A STUDY OF FUEL SYSTEM INTEGRITY AND ELECTRIC SAFETY OF HFCV

Kwang-Bum LEE
Jae-Wan LEE
Jong-Soo KIM
Gee-Joong YONG
Korea Automobile Testing and Research Institute
Republic of Korea
Paper Number 11-0412

ABSTRACT

This research consists of two parts. The first part is to evaluate the fire risk due to the hydrogen leakage or diffusion from the hydrogen storage system. The second part is to verify compliance with the fuel leakage limit of a hydrogen fuel cell vehicle in the event of collision. To evaluate the fire risk of the fuel storage and delivery system in a hydrogen fuel-cell vehicle, sensors were installed at locations where leaking hydrogen was likely to be trapped. These sensors were installed in the engine compartment, the occupant compartment and in the rear of a vehicle. The fuel processing system and fuel-cell stacks were located in the engine compartment. The behavior of leaking hydrogen was investigated when a vehicle was at rest, moving, and after shut-down caused by hydrogen leakage. In some area the concentration reached up to 4%. The optimization of number of sensors and locations was also investigated for effective detection.

To assess the vehicle fuel system integrity and electrical safety in the event of a crash, three different crashes were carried out. One full frontal impact test at the speed of 48 km/h, one side impact test at the speed of 50 km/h with a deformable moving barrier and one rear impact test at the speed of 48 km/h with a moving barrier were conducted. The hydrogen fuel storage systems were filled to 90 % of the nominal working pressure with helium gas at each test. Even though the hydrogen fuel cell vehicle subject to tests was equipped with crash sensors that enabled the high pressure valve of the storage container to be closed automatically in the event of a crash, all crash sensors were removed to simulate severe test conditions in these experiments. After each crash, the amounts of hydrogen leakages were measured, and electrical safety were examined.

In this experiment 8 research institutes, including the Korea Automobile Testing and Research Institute, Hyundai Motor Company, took part. This project was supported by the Ministry of Land, Transportation and Maritime Affairs of the Republic of Korea.

INTRODUCTION

The purpose of this research is to secure the safety of the fuel storage and delivery system in a hydrogen fuel cell vehicle by assessing the danger with sensors installed where leaking hydrogen is likely to be trapped. In the hydrogen fuel-cell vehicle, the storage container is located in the rear of a vehicle and the fuel processing system (FPS) and fuel-cell stacks are located in the engine compartment. The hydrogen fuel from the storage containers is supplied to the fuel cell stacks, where electricity is generated, through FPS with a series of pressure regulators that reduce the pressure to approximately 1 MPa before entering the fuel cell stack. Excessive hydrogen is returned to the FPS through the gas recovery system or discharged. Hydrogen is likely to leak from the high pressure components (35 MPa) and low pressure components (1 MPa) of the storage system, fuel cell stacks, and piping of the hydrogen fuel delivery system.

In this study, the behavior of leaking hydrogen was investigated when a vehicle was at rest, when a vehicle was moving, and after a vehicle was shut-down because of the hydrogen leakage. A hydrogen fuel cell vehicle uses hydrogen with high pressure (35 or 70 MPa) and a battery above 400 Volts. Due to this nature the safety of a hydrogen fuel cell vehicle, against the risk of fire, electric isolation failure or electric shock, should be secured in the event of a collision. There is no provision regarding the hydrogen leakage of a hydrogen fuel cell vehicle in Article 91 (Fuel System) in the Korean Motor Vehicles Safety Standards. In this study the Japanese Motor Vehicles Safety Standards (Attachment 17) and GTR Draft ware utilized to evaluate the fuel system integrity of a sport utility vehicle by measuring the pressure drop when the vehicle was impacted.

RESEARCH

Research for the behavior of leaking hydrogen

Leakage test for a vehicle at rest

(A) Locations of leaking points

Eleven leaking points were chosen, mainly fittings near the storage system. Eight leaking points were fittings connected directly to the storage system and three leaking points connected directly to the FPS. The hydrogen flow rate was 40 liters/min (LPM) which was the maximum allowable limit before the excess flow valve (EFV) began to operate. The experiments were continued until the hydrogen sensors detected 4 % hydrogen in air under the condition that the maximum post crash hydrogen leakage was equivalent to maximum post crash leakages of 120~130 LPM from gasoline vehicles.

Twelve on-board hydrogen sensors were located on the floor near the storage container. Outside the vehicle eight hydrogen sensors were installed at 1.5 m high around the vehicle where a human might smell the hydrogen and nine hydrogen sensors were installed at 3 m high around the vehicle, taking into consideration of parking area. Considering the possibility of hydrogen leakage into the passenger compartment, one near the stack, one near the FPS, one on the instrument panel and two in the interior were installed. With thirty four sensors in total the concentration of leaking hydrogen and response time were measured.

(B) Test Results of Hydrogen Leakage

Test results were collected from two areas, the underbody and engine compartment of a hydrogen fuel cell vehicle. Hydrogen leakage was simulated along the direction of hydrogen leakage at each fitting on the underbody. Figure 1 shows that hydrogen concentrations at Sensors No. 20, 31 and 32, which were measured with respect to the directions and flow rates at 8 leaking points on the underbody. It was expected that above 3 sensors were likely to detect any leakage from the underbody. Especially Sensors No. 31 and 32 were originally installed by the manufacturer and Sensor No. 32 covered any leakage from all area. Sensor No. 20 was found to detect any leakage faster and from the wider area than Sensor No. 31.

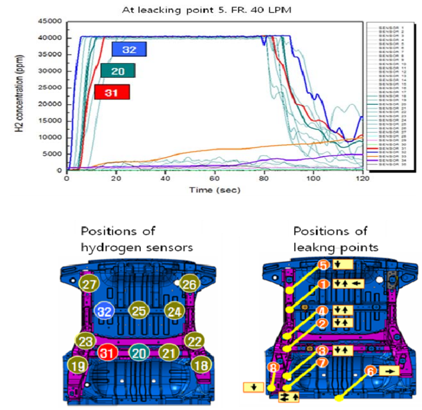

Figure 1. Hydrogen concentration at Sensors No. 20, 31 and 32, measured with respect to the directions and flow rates at 8 leaking points on the underbody.

Figure 2 shows the sensor locations and leaking points in the engine compartment. Hydrogen leaked from 3 points and measurements were made at the sensors shown in Figure 3. Sensors No. 28, 29, and 30 were installed near the stack, FPS and instrument panel respectively by the manufacturer.

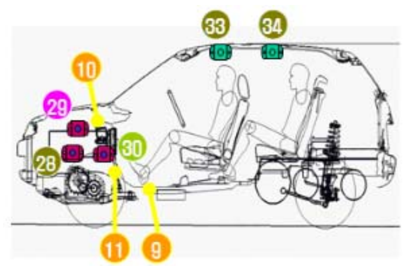

Figure 2. The sensor locations and leaking points in the engine compartment.

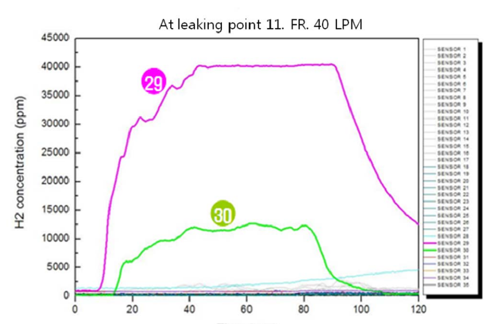

Figure 3. Hydrogen concentration at each sensor in the engine compartment. The flow rate was 40 LPM forward.

The results show that Sensor No. 29 in FPS was found to detect any leakage faster and more effectively than Sensor No. 30 on the instrument panel in any case. It was concluded that Sensor No. 29 in FPS was located at the optimum location and Sensor No. 30 on the instrument panel might be redundant and removed.

Leakage test for a moving vehicle

(A) Simulation of leakage

Before the experiment, the behavior of hydrogen flow was analyzed by simulation for a moving vehicle. Hydrogen was supposed to leak from high pressure lines at the maximum allowable limit of 131 LPM [3] while a vehicle was moving at 36 km/h. The simulation package was STAR-CCM+. Figure 4 shows the simulation results.

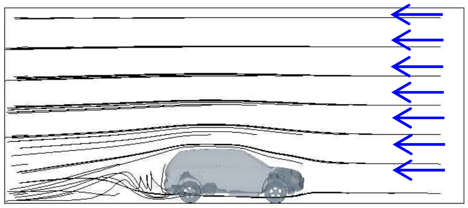

Figure 4. Simulation of hydrogen leakage for a moving vehicle.

Figure 5 shows that hydrogen concentration in air of 4 % or more was localized near leaking points. Because hydrogen was rapidly diffused to the outside by outside air flow, other sensors barely detected hydrogen.

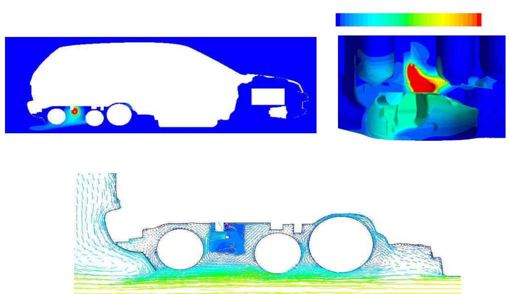

Figure 5. Analysis of hydrogen leakage for a moving vehicle.

(B) Leakage Experiment for a moving vehicle

In this experiment SUV hydrogen fuel cell vehicle was used. The head wind of 10 m/sec was blowing to the vehicle with a fan to simulate driving. Eleven possible leaking points at the storage system and delivery subsystem were shown in Figure 6. Leaking points were mainly connections. At these leaking points hydrogen was leaking with the hydrogen leakage simulation system.

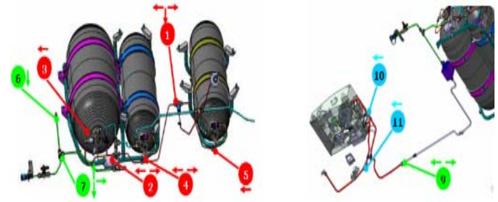

Figure 6. Possible leaking points.

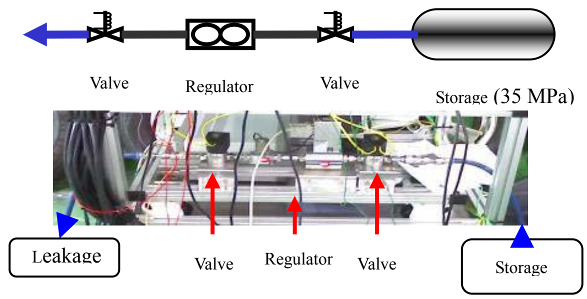

Figure 7. Hydrogen leakage simulation system.

To detect leaking hydrogen 34 sensors in and out of the vehicle were installed as in Figure 8. At each leaking point hydrogen leakage was controlled at 10, 40, and 131 LPM. The flow rates were set at 10 LPM for a low flow rate, at 40 LPM for the onset of Excess Flow Valve (EFV), and 131 LPM for the maximum hydrogen leakage based on the heat energy equivalent to maximum post crash leakages from gasoline vehicles specified in US FMVSS 301. The direction of leakage from each leaking point was set for the front (FF), rear (RR) and side (LH, RH).

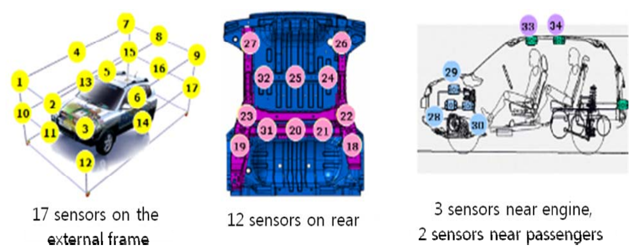

Figure 8. Locations of 34 sensors.

The test consisted of two parts. The first part was from the beginning of leakage to the point where a hydrogen concentration in air by volume reached 2 % (the onset of EFV, where the car was shut-down). Time to reach 2 % concentration was measured for this part. The second part was after the shut down. At 10 seconds and 60 seconds after the shut-down, a hydrogen concentration in air was measured. The duration period was measured, which meant the time for the hydrogen concentration in air to stay higher than 4 % after shut-down.

In case of a stationary vehicle a large amount of hydrogen was expected to leak if EFV shut-down the valve on detecting a hydrogen concentration in air of 2 %. The delay time between shut-down and detection of 2 % should be reconsidered. However, because the conditions for shut-down were related to emergency, the conditions should be reviewed from many aspects.

On detecting a hydrogen concentration in air of 2 % by volume on any leaking points, the vehicle was shut-down. Though a concentration might reach 4 % within 10 seconds after detecting, concentrations everywhere dropped below 4 % after one minute. The results from this study will be a ground to establish a guide for the desirable number and locations of sensors to be installed in and out of a vehicle.

Crashworthiness test and Analysis

Vehicle Preparations

The purpose of this test was to assess the fuel system integrity in the event of a rear collision. The mock-up vehicle was impacted the frontal and the rear impact test of 48 km/h, the side impact test of 50 km/. After the crash the amount of hydrogen leakage were examined. The mock-up vehicle was equipped with the hydrogen fuel storage system built by the manufacturer. Additional structural change was made to adjust weight distribution equivalent to the related parts such as the fuel cell stack, electric motors, batteries, etc. The hydrogen fuel storage system was filled to 90 % of nominal working pressure with helium gas. Air tightness was verified before the test. The hydrogen fuel cell vehicle is equipped with crash sensors that enabled the high pressure valve of the storage container to be closed automatically after a crash. However in this experiment all crash sensors were removed to simulate severe test conditions. [1),2),4),7),9)]

Verification of compliance and Analysis

(A) Overview: Article 91(Fuel System) in the Korean Motor Vehicle Safety Standards(KMVSS) applies to hybrid vehicles, electric vehicles and vehicles using gasoline, diesels and CNG. Passenger vehicles and buses with GVW of 4.5 tons or less are subject to this regulation. These vehicles shall meet fuel spillage requirements after and during the crash. In any rollover test, from the onset of rotational motion, vehicles shall meet fuel spillage requirements for the first 5 min of testing at each successive 90° increment on the longitudinal center line of a vehicle.

(B) Relevant standards: Japanese Safety Standard Attachment 17 (Technical Standard for Fuel Leakage in Collisions, etc.) and Attachment 100 (Technical Standard for Fuel Systems of Motor Vehicles Fueled by Compressed Hydrogen Gas). This standard applies to the fuel tank and fuel lines of vehicles using compressed hydrogen gas in the events of frontal and rear collisions. Hydrogen leakage shall not exceed 131 LPM (118 LPM at GTR Draft) for the first 60 min after the impact.

(C) Test procedures and Methods: Based on Article 91 (Fuel System) in the Korean Motor Vehicles Safety Standards and the Japanese Motor Vehicles Safety Standards (Attachment 17 & 100), amount of fuel leakage and body-acceleration were measured.

- Pressure sensors were installed in the test vehicle where hydrogen fuel system including the hydrogen tank was installed.
- The Fuel tank and fuel system was filled with helium gas at high (33 MPa) and low (1 MPa) pressure parts. Soap bubbles were used to test the leakage.
- The mass of test vehicle consisted of the unloaded vehicle and two dummies, equivalent to 156 kg.
- The Side impact of the moving barrier was 950kg.
- The Rear impact of the moving barrier was 1,805kg.
- Acceleration sensors were installed at the vehicle's center of mass, right and left of B-pillar and in the fuel tank.
- The hydrogen fuel storage system was filled to 90 % of nominal working pressure with helium gas.
- The degree of deformation was measured in vehicle's body and around fuel tank before and after the test.
- The temperature was measured around the test vehicle.
- High speed cameras were used when necessary.

Test results

(A) The Frontal Impact Test

 Pressure measurement after test

Figure 9 is the pressure measurement after the test. The high (31.5 MPa) and low (0.8 MPa) pressure stayed constant showing no reduction in pressure.

 Measurement of deformation in body and area near the fuel tank

The biggest deformation, 41.69 mm occurred along the longitudinal center line, which was measured the hydrogen receptacle points. In the area around the fuel tanks, brackets supporting the front fuel tank showed the biggest damage, 41.38 mm.

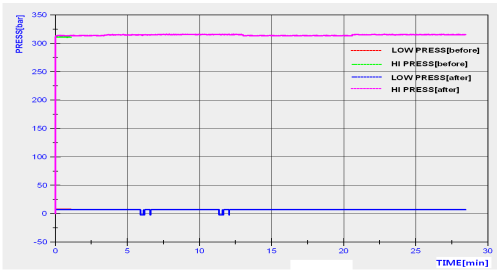

Figure 9. Pressure measurement after the frontal impact test.

□ Pictures showing the test

Pictures in Fig. 10 show the vehicle of frontal impact test scene. After the test, the occupant safety requirements met KMVSS article 91, 102.

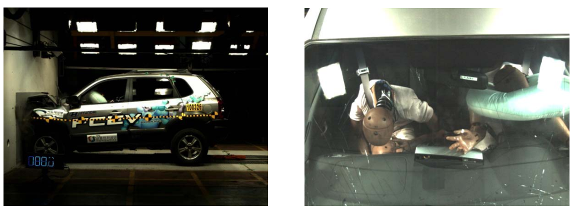

Figure 10. The test vehicle of frontal impact test.

□ Test data

□ Acceleration of the vehicle

Figure 11 shows locations of acceleration sensors.

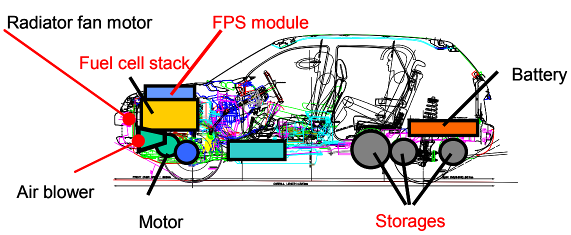

Figure 11. Locations of acceleration sensors.

Figure 12 shows the acceleration measured at body, B-pillar, storages of the vehicle. Figure 12 is a graph comparing the measured acceleration values for B-pillar on the left and the test car's center of gravity and the measured acceleration value for the storages. The value of any acceleration represents the vehicle traveling direction (X-axis) and the value of the acceleration waveform (pulse) and the maximum were similar to the body and storages. The middle of the storage was the highest value of acceleration.

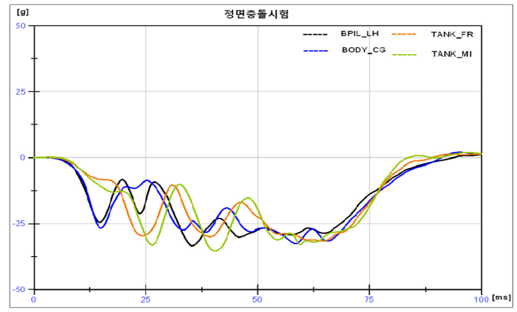

Figure 12. Acceleration graphs of the B-pillar and Body.

□ Electrical safety measures of post crash

Picture in Figure 13 show the insulation resistance measurement scene. After the Frontal Impact Test, 3.1 kΩ/V values for the battery and body insulation resistance measurement were to meet the criteria. (100Ω/V) [1),3),5),6),8)]

Figure 13. Insulation resistance measurement.

(B) The Rear Impact Test

□ Pressure measurement after test

Figure 14 is the pressure measurement after the rear impact test. The high (33 MPa) and low (1 MPa) pressure stayed constant showing no reduction in pressure.

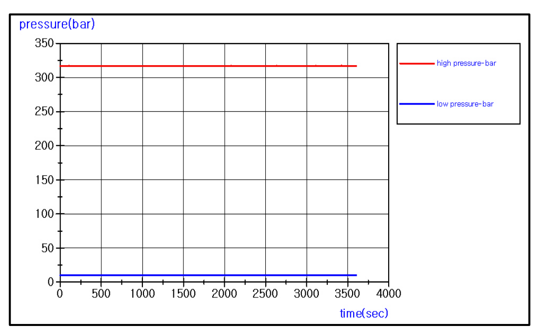

Figure 14. Pressure measurement after the rear impact test.

□ Measurement of deformation in body and area near the fuel tank

Table 1 show the amount of deformation in the body and in the area near the fuel tank. The biggest deformation, 245 mm occurred along the longitudinal center line, which was measured between the mid points of front and rear bumpers. In the area around the fuel tanks, brackets supporting the rearmost fuel tank showed the biggest damage, 172 mm.

Table 1. Measurement of body deformation

Measured length	Deformation (mm)
Body length along longitudinal center line	245.1
Body length at one quarter line from the left	243.3
Body length at left end of bumper	200.3
Body length at one quarter line from the right	238.3
Body length at right end of bumper	236.9

□ Pictures showing the test

Pictures in Figure 15 show the vehicle before and after the test. Other than some weights to adjust the total weight of the vehicle, no additional system was installed in the engine compartment and the luggage compartment of the vehicle. After the test, the rearmost fuel tank was displaced toward the front by 172 mm, but not damaged.

Figure 15. Rear-right view of the test vehicle before and after test.

□ Test data

□ Acceleration of the vehicle

Figure 16 shows the acceleration measured at left/right sides of B-pillar of the vehicle. The maximum acceleration was 27.2 g at 23.8 msec on the left side of B-pillar, 21.9 g at 39.7 msec on the right side B-pillar.

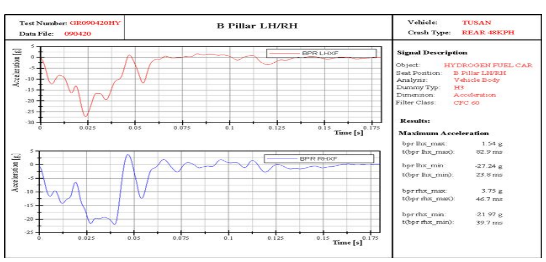

Figure 16. Acceleration graphs of the B-pillar.

□ Acceleration of fuel tank

Figure 17 and Figure 18 show the acceleration for each fuel tank. The first tank from the front showed maximum acceleration 89.4 g at 26.8 msec. the sensor at the middle one was broken due to the damage of lower part of the vehicle resulting in no measurement. The rearmost tank showed 102.2 g at 14.8 msec.

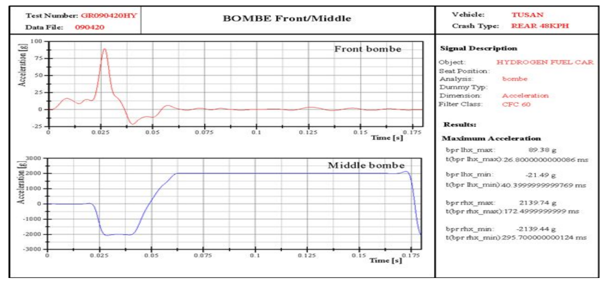

Figure 17. Acceleration graphs of the first and the second fuel tanks.

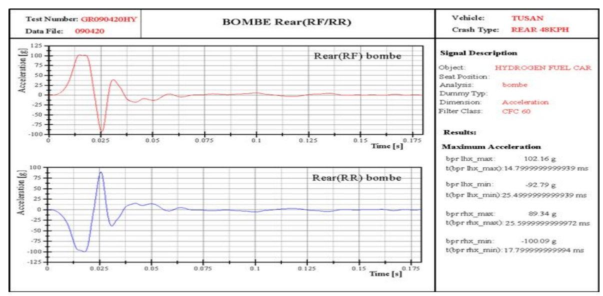

Figure 18. Acceleration graph of the rearmost fuel tank.

□ Rupture test of hydrogen fuel tank [7),10)]

It was possible that the shock from the impact caused some deterioration to the tank's function to be filled at high pressure repeatedly. The tank was ruptured at the pressure of 103.8 MPa. This was high enough to satisfy the criteria, 82.2 MPa, which was 2.35 times the nominal working pressure, the EIHP standard. The tank withstood the pressure cycling test of over 11,250. Therefore there was no functional deterioration in the tested fuel tanks.

Figure 19. Rupture test of hydrogen fuel tank after rear test.

(C) The Side Impact Test

□ Pressure measurement after test

Figure 20 is the pressure measurement after the test. The high (31.5 MPa) and low (0.8 MPa) pressure stayed constant showing no reduction in pressure.

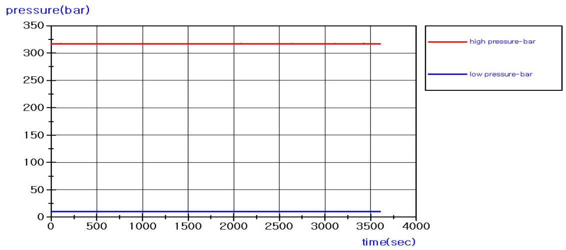

Figure 20. Pressure measurement after the side test.

□ Measurement of deformation in body and area near the fuel tank

Around the fuel tank and body is measured the lateral deformation. The biggest deformation, 168 mm occurred displacement which was measured H-point height of the baseline on the left side door and the right side door. Deformation around the fuel tank caused the most part is the fuel inlet area. Deformation in the direction perpendicular to the vehicle central longitudinal section is 39mm.

□ Pictures showing the side test

Pictures in Figure 21 show the vehicle of side impact test scene. After the test, the occupant safety requirements met KMVSS article 91, 102.

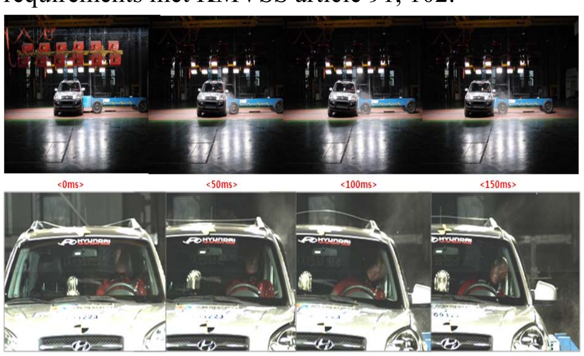

Figure 21. The test vehicle of side impact test.

□ Test data

□ Acceleration of the vehicle

Figure 22 shows the acceleration measured at body, motor, stack, battery, FPS of the vehicle. Accelerations at stack and FPS were relatively lower because they were located in front of vehicle. The motor was the highest value of acceleration.

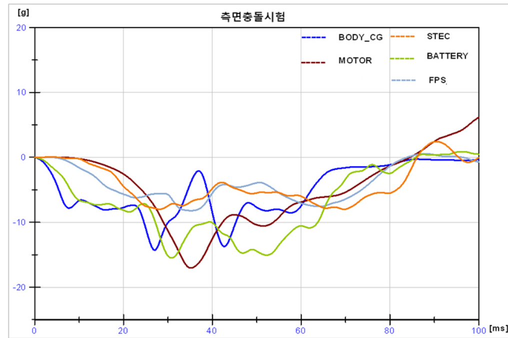

Figure 22. Acceleration graphs of the body and others.

ⓑ Electrical safety measures of post crash

Picture in Figure 23 show the insulation resistance measurement scene. After the Frontal Impact Test, 4.8 kΩ/V values for the battery and body insulation resistance measurement were to meet the criteria. (100Ω/V) [1),3),5),6),8)]

Figure 23. Insulation resistance measurement.

© Electrical safety measures of in use

· Protection against direct contact

- The live parts inside the passenger compartment or luggage compartment [5),6)]

Using the IPXX D test finger, evaluation tests were carried out passenger compartment and supercapacity of luggage compartment.

Figure 24. IPXX D (test wire) and luggage evaluation.

- The live parts in areas other than the passenger compartment or luggage compartment [5),6)]

Using the IPXX B test finger, evaluation tests were carried out junction box of bonnet.

Figure 25. IPXX B (test wire) and bonnet evaluation.

· Isolation Resistance

The minimum of electrical insulation resistance should be more than 100 Ω/V (DC), 500 Ω/V(AC). [5,6] Insulation resistance of AC and DC input and output with both the vehicle chassis was evaluated above 1.28 kΩ /V

Figure 26. Insulation resistance evaluation.

· Protection against indirect contact

The test criteria of Protection against indirect contact should be less than 100 mΩ. [5,6] The high voltage box enclosure and the Chassis was evaluated 5.4 mΩ. The supercapacitor enclosure and the chassis was evaluated 45.4 mΩ.

Figure 27. The high voltage box enclosure and the chassis evaluation.

Figure 28. The supercapacitor enclosure and the chassis evaluation.

CONCLUSIONS

The behavior of leaking hydrogen was investigated when a vehicle was at rest, when a vehicle was moving, and after the vehicle was shut-down because of the hydrogen leakage. To investigate the behavior of the leaking hydrogen, flow was analyzed by simulation for a moving vehicle. The simulation package was STAR-CCM+. In the simulation the vehicle was moving at 36 km/h and the hydrogen was supposed to leak from high pressure lines at the maximum allowable leakage of 131 LPM. During the test, the head wind of 10 m/sec was blowing to the vehicle with a fan to simulate driving. Thirty four sensors were installed at points where the leaking hydrogen was expected to be trapped. The test was done at leaking rates of 10, 40 and 131 LPM.

Next, in the frontal impact test, the test vehicle was impacted 48 km/h full frontal impact with hybrid Ⅲ 50 % male dummies. The test showed no leakage although some body deformation occurred. The electrical isolation and electrical continuity met the requirements in-use and post-crash. In case of frontal post-crash, it is not easy to measure electrical continuity because of severe damage to frontal part of vehicle.

In the rear impact test, the test vehicle was impacted form the rear by a moving barrier at the speed of 48 km/h. The test showed no leakage although some body deformation occurred. The results of tank rupture test also satisfied the safety standard of high pressure tank (EIHP). Functional deterioration of tank was not observed.

In the side impact test, the test vehicle was impacted 50 km/h side impact with deformable moving barrier (950 kg). The test showed no leakage although some body deformation occurred. The electrical isolation and electrical continuity met the requirements in-use and post-crash.

ACKNOWLEDGEMENT

This research was supported by a grant (07-Transport System-Furture-02) from Transportation System Innovation Program funded by the Ministry of Land, Transport and Maritime Affairs, Republic of Korea.

REFERENCES

[1] Korean Motor Vehicles Safety Standards, Article 91(Fuel Device) & 102(Passenger Protection at the Time of Collision)

[2] Japanese Motor Vehicles Safety Standards (Attachment 17) Fuel Leakage in Collision

[3] Japanese Motor Vehicles Safety Standards (Attachment 100 : Technical Standard for Fuel Systems of Motor Vehicles Fueled by Compressed Hydrogen Gas)

[4] http://www.unece.org/trans/main/wp29/grsp/informal group on hfcv-SGS

[5] http://www.unece.org/trans/main/wp29/grsp/informal group on electric safety

[6] UN ECE Regulation No. 100 "Uniform Provisions Concerning The Approval Of Battery Electric Vehicles With Regard To Specific Requirements for The Construction AND Functional Safety"

[7] UN ECE Regulation No. 110 "SPECIFIC COMPONENTS OF MOTOR VEHICLES USING COMPRESSED NATURAL GAS (CNG) IN THEIR PROPULSION SYSTEM"

[8] FMVSS 305, NHTSA. "Electric-powered vehicles: electrolyte spillage and electrical shock protection"

[9] FMVSS 303, NHTSA. "Fuel system integrity of compressed natural gas vehicles"

[10] FMVSS 304, NHTSA. "Compressed natural gas fuel container integrity"