SAFETY DESIGN OF COMPRESSED HYDROGEN TRAILERS WITH COMPOSITE CYLINDERS

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ABSTRACT

Compressed hydrogen is delivered by trailers in steel cylinders at 19.6 MPa in Japan. Kawasaki Heavy Industries, Ltd. developed two compressed hydrogen trailers with composite cylinders in collaboration with JX Nippon Oil in a project of the New Energy and Industrial Technology Development Organization (NEDO).

The first trailer, which was the first hydrogen trailer with composite cylinder in Japan, has 35 MPa cylinders and the second trailer has 45 MPa cylinders. These trailers have been operated transporting hydrogen and feedstock to hydrogen refueling stations without the accident. This paper describes the safety design, including compliance with regulations, the influence of vibrations, and safety verification in case of a collision.

1. Introduction

In Japan, a total of 13 companies, automobile manufacturers and hydrogen providers agreed to make joint efforts to introduce fuel cell vehicles (FCV) into the domestic market, start the spread of hydrogen infrastructure. According to their joint announcement, the automobile manufacturers aim to sell FCV production cars, while the energy companies aim to antecedently establish about 100 hydrogen stations mainly in four metropolitan areas of Japan by 2015 [1)].

In order to start the spread of FCVs, it is necessary not only to improve the durability and reliability of the vehicle itself and hydrogen stations, and make efforts to reduce costs, but also to do empirical research in order to review necessary standards and systems, and verify the business feasibility of assumed commercialization. For this purpose, the New Energy and Industrial Technology Development Organization (NEDO) is promoting various types of research and development of hydrogen infrastructure and supply systems. In particular, NEDO is promoting research into the deregulation of 10 items concerning hydrogen infrastructure under the “Regulation Reviews concerning Construction and Operation of Hydrogen Stations” project. In addition, under the “Technical and Social Demonstration of Regional Hydrogen Supply Infrastructure” project, NEDO obtained data from a demonstration experiment of a hydrogen station under conditions close to the actual use of the station. Based on the data, it is verifying and assessing energy efficiency of the hydrogen station and the hydrogen supply cost, and studying practical solutions to issues for the practical utilization of hydrogen supply infrastructure, etc.

Among these R&D items, Kawasaki Heavy Industries has developed the first high-pressure hydrogen trailer to contain composite cylinders in Japan. This trailer transports to hydrogen stations high-pressure hydrogen produced in a hydrogen manufacturing plant, in order to supply the hydrogen to FCVs. Up to now, high-pressure hydrogen has been conventionally carried by a 19.6 MPa trailer with steel cylinders that contain about 200 kg of hydrogen. The trailer cannot load hydrogen of more than

200 kg due to the fact that the steel cylinders are heavy. Our new trailer uses composite cylinders that can increase the pressure of hydrogen to transport while also reducing weight. Consequently, the trailer will be able to load hydrogen of 400 kg or more in the future.

This paper outlines our new trailer and reports legal measures for the safety of this trailer. In addition, it presents the details of Kawasaki Heavy Industries' independent review of trailer collisions and vibrations.

2. System for Development of High-pressure Hydrogen Trailer

Both 35 and 45 MPa high-pressure hydrogen trailers were developed respectively under the "Regulation Reviews concerning Construction and Operation of Hydrogen Stations" and "Technical and Social Demonstration of Regional Hydrogen Supply Infrastructure" projects.

As a member of the Research Association of Hydrogen Supply/Utilization Technology (HySUT), Kawasaki Heavy Industries took charge of the development of the relevant trailer, while JX Nippon Oil & Energy Corporation was charged with the operation of the trailer.

3.0 Positioning and General Specifications of the Developed Trailer

3.1 35 MPa high-pressure hydrogen trailer

The 35 MPa high-pressure hydrogen trailer is the first high-pressure hydrogen trailer in Japan that contains composite cylinders. The specifications and a photograph of the trailer are shown in Table 1 and in Fig. 1, respectively. For the pressure specifications, 35 MP that conforms to a maximum pressure of 35 MPa under JIGA-T-S/12/04[2)] and JIGA-T-S/13/04[3)], the standard for composite cylinder and accessories on a Japanese compressed hydrogen transportation vehicle, was employed for the 35 MPa cylinders. A load of hydrogen in the 20 cylinders was determined based on the required minimum amount of hydrogen in the regulation reviews project.

Table 1. Specifications of 35 MPa high-pressure hydrogen trailer

35 MPa high-pressure hydrogen trailer	
Length	9,560mm
Width	2,490mm
Height	3,230mm
Weight	11,330kg
Number of cylinders	20
Cylinder weight	110kg

Composites cylinders	
Length	2,030mm
Diameter	416mm
Weight	101kg
Pressure	35MPa
Water volume capacity	205L
Composites Type	Type3

(a) Appearance of 35 MPa trailer

(b) Appearance of composite cylinders

Figure 1. Appearance of 35 MPa high-pressure hydrogen trailer

3.2 45 MPa high-pressure hydrogen trailer

As a part of a transport model for the first future hydrogen station in Japan, the 45 MP high-pressure hydrogen trailer is filled with hydrogen at a hydrogen delivery facility, transports the high-pressure hydrogen, stores it in an off-site hydrogen station, and supplies the hydrogen to other hydrogen stations. The specifications and the appearance of the trailer are shown in Table 2 and in Fig. 2, respectively. For the pressure specifications, the pressure during commercial transport by cylinder in Japan is set at 45 MPa. Consequently, 45 MPa was employed for the 45 MPa cylinders. The load of hydrogen in the 24 cylinders was determined based on the required minimum amount of hydrogen in the social demonstration project.

Table 2. Specifications of 45 MPa high-pressure hydrogen trailer

45 MPa high-pressure hydrogen trailer	
Length	10,260mm
Width	2,490mm
Height	3,360mm
Weight	17,150kg
Number of cylinders	24
Cylinder weight	260kg

Composites cylinders	
Length	3,025mm
Diameter	436mm
Weight	220kg
Pressure	45MPa
Water volume capacity	300L
Composites Type	Type3

(a) Appearance of 45MPa trailer

(b) Appearance of composite cylinders

(c) Retractable roof

Figure 2. Appearance of 45 MPa high-pressure hydrogen trailer

4 Development Concept

For the development of a high-pressure hydrogen trailer with composite cylinders, preconditions for the operation of the high-pressure hydrogen trailer, a concept for the development of the trailer, and a concept for hydrogen handling were established.

Preconditions for the operation of the trailer

•The driver is a qualified person (high-pressure gas transportation supervisor, holders of heavy truck license and trailer license).

•The route for operation of the trailer is predetermined.

•The trailer is inspected before and after its operation to check for leakage or looseness.

•Each cylinder has a main valve. The valve must be closed before the trailer is operated.

For this reason, the trailer is not to be used by general users, while its operation route is predetermined. Consequently, it is assumed that the trailer will have a low probability of encountering any accidents. Even in the potential case of a hydrogen leak, the leak can be quickly identified before and after the trailer is operated. Because the cylinder main valve is closed, a large amount of hydrogen will not leak from the cylinder even if the pipe in the operation box is ruptured.

Based on these preconditions, the concepts of hydrogen handling were determined as follows.

•Not to leak hydrogen.

•To prevent unusual increase in hydrogen pressure.

•To avoid the accumulation in case of hydrogen leak.

Matters of the safety design for the trailer that are stipulated under the High Pressure Gas Safety Act, and the details of Kawasaki Heavy Industries' independent review are individually described based on these concepts.

5.0 Safety Design for the Trailer

The status of the high-pressure hydrogen trailer is divided into road transport and parking at a hydrogen station. The status of the trailer and safety measures that are stipulated under the High Pressure Gas Safety Act and those based on Kawasaki Heavy Industries' independent review are shown in Table 3.

Table 3. Correspondence list for the concept of hydrogen handling

<table>
<tr><th rowspan="2">Concept</th><th colspan="2">Situation</th><th colspan="3" rowspan="2">Measure</th></tr>
<tr><th>Transport</th><th>Feedstock</th></tr>
<tr><td rowspan="8">Not to leak hydrogen</td><td rowspan="5">Yes</td><td rowspan="5">-</td><td rowspan="4">Collision</td><td>Bumper:</td><td>Bumper that meets standards of the Road Transport Vehicle Act</td></tr>
<tr><td>Frame</td><td>Frame that meets standards of the High Pressure Gas Safety Act</td></tr>
<tr><td>Cylinder band</td><td>Cylinder band that meets standards of the High Pressure Gas Safety Act</td></tr>
<tr><td>Operation box</td><td>Operation band that meets standards of the High Pressure Gas Safety Act and Road Transport Vehicle Act</td></tr>
<tr><td>Vibrations</td><td colspan="2">Higher inherent frequencies</td></tr>
<tr><td rowspan="2">Tipping over</td><td colspan="2">Road Transport Vehicle Act
Trailer that does not tip over even if it leans 30˚</td></tr>
<tr><td colspan="2">EBS to control overturning is installed (KHI)</td></tr>
<tr><td>-</td><td>Yes</td><td>Fixed method to the ground</td><td colspan="2">Administrative guidance</td></tr>
<tr><td>-</td><td>Yes</td><td>Emergency</td><td colspan="2">High Pressure Gas Safety Act</td></tr>
<tr><td>Yes</td><td>Yes</td><td>Joints</td><td colspan="2">Special structure joint (KHI)</td></tr>
<tr><td>Yes</td><td>Yes</td><td>Seals</td><td colspan="2">Metal seal (KHI)</td></tr>
<tr><td rowspan="2">To prevent unusual increase in hydrogen pressure</td><td>Yes</td><td>Yes</td><td colspan="3">Using the cylinders passed fire bonfire test</td></tr>
<tr><td>-</td><td>Yes</td><td colspan="3">Use of pressure-dependent devices</td></tr>
<tr><td>To avoid the accumulation of leaked hydrogen</td><td>Yes</td><td>Yes</td><td colspan="3">Structure with openings in two or more directions</td></tr>
</table>

5.1 Measures for avoiding hydrogen leaks

The factors of hydrogen leaks thinkably include joint looseness, leaks from seals and breakage of high-pressure line equipment. There is not a standard for joint looseness, but Kawasaki Heavy Industries voluntarily employs a joint of special structure resistant to looseness. For the seal section, a metal seal is employed to resist leakage. The high-pressure line equipment can be broken by collision, vibrations or tipping over. Different measures for these damage modes are described below.

The structures of the bumper and the operation box are stipulated under the High Pressure Gas Safety Act. The bumper and the operation box are designed according to sizes meeting the requirements of the Act, which are shown Figs. 3 and 4. Under the Act, a curdle frame must have a safety factor of 1.5 against a yield force of a fixed member such as cylinder. The cylinder containing gas is required to have a structure that will not yield to force generated if accelerations of 1.0 G and 2.0 G occur in the upward and downward directions, respectively, and accelerations of 2.0 G and 1.0 G occur in the back-and-forth and lateral directions, respectively. Consequently, the container frame was evaluated and designed by analysis. A band fixing the cylinder must anchor the cylinder body in two or more points and must move no more than 13 mm in the horizontal direction even if the force 8-times larger than the mass of the cylinder is applied to the cylinder in the horizontal direction. This requirement was evaluated by analysis, The test cylinder shown in Fig. 5 was used to conduct a test in which the test cylinder is actually pushed from an axial direction and from a direction perpendicular to the axial direction. As a result, the cylinder was confirmed to move no more than 13 mm.

[1] Collision

There is not a standard for collision, but Kawasaki Heavy Industries voluntarily conducted an analysis that simulated a collision between a standard-sized car and this trailer. Due to the absence of a collision standard, however, the trailer was made to collide against the immediate rear of the car at a speed of 40 km/h, in order to conduct its independent analysis of the collision. The result is shown Fig. 6. For this collision, a Dodge Neon that is on public view in the National Crash Analysis Center (NCAC) was used. As a result of the collision analysis, no member deformed by force in the collision bumped against the cylinder. An acceleration of 2 G occurred on the cylinder. In addition to the result of the above evaluation test for the cylinder band, it was confirmed from this result that the cylinder would no

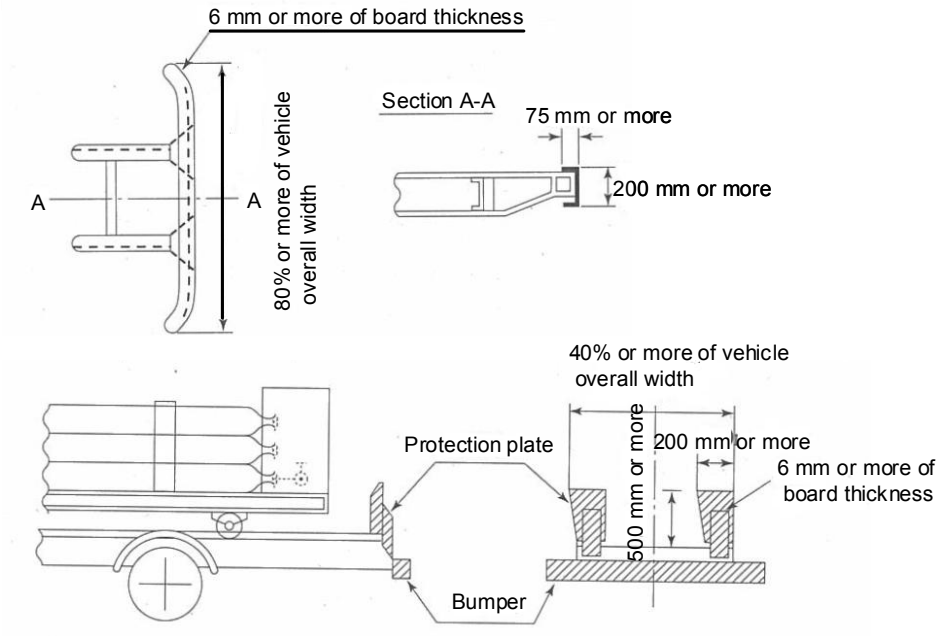

Figure 3. Bumper structure under the High Pressure Gas Safety Act

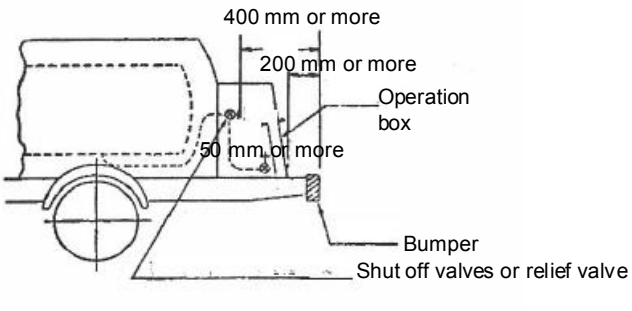

Figure 4. Bumper structure under the High Pressure Gas Safety Act

Figure 5. Cylinder band test

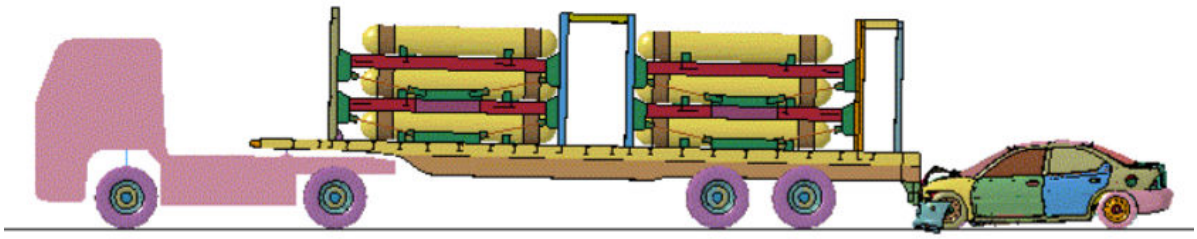

Figure 6. Results of collision simulation

[2] Vibrations

A standard for vibration measures does not exist in Japan. Therefore, the vibrations in the beam that anchors the cylinder to the trailer were measured. The representative vibration measurements are shown in Fig. 7. The large amplitude of the beam was determined at a certain frequency. For this reason, the inherent frequencies of pipes and cylinder fixings were designed so as to avoid a frequency that increases this amplitude. The vibration test for the cylinder was, as shown in Fig. 8, based on the measured value of acceleration on the trailer, and on the conditions under which screw looseness caused by short-time vibration and the breakage of the cylinder band can be assessed. As a result, screw looseness and equipment breakage were not observed. In addition, vibrations in the cylinder during transport by the trailer were measured. Large vibrations were not obtained.

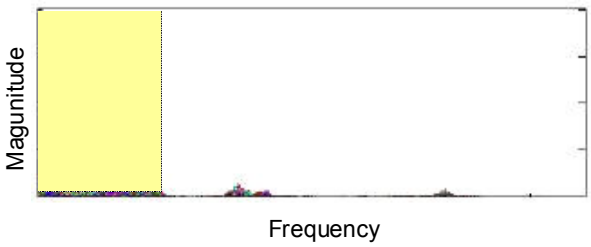

Figure 7.Vibration measurements

Figure 8. Vibration test

[3] Tipping over

Under the safety standards for road trucking vehicles, all trailers must have a structure in which they will not tip over even at an inclination of 30˚. For this reason, the center of gravity of the trailer was examined so that its structure conforms to the High Pressure Gas Safety Act. For Kawasaki Heavy Industries' independent measures, a system called EBS that controls overturning is installed on the trailer so as to resist overturning.

5.2 Measures for unusual increase in hydrogen pressure

The factors that cause an unusual increase in hydrogen pressure thinkably include rises in temperature at the time of fire and excessive filling of hydrogen. In order to prevent the cylinder's temperature from increasing, a cylinder and its accessories that are stipulated under JIGA-T-S/12/04 and have passed a flame exposure test are used. Cylinders used for the 35 MPa and 45 MPa trailers have the lengths of about 2 m and 3 m, respectively. Because they are long, as shown in Fig. 8, a fusible pressure relief valve is placed at a cylinder main valve and at a position piped from the opposite of the main valve, and a solid steel plate is put into the lower part of a curdle, so as to prevent any partial increase in the cylinder's temperature and tripping of the safety valves.

In order to prevent a rise in cylinder pressure that is caused by excessive filling of hydrogen, a mechanical safety valve is installed.

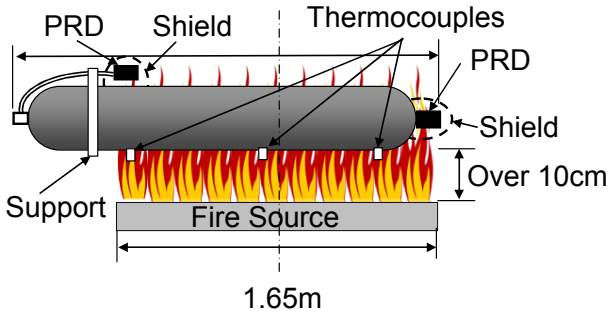

Figure 7. Long cylinder

5.3 Measures for avoiding accumulation of leaked hydrogen

In order to avoid the accumulation of leaked hydrogen, and to meet exemplified standards of general rules, the High Pressure Gas Safety Act, the curdle section that mounts a cylinder is structured to have openings in two or more directions. In order to prevent hydrogen from accumulating and thus conform to this Act, a punched metal plate is placed on the side of the cylinder, a louver at the door in the operation room, and an air hole on the ceiling of the cylinder.

6.0 Current Situation of High-pressure Hydrogen Trailers

6.1 35 MPa high-pressure hydrogen trailer

The 35 MPa trailer, which was filled with hydrogen at Yokohama's Asahi Hydrogen Station in August 2012, transported hydrogen to Tokyo's Suginami Hydrogen Station and stored it there, marking the start of hydrogen supply. The trailer has supplied hydrogen four times for a total transport distance of 1,046 km so far. Faults such as looseness of cylinder fixings and pipe joints, hydrogen leaks and temperature increases have not occurred.

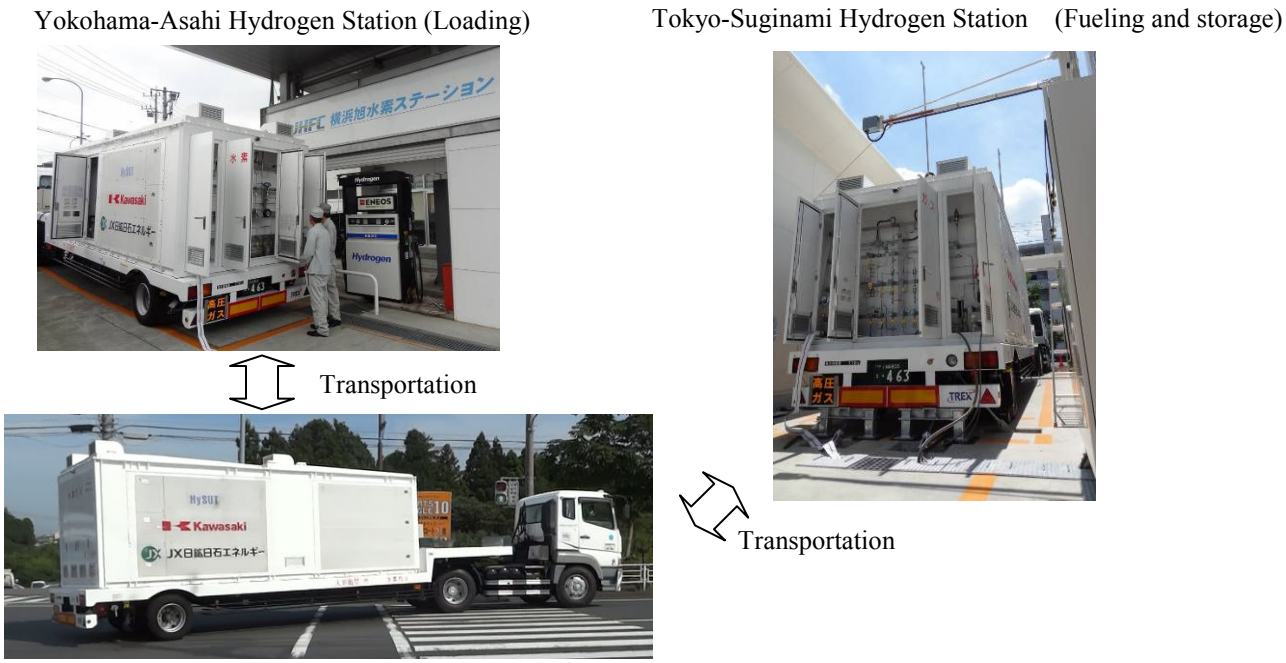

Figure 8. Current situation of high-pressure hydrogen trailers

6.2 45 MPa high-pressure hydrogen trailer

The 45 MPa trailer will be filled with hydrogen at a delivery facility in Negishi, transport hydrogen to Ebina-chuou Hydrogen Station and store it there, and start the supply of hydrogen in May 2013.

7. CONCLUSIONS

Kawasaki Heavy Industries, Ltd. developed two compressed hydrogen trailers with composite cylinders in collaboration with JX Nippon Oil in a project of the New Energy and Industrial Technology Development Organization (NEDO). The first trailer, which was the first hydrogen trailer with composite cylinder in Japan, has 35 MPa cylinders and the second trailer has 45 MPa cylinders.

Before we designed the hydrogen trailers, we established a concept for the development of the trailer, and a concept for hydrogen handling.

We evaluated compliance with regulations, the influence of vibrations, and safety verification in case of a collision and we developed the trailers.

Now the trailer has supplied hydrogen four times for a total transport distance of 1,046 km so far. Faults such as looseness of cylinder fixings and pipe joints, hydrogen leaks and temperature increases have not occurred.

This study is a part of the research project that was outsourced by NEDO.

Reference

1) http://www.meti.go.jp/press/20110113003/20110113003-1.pdf

2) JIGA-T-S/12/04, Compound container on the compressed hydrogen transportation vehicle, Japan Industrial Gases association, 2004

3) JIGA-T-S/13/04, Accessories on the compressed hydrogen transportation vehicle, Japan Industrial Gases association, 2004