Research and Application of Test and Evaluation System for Fuel Cell Vehicles

Dong Hao, Shan Ren, Yanyi Zhang and Renguang Wang*

China Automotive Technology and Research Center Co., Ltd. Tianjin 300300, China

*Corresponding author e-mail: wangrenguang@catarc.ac.cn

Abstract. With the rapid development of fuel cell vehicles, in order to meet the requirements of test and evaluation, the special test and evaluation system were studied and established for fuel cell vehicles and its main components. Just because the hydrogen is used as fuel with water produced, its emission, energy consumption and cold starting performances become special and important. With brief introduction of the frame of test and evaluation system for FFCVs, there main whole vehicle performances test, which are the FCV subzero cold starting, FCV energy consumption and range, FCV hydrogen safety test in confined space, were discussed in detail including methods analysis, device development and application results discussion. The practical tests results show that the necessity of test system development and correctness of presented methods and devices.

1. Introduction

With rapid development of Fuel Cell Vehicles (FCVs), the lack of standards and test methods have become the block of test and evaluation of FCVs, which makes the special test and evaluation system development in great needing. The FCVs firstly are the motor vehicles, then they are the electric vehicles, and at last they are the FCVs, therefore the FCVs should meet the common requirements of conventional vehicles and electric vehicles, especially those of about high voltage and electric motors. But the different technology routs (shown in figure 1) make the FCVs need different test methods and devices.

Figure 1. Difference of FCV, PHEV and BEV
China automotive and technology research center Co., Ltd. (CATARC) has conducted related research on FCVs for nearly 20 years on the fields of test and standards. And its FCV test Lab founded the FCV test and evaluation working group in China in 2017 to develop test and evaluation system on whole vehicles and main components of the FCVs. With brief introduction of these two systems, the test methods and test equipment development for these three main performance of FCVs were presented, which includes subzero cold starting of FCV, energy consumption and range of FCV, and hydrogen safety of FCV in confined space.

2. Analysis on test and evaluation system for FCV

The fuel of hydrogen and water production of FCVs make its vehicle performance such as dynamics, economy, collision safety, environmental adaptability, and EMC quite different from those of conventional vehicles and other kinds of electric vehicles. Especially the hydrogen consumption, electric energy consumption and range connected with economy; the emission, leakage and collision which causing hydrogen safety concerned; and subzero temperature which making the environmental adaptability a problem.

Basing on discussion and analysis, the test items with test parameters (for example safety requirements shown in table 1) were defined and corresponding test methods were established, which from the frame of test and evaluation system for FCVs, shown in figure 2.

| Table 1. Some safety test requirements |
|---------------------------------------|
| **Test classification**     | **Test item**                               |
| Hydrogen safety             | H2 leakage in confined space                |
|                           | Alarm function for hydrogen                |
|                           | Installation strength of H2 system         |
| Hydrogen emission          | Idle emission                              |
|                           | Cycle emission                             |
| Electric safety            | General safety                             |
| Collision safety           | Wading safety                              |
|                           | Passenger car collision                    |
|                           | Commercial vehicle rollover                |

Figure 2. Frame of test and evaluation system for whole vehicles of FCVs
3. Analysis on test & evaluation system for main parts

The main parts of FCVs include other assembly, subsystem and parts with exception of whole FCVs, such as fuel cell engine, H2 system on board, air compressor and H2 circulator, etc. In fact, there are many parts can be taken into this test and evaluation system, only some main parts liking air and H2 supply were listed in this paper, shown in figure 3.

4. Analysis on subzero cold starting of FCVs

The water produced by fuel cell can get frozen, which may cause starting failure of fuel cell engine and the launch of FCVs. Therefore many control strategies were developed to deal with subzero cold starting. The subzero cold starting performance is very important but there is no standards in China to test and evaluate. Under this condition, the cold starting test ability was formed with design of special environmental chamber for FCVs, and one organization standard was formulated by CATARC engineers, which is the T/CSAE 122-2019<test method of subzero cold starting performance for FCV> [1].

4.1. Brief introduction of T/CSAE 122

Basins on the test results of cold starting for several FCVs, the different control strategies for subzero cold starting were analyzed in detail and practically tested. And the vehicle soaking time, judgement of starting status, vehicle conditions, test parameters, test devices and test steps were defined or developed by CATARC engineers step by step, and the method was modified and improved gradually according to technology routs of different FCVs. The main test steps were formed with reference of China national standard, GB/T 24554-2009 <test methods for the performances of fuel cell engine> [2].

4.2. Development& application of test device

Because of the difference of subzero cold starting between FCVs and conventional vehicles. A special data collection system (flow chart was shown in figure 4) [3] was developed to meet the requirements of FCVs for the test and evaluation of cold starting. And the special test device system were developed to measure, display and store the related data.

With the developed test system, several FCVs were tested to verify the test system and new methods. A fuel cell bus was taken as an example to explain the whole test of cold stating performance under -25℃. The whole test process was divided into three steps: 1) Early stating stage. The battery is discharged to supply its PTC (positive temperature coefficient) heater to warmup itself with constant power, and at the same time the fuel cell stack use its own PTC to warmup itself. 2) Medium stage. The air conditioner system was started to make the fuel cell engine operate at smaller power. 3) Last stage.
When output power of the fuel cell stack reached 17 kW and the battery changed from discharge state into charge state. Then the whole starting process ends.

During the starting process, the related parameters were measured and collected by means of data collection system. It took 45 min from time of power on to the time when the fuel cell stack power reached 17 kW (set by vehicle manufacture). And all the energy consumption results were listed in table 2.

![Figure 4. Software frame of data collection system for cold starting](image)

| Items                | Energy consumption (kWh) |
|----------------------|--------------------------|
| Power battery        | 9.67                     |
| Fuel cell stack      | 1.49                     |
| PTC for power battery| 5.84                     |
| PTC for fuel cell stack | 2.31                  |
| Air conditioner      | 2.03                     |

The total energy consumed during starting process is the addition of output energy from battery and fuel cell stack. Seen from table 2, the total energy is 11.16 kWh, and two PTCs consumed energy is 10.18 kWh, which takes 91.22% of the total energy. The power changing conditions were presented in figure 5 and figure 6 respectively.

In the test, there were several problems may be occurred such as: 1) hydrogen leakage at subzero temperature, which could cause H2 concentration higher than safety limit (10000 ppm) to interrupt the test process; 2) cold starting failed modes. Some were caused by lower warming or heating capability, some were caused by no working of accessory parts at lower temperature. 3) Energy consumption during cold starting process. There was some FCVs heated using off board electricity energy. Therefore how to evaluate the heating energy consumption is still a topic needing further research and discussion.

5. Test of energy consumption and range for FCVs

The FCVs are one kind of electric vehicles, but their using of H2 as fuel make current China standards cannot be used to test their energy consumption and range, which are GB/T 19753 - 2013 <test methods for energy consumption of light duty hybrid electric vehicles> [4], GB/T 19754 - 2015 <test methods for energy consumption of heavy duty hybrid electric vehicles> [5], and GB/T 18386 - 2017 <Electric vehicles–Energy consumption and range –Test procedures> [6].
5. Basing on the configurations of FCVs, it can be classified into two kinds, which are the FCVs powered by bigger power fuel cell engine and the FCVs powered by bigger power battery and smaller fuel cell engine (or range extended FCVs). These two types of FCVS are the electric-electric hybrid vehicles, but for the former one, its power battery has lower capability and its contribution to the range could be neglected. For the range extended FCVs, their H2 consumption and electric consumption must be both tested and evaluated. And there are some FCVs designed for off board charging, but no charge in practical conditions, this case was not considered in this paper. There is another China standard, GB/T 35178-2017 <Fuel cell electric vehicles-Hydrogen consumption-Test methods> [7], which provides three method to calculate H2 mass (pressure method gravimetric method flow method, shown in figure 7), but it cannot be used directly to test energy consumption and range for current FCVs in China.

5.1. Main ideas for energy consumption test and calculation

According to current conditions of FCVs and related standards in China, authors of this paper and Prof. Hou Y.P. from Tongji University, invented a new method to test and calculate energy consumption and range for FCVs. This new method can be used for both passenger vehicles and commercial vehicles with different configurations, and will become a new China national standard. Its main ideas were explained as followings.

The sketch of powertrain system of FCVs was presented in figure 8. For two kinds of FCVs, their main components are almost same with different capability configurations. And the new method has two main ideas, which are: 1) the range should be tested directly using dynamometer; 2) the total H2 and electric energy form battery in range test should be measured, and according to their own percentage of total energy consumed to decide whether or not to consider electric energy consumed. Then calculate the H2 consumption and electricity consumption, but percentage criteria to consider electricity or not should be discussed furtherly (5% is suggested here).
Some requirements of this new method include: 1) with 100% SOC of H2 cylinder and 100% SOC of Battery, the FCV runs on the dynamometer until it reaches the speed limit or energy limit. During the test process, the range, H2 mass, total electric energy from grid, current and voltage of power battery and fuel cell stack should be measured or calculated for further analysis. An off board rechargeable fuel cell passenger car was tested and taken as an example to show the whole calculation process.

![H2 mass calculation methods](image)

**Figure 7.** H2 mass calculation methods [7]

![Sketch of powertrain system of FCV](image)

**Figure 8.** Sketch of powertrain system of FCV

### 5.2. Data analysis of energy consumption for off board rechargeable FCVs

During the test, the range (D), total mass of consumed H2 (mH2), electric energy from grid (E), current and voltage of power battery and fuel cell stack have been gotten. Then follow equation 1 to equation 9 were used to calculate energy consumption, where the T is total test time; IFC and IBAT are the current (A) of FC stack and battery respectively; UFC and UBAT are the voltage (V) of FC stack and battery respectively.

Total energy from FC stack ($E_{FC}$, kWh):

$$E_{FC} = \int_{0}^{T} I_{FC} U_{FC} dt / 1000$$  \hspace{1cm} (1)

Total energy from battery ($E_{BAT}$, kWh):

$$E_{BAT} = \int_{0}^{T} I_{BAT} U_{BAT} dt / 1000$$  \hspace{1cm} (2)

Total energy from battery and FC stack ($E_{D}$, kWh):

$$E_{D} = E_{FC} + E_{BAT}$$
\[ E_d = E_{FC} + E_{BAT} \]  

(3)

Percentage of total energy from FC stack (\( \eta_{FC} \)):

\[ \eta_{FC} = \frac{E_{FC}}{E_d} \times 100\% \]  

(4)

Percentage of total energy from battery (\( \eta_{BAT} \)):

\[ \eta_{BAT} = \frac{E_{BAT}}{E_d} \times 100\% \]  

(5)

Range contributed by battery (\( D_{BAT} \), km):

\[ D_{BAT} = D \cdot \eta_{BAT} \]  

(6)

Range contributed by FC stack (\( D_{FC} \), km):

\[ D_{FC} = D \cdot \eta_{FC} \]  

(7)

H2 consumption per 100km (\( C_{H2} \), kg/100km):

\[ C_{H2} = 100 \times \frac{m_{H2}}{D_{FC}} \]  

(8)

Electricity consumption per 100km (\( C_E \), kWh/100km):

\[ C_E = 100 \times \frac{E}{D_{BAT}} \]  

(9)

5.3. Development and application of energy test system

In order to evaluate energy consumption for FCVs, a special multichannel energy test system (shown in figure 9) was developed by engineers from FC Lab of CATARC. The new system has been used to test several FCVs. The test results such as Mirai of Toyota and NEXO of Hyundai are the same as those of public declared, which can prove that the new test system and method are reliable and correct. The following example is a range extended SUV in China, its results were listed in table 3.

Figure 9. Multi-channel energy test system for FCVs
Table 3. Test and calculation of energy consumption

| Item and unit                  | Measurement and calculation results |
|-------------------------------|-------------------------------------|
| Range (km)                    | 300                                 |
| Energy from battery (kWh)     | 10                                  |
| Energy from FC stack (kWh)    | 55                                  |
| Energy from battery and FC stack (kWh) | 65                          |
| Percentage of battery (%)     | 15                                  |
| Percentage of FC stack (%)    | 85                                  |
| Range contributed by battery(km) | 45                          |
| Range contributed by FC stack(km) | 255                         |
| Total H2 consumed (kg)        | 3                                   |
| Charging energy from grid (kWh) | 11                          |
| Electricity consumption (kWh/100km) | 24.4                         |
| H2 consumption (kg/100km)     | 1.18                                |

6. H2 safety test for FCVs in confined space
The H2 used as fuel in FCVs has led to special safety requirements. The corresponding safety descriptions are provided on GTR No.13 [8], and the SAE J2579 introduces in detail the technology of H2 safety test requirements for FCVs in confined space [9]. In China national standard, GB/T 24549-2009 [10], there are also some requirements for H2 leakage limit in confined space without test methods. There is no standards or regulations that provide defined descriptions for test methods. Therefore, basing on the test equipment development and real test results, an organization standard, T/CSAE123 2019<Fuel cell electric vehicles -Test methods and safety requirements for hydrogen leakage and emission in confined space> [11] was formulated by authors and their team, and its main parts will be added into China national standard GB/T 24549 for revision. Taking the surround conditions and operation modes of fuel cell passenger vehicles, test duration, position of H2 sensors, vehicle conditions, and test procedure were descripted in detail in T/CSAE123 2019 [11].

6.1. Development and application of test equipment
The test system used for T/CSAE123 2019 was developed by the engineers from FC Lab of CATARC. During the development process, it was found that it is difficult to calculate the air exchange rate. The parking space such as a garage without mechanical ventilation devices was taken as an example to introduce the calculation process.

When the FC car was parked in space with air exchange rate of 0.03 ACH(air exchange rate per hour), the relation of H2 concentration and space condition can be expressed using equation 10 [12].

\[
C_{H2}(t) = \frac{H}{H + A_{room}} - \frac{H}{H + A_{room}} e^{-\frac{(H + A_{room})t}{V_{room}}}
\]  
\[
A_{room} = \frac{ACH \times V_{room}}{60}
\]

Where, \(C_{H2}(t)\) is H2 concentration changing with time in the space \([1.0=100\%]\); \(H\) is total H2 leakage rate of vehicle \([L/min]\); \(A_{room}\) is in and out air flow rate of the space\([L/min]\); \(ACH\) is air exchange rate per hour; \(V_{room}\) is space volume subtracts the volume of vehicle materials.

When the car parked with the state of FC engine off, the H2 concentration defined by equation 10 will approach a stable value, which can be expressed by equation 12 [12]: 
Where, $C_{CH2}$ is the stable H2 concentration in the space (%); others are same as equation 10.

Substituting H and ACH into equation 12, the function with different H2 leakage rate is available, which can be used to calculate the stable H2 concentration in a garage.

Basing on the space requirements and basic dimension of M1 vehicles, the internal sizes of the test chamber were defined, with the accurate control of air exchange rate to simulate different ventilation requirements. Because of features of H2, the H2 sensors were installed at different positions. And a special ventilation system was adopted to exchange the higher level H2 out of test space when the H2 concentration reaches alarm level. With self-developed control and calculation system for the test chamber, the first chamber for H2 safety test of FCV in confined space was developed successfully (picture shown in figure 10).

### 6.2. Analysis of application results

The new test system was used to test several FC passenger cars with satisfied results. The H2 concentration plots in test chamber with power off of a test FCV car was shown in figure 11 [13], and the H2 concentration plots in test chamber with combined operation modes of this FCV car is shown in figure 12 [13]. The test results show that H2 concentrations is under the alarm limit.

![Figure 10. Chamber for FCV H2 safety in the confined space](image)

![Figure 11. H2 concentration in test chamber with a FCV car power off](image)
7. Conclusion
Basing on analysis of the requirements of test of FCVs and research of related standards, the test and evaluation systems for fuel cell vehicles and main parts were established with satisfied results. And three main performances were taken as examples to show development and application of the test methods, test devices and standards, which are subzero cold starting test, energy consumption and range test, H2 safety test in confined space. The test results show that these test methods can meet the test requirements of current fuel cell vehicles in China.

Acknowledgments
The work was financially supported under the grants of Tianjin Municipal Science and Technology Commission Program (Project No. 17ZXFWGX00040), and CATARC guide research program (Project No.19223402). Corresponding author email: wangrenguang@catarc.ac.cn

References
[1] T/CSAE 122-2019, Test method of subzero cold starting performance for FCV, CSAE, 2019.12
[2] GB/T 24554-2009, Test methods for the performances of fuel cell engine, Beijing: China Standards Press, 2010.1
[3] Shu S.T., Hou Y.P., Hao D., Wang R.G, “Development of data acquisition system for freezing start test of FCV,” Battery Bimonthly, 2019, 49 (05): 396-398.
[4] GB/T 19753-2013, Test methods for energy consumption of heavy light hybrid electric vehicles, Beijing: China Standards Press, 2013
[5] GB/T 19754-2015, Test methods for energy consumption of heavy duty hybrid electric vehicles, Beijing: China Standards Press, 2015
[6] GB/T 18386-2017, Electric vehicles-Energy consumption and range –Test procedures, Beijing: China Standards Press, 2015
[7] GB/T 35178-2017, Fuel cell electric vehicles-Hydrogen consumption-Test methods, which provide three method to calculate H2 consumption, Beijing: China Standards Press, 2017.11
[8] UN GTR No.13, Global Technical Regulation concerning the hydrogen and fuel cell vehicles, http://www.ece.org/trans/main,March 2,2020
[9] SAE J2579-201303, Standard for Fuel Systems in Fuel Cell and Other Hydrogen Vehicles. https://saemobilus. sae.org/ content/ J2579 201303, JAN, 01, 2020.
[10] GB/T 24549-2009,Fuel cell electric vehicles-Safety requirements, Beijing: China Standards Press, 2009.10
[11] T/CSAE123 2019. Fuel cell electric vehicles -Test methods and safety requirements for hydrogen leakage and emission in confined space, CSAE, 2019.12
[12] SAE J2578-201408, Recommended Practice for General Fuel Cell Vehicle Safety, https://saemobilus.sae.org/content/J2578_201408, JAN, 01, 2020

[13] Dong Hao, Xiaobing Wang, Yanyi Zhang, Renguang Wang, Guang Chen, Jun Li, Experimental Study on Hydrogen Leakage and Emission of Fuel Cell Vehicles in Confined Spaces, Automotive Innovation, https://doi.org/10.1007/s42154-020-00096-z