# EFFECTIVENESS OF A BLOWER IN REDUCING THE HAZARD OF HYDROGEN LEAKING FROM A HYDROGEN-FUELED VEHICLE

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## ABSTRACT

To handle a hydrogen fuel cell vehicle (HFCV) safely after its involvement in an accident, it is necessary to provide appropriate emergency response information to the first responder. In the present study a forced wind of 10 m/s or faster with and without a duct was applied to a vehicle leaking hydrogen gas at a rate of 2,000 NL/min. Then, hydrogen concentrations were measured around the vehicle and an ignition test was conducted to evaluate the effectiveness of forced winds and the safety of emergency response under forced wind conditions. The results: 1) Forced winds of 10 m/s or faster caused the hydrogen concentrations in the vicinity of the vehicle to decline to less than the lower flammability limit, and the hydrogen gas in the various sections of the vehicles were so diluted that even if ignition occurred the blast-wave pressure was moderate. 2) When the first responder had located the hydrogen leakage point in the vehicle, it was possible to lower the hydrogen concentrations around the vehicle by aiming the wind duct towards the leakage point and blowing winds at 10 m/s from the duct exit.

## 1.0 INTRODUCTION

It is necessary to develop an emergency procedure for handling a hydrogen fuel cell vehicle (HFCV) involved in an accident such as a collision or a fire in order to enhance the safety of in-use HFCVs and to reassure the users about the safety of their vehicles. In the series of the first responder’s procedure for the handling of an accident-involved HFCV, one problem situation from the perspective of safety is where it is critical for the first respondent to approach the HFCV as quickly as possible.

One example of such situation is where hydrogen is leaking from a crashed HFCV and the persons trapped inside the vehicle must be rescued. Another example is where an HFCV from which hydrogen is leaking must be removed from the underground car park to a safe ventilated place. It has been found that a safe handling method for such situations is to disperse leaking hydrogen gas to concentrations below its lower flammability limit by using a blower.

Hydrogen release and dispersion behaviors were investigated by many researchers through computational fluid dynamics (CFD) simulation and experimental measurement. Hydrogen dispersion and ignition tests using real vehicles were carried out by Maeda et al. [1] [2] and Gentilhomme et al. [3]. Maeda et al. [2] confirmed that even if hydrogen leaks from the underfloor section of a vehicle at a flowrate of 1,000 NL/min and is ignited in the engine compartment, the persons present in the vicinity of the vehicle are not injured.

Tamura et al. [4] experimentally investigated hydrogen dispersion in the vicinity of a vehicle which was releasing hydrogen horizontally in its underfloor section at a single volumetric flow of 2,000 NL/min while forced winds of a maximum 2 m/s were applied to the vehicle from its lateral or frontal side (Fig. 1). Tamura et al. [4] reported that forced winds of 2 m/s enlarged the region of hydrogen concentrations equal to or exceeding the lower flammable limit, thus failing to disperse leaked hydrogen sufficiently. It was suggested that the velocity of forced wind needs to be increased or the wind blowing method should be improved to disperse hydrogen gas to safe levels.

To investigate the method for rescuing safely in the state of a hydrogen leak from hydrogen vehicle, forced winds of 10 m/s or faster were applied directly or through a duct to a vehicle that was leaking hydrogen gas at a rate of 2,000 NL/min. Then, hydrogen concentrations were measured around the vehicle and an ignition test was conducted to evaluate the effectiveness of forced winds and the safety of emergency response under forced wind conditions.

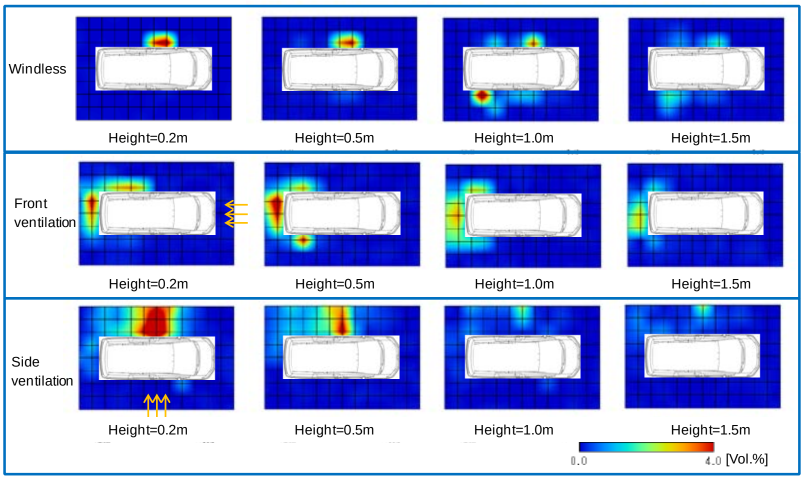


Figure 1. Isosurface of hydrogen concentrations around vehicle (by experiments)1)

## 2.0 MEASUREMENT OF HYDROGEN CONCENTRATIONS

### 2.1 Test Procedure

### 2.1.1 Side Crash Test

A gasoline-fueled mini-van was employed as the test vehicle. To obtain a body shape simulating that of a vehicle fresh from a crash accident, a side crash test was performed on the test vehicle (Fig. 2) according to the test method used in JNCAP or the Japan New Car Assessment. Specifically, a 950 kg moving deformable barrier mounted with an aluminum honeycomb impact absorber of a rigidity equivalent to the rigidity of a passenger car was made to collide into the test vehicle at an impact speed of 55 km. As a result the test vehicle had its side door dented and its side windows broken.

(a) Side crash test (b) View of damage to vehicle

Figure 2. Side crash test (based on JNCAP method)

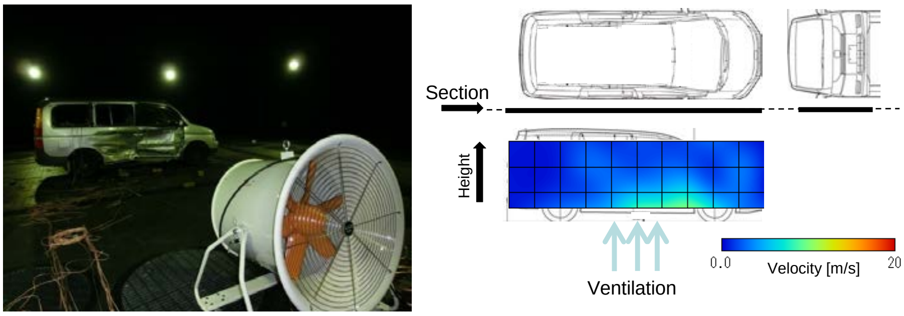
After the crash test, the vehicle was taken to an indoor testing site at the Hydrogen and Fuel Cell Vehicle Safety Evaluation Facility of the Japan Automobile Research Institute, where there were practically no natural winds. A hydrogen leakage test was conducted at this indoor site.

### 2.1.2 Blower

While hydrogen gas was leaking from the test vehicle, forced winds were delivered to the vehicle by a blower in two modes – 1) directly from the blower and 2) through a duct attached to a blower. Fig. 3 shows the locational relationship of the test vehicle and the blower and the distribution of wind velocities. A blower with a maximum air-capacity of 460 $m^3$ was placed 2 m forward or lateral to the test vehicle. The maximum velocity of winds from the blower was about 20 m/s and the wind width was 2 m as measured on the front and lateral faces of the vehicle. When the blower was placed 5 m from the vehicle, the maximum wind velocity and the wind width proved to be about 10 m/s and 3m, respectively.

(a) Blower 2 m forward to vehicle; wind velocity distribution on vehicle front

(b) Blower 5 m forward to vehicle; wind velocity distribution on vehicle front



(c) Blower 5 m lateral to vehicle; wind velocity distribution on vehicle side

Figure 3. Blower-vehicle positions and wind velocity distribution

In the case of delivery of winds from a duct, a smaller blower with a maximum air-capacity of 50 m$^3$ was employed (Fig. 4). A duct of a 320 mm internal diameter was attached to the blower, and the maximum wind velocity was about 10 m/s as measured at the center of the duct exit. When the hydrogen concentrations around the vehicle stabilized after hydrogen leakage, the delivery of winds from the duct was started towards the vehicle from its front or lateral side.

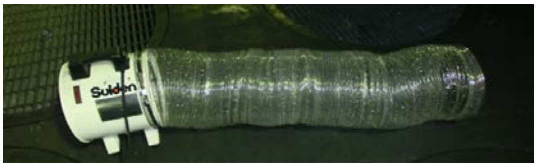


Figure 4. Blower fitted with a duct

### 2.1.3 Hydrogen Leakage

Fig. 5 summarizes the hydrogen leakage method applied in the present study.

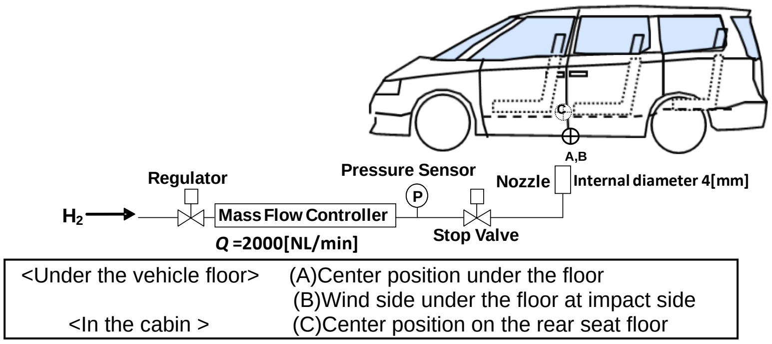


Figure 5. Outline of the hydrogen leakage method

Hydrogen was released upwards from a pipe with an internal diameter of 4 mm located at position (A), (B) or (C). The hydrogen flow-rate was regulated by a mass flowmeter at 2,000 NL/min which is a flow-rate equivalent to the hydrogen consumption amount of a standard passenger car HFCV with a 200 kW output power. It was assumed that hydrogen leakage occurred due to the operation failure of the excess flow check valve.

### 2.1.4 Measurement of Hydrogen Concentration

Hydrogen was released from the center position of the vehicle's underfloor section, the blower was turned on for wind delivery, and then hydrogen concentrations were measured at various points in the vicinity of the test vehicle, an example of which is shown in Fig. 6.

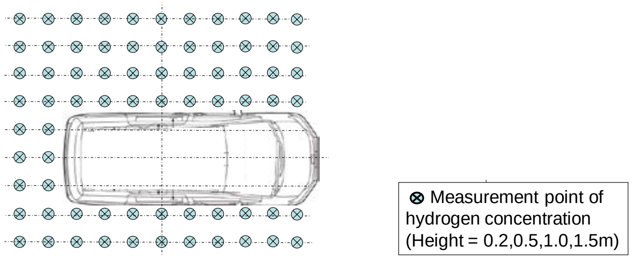


Figure 6. Hydrogen concentration measurement points (blower on vehicle's lateral side)

The hydrogen concentration measurement points were located at 0.5 m intervals and at heights of 0.2 m, 0.5 m, 1.0 m and 1.5 m above ground. As the hydrogen densitometers, thermal conductivity hydrogen sensors (New Cosmos Electric Co., Ltd. XP-314) were used. Hydrogen concentrations were also measured inside the vehicle sections as shown in Fig. 7.

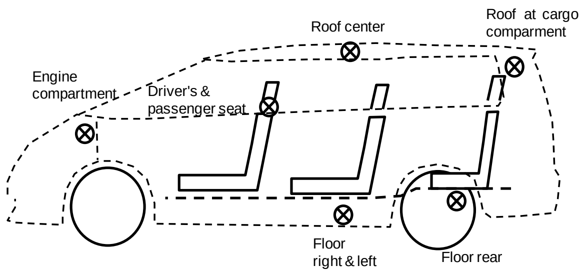


Figure 7. Hydrogen measurement points inside vehicle sections

## 2.2 Results and Discussions

### 2.2.1 Distribution of Hydrogen Concentrations around the Vehicle

Fig. 8 shows the isosurface images of hydrogen concentrations around the test vehicle leaking hydrogen at a flowrate of 2,000 NL/min from point A at its underfloor center. The isosurface images compare a windless state with the situations of winds delivered by a blower 2 m away from a position lateral to the vehicle.

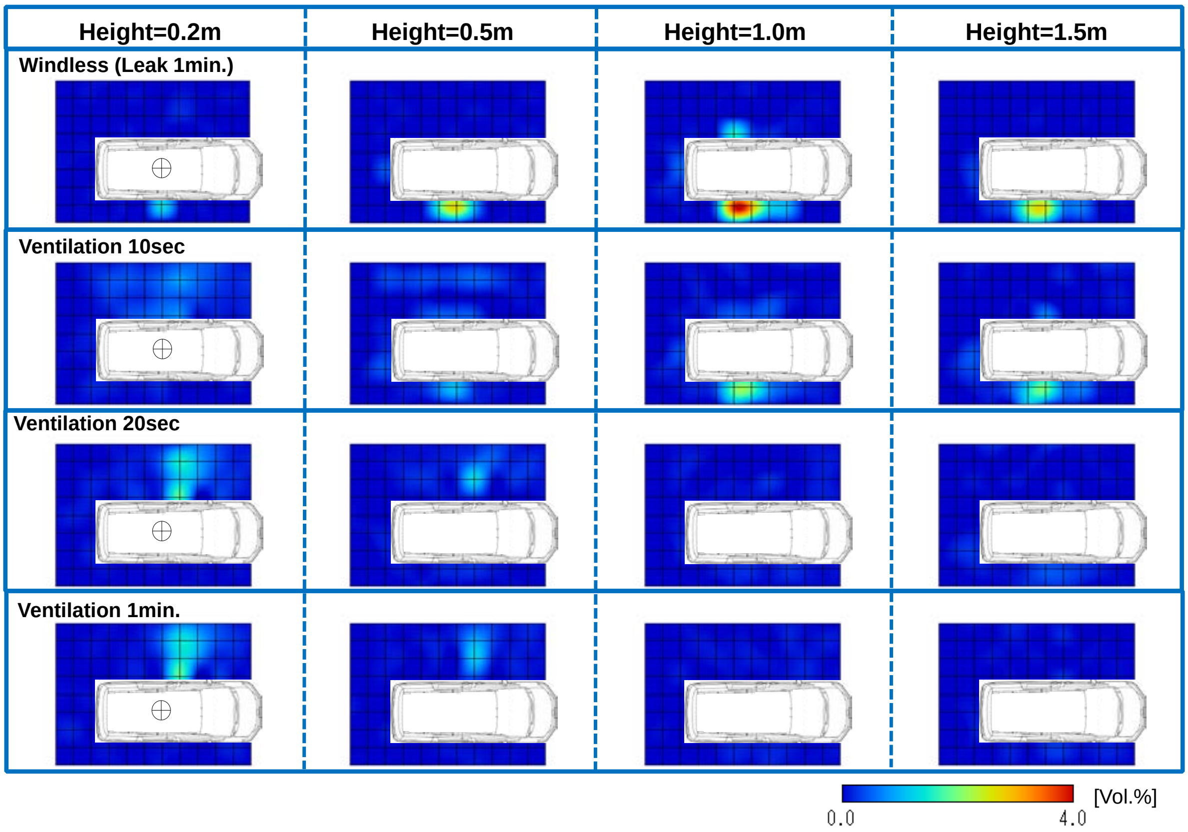


Figure 8. Isosurface of hydrogen concentrations around vehicle (hydrogen flowrate of 2,000 NL/min, leakage point A, blower 2 m from vehicle side)

In a windless condition, hydrogen flowed upward along the side surfaces of the test vehicle and generated some areas where hydrogen concentration exceeded the lower flammable limit of 4 vol%. Then, the blower was turned on; the hydrogen gas was gradually dispersed leeward and the hydrogen concentrations around the vehicle declined below 2 vol%.

Isosurface changes in hydrogen concentrations due to forced winds from the blower are shown, with Fig.s 9 and 10 showing the cases of the blower placed 2 m and 5 m in front of the vehicle, respectively. (The flowrate of leaking hydrogen was 2,000 NL/min, and the leakage point was at point A or the vehicle’s underfloor center.)

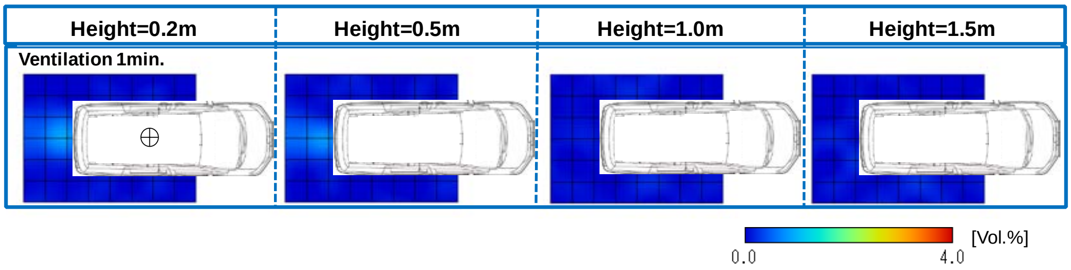


Figure 9. Isosurface of hydrogen concentrations around vehicle (hydrogen flowrate of 2,000 NL/min,leakage point A, blower 2m from vehicle front)

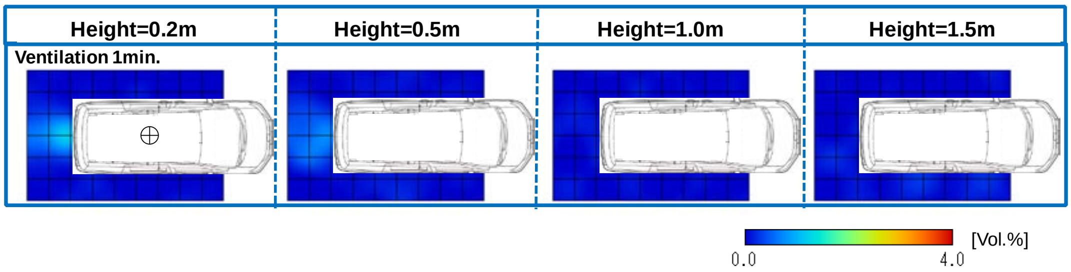
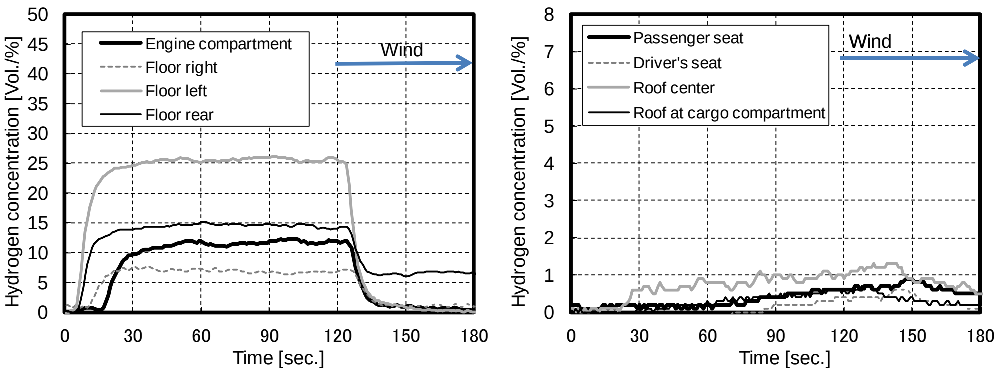


Figure 10. Isosurface of hydrogen concentrations around vehicle (hydrogen flowrate of 2,000 NL/min, leakage point A, blower 5 m from vehicle front)

When the blower was placed forward to the test vehicle, the hydrogen gas was gradually dispersed leeward and the hydrogen concentrations around the vehicle declined to below 2 vol%. The above test results confirmed that hydrogen gas leaking from the underbody of a vehicle at a flowrate of 2,000 NL/min can be diluted to below 4 vol% by delivering winds of about 10 m/s to the vehicle.

### 2.2.2 Hydrogen Concentrations inside and on the Vehicle

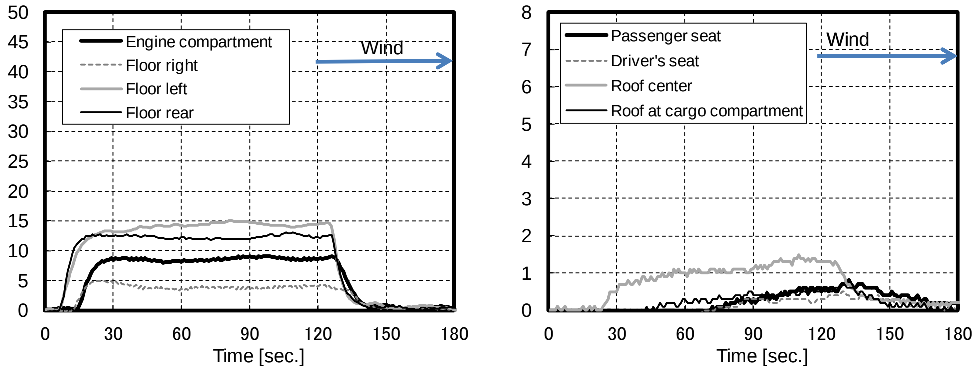
Fig. 11 shows the hydrogen concentrations measured in the underfloor section and cabin of the vehicle when winds were blown from 2m in front of the vehicle. Hydrogen was made to leak from point A at a flowrate of 2,000 NL/min for 180 sec while the blower was turned on from the 120th sec after the start of hydrogen leakage.



(a) Underfloor section (b) Inside cabin

Figure 11. Hydrogen concentrations inside vehicle (hydrogen flowrate of 2,000 NL/min, leakage point A, blower 2m from vehicle front)

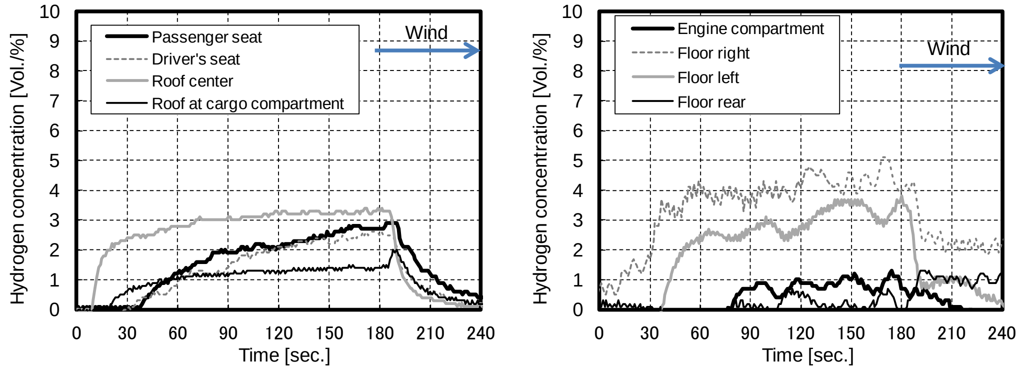
In a windless condition, hydrogen concentrations in the underfloor section exceeded 10 vol% while hydrogen also entered into the cabin from the window broken in the side crash test [4]. Once the blower was turned on, however, the hydrogen concentrations in the underfloor section and cabin gradually declined.



(a) Underfloor section (b) Inside cabin

Figure 12. Hydrogen concentrations inside vehicle (hydrogen flowrate of 2,000 NL/min, leakage point A, blower 5m from vehicle side)

Fig. 12 shows the hydrogen concentrations measured in the underfloor section and cabin of the vehicle when winds were blown from 5 m lateral to the vehicle. Similar to the case of forced winds from the front side of the vehicle, forced winds from the lateral side caused hydrogen concentrations to decline in both underfloor section and cabin.

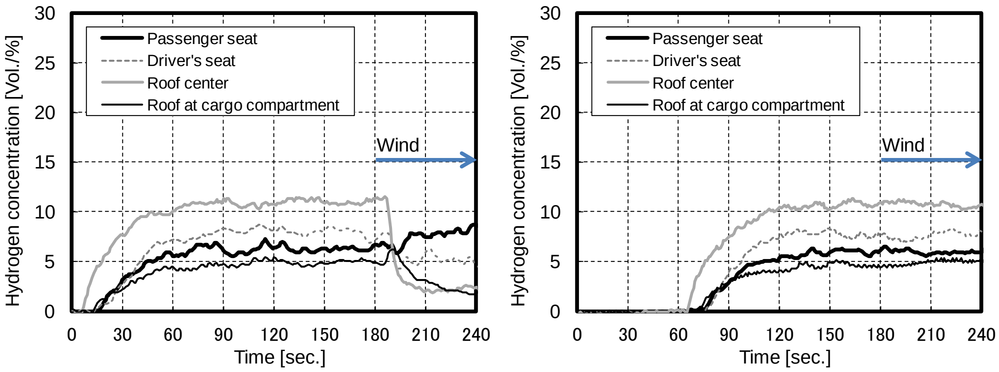


(a) Underfloor section (b) Inside cabin

Figure 13. Hydrogen concentrations inside vehicle (hydrogen flowrate of 2,000 NL/min, leakage point B, blower 5m from vehicle front)

Fig. 13 shows the hydrogen concentrations measured in the underfloor section and cabin of the vehicle when winds were blown from 5 m in front of the vehicle. This time, hydrogen was leaked from point B at the same flowrate of 2,000 NL/min for the first 180 sec while the blower was turned on from the 180th sec.

While point B was located on the vehicle’s crash impact side, hydrogen continued to accumulate inside the underfloor section and cabin in the absence of forced winds. Once wind delivery was started, the hydrogen concentrations gradually declined.



(a) Blower 5m from vehicle’s side (b) Blower 5m from vehicle’s front

Figure14. Hydrogen concentrations inside cabin (hydrogen flowrate of 2,000 NL/min, leakage point C)

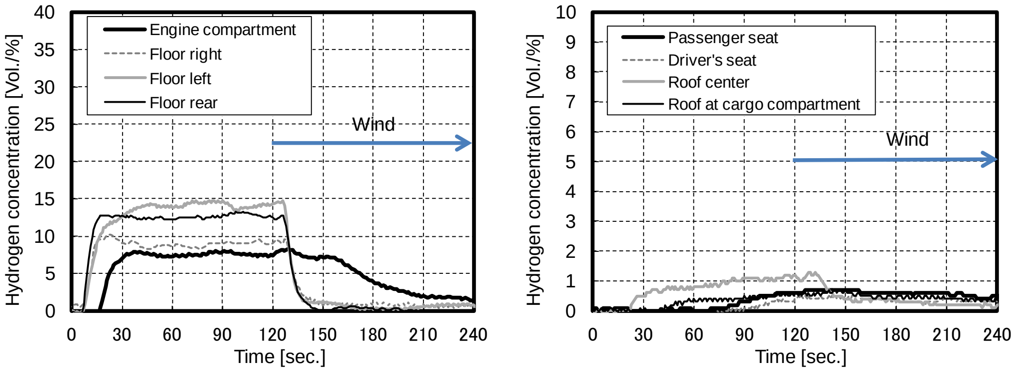
Fig. 14 shows the hydrogen concentrations measured inside the cabin when hydrogen gas was leaked from point C located also inside the cabin. Fig. 14(a) relates to the test setup where the blower was placed 5m lateral to the vehicle and the wind delivery started from the 180th sec. It was found that the hydrogen concentrations at the roof center, cargo compartment roof and driver’s seat all declined as winds entered into the cabin from the broken window.

In contrast, the hydrogen concentration at the passenger seat which was located opposite to the crash side proved higher than when there were no winds. This was presumably because the hydrogen leaking from the cabin floor center was carried towards the passenger seat by the winds that had entered from the broken window.

In the case of Fig.14 (b) relating to the test setup where the blower was placed 5 m forward to the vehicle, the hydrogen concentrations inside the cabin remained constant presumably because practically no winds entered from the broken window to influence the hydrogen accumulating inside the cabin.

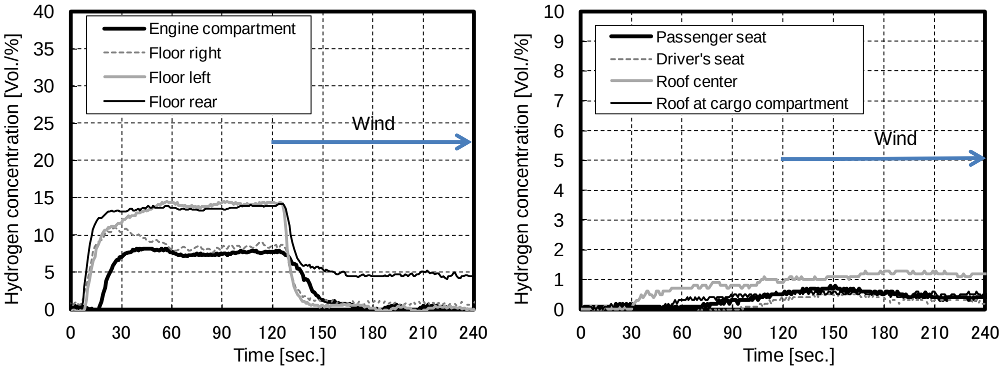
### 2.2.3 Hydrogen Concentrations and Winds from a Duct

Fig.s 15 and 16 show the hydrogen concentrations in the underfloor section and cabin of the vehicle when winds were delivered by a duct from lateral and frontal directions, respectively.



(a) Underfloor section (b) Inside cabin

Figure 15. Hydrogen concentrations inside vehicle (hydrogen flowrate of 2,000 NL/min, leakage point A, duct aimed at vehicle side)



(a) Underfloor section (b) Inside cabin

Figure 16. Hydrogen concentrations inside vehicle (hydrogen flowrate of 2,000 NL/min, leakage point A, duct aimed at vehicle front)

Hydrogen concentrations in both underfloor section and cabin declined after the delivery of winds from a duct. Consequently the use of a duct fitted to a blower is considered effective in diluting leaked hydrogen. One advantage of a duct is that it can increase the wind velocity of a small blower. One disadvantage is that because of its narrow wind width, a duct is usable only when the point of hydrogen leakage has been located.

## 3.0 IGNITION TEST

### 3.1 Test Procedure

An ignition test was conducted on leaked hydrogen under ventilated conditions to examine the effect of ignition on the vehicle and its surroundings. The igniter which was used as spark source had an ignition energy of 30 mJ and a spark gap of 1 mm.

Blast-wave pressures were measured with two blast-pressure pencil probes installed near the hydrogen leakage points on both sides of the vehicle, at 0.2 m above ground. The blast-pressure probes each consisted of piezoelectric transducers of various ranges enclosed in an aerodynamic pencil-shaped housing. The sensors had a rising time of less than 4 μs. Data from the sensors was continuously logged in a buffer at a rate of 25 kHz, and was saved automatically with the ignition signal.

### 3.2 Results and Discussions

### 3.2.1 Difficulty of Ignition

Table 1 shows the ignition results of hydrogen leaked at a flowrate of 2,000 NL/min in the vehicle and diluted by winds from a blower. It was found that ignition took place when there were no forced winds but the incidence of ignition declined in the presence of forced winds.

Table 1. Ignition under forced winds (hydrogen flowrate: 2,000 NL/min)

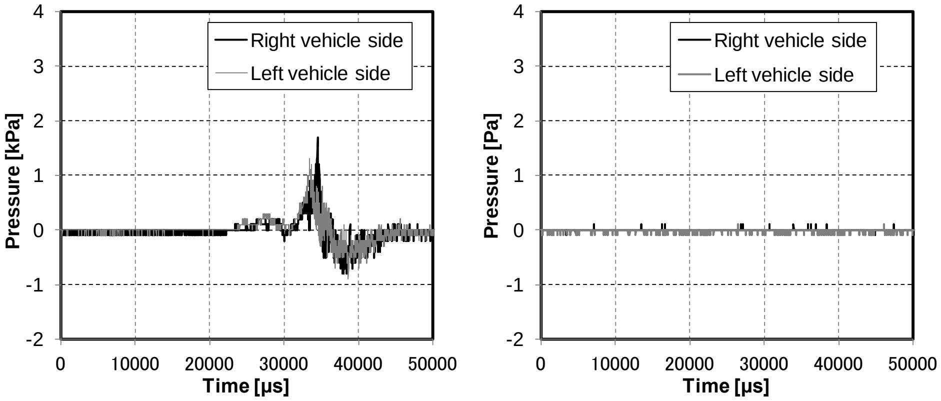
| Blower position | | Leakage position | Ignition position | Ignition |
|---|---|---|---|---|
| None | | A | Rear of the leakage position | Yes |
| Front side | 2m | | | No |
| | 5m | | | No |
| Side | 2m | | | No |
| | 5m | | | No |
| None | | A | Side of the leakage positon | Yes |
| Front | 2m | | | No |
| | 5m | | | No |
| Side | 2m | | | Yes |
| None | | A | Wheel housing | Yes |
| Front | 2m | | | No |
| | 5m | | | No |
| Side | 2m | | | No |
| None | | Center position under the rear floor | Backside of the rear bumper | Yes |
| Front | 5m | | | Yes |
| None | | Under the engine compertment | Upper of the firewall | Yes |
| Side | 5m | | | Yes |
| None | | C | Center of the cabin roof | Yes |
| Side | 5m | | | No |

### 3.2.2 Blast-wave Pressure and Behaviour

Fig. 17 shows examples of ignition testing with and without forced winds; hydrogen gas leaked from point C, and the ignition point was set on the reverse side of the rear bumper.

Fig. 18 shows the blast-wave pressures of ignition as measured on the lateral sides of the vehicle and 0.2 m above ground. While the maximum blast-wave pressure reached 1.7 KPa without forced winds, practically no blast-wave pressure was recorded in the presence of forced winds.

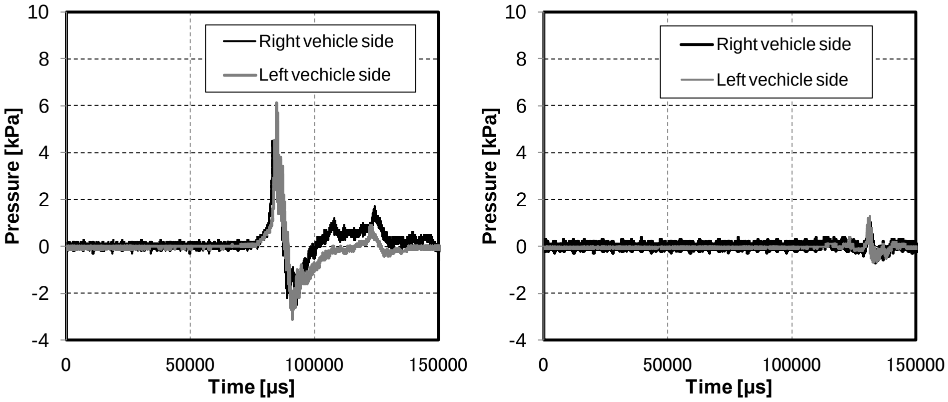
Figure 17. Leakage from rear-floor center and ignition on reverse side of rear bumper



(a) No forced winds (b) Winds from 5m forward to vehicle
Figure 18. Blast-wave pressures at vehicle’s both sides, 0.2 m above ground
(hydrogen flow rate: 2,000 NL/min)

Fig. 19 shows the ignition test case where the hydrogen leak point was at the center of the engine compartment base and the ignition point at the center of the firewall top. Fig. 20 shows the blast-wave pressures of ignition as measured on the lateral sides of the vehicle and 0.2m above ground.

Figure 19. Leakage from engine compartment base center and ignition at firewall top center

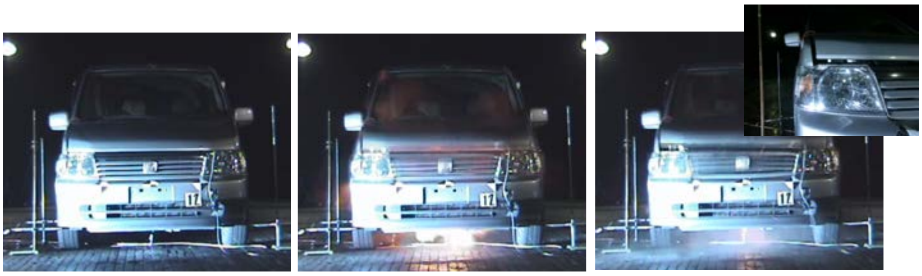


(a) No forced winds (b) Winds from 5m forward to vehicle

Figure 20. Blast-wave pressure at vehicle's both sides, 0.2m above ground
(hydrogen flow rate: 2,000 NL/min)

While the maximum blast-wave pressure reached as high as 6 KPa without forced winds, it fell to less than 1 KPa in the presence of forced winds.

Fig. 21 shows the sequence photographs of ignition. In the absence of forced winds, ignition took place and resulted in a blast that deformed the hood. In the presence of forced winds, although ignition took place the resultant blast was so moderate that none of the vehicle's adjacent parts were deformed or damaged.



(a) No forced winds

(b) Winds from 5m forward to vehicle

Figure 21. Sequence photographs of ignition

The aforementioned test results indicated that safe approach to an accident-struck HFCV for rescue activity will become possible if winds are continuously delivered towards a side or the front of the vehicle by using a blower with a wind velocity of 10 m/s or faster.

## 4.0 CONCLUSION

Employing a vehicle fresh from a side crash test, a series of tests was conducted to examine the effect of forced winds on the dispersion of hydrogen leaking at a rate of 2,000 NL/min and on the post-ignition safety of the accident-struck HFCV. The following results were obtained:

1) When winds of 10 m/s or faster were delivered to a front- or side-crashed vehicle from the lateral side having a broken window, the hydrogen concentrations around the vehicle declined below the lower flammable limit and the hydrogen inside the vehicle was mostly diluted. Consequently the delivery of winds proved effective in decreasing ignition possibility and, even if ignition occurs, in moderating the blast-wave pressure of ignition.

2) Similarly, if the first responder has located the position of hydrogen leakage, hydrogen concentrations around the vehicle could be lowered by delivering winds from a duct (wind velocity of 10 m/s or faster at the duct exit).

Overall, the present study found that the safety of rescue activity for a hydrogen-leaking vehicle can be enhanced by applying winds from a blower of an about 10 m/s wind velocity and approaching the vehicle leeward from the blower area.

## REFERENCE

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