A STUDY ON THE EFFECTIVITY OF HYDROGEN LEAKAGE DETECTION FOR HYDROGEN FUEL CELL MOTORCYCLES

Kiyotaka, M.,[1] and Yohsuke, T.[2]
1. FC-EV Research Division, Japan Automobile Research Institute, 1328-23, Takaheta, Osaka, Shirosato, Ibaraki, 311-4316, Japan, kmaeda@jari.or.jp
2. FC-EV Research Division, Japan Automobile Research Institute, 1328-23, Takaheta, Osaka, Shirosato, Ibaraki, 311-4316, Japan, ytamura@jari.or.jp

ABSTRACT

Unlike four-wheel fuel-cell vehicles, fuel-cell motorcycles have little semi-closure space corresponding to the engine compartment of four-wheel fuel-cell vehicles. Furthermore, motorcycles may fall while parked or running. We conducted hydrogen concentration measurement and ignition tests to evaluate the feasibility of detecting leaks when hydrogen gas leaked from a fuel-cell motorcycle, as well as the risk of ignition. We found that the installation of hydrogen leak detectors is effective because it is possible to detect minute hydrogen leaks by installing leak detectors at appropriate points on the fuel cell motorcycle, and risks can be reduced by interrupting the hydrogen leak immediately after detection.

1.0 INTRODUCTION

Fuel cell vehicles which are one of the next generation environment-friendly vehicles have been sold since December 2014 as the first mass produced products. Appendix 100 of the Road Transport Vehicles Act in Japan states that four-wheel fuel-cell vehicles (FCV) shall be equipped with at least one hydrogen sensor between hydrogen tanks and a fuel-cell (FC) stack. If a hydrogen leak is detected, a warning shall be given to the driver and the shut-off valves shall be automatically closed [1]. Besides, UN Global Technical Regulation on hydrogen and fuel cell vehicles (gtr No.13) states that a mechanism to close the shut-off valves automatically shall be equipped to prevent a leak of over 3±1 Vol.% hydrogen concentration is detected [2].

On the other hand, unlike four wheel FCVs, FC motorcycles have little semi-closure space which is comparable to an engine compartment of gasoline vehicles and may fall while it is parked or running. In FC motorcycles, there are no reports evaluating whether or not a hydrogen leak can be detected or the risk if a hydrogen is leaked.

In this paper, we measure hydrogen gas concentrations to check if a hydrogen leaks can be detected by hydrogen-leak detectors installed in each part of an FC motorcycle, and if a leak can be detected, we evaluate which positions are appropriate for detecting the leak. We also conducted ignition tests to evaluate the risk of a hydrogen leak from an FC motorcycle to consider whether or not installing a mechanism to shut down the leaking of hydrogen gas is effective.

2.0 CONSIDERATION OF ACCURATE HYDROGEN LEAK DETECTION POINTS

2.1 Experiment

In this study, we based our information on a scooter type FC motorcycle [3], then, a commercially available gasoline-engine motor scooter was purchased and altered. A specification sheet for the commercially available vehicle used for altering is shown in Table 1. In this model, the hydrogen tank is installed in the lower part in between the wheels, and the FC stack is installed in the trunk. We installed a metal box which simulates an FC stack (Simulated FC stack) in the trunk of the vehicle. We also installed pipes for hydrogen leaks and hydrogen gas detectors on the vehicle.

Table 1. Specification of the commercially available vehicle used for altering

Item	Value
Length (mm)	2,055
Width (mm)	740
Height (mm)	1,355
Wheelbase (mm)	1,465
Vehicle weight (kg)	161
Seating capacity (people)	2
Engine displacement (cm^3)	199

1/4-inch pipes were used for testing, and the diameter of the leak holes were 4.57 mm. Four leak pipes were mounted in the vehicle: 3 of the pipes were mounted near the hydrogen tank valve which is placed between the tank and the FC stack (leak points A), one pipe was mounted near the frame under the seat which is considered to be a location where high hydrogen concentrations can be detected (leak point B). Leak directions for leak points A were upper, lower, and backward direction of the vehicle, and for leak point B, it was the upper direction. The hydrogen tank, the FC stack, and the lithium-ion battery mounted positions for the consulted scooter type FC motorcycle, and the mounted pipes are shown in Figure 1. Examples of the mounted pipes are shown in Figure 2, and the simulated FC stack is shown in Figure 3.

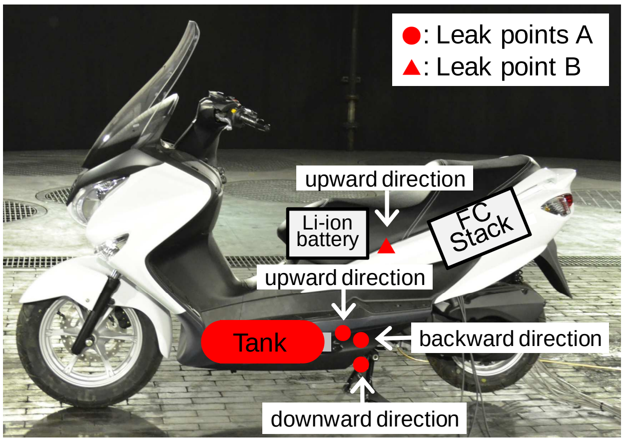

Figure 1. Hydrogen tank, FC stack, lithium-ion battery, and hydrogen leak pipes mounted positions

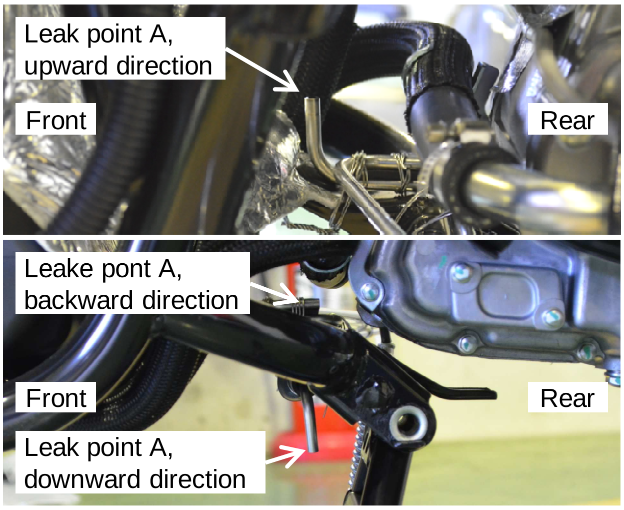

Figure 2. Examples of leak positions and their directions

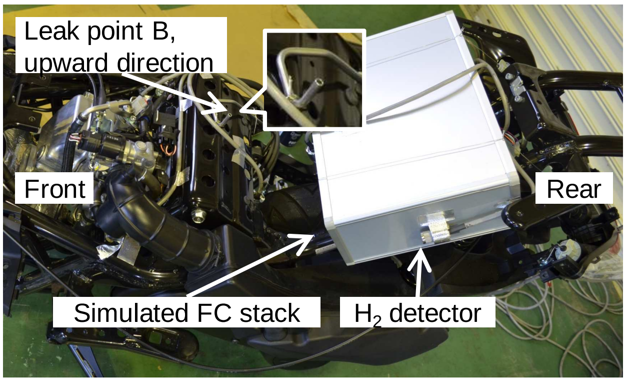

Figure 3. Simulated fuel cell stack mounted position

Measurements of hydrogen concentrations were conducted by mounting a total of 10 thermal conductivity type hydrogen detectors on the vehicle body (AB-5618, diffusion type, New cosmos electric co., LTD, Japan, and XP-314, suction type, New cosmos electric co., LTD, Japan). Actual measurement values of 90 % response time for a diffusion type was approximately 8 seconds, and a suction type was approximately 9 seconds. Indication accuracies for both of the types are ±5 %, resolution for the diffusion type is 0.5 vol.%, measurement limits are 0 %. All of the measurement points are shown in Table 2, and a side view of measurement points and a schematic view of the leak points of the vehicle are shown in Figure 4.

Table 2. Hydrogen concentration measurement points

Symbol	Measurement point	H_2 detector type
H1	Center stand fixing point upper	Diffusion
H2	Center stand fixing point upper left	Diffusion
H3	Center stand fixing point upper right	Diffusion
H4	Rear tire front	Suction
H5	Fuel cell stack front	Suction
H6	Fuel cell stack downside	Diffusion
H7	Fuel cell stack left hand	Diffusion
H8	Fuel cell stack right hand	Diffusion
H9	Seat inner side	Diffusion
H10	Rear end of the frame upper	Diffusion

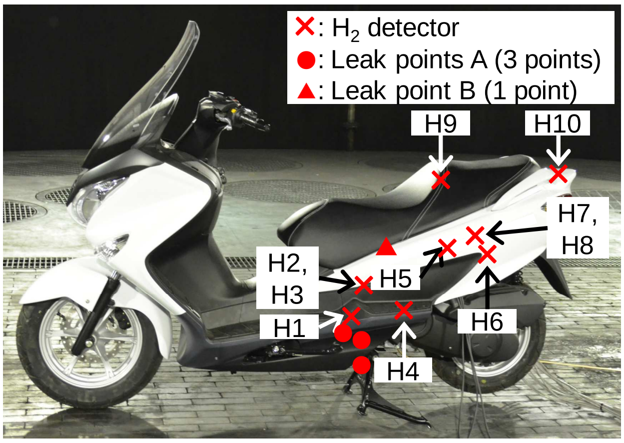

Figure 4. Hydrogen concentration measurement points

The vehicle was placed in two positions: upright as in the parked state with the center stand up and lying on the left to simulate a fall. Two leak conditions were adopted. One is a continuous leak that assumes that there are no leak detection mechanisms, the other is an on-off leak that assumes momentary closure of the shut-off valve if a leak is detected. Continuous leaks were continued for 120 seconds or over. In order to understand the relationships between hydrogen concentrations and hydrogen flow rates more accurately, we conducted the tests up to 1000 NL/min. However, it is said that the maximum hydrogen consumption rates for the FC motorcycles are approximately 300 NL/min. In the on-off leaks, it was assumed that approximately 5.5 NL of hydrogen gas in the pipe leaks, when the shut-off valve is closed within 0.3 seconds. Flow rates were controlled by using a mass flow controller (CMQ1000, Azbil corporation, Japan), and leak times were controlled by a timer (H3CR-A, Omron corporation, Japan). Table 3 shows leak conditions.

Table 3. Hydrogen concentration measurement test conditions

Item	Condition
Vehicle condition	upright, lying on the left
Leak position	A : Near the center stand fixing point
	B : Below the Seat
Leak direction	A : upward, backward, downward
	B : upward
Flow rate (NL/min)	Continuation : 10, 50, 100, 250, 500, 1000
Release time (s)	Continuation : Over 120
	On-off : 0.3

2.2 Results and discussion

In the example of a continuous leak of 100 NL/min, the results in the upward direction from the leak positions A in the vehicle that was standing upright is shown in Figure 5.

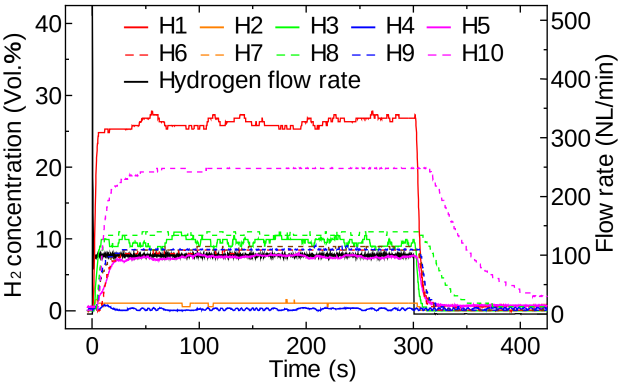

Figure 5 Results of hydrogen concentration for continuation leak
(Upright, leak position A, upward leak, 100 NL/min)

In this case, it takes approximately 60 seconds till all of the hydrogen measurement points stabilize to roughly steady states.

Next, the relationships between leak directions in 3 directions (i.e. upward, backward, and downward) and the maximum hydrogen concentrations after the steady states at a rate of 100 NL/min leak from the vehicle that is standing upright or lying are shown in Figure 6.

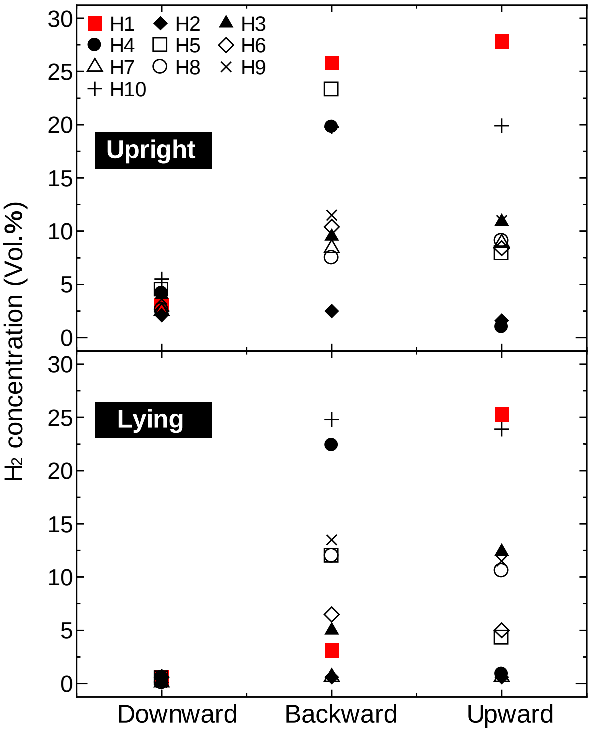

Figure 6. Comparison of hydrogen concentrations at 100 NL/min

In the same vehicle conditions, measured hydrogen concentrations for upside leaks are higher than the others. Therefore, this direction is the most valid for detecting the hydrogen leaks. The maximum concentrations at H1 are approximately 28 vol.% for upright and approximately 25 vol.% for lying. In the following, we conducted that the measurements for the upside leaks that are the most valid to detect the hydrogen leaks. Relationships between the maximum hydrogen concentrations after the steady sates and the flow rates at the leak points A are shown in Figure 7, and the leak point B are shown in Figure 8, respectively.

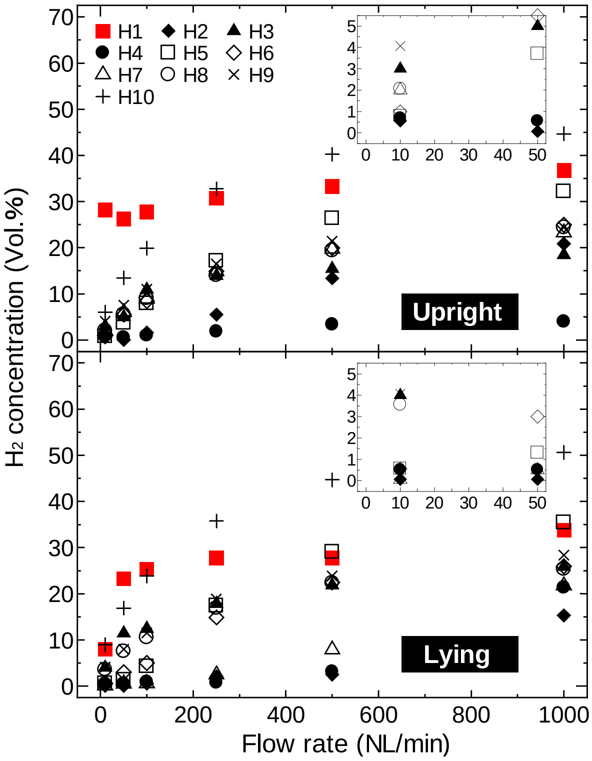

Figure 7. Relationship between hydrogen flow rate and maximum hydrogen concentration (Leak position A, upward leak)

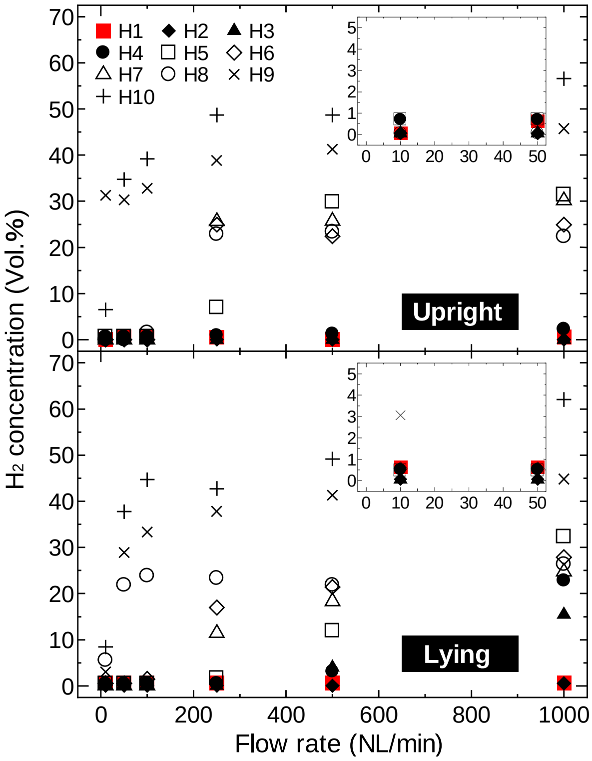

Figure 8. Relationship between hydrogen flow rate and maximum hydrogen concentration (Leak position B, upward leak)

Hydrogen concentrations at H1 for each part of leak points A and point B tend to be proportional to the hydrogen flow rates. Though FC motorcycles have little semi-closure space, similar results were also observed in the tests which were conducted by using a four wheel gasoline vehicle which has semi-closure space [4]. At the leak point B, hydrogen concentrations near the simulated FC stack, H5 to H8, started increasing when hydrogen flow rate exceed 250 NL/min, and over 10 vol.% hydrogen concentrations were measured at some points. This is considered to be due tothe leaked hydrogen hit under the Seat, then diffused near the simulated FC stack. In the case of lying, hydrogen concentrations at the right hand of the simulated FC stack are higher than that at the left hand, and these concentrations are more than 3 vol.% for all hydrogen flow rates.

High hydrogen concentrations observed points are at H1 from 8 to 36 vol.% and at H10 from 6 to 50 vol.% for leak poins A, and at H9 from 3 to 46 vol.% and at H10 from 7 to 62 vol.% for leak point B. On the other hand, there were lower hydrogen concentrations. For example, at H2 are 0 vol.% for all flow rates and vehicle conditions when hydrogen is leaked from the leak point B. Therefore, measurement positions which are considered easy for detecting are H1, which lies on the upper position of the leak pipe; H9, which is on the surface below the Seat; and H10, which is on the highest position on the back. Because over 3 vol.% hydrogen concentrations are detected in the case of 10 NL/min continuous leaks.

Next, as an example, the results of the on-off leak in the upward direction from the lower part of the vehicle which is standing upright is shown in Figure 9.

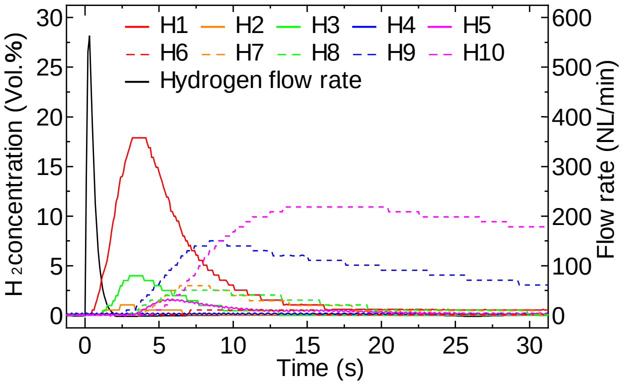

Figure 9. Results of an on-off leak (Upright, leak points A, upward leak, about 5.5 NL leak)

In analogy with the steady leaks, hydrogen concentrations at H1, which lies at leak positions upper, and H10, which lies at rear top, are higher than the others. The maximum concentrations of these are 18 vol.% at H1 and 11 vol.% at H10. The observed tendencies showed that hydrogen concentrations are higher at H1 and H10 were also observed when the vehicle is lying.

Based on the above results, independent of the vehicle states, by installing hydrogen leak detectors between a hydrogen tank and an FC stack, and at rear frame upper space, a hydrogen leak could be detected at least 3 vol.% in the case of continuous leak of 10 NL/min and an on-off leak. Therefore, by installing contact burning-type hydrogen detectors which are usually used for FCVs and can detect below 4 vol.% hydrogen leaks, a leak could be detected faster and more accurate than the other points. Under these test conditions, spaces between H1 and H5 or H1 and H9, which lie in below the Seat, and at H10 are considered to be more accurate points.

3.0 IGNITION TEST

3.1 Methods

Next, we conducted ignition tests to evaluate the risk if a hydrogen leak occurs from an FC motorcycle and then ignites. The ignition points were H1 and H10 where we measured hydrogen concentrations were higher than the others in the previous chapter tests. Electric sparks with 1 mm length of gap and energy of 30 mJ were used in ignition tests. The vehicle was tested in 2 states: upright, and lying. Leak position was at leak point A, and leak direction was upside. The spark times for the continuous leaks were set at 120 seconds after the leak had begun, and for the on-off leaks were set at the time when the maximum hydrogen concentrations were detected on the leak tests. If an ignition did not occur for the on-off leak, the spark had been continued till an ignition occurs. Heat fluxes were measured by thin foil flexible heat flux sensors (Captec, HF-20), and noise pressure was measured by microphones (PCB, 378B02), blast waves were measured by blast sensors (PCB, 137B23B). Thermal images were also recorded to judge whether or not an ignition occurred. The sensors set positions for upright were at 0 m on the left hand of the center stand and at 2 m away from measurement point, and for lying state it was just below the vehicle and at 2 m away from the vehicle. The test conditions are shown in Table 4, and an over view is shown in Figure 10. As we described in the next section, the reason why the maximum flow rate in Table 4 is 250 NL/min is that this flow rate could injure people. Therefore, we didn't conduct the ignition tests over 250 NL/min flow rate.

Table 4. Ignition test conditions

No	Vehicle condition	Leak time (s)	Flow rate (NL/min)	Maximum hydrogen concentration (Vol.%)*	Ignition point	Ignition time (s)
1	Upright	120	10	6	H10	120
2	Upright	120	10	26	H1	120
3	Upright	120	50	13	H10	120
4	Upright	120	50	25	H1	120
5	Upright	120	100	20	H10	120
6	Upright	120	100	27	H1	120
7	Upright	120	250	33	H10	120
8	Upright	0.3	-	11	H10	16
9	Upright	0.3	-	11	H10	till ignition
10	Upright	0.3	-	18	H1	3.5
11	Upright	0.3	-	18	H1	till ignition
12	Lying	120	10	9	H10	120
13	Lying	120	50	22	H1	120
14	Lying	120	100	25	H1	120
15	Lying	120	250	35	H10	120
16	Lying	0.3	-	12	H1	3.5
17	Lying	0.3	-	12	H1	till ignition
18	Lying	0.3	-	13	H10	10

* Results of hydrogen concentration measurement tests

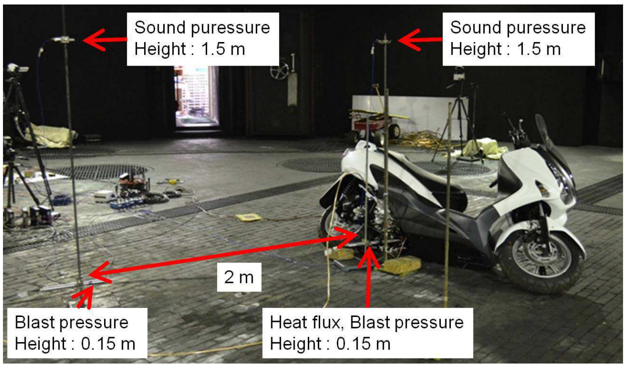

Figure 10. Overview of ignition test

3.2 Result and discussion

The test results are shown in Table 5. We evaluated influences of noise level, blast wave pressure, and heat flux on the human body when leaked hydrogen is ignited. Consequences of how noise levels affect the human body are known as follows: if they hear 110 dB noise level for 30 minutes a day, it causes hearing impairment, 120 to 130 dB noise levels cause a sense of pain, 150 dB noise level injures the ear drum then instantly loses hearing [5]. In the case of continuous leaks of below 100 NL/min, the maximum noise level when an ignition occurs was 123.4 dB at 0 m away from the vehicle which was upright and that was test number 6. In the case of on-off leak, the maximum noise level was 126.1 dB at 0 m away from the vehicle which was upright, and that was test number 17. In other words, these noise levels do not have an impact on the human body, since they feel pain in their ears when they are standing. On the other hand, in the case of a continuous leak of 250 NL/min, measured noise levels were 140 dB which exceeded the upper limit measurement value at 0 m away from the vehicle for test number 7 the vehicle was upright and for test number 15 the vehicle was lying. Therefore, if humans hear an ignition noise similar to the test conditions, at the very least humans will feel a sense of pain and could lose hearing in some situations. Next, we evaluated influences of blast wave pressure on the human body. The impact that blast wave pressure has on the human body are as follows: the peak pressure of 16.5 kPa could damage the eardrums of 1% of the people, the peak pressure of 100 kPa could kill of 1% of the people [5]. The maximum measured blast pressure in the tests was test number 7, which was conducted by leaking hydrogen continuously at a rate of 250 NL/min with the vehicle standing. The results of the test are shown in Figure 11, and the successive pictures are shown in Figure 12. In Figure 11, the measured blast pressure 0 m away from the vehicle at a height of 0.15 m is 14.2 kPa. It shows that the blast wave pressure has little effects on the human body in all tests if standing. Besides that, we can see in Figure 12 that several parts of exterior materials in the downward of the vehicle were gone off, but the vehicle is not seriously damaged.

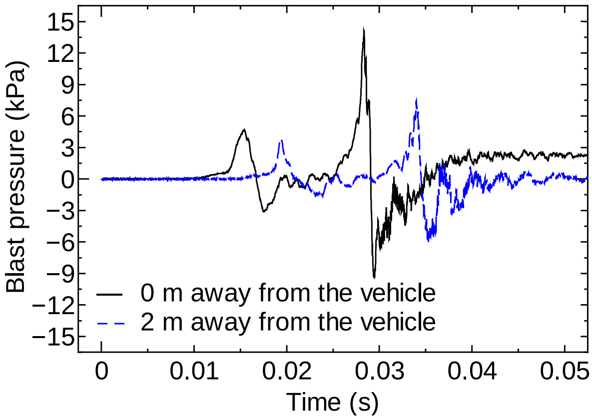

Figure 11. Examples of blast pressure

Figure12. Successive pictures of ignition test number 7

Table 5. Ignition tests results

No	Total leak volume (NL)	Result	Noise level 0 m (dB)	Noise level 2 m (dB)	Blast pressure 0 m (kPa)	Blast pressure 2 m (kPa)	Heat flux 0 m (kW/m2)
1	-	No ignition	N.D.	N.D.	N.D.	N.D.	N.D.
2	-	Ignition	117.2	114	N.D.	N.D.	N.D.
3	-	Ignition	N.D.	N.D.	N.D.	N.D.	N.D.
4	-	Ignition	119.5	114.7	0.1	0	N.D.
5	-	Ignition	86.1	83.8	N.D.	N.D.	N.D.
6	-	Ignition	123.4	120.2	N.D.	N.D.	0
7	-	Ignition	Over 140	Over 140	14.2	7.5	1.9
8	5.94	No ignition	N.D.	N.D.	N.D.	N.D.	N.D.
9	5.97	Ignition	N.D.	N.D.	N.D.	N.D.	N.D.
10	5.55	No ignition	N.D.	N.D.	N.D.	N.D.	N.D.
11	5.92	Ignition	109.2	102.9	N.D.	N.D.	N.D.
12	-	No ignition	N.D.	N.D.	N.D.	N.D.	N.D.
13	-	Ignition	119	116.6	0.1	0.1	N.D.
14	-	Ignition	121.5	117.8	0.3	0.1	1.2
15	-	Ignition	Over 140	135.9	5.3	3.7	2.2
16	5.64	No ignition	N.D.	N.D.	N.D.	N.D.	N.D.
17	5.56	Ignition	126.1	124.6	0.3	0.2	N.D.
18	4.84	Ignition	N.D.	N.D.	N.D.	N.D.	N.D.

Lastly, we evaluate the influences of heat flux. Generically, the impact heat flux has on the human body is known as follows: the heat flux of 0.1 m away from a 100 W filament lamp is 6.4 kW/m^2, the heat flux of 10 kW/m^2 could cause a burn injury on skin if it is exposed for 10 seconds, the heat flux of 50 kW/m^2 could cause a burn injury on skin if it is exposed for a second [7]. The maximum heat flux was measured in test number 15, where the flow rate was 250 NL/min and the vehicle was lying, and its heat flux was 2.2 kW/m^2 at 0 m away from the vehicle. Therefore, in all the test conditions, it was concluded that the heat fluxes are not so high that the human body could seriously be impacted.

From the results above, the on-off leaks could not affect the human body. On the one hand, the continuous leaks of below 100 NL/min could not have a great impact on the human body if ignition occurs, on the other hand the 250 NL/min leaks could cause impaired hearing due to the noise level. Therefore, ignition risks in fuel-cell motorcycles can be reduced by installing hydrogen-gas leak detectors and by providing a mechanism to close the shut-off valve immediately if a leak is detected, so we conclude that it is effective to install hydrogen leak detectors.

4.0 SUMMARY

We measured hydrogen gas concentrations to check if a hydrogen leak can be detected by hydrogen-leak detectors installed in each part of an FC motorcycle, and if a leak can be detected, we evaluated which positions are appropriate for detecting a leak. We also conducted ignition tests to evaluate the risk of hydrogen leaks from an FC motorcycle to consider whether or not installing a mechanism to shut down the leaking of hydrogen gas is effective.

As a result, independent of the vehicle states, by installing hydrogen leak detectors between a hydrogen tank and an FC stack, and at the rear frame upper space, a hydrogen leak could be detected at least 3 vol.% in the case of a continuous leak of 10 NL/min and an on-off leak. Therefore, by installing contact burning-type hydrogen detectors which are usually used for FCVs and can detect below 4 vol.% hydrogen leaks, a leak could be detected faster and more accurate than the other points.

As for the results of risk evaluations, in the case of leaked hydrogen ignition, it was indicated that minute leaks which generically can occur do not affect the human body if it is ignited. On the other hand, if a human was near the vehicle and a tremendous amount of leaked hydrogen, such as 250 NL/min, was ignited, the human body could experience impaired hearing due to the noise level. Therefore, ignition risks in fuel-cell motorcycles can be reduced by installing hydrogen-gas leak detectors and by providing a mechanism to close the shut-off valve immediately if a leak is detected, so we concluded that it is effective to install hydrogen leak detectors.

ACKNOWLEDGEMENT

This study is part of the studies consigned by the New Energy and Industrial Technology Development Organization (NEDO) in Japan.

REFERENCES

1. Ministry of Land, Infrastructure, Transport and Tourism, the Road Transport Vehicles Act in Japan, Appendix 100, Technical standard on fuel devise for vehicles run on compressed hydrogen gashttp://www.mlit.go.jp/common/000190517.pdf [in Japanese]
2. Global technical regulation No. 13， Global technical regulation on hydrogen and fuel cell vehicles， http://www.mlit.go.jp/jidosha/un/UN_gtr013.pdf
3. Ministry of Economy, Trade and Industry, High Pressure Gas Safety Office, Standard relevant to tanks on Hydrogen Fuel Cell Motorcycles, http://www.meti.go.jp/committee/sankoushin/hoan/koatsu_gas/pdf/009_07_00.pdf [in Japanese]
4. Maeda Y. et. al., Diffusion and Ignition Behavior on the Assumption of Hydrogen Leakage from a Hydrogen-Fueled Vehicle, SAE Technical Paper, 2007-01-0428
5. Like these blasts and like those blasts, Examples of blast, Japan explosives industry association, p.30 2000 [in Japanese]
6. F. P. Lees et. al., Industrial safety engineering hand book, Kaibundo, 1989, p. 623[in Japanese]
7. Techno office, Indexes of heat flux, http://www.techno-office.com/file/heatflux-estimate.pdf [in Japanese]