

Development of Hydrogen Ventilation Structure for Fuel Cell Systems

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ABSTRACT

A new hydrogen ventilation structure for fuel cell systems has been developed that uses a waterproof and dustproof filter for simplification towards multipurpose development of fuel cell powertrains. A 78% reduction in terms of volume was achieved compared to conventional model hydrogen ventilation structures for fuel cell systems with ducts installed. In this paper, under the assumption of normal operation and the possible occurrence of a hydrogen leak, it was confirmed that the hydrogen concentration in the hydrogen system and under the front hood was equal to or less than the unusual detection for hydrogen concentration through the hydrogen ventilation structure that was adopted. Furthermore, this structure newly introduces what is known as a "forced ventilation system," where part of the air supplied to the cathode electrodes is taken into the hydrogen ventilation structure, which has enabled reducing the concentration of hydrogen inside the hydrogen ventilation structure of the fuel cell system during normal operation compared to its concentration in conventional models.

1. Introduction

Fuel Cell Vehicles (FCV) are vehicles which run on kinetic energy converted from electricity that is generated through a reaction between hydrogen and oxygen. The hydrogen that serves as their fuel emits only water when it reacts with oxygen and does not emit any carbon dioxide, making FCV considered to possess outstanding potential as environmentally conscious vehicles⁽¹⁾. With the CLARITY FUEL CELL released in 2016, Honda aimed at creating a comfortable environment for sedans based on the idea of "man maximum" and "machine minimum," and successfully installed the fuel cell powertrain under the front hood⁽²⁾. One of the elements to achieve this was a structure which efficiently releases hydrogen that has passed through the fuel cell stack to the outside of the vehicle.

Figure 1 shows a fuel cell system installed in a 2016 model vehicle, as well as a diagram of the fuel cell system. The portion colored orange indicates the duct, which was installed above the fuel cell stack to utilize a ventilation method which took advantage of the difference in height to discharge the hydrogen that had passed through to the outside of the vehicle through the duct. In addition, in hydrogen ventilation structures for fuel cell systems (hereinafter, "hydrogen ventilation structures") in 2016 models, hydrogen system parts were covered with system covers to achieve a safety performance design for handling hydrogen. These covers were comprised of three elements:

a barrier consisting of the stack case and system cover, a hydrogen sensor, and a duct. If the hydrogen system parts became damaged due to a vehicle collision, etc., it could result in hydrogen leaking inside of the structure. If there were a possibility that this could happen, it would be detected by the hydrogen sensor, and the hydrogen supply

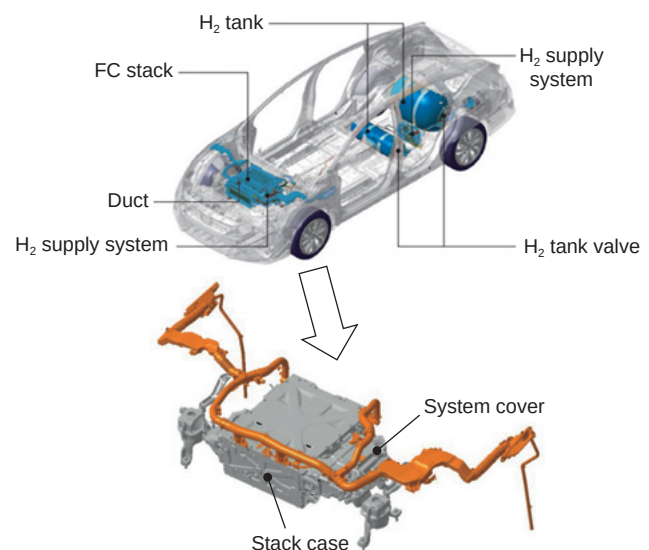


Fig. 1 Hydrogen ventilation structure of CLARITY FUEL CELL

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would be shut off. Furthermore, the duct was used to vent the hydrogen to the outside of the vehicle once it had been reduced to a level of concentration where it would no longer be flammable⁽³⁾. In addition, since hydrogen molecules are small, even during normal operation, hydrogen at an extremely low flow rate of several cm³/min would pass through the sealing material of the stack and be discharged into the hydrogen ventilation structure, so even the hydrogen discharged through permeation was constantly discharged to the outside of the vehicle through the duct.

On the other hand, in the development of fuel cell powertrains not only for passenger vehicles but also for commercial vehicles, there was an issue with versatility as it was necessary to design differently shaped ducts each time according to the applicable products. In addition, when assuming a fuel cell system with multiple linked powertrains to obtain the output, it was assumed that the design of the duct would become even more complicated.

Regarding the international regulations, a United Nations Regulation (UN-R134)⁽⁴⁾ based on the UN's Agreement Concerning the Adoption of Uniform Technical Prescriptions for Wheeled Vehicles, etc. should be adhered to for fuel cell vehicle development. Enacted in 1958, this agreement attempted to unify the standards related to safety performance and the environment for each type of vehicle device and have them approved by all parties involved. The following information is related to the fuel cell vehicles themselves, as well as to their hydrogen storage containers and accessories. The items in this agreement related to this paper are shown in Table 1. The first requirement is that the concentration of hydrogen inside the passenger compartment should be below a standard value in the event that a hydrogen leak could occur during a single fuel cell system component malfunction located downstream from the main hydrogen shut-off valve of the tank. The second requirement is that a warning should be provided when a hydrogen leak could occur during a single fuel cell system component malfunction during operation, resulting in the concentration of hydrogen in the enclosed or semi-enclosed space in the vehicle exceeding 3%, and also that it is possible to isolate the storage system by shutting off the main hydrogen shut-off valve on the tank if this concentration exceeds 4%.

In addition to the aforementioned regulations, Honda implements development after first establishing its own target values in order to achieve a safety performance design for handling hydrogen. First, a hydrogen concentration sufficiently lower than a flammable concentration was established as a safety performance target for inside of the hydrogen ventilation structure during normal operation. The design helps prevent hydrogen from accumulating when it is released under the front hood, which is dotted with ignition sources and releases it to the exterior of the vehicle through gaps in the body. The safety performance target, which is based on satisfying the standards for hydrogen concentration in the passenger compartment listed in 7.1.4.2 on Table 1, has been set as inside the hydrogen ventilation

Table 1 Excerpt from UN-R134

Item Number	Contents
7.1.4.2	Any single failure downstream of the main hydrogen shut-off valve shall not result in accumulations in levels of hydrogen concentration in the passenger compartment according to test procedure.
7.1.4.3	If, during operation, a single failure results in a hydrogen concentration exceeding 3.0 per cent by volume in air in the enclosed or semi-enclosed spaces of the vehicle, then a warning shall be provided. If the hydrogen concentration exceeds 4.0 per cent by volume in the air in the enclosed or semi-enclosed spaces of the vehicle, the main shut-off valve shall be closed to isolate the storage system.

Table 2 Comparison of regulations between Honda and UN-R134

Vehicle Condition	Honda	International Regulation (UN-R134)
Normal operation condition	• Hydrogen concentration in vehicle	No regulations
Single malfunction condition	• Hydrogen concentration in vehicle • Warning and hydrogen supply cutoff when concentration rises	• Hydrogen concentration in vehicle (passenger compartment only) • Warning and hydrogen supply cutoff when concentration rises

structure. In addition, when hydrogen system parts are damaged and hydrogen leaks inside of the structure, the leakage is detected by a hydrogen sensor and the hydrogen supply is shut off. Should this happen, the requirements listed in 7.1.4.3 on Table 1 would be satisfied as well. Also, design standards have been established at Honda that help prevent ignition from possibly occurring: even if hydrogen is released under the front hood - which is dotted with ignition sources - from inside the hydrogen ventilation structure through the filter, limiting the amount of hydrogen leaking from the filter as the hydrogen supply is shut off, while suppressing it below a flammable concentration and helping to prevent it from igniting.

Table 2 shows a comparison of Honda's regulations and the international regulations. Vehicle conditions are divided into "Normal operation condition" and "Single malfunction condition," and the regulations and standards are listed in Table 2. While Honda has established hydrogen concentration regulations in the vehicle during the normal operation condition, there is no regulation for this in the international regulations. As noted previously, regulations have been established for the single malfunction condition in the international regulation: specifically, regulations for the hydrogen concentration inside the

passenger compartment and a requirement for providing an alarm/shutting off the hydrogen supply when the hydrogen concentration increases. Honda has established hydrogen concentration regulations for each part of the vehicle rather than just for inside the passenger compartment and has also established regulations for providing warnings and shutting off the hydrogen supply when the hydrogen concentration increases. Therefore, in addition to incorporating the international regulations, Honda has established even higher safety performance standards and is conducting safety performance design to achieve them.

2. Development Goals

Figures 2 and 3 show the appearance of the CR-V e:FCEV with a simplified version of the hydrogen ventilation structure. Installing a waterproof and dustproof filter on the side of the stack case instead of a hydrogen discharge duct adds a ventilation function while simultaneously satisfying safety performance. As a result, as shown in Fig. 4, the hydrogen ventilation structure can be reduced by 78% in terms of volume compared to conventional models. Thus, the aims of development of this structure were defined as follows:

- (1) It should satisfy the hydrogen concentration standards defined within Honda just as with conventional models, even if the hydrogen ventilation structure uses a waterproof and dustproof filter; and
- (2) Safety performance should be established through a hydrogen ventilation structure using forced ventilation.

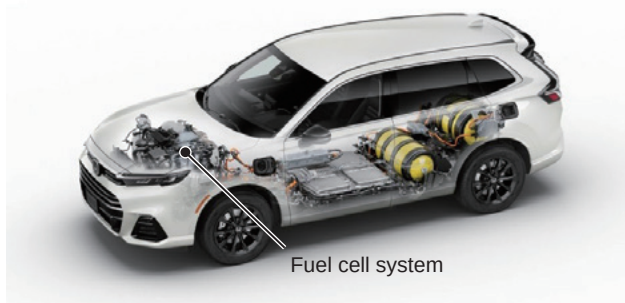


Fig. 2 FC system installation layout in CR-V e:FCEV

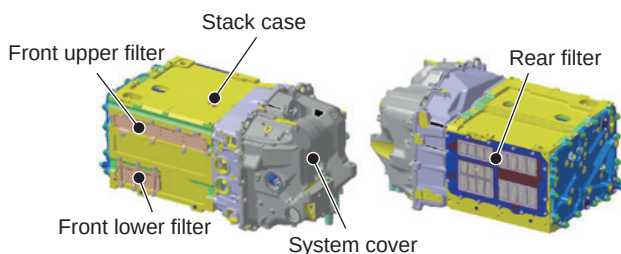


Fig. 3 FC system of CR-V e:FCEV

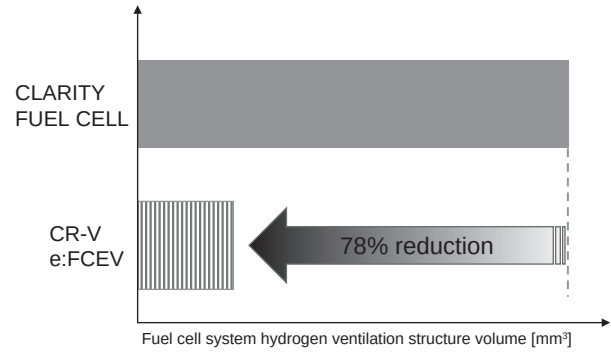


Fig. 4 Structure volume of hydrogen ventilation

3. Overview of Hydrogen Ventilation Structure

3.1. Forced Ventilation System

A forced ventilation system was newly introduced for this model to dilute the hydrogen in the hydrogen ventilation structure. Figure 5 shows a system diagram that includes a forced ventilation line. This structure splits off part of the air supply for the cathode electrode, and an orifice is installed midway to reduce the flow rate into the hydrogen ventilation structure. The flow rate of the air flowing into the forced ventilation line changes depending on the amount taken in, and if the air taken in increases, the air flow rate towards the forced ventilation line increases as well. During normal operation, hydrogen that passes through the fuel cell stack and is discharged inside the hydrogen ventilation structure is diluted by the air discharged from the forced ventilation line to this structure and is discharged under the front hood through the waterproof and dustproof filter. However, this forced ventilation system is only effective when the fuel cell system is running; it does not work when the vehicle is stopped and the fuel cell system is not running. Therefore, the hydrogen concentration inside the hydrogen ventilation structure should be less than the

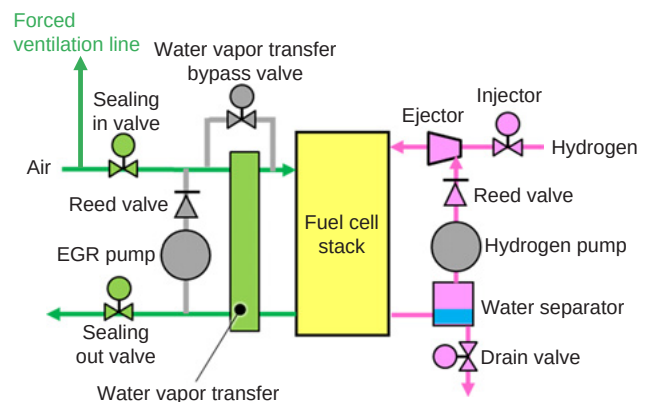


Fig. 5 Forced ventilation line in FC system

standard value even under ventilation conditions where only a waterproof and dustproof filter is used.

3.2. Waterproof and Dustproof Filter

Figure 6 shows the fuel cell stack composition. Filters are installed facing the front and rear of the vehicle in order to efficiently draw air into the stack case, which is part of the hydrogen ventilation structure, while driving. Figure 7 shows the front upper filter. While having the filter take up a large amount of surface area is desirable in order to draw air into the hydrogen ventilation structure from the front, touching the filter directly may cause dust to accumulate, making it unlikely to obtain desired ventilation performance. In addition, the filter could become damaged by force (e.g. from a person's finger) and come into contact with the electrified part inside of the stack case, which could result in an electric shock or a short circuit if water or dust entered. In this model, therefore, a filter cover is used with gaps above and below it to help prevent the accumulation of water and dust, as well as a structure with a gap that helps prevent the filter from being damaged by force.

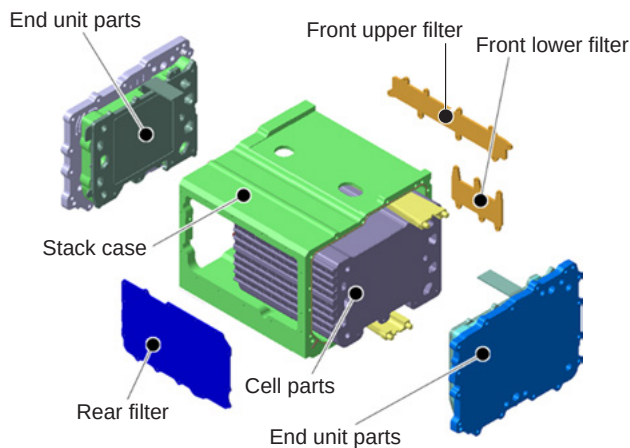


Fig. 6 FC stack of CR-V e:FCEV

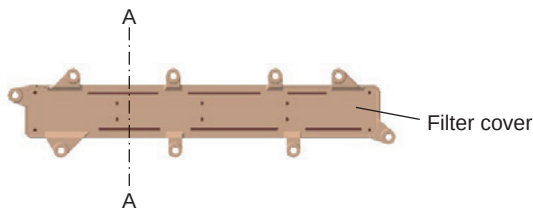
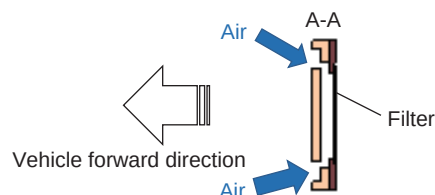


Fig. 7 Front upper filter assembly



3.3. Hydrogen Sensor Roles and Positioning

The hydrogen sensor should be positioned so as to immediately detect when a hydrogen leak may have occurred due to hydrogen system parts becoming damaged due to a vehicle collision, etc. On the other hand, if the detection threshold for irregular hydrogen concentration is exceeded during normal operation, the sensor would erroneously determine that a hydrogen leak may have occurred and stop the system operation, even if the parts have not been damaged, etc. Thus, when determining where to install the hydrogen sensor, the inside of the hydrogen ventilation structure should be ventilated appropriately to help ensure that the detection threshold is below that for irregular hydrogen concentration. It is important that there be no erroneous detections from the sensor that may have been caused by increases in hydrogen concentration inside the hydrogen ventilation structure when parts have not been damaged, etc., during normal operation. In addition, it is necessary to consider a position where the sensor is able to detect a malfunction immediately when one may occur. Figure 8 shows the hydrogen concentration distribution inside of the structure during normal operation. Taking the aforementioned concept into account, the sensor was installed near the front filter since installing it near the filter in the hydrogen ventilation structure would provide it with constant ventilation, and since installing it in the area of the stack case where hydrogen accumulates would allow it to be able to immediately detect malfunctions when they may occur.

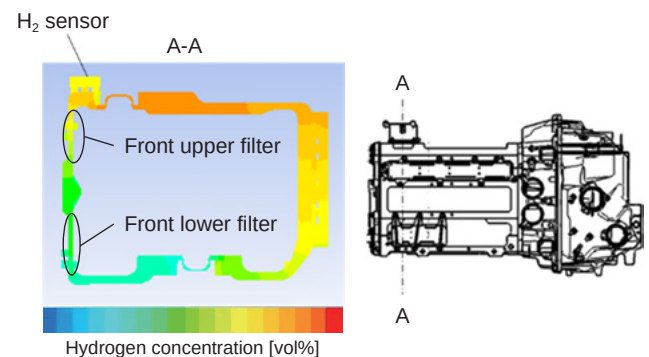


Fig. 8 H₂ sensor layout

4. Test Results

4.1. Test Verification Assuming Hydrogen Permeation

This section shows the test results for hydrogen concentration inside of the hydrogen ventilation structure during normal operation. Testing was made in conditions wherein no power was being generated, when the forced ventilation system could not be used, during normal operation. For hydrogen permeation, the permeation flow rate was reproduced using a jig while taking design variations in fuel

cell stack sealing into account. In addition, hydrogen sensors were installed in the upper and lower parts of the stack case where hydrogen may remain inside the hydrogen ventilation structure due to the nature of that structure. Figures 9 and 10 show the measuring positions of the hydrogen sensors. In addition, the hydrogen sensors mounted on the vehicle are in (2) and (5) of Fig. 9. Also, the verification conditions for testing considered the tilt of the vehicle in order to reproduce various driving situations. This was conducted in order to confirm that the hydrogen concentration did not exceed the detection threshold for irregular hydrogen concentration due to the tilt, which may cause hydrogen to tend to accumulate and help prevent efficient ventilation of the hydrogen inside of the hydrogen ventilation structure.

First, the results for the hydrogen concentration within the hydrogen ventilation structure while in a horizontal orientation are shown in Fig. 11. These results clarified that most of the measurement positions had a hydrogen concentration of less than half that of the detection threshold for irregular hydrogen concentration, and hydrogen was diffused almost uniformly within the hydrogen ventilation structure. The location with the highest concentration is the measurement position in (8) of Fig. 11, which was close to

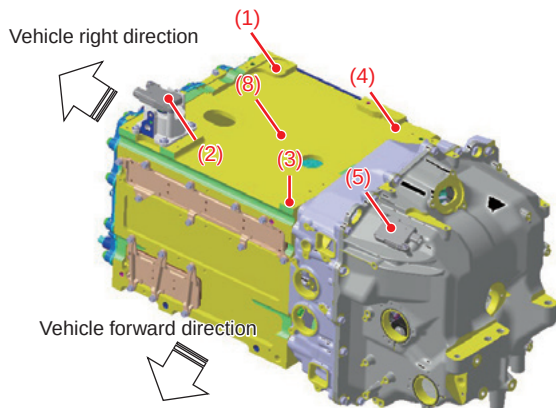


Fig. 9 Perspective view of FC system and hydrogen concentration measurement position

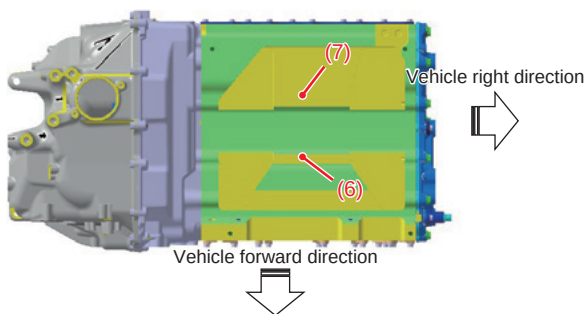


Fig. 10 Bottom view of FC system and hydrogen concentration measurement position

directly above the center of the stack case. However, this hydrogen concentration was roughly 60% compared to the detection threshold for irregular hydrogen concentration and was sufficiently lower than a flammable concentration.

Next, the results of the hydrogen concentration for the hydrogen ventilation structure with the vehicle tilted are shown in Fig. 12. The maximum concentration indicated was almost directly above the center of the hydrogen ventilation structure, the same as under the horizontal condition. Hydrogen tended to accumulate at the highest locations depending on the direction of the tilt, where the hydrogen concentration tended to increase. These results confirmed that the detection threshold for irregular hydrogen concentration is not exceeded even if the hydrogen sensor is installed in the upper part of the inside of the system ventilation structure.

4.2. Test Verification Assuming Hydrogen Leakage

A hydrogen sensor is used to detect when hydrogen leakage may occur, and the system has been designed to perform as well as possible by limiting the amount of hydrogen leakage if one could occur. This section shows the results from measuring the hydrogen concentration when hydrogen system parts become damaged and may cause

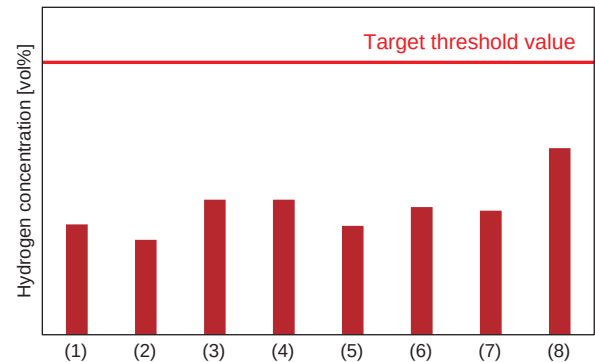


Fig. 11 Hydrogen concentration results for hydrogen ventilation structure in horizontal orientation

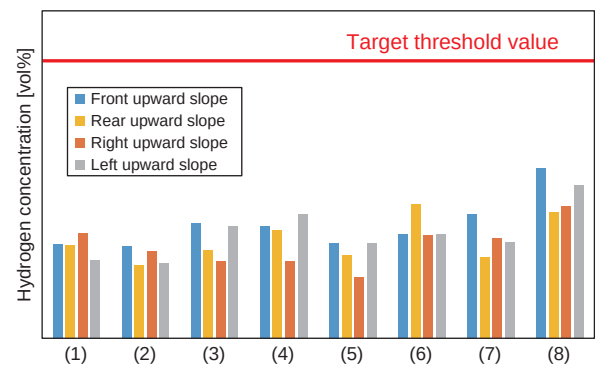


Fig. 12 Hydrogen concentration results for hydrogen ventilation structure in tilted orientation

hydrogen leakage, utilizing simulation of an actual vehicle. Testing was conducted with the leaking area positioned the furthest away in a straight line from the on-board hydrogen sensor, so that detection time would be the slowest, and assuming a hydrogen leak rate of several thousand cm^3/min max. Figure 13 shows the hydrogen concentration measurement positions. The testing method mirrored the behavior of an actual vehicle during a malfunction. First, hydrogen was discharged from the presumed leakage area to the inside of the hydrogen ventilation structure at the flow rate at which it is assumed that a hydrogen leak could occur. Next, hydrogen release was stopped once the concentration detected by the hydrogen sensor reached the supply shut-off level. At this point, the forced ventilation line would normally operate in an actual vehicle, but it is advantageous in reducing hydrogen concentration detection time. Thus, under the presumed operating conditions, testing was performed by simulating conditions that would not be advantageous for detection by allowing a minimum flow rate to be distributed as air towards the forced ventilation line to flow into the hydrogen ventilation structure.

The hydrogen that leaked into the hydrogen ventilation structure was released under the front hood through the waterproof and dustproof filter. By measuring the hydrogen concentration at each installation point, it was confirmed whether or not the hydrogen concentration at locations presumed to be fire sources was below the detection threshold for irregular hydrogen concentration.

First, the results of hydrogen concentration under the front hood in a horizontal orientation are shown in Fig. 14. Based on these results, the hydrogen concentration at all of the measurement positions was almost zero relative to the detection threshold for irregular hydrogen concentration. It is assumed that the hydrogen concentration did not increase since it was immediately released to the exterior of the vehicle from the gaps in the body after being released under

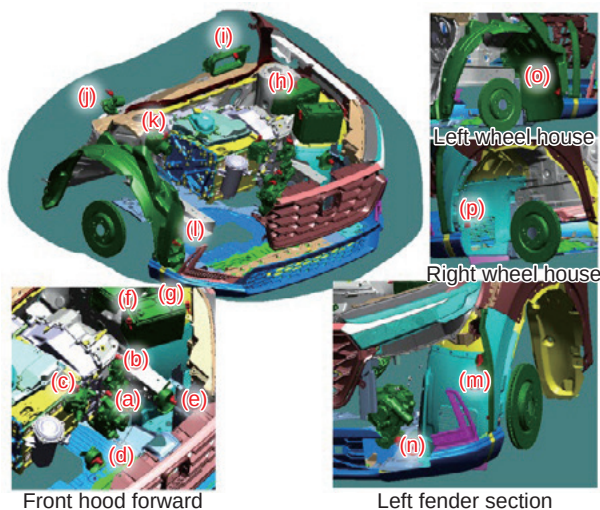


Fig. 13 Hydrogen concentration measurement positions

the front hood from the waterproof and dustproof filter.

Next, Fig. 15 shows the results of hydrogen concentration under the front hood when it is assumed that the vehicle is tilted, as shown in Fig. 16. Based on these results, it was revealed that the hydrogen concentration was sufficiently low relative to the detection threshold for irregular hydrogen concentration, as it also was when the vehicle was horizontal. However, influence from the tilt was observed: for example, it was revealed that hydrogen concentration has a high value at the measurement positions in (c) of Fig. 13 that correspond to near the front side of the fuel cell system when the front part of the vehicle rises. In other words, based on these results, it can be concluded that the hydrogen diffuses under the front hood through the waterproof and dustproof filter.

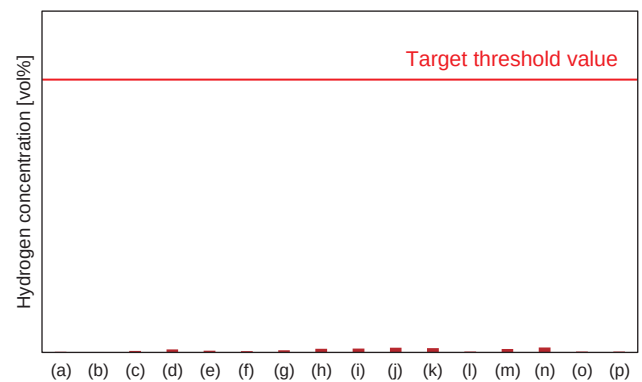


Fig. 14 Hydrogen concentration results in front hood in horizontal orientation

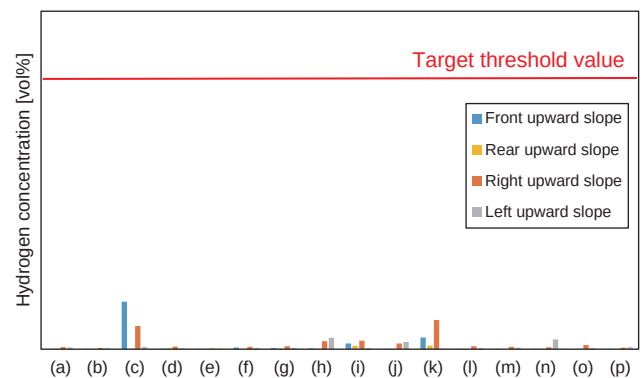


Fig. 15 Hydrogen concentration results in front hood in tilted orientation

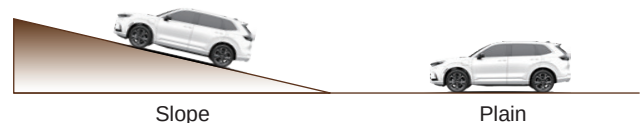


Fig. 16 Image of parking slope

4.3. Effects of Forced Ventilation Line

As mentioned previously, in order to further reduce the concentration of the hydrogen released under the front hood from the hydrogen ventilation structure, a forced ventilation system is being introduced to allow part of the air supply for the cathode electrodes of the fuel cell stack to flow into the hydrogen ventilation structure. Figure 17 shows the difference in maximum hydrogen concentration inside the hydrogen ventilation structure, depending on the presence or absence of a forced ventilation system. It was revealed that the inflow of air greatly diluted the hydrogen concentration within the hydrogen ventilation structure. Also, Fig. 18 shows the difference in detection time for on-board hydrogen sensors, depending on the air volume level from forced ventilation. Based on these results, it was revealed that detection timing could be increased by introducing a forced ventilation system, through which detection time was successfully reduced by 55%. The reason why the forced ventilation system was effective at detection during hydrogen leakage became clear from these results. It is assumed that the air from the forced ventilation

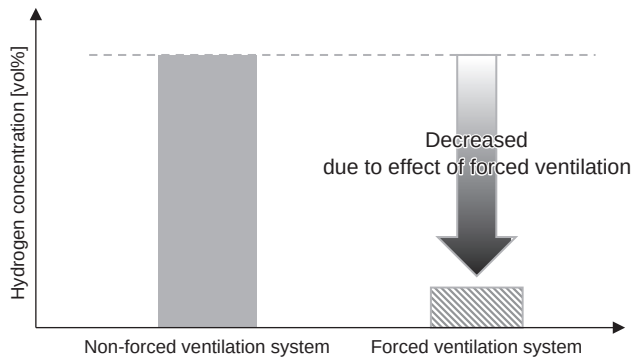


Fig. 17 Comparison of hydrogen concentration between non-forced ventilation system and forced ventilation system

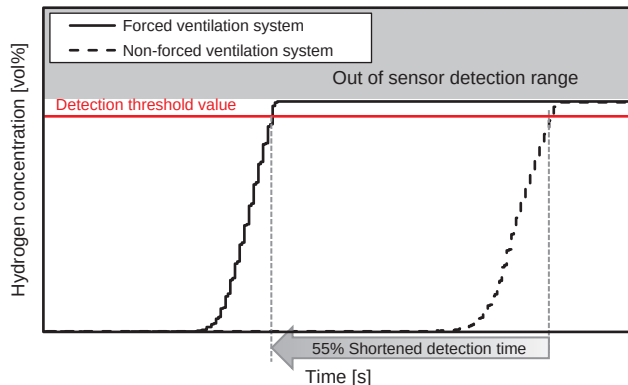


Fig. 18 Comparison of detection time between non-forced ventilation system and forced ventilation system

system guiding the leaking hydrogen towards the hydrogen sensor facilitated this detection timing. In addition, the reason why the concentration value remains constant once the hydrogen concentration value exceeds the detection threshold is because it falls outside of the concentration detection range of the hydrogen sensor.

5. Conclusion

The following two points were confirmed for this mode: the volume of the hydrogen ventilation structure was reduced by 78% through fuel cell powertrain simplification; and a new hydrogen ventilation structure with a waterproof and dustproof filter was successfully adopted.

- (1) Testing was conducted similarly on the conventional model during normal operation and during a malfunction, as well as under the presumption that the vehicle was tilted, and it was confirmed that the standards were satisfied, even with Honda's independent target values that are stricter than those of the international regulation.
- (2) Introduction of a forced ventilation structure system together with positioning of the waterproof and dustproof filter reduced hydrogen concentration within the hydrogen ventilation structure during normal operation, and it was even possible to reduce the concentration to below the flammable state. Also, the timing for detecting hydrogen leakage through hydrogen sensors was increased by 55%.

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