for research on fuel cell vehicle collisions.

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