EVALUATION ON MEASUREMENT PROCEDURE FOR POST-CRASH HYDROGEN CONCENTRATION

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Paper Number 15-0047

ABSTRACT

To examine the measurement method for post-crash hydrogen or helium concentrations in the cabins and other enclosed spaces of vehicles which is provided in the UN Global Technical Regulation on hydrogen fuel cell vehicles (HFCV-gtr), the present study investigated 1) wind velocity conditions not affecting the hydrogen concentrations in the cabin, 2) the effect of the impact absorber of a moving deformable barrier, and 3) the feasibility of substituting the hydrogen concentration measurement with helium gas. The results indicated that the HFCV-gtr measurement method posed problems in its accuracy and reliability because hydrogen concentrations in the cabin varied under the influence of a 0.1 m/s wind and in the presence of an impact absorber in contact with the test vehicle. Furthermore it was found that although HFCV-gtr defines a permissible hydrogen concentration of 4vol% to be equivalent with a permissible helium concentration of 3vol%, this equivalence could not be verified. Consequently it is necessary to replace the HFCV-gtr measurement method for in-cabin hydrogen concentrations with a simpler method immune to external disturbances.

INTRODUCTION

Currently the UN Global Technical Regulation on hydrogen fuel cell vehicles (HFCV-gtr)[1] regulates the hydrogen leakage of HFCVs and the hydrogen concentrations in enclosed spaces such as the cabin and the trunk room, after a crash test. HFCV-gtr permits a maximum hydrogen leakage of 118 NL/min and a maximum hydrogen concentration of 4vol%; in addition, HFCV-gtr allows the use of helium gas in place of hydrogen gas for ensuring the safety of crash tests. The maximum permissible helium leakage is set at 88.5 NL/min (= permissible hydrogen leakage flow rate x 0.75), and the maximum permissible helium concentration set at 3vol% (= permissible hydrogen concentration of 4vol% x 0.75) in view of the leakage-related properties of the two gases[2]. Nevertheless, in case hydrogen does not start leaking from the fuel system within 5 sec since the closure of the main stop valve after the crash, HFCV-gtr allows the omission of the hydrogen concentration measurement.

Unlike the gasoline vehicles and compressed natural gas vehicles that are required to measure only their fuel leakage flow rates after a crash test, HFCVs are required to measure both fuel leakage flow rate and hydrogen concentration, thus subjected to more complex measurement procedures.

Regarding the HFCV-gtr measurement methods for post-crash hydrogen and helium concentrations, there was a study on their possible replacement with the measurement of oxygen concentrations[2]. In another study, a crash test was performed with hydrogen sensors installed inside the test vehicle[3,4]. On the other hand, the present authors in their previous study investigated hydrogen concentrations in the vehicle underbody and the cabin with varied leakage locations, directions, flow rates and flow velocities (nozzle diameters) on the assumption that a side window pane is broken open in a side crash[5]. It was found that when hydrogen gas was leaked from the underbody, hydrogen rose along the side doors and infiltrated into the cabin from the lower side of the open window. This finding suggested that the presence of winds or a moving deformable barrier in the infiltration route of hydrogen

might affect the hydrogen concentrations in the cabin; also that for the cases where more complex hydrogen infiltration routes and more open windows are involved, it would be necessary to verify the validity of substituting hydrogen gas with helium gas, two types of gases with different diffusion coefficients.
Additionally the present study evaluated the hydrogen and helium concentration measurement methods by investigating , (1) wind velocities not affecting the hydrogen concentrations ,(2) the effects of moving deformable barriers (MDB), and (3) the reliability of the helium substitution test.

DESCRIPTION OF EXAMINATIONS

Test vehicles: A 2,000cc gasoline vehicle (mini-van, sized L4,630 x W1,695 x H1,710mm, interior size of L2,775 x W1,505 x H1,350mm) was employed as the test vehicle, which was collided with a 950 kg carriage serving as MDB at a crash speed of 55 km/h according to the Japan New Car Assessment Program test method. Figure 1 shows the post-crash view of the test vehicle and the MDB both of which came to a stop with the MDB impact absorber (honey-comb structure made of aluminum) in contact with the crashed side door of the test vehicle. The lateral center window of the test vehicle had broken open as a result of the crash.

Figure1. Test vehicle and side impact MDB after side crash test

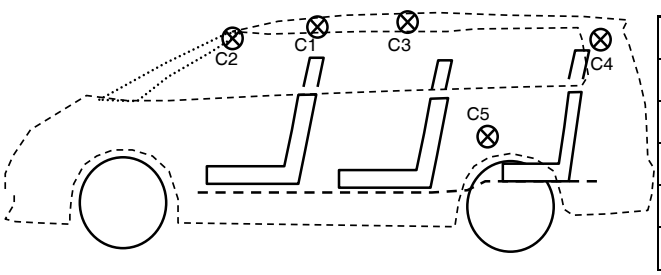
Because the post-crash measurement method of HFCV-gtr requires the measurement of hydrogen or helium concentrations and leakage, the crashed test vehicle was transported to the explosion resistance fire test cell of the Japan Automobile Research Institute in order to conduct an experiment in a safe, windless condition. The effect of the MDB was examined after placing a simulated impact absorber in contact with the test vehicle as shown in Figure 2.

Figure2. Simulated side impact MDB

Leakage conditions: Hydrogen (or helium) was leaked upward from the nozzles located at the center of the vehicle's underbody and at the center of the cabin floor, with the flow rate regulated by a mass flow controller. Only one (upward) nozzle direction was applied because previous studies[4,5] had found that hydrogen concentration distribution and the maximum concentration did not differ significantly between upward and downward nozzle directions when the hydrogen flow rate was about 2,000 LN/min.

In light of the fact that the fuel systems of HFCVs have pipes of a 1/4-inch (approx. 4 mm) inner diameter, nozzles of three different diameters (i.e., 1, 2, 4 mm) were applied. Considering the fact that HFCV-gtr permits a maximum hydrogen leakage of 118 NL/min, three different flow rates were applied--118 NL/min, 69 NL/min (a half), and 35 NL/min (a quarter). Two different leakage durations were applied--800 sec during which hydrogen concentrations were known to become constant inside the vehicle and 30 sec during which the hydrogen gas (estimated 59L) remaining in the piping after the closure of the main stop valve would be completely released at the maximum permissible hydrogen leakage of 118 NL/min for vehicle crash tests. To examine the effect of winds, an explosion-proof fan 600 mm in diameter was placed 5m away from the vehicle side.

Figure 3 shows the hydrogen concentration measurement positions in the cabin. Hydrogen and helium concentrations were measured using thermal conductivity hydrogen sensors (New Cosmos Electric Co., Ltd. XP-314).

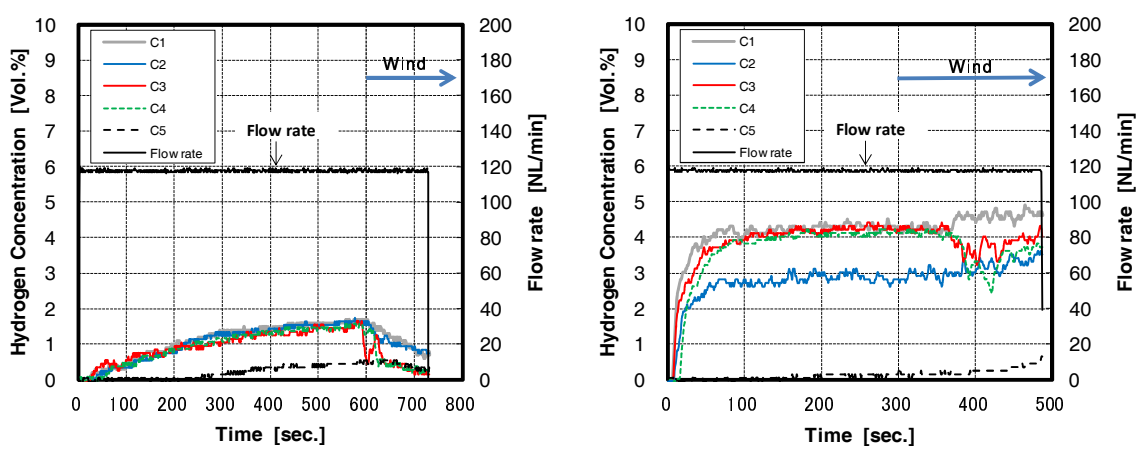


Position	Hydrogen concentration measurement position
C1	50mm below the roof above the driver's seat
C2	Near the mirror
C3	The center of the vehicle roof
C4	50mm below the roof at cargo compartment center
C5	50 mm above the floor at rear seat

Figure3. Hydrogen concentration measurement positions in the cabin

RESULTS AND DISCUSSION

Effect of winds on in-cabin hydrogen concentrations: The effect of winds blown from a side of the test vehicle was investigated concerning hydrogen concentrations in the cabin. Hydrogen was leaked from the vehicle underbody center or the cabin floor center continuously at a flow rate of 118 NL/min when a wind of 0.1 m/s was applied from a side direction. Figure 4 shows the hydrogen concentrations measured under the above conditions. The wind blowing was started 600 sec after the crash in Figure 4(a), and 300 sec after in Figure 4(b).

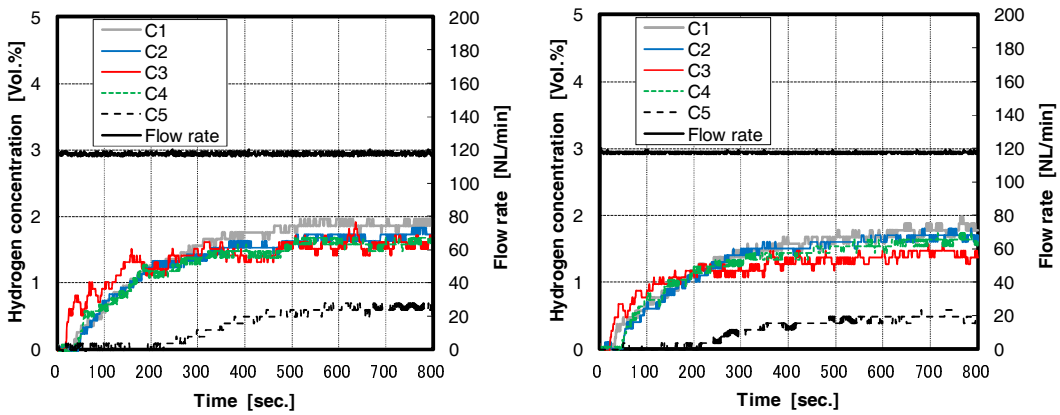


(a) Leakage point: Center of vehicle underbody ***(b) Leakage point:Center of cabin floor***

Figure4. Hydrogen concentrations in time sequence
(Wind velocity: 0.1 m/s and upward, Nozzle diameter: 4 mm, Flow rate: 118 NL/min)

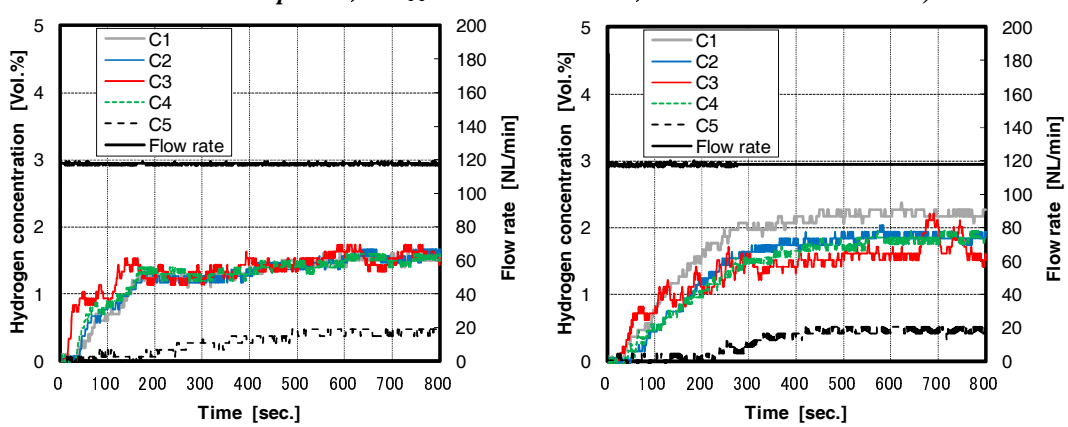
In both figures, in-cabin hydrogen concentrations were affected when winds were blown. Due to measurement accuracy limitations, the effect of winds below 0.1 m/s could not be examined in the present study. According to the Beaufort scale of wind force[5], a wind velocity of 0.1 m/s corresponds to a Beaufort number of 0 and is rated as "Calm". In other words, 0.1 m/s represents practically a windless state. Accordingly it can be considered problematic to conduct a measurement, verification or reproduction test on hydrogen concentrations in an outdoor testing facility where natural winds easily exceed 0.1 m/s. Similarly, it should be necessary to consider the effect of winds even in an indoor testing facility in warm seasons when the air conditioning is in operation. For example, the wind velocity around a test vehicle in the indoor crash test facility of the Japan Automobile Research Institute in summer (July) is an average of 0.5 m/s and a maximum of 3 m/s. Accordingly it is necessary to take account of wind factors even in an indoor testing sites.

Effect of the MDB impact absorber: The effect of the presence or the absence of an MDB impact absorber was examined in relation to in-cabin hydrogen concentrations. Figures 5, 6 and 7 show the hydrogen concentrations in time sequence measured under varied test conditions concerning the nozzle location (vehicle underbody center), nozzle diameters (1, 2, 4mm), flow rates (118 NL/min continuously), and the impact absorber's condition (present in contact with the vehicle side door, removal from the crash site).



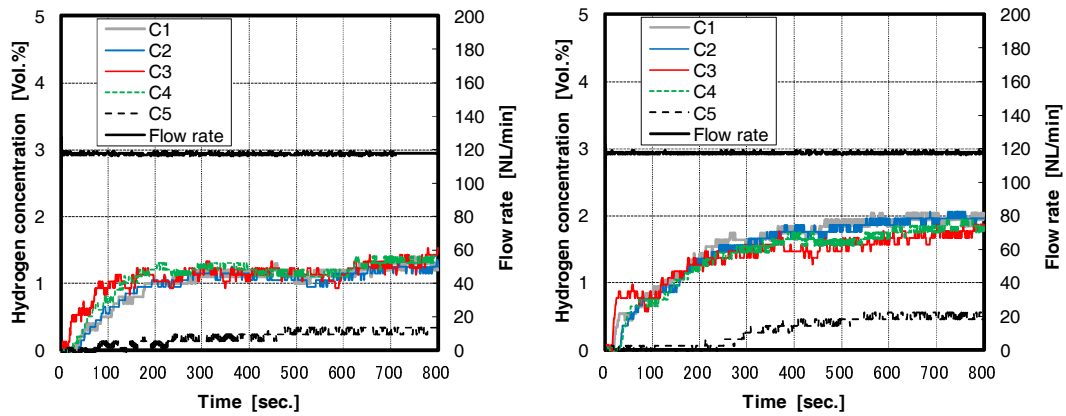
(a) Impact absorber contact case *(b) No impact absorber case*

Figure5. Hydrogen concentrations in time sequence (Leak point: center of vehicle underbody, Leak direction: upward, Nozzle diameter: 4 mm, Flow rate: 118 NL/min)



(a) Impact absorber contact case *(b) No impact absorber case*

Figure6. Hydrogen concentrations in time sequence (Leak position: center of vehicle underbody, Direction: upward, Nozzle diameter: 2mm, Flow rate: 118 NL/min)



(a) Impact absorbing contact case *(b) No impact absorber case*

Figure7. Hydrogen concentrations in time sequence (Leak position: center of vehicle underbody, Direction: upward, Nozzle diameter: 1mm, Flow rate: 118 NL/min)

Comparison between an impact absorber in contact with the side door and the absence of an impact absorber at the crash site indicated differences in in-cabin hydrogen concentrations. Tables 2 and 3 show the comparison results in terms of maximum hydrogen concentrations under varied test conditions.

Table2. Maximum hydrogen concentrations when in contact with impact absorber [vol%]

Leak position	Direction	Nozzle Dia. [mm]	Flow rate [NL/min.]	Door	Wind	Leak time [sec.]	C1	C2	C3	C4	C5	Max (Position)
Underbody center	Upper	4	118	Close	No	800	2.0	1.8	1.9	1.7	0.7	2.0(C1)
		2					1.6	1.7	1.7	1.6	0.5	1.7(C2,C3)
		1					1.4	1.3	1.5	1.4	0.3	1.5(C3)
		4	69				1.4	1.3	1.5	1.2	0.5	1.5(C3)
			35				0.9	0.7	1.0	0.8	0.3	1.0(C3)
			118			30	0.5	0.3	0.7	0.4	0.1	0.7(C3)

Table3.
Maximum hydrogen concentrations with only test vehicle (No impact absorber case) [vol%]

Leak position	Direction	Nozzle Dia. [mm]	Flow rate [NL/min.]	Door	Wind	Leak time [sec.]	C1	C2	C3	C4	C5	Max (Position)
Underbody center	Upper	4	118	Close	No	800	2.0	1.8	1.6	1.7	0.6	2.0 (C1)
		2					2.4	2.0	2.2	2.0	0.5	2.4(C1)
		1					2.0	2.1	1.9	1.9	0.6	2.1(C2)
		4	69				1.3	1.3	1.3	1.2	0.5	1.3(C1,C2,C3)
			35				0.9	0.9	0.9	0.9	0.3	0.9(C1,C2,C3,C4)
			118			30	0.5	0.4	0.7	0.5	0.1	0.7(C3)

As indicated in Tables 2 and 3, the maximum hydrogen concentrations varied among the measurement positions, thus confirming the effect of impact absorbers on maximum hydrogen concentrations. The explanation of this effect is that as leaked hydrogen ascended along the doors and infiltrates into the cabin from an open window[4,5], the presence of the impact absorber in a hydrogen dispersion route affected the hydrogen infiltration into the cabin.

For the above reason, it should be difficult to accurately evaluate the diffusion behavior of hydrogen gas leaking from an HFCV in the presence of an MDB or a fixed barrier each equipped with an impact absorber.

Due to the HFCV-gtr requirement to measure in-cabin hydrogen concentrations immediately after a crash test, it should be necessary to remove the MDB near or in contact with the test vehicle to a sufficiently distant place so that the in-cabin hydrogen concentrations will not be affected.

Helium substitution test procedure: If the test condition of a 118 NL/min permissible hydrogen leakage is substituted with helium, the permissible helium leakage is 88.5 NL/min by applying a He/H_2 permissible leakage ratio of 0.75 (= 88.5/118). Based on the observation that gas concentrations in an enclosed space are in proportion to the gas leakage flow rate, HFCV-gtr[1] gives the following Equation **(1)** for the calculation of permissible helium concentration X_{He} conducive to a permissible hydrogen concentration of 4vol%.

$$X_{He} = 4vol\%\ H_2 \times 0.75 = 3vol\% \qquad \textbf{(1)}$$

To verify if Eq.(1) is reliable under various test conditions, the present study investigated the He/H_2 ratios in the cabin under identical test conditions between hydrogen leakage at 118 NL/min and a helium leakage at 88.5 NL/min. Figures 8, 9 and 10 show the results of this test. Because the concentration values measured at the C5 position near the cabin floor proved exceptionally low, the concentrations only at C1 through C4 are shown in the following three figures.

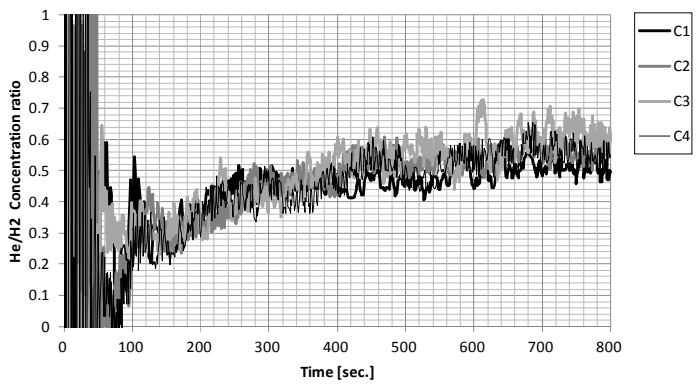


Figure8. He/H_2 concentration ratios
(Leakage point: center of vehicle underbody, Nozzle direction: upward, Nozzle diameter: 4 mm, Hydrogen flow rate: 118 NL/min, Helium flow rate: 88.5 NL/min)

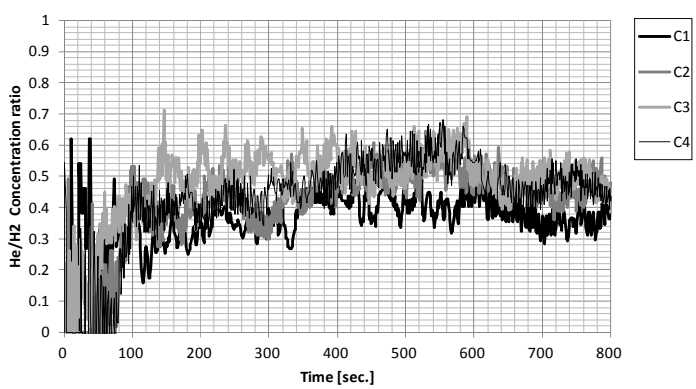


Figure9. He/H_2 concentration ratios
(Leakage point: center of vehicle underbody, Nozzle direction: upward, Nozzle diameter: 1 mm, Hydrogen flow rate: 118 NL/min, Helium flow rate: 88.5 NL/min)

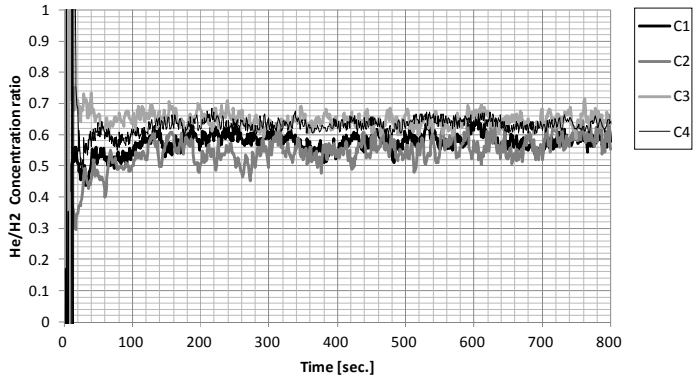


Figure10. He/H_2 Concentration ratios
(Leakage point: center of cabin floor, Nozzle direction: upward, Nozzle diameter: 4mm, Hydrogen flow rate: 118 NL/min, Helium flow rate: 88.5 NL/min)

The results indicated that the He/H_2 concentration ratio varied in the early phase of the test but gradually stabilized in the following phase onward. Nevertheless the ratio, instead of stabilizing at 0.75, varied according to leakage locations and nozzle diameters. The primary cause of this discrepancy was attributed to the fact that the aforementioned Equation (1) does not take account of differences in the diffusion behaviors of hydrogen and helium. Therefore, since no correspondence was found between a permissible hydrogen concentration of 4vol% and a permissible helium concentration of 3vol%, the validity of the helium substitution measurement method provided in HFCV-gtr was considered questionable.

CONCLUSIONS

To examine the measurement method for post-crash hydrogen concentrations provided in HFCV-gtr, the present study investigated 1) wind velocity conditions not affecting the hydrogen concentrations in the cabin, 2) the effect of the impact absorber of a moving deformable barrier, and 3) the feasibility of substituting the hydrogen concentration measurement with helium concentration measurement. As the results indicated that hydrogen concentrations in the cabin were affected by the presence of a 0.1 m/s wind in the testing facility and an impact absorber in contact with the test vehicle, the HFCV-gtr measurement method is considered to pose some problems in its accuracy and reliability. In addition, since the correspondence between a permissible hydrogen concentration of 4vol% and a permissible helium concentration of 3vol% assumed in HFCV-gtr could not be confirmed, the existing helium substitution measurement method was also considered questionable. Consequently it is necessary to replace the HFCV-gtr measurement method for in-cabin hydrogen concentrations with a simpler method immune to external disturbances.

Finally, the present study was carried out as part of the “technology development project for hydrogen production, transport and storage systems” commissioned by New Energy and Industrial Technology Development Organization (NEDO), a national research and development agency of Japan.

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