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Evaluation of Structural Safety and Leak Test for Hydrogen Fuel Cell-Based Truck Storage Systems

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수소트럭 수소저장시스템에 대한 구조안전성 및 기밀성능평가

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ABSTRACT

Recently, hydrogen has gained considerable attention as an eco-friendly fuel, which helps in reducing carbon dioxide content. Specifically, there is a growing interest in vehicles powered by a hydrogen fuel cell, which is spotlighted as an environmental-friendly alternative. A hydrogen transport system, fuel cell system, fuel supply system, power management system, and hydrogen storage system are key parts of a hydrogen fuel cell truck. In this study, a hydrogen storage system is built and analyzed. The expansion length of the storage vessel at maximum operating pressure (87.5 MPa) was calculated with ABAQUS, and then the optimized system was designed and built. The leak and bubble tests were performed on the built storage system. The leakage of the system was measured to be under 5 cc/hr. Hence, it can be used as a research test for the safety evaluation of leading systems of hydrogen fuel-powered commercial vehicles.

Key Words : Hydrogen(수소), Leak Test(기밀시험), Hydrogen Fuel Cell Truck(수소연료전지트럭), Hydrogen Storage System(수소저장시스템), Structural Safety(구조적 안전성)

1. Introduction

As interest in environmental issues such as air pollution and global warming increases, there is high demand for reducing carbon dioxide, which is the cause of greenhouse gases (GHGs) [1,5]. In particular, hydrogen is attracting attention as an eco-friendly energy source that can replace fossil fuels to reduce carbon dioxide [6]. Currently, South Korea is aiming to reduce its GHG emissions by 37% compared with its business-as-usual (BAU) level according to the 2030 National GHG Reduction Roadmap.

The government is pushing ahead with policies to reduce GHGs and fine dust [9], and one of these policies is related to hydrogen electric vehicles. Hydrogen electric vehicles can reduce carbon dioxide by 25 to 30% compared with internal combustion engines. Hydrogen electric vehicles could

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be a competitive solution for reducing GHGs if long-distance and heavy-weight vehicles with high utilization rates are developed [2,3]. Thus, the government will develop hydrogen trucks and supply 30,000 vehicles by 2040 according to the Hydrogen Economy Vitalization Roadmap announced in January 2019.

To mass-produce competitive fuel-cell vehicles, it is necessary to evaluate durability and safety in a state in which each component is modularized [1]. Hydrogen transport systems, electric propulsion and power management systems, fuel-cell systems, fuel-supply systems, and hydrogen storage systems are the core technologies of hydrogen trucks. Among these technologies, the hydrogen storage system consists of a composite vessel that withstands high pressures of 70 MPa or more, a valve, a pipe, and a frame for fixing the vessel. It is necessary to evaluate the structural safety and Leak Test, which determines gas leakage from the hydrogen storage system, to check whether the vessel and piping interfere with expansion after mounting the composite vessel and the frame.

This study has conducted a mutual interference structure analysis regarding the hydrogen storage system mounted in the hydrogen truck. Furthermore, a test method was derived by analyzing domestic and international standards. A Leak Test was conducted by applying the derived test method; thus, the safety of the hydrogen storage system was verified through structural analysis and a Leak Test.

2. Hydrogen Storage System Design

2.1 Layout Creation and Theories

Mutual interference structure safety was conducted regarding the hydrogen storage system mounted on the hydrogen truck. The hydrogen storage system was designed to measure 2,212 mm× 1,411 mm. A Type 4 composite vessel was utilized as a vessel with an inner volume of 52 L and a working pressure of 70 MPa. Through this design, the space was optimized with a 2×3 row arrangement and composed of 12 vessels and two systems, and the layout was created as shown in Fig. 1.

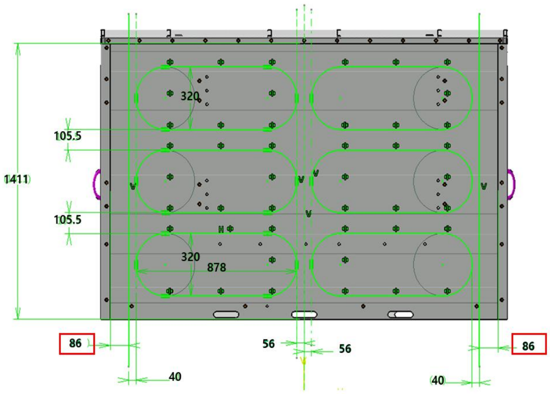


Fig. 1 Layout of hydrogen storage system

When pressure is applied to a Type 4 composite vessel, the vessel expands. Mutual interference structure analysis was conducted using ABAQUS to determine whether interference occurred between the frame and the vessel during expansion. This analysis was conducted to determine whether expansion would occur when a pressure of 87.5 MPa was applied under a harsher condition by applying 1.25 times the working pressure.

The conditions of the structural analysis were explored to check whether expansion would occur.

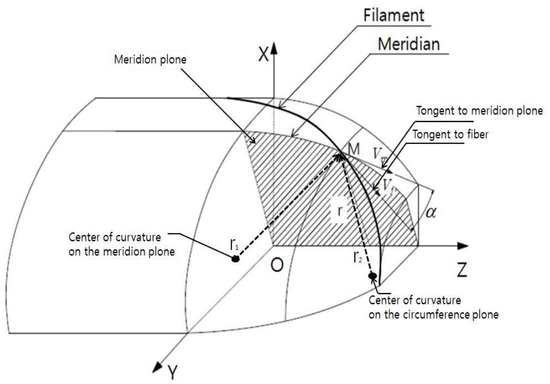


Fig. 2 Schematic diagram of iso-tensoid dome theory

The liner for winding fibers in a composite vessel, shown in Fig. 2, was designed based on netting theory and isotensoid dome theory [4]. Netting theory assumes that the fibers withstand all internal pressures, and isotensoid dome design theory assumes that the carbon fiber content and the number of fibers in which the meridian passes through the section in the vertical direction on the dome are constant [4,7,8].

2.2 Results of Mutual Interference Structure Analysis

Figs. 3 and 4 show the displacements of the Z-direction (longitudinal direction of the vessel) and R-direction (diameter direction of the vessel).

In the longitudinal direction of the vessel, a maximum of 6.6 mm deformation occurred from the summation of the left and right sides, and in the vessel diameter direction, a maximum of 2.0 mm deformation occurred from the summation of the left and right sides. Thus, when the optimal layout was prepared in the hydrogen storage system, the free space was 86 mm, and, theoretically, mutual interference could not occur because smaller vessel deformation occurred to a lesser degree than that of the free space.

Fig. 3 R-dir. Displacement

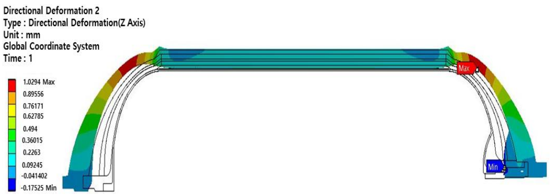


Fig. 4 R-dir. Displacement

3. Derived Method for Evaluating Leak Test of Hydrogen Storage System

3.1 Comparison Analysis of Domestic and Foreign Standards

3.1.1 Attached Table 4, Ministry of Land, Infrastructure, and Transport Regulation on the Safety of Pressure-Resistant Vessels for Automobiles

Regarding domestic regulation, the Regulation on the Safety of Pressure-Resistant Vessels for Automobiles have been released by the Ministry of Land, Infrastructure, and Transport. The Regulation provide rules on compressed natural gas, liquefied natural gas, and pressure-resistant vessels for liquefied petroleum gas in addition to pressure-resistant vessels for hydrogen gas. The provisions related to compressed hydrogen gas prescribe a limit on the capacity of 450 L or less and the vessel types as Ⅲ or Ⅳ composite vessels.

3.1.2 EC 79

Regarding international industry regulations, EC 79 is typically applicable. As a hydrogen vehicle regulation initiated by the European Parliament, EC 79 includes provisions on liquefied hydrogen, compressed hydrogen, and other related systems; this chapter describes only vessels that can store compressed hydrogen. Compressed hydrogen storage vessels are limited to vessels aged 20 or fewer years and with 5,000 charging cycles, including all types of composite vessels, including steel vessels.

3.1.3 Global Technical Regulation (GTR)

The GTR are industrial regulation established by the World Forum for Harmonization of Vehicle Regulations (WP29), an affiliate of the United Nations Economic Commission for Europe, for introducing a safe market for hydrogen electric vehicles.

Table 1 Standard of pressure vessel for fuel cell vehicle

Ministry of Land, Infrastructure, and Transport Regulations on the safety of pressure vessel for vehicle Annex 4
4.2.11.1 Leak: The leak test shall be performed with a randomly selected Type-4 vessel. 4.2.11.2 The container shall be thoroughly dried. 4.2.11.3 The container shall be pressurized to nominal working pressure and hold for **at least 3 minutes** with **dry air or gaseous nitrogen** mixed with detectable gas such as hydrogen or helium.
ISO 11119-3
8.5.15 Leak test 8.5.15.1 Leak testing shall be performed at a minimum of the test pressure, P_h × 2/3. Acceptable leak testing methods include, but are not limited to, bubble testing using **dry air or gas or measurement of trace gases** using a mass spectrometer. 8.5.15.2 Leakage greater than 10^{-3} mbar/liter/sec, i.e., approximately 1 visible bubble in 2 min or **6 cc/hr** in the bubble leak test, shall be considered a failure.
GTR 13
6.2.4.3. Localized gas leak test (pneumatic) A bubble test may be used to fulfill the requirement. The following procedure is used when conducting the bubble test: (a) The exhaust of the shutoff valve and other internal connections to hydrogen systems shall **be capped for this test** (as the test is focused on external leakage). At the discretion of the tester, the test article may be immersed in the leak-test fluid, or leak-test fluid may be applied to the test article when resting in the open air. Bubbles can vary greatly in size, depending upon the conditions. The tester shall estimate the gas leakage based on the size and rate of bubble formation. (b) Note: For a localized rate of **0.005 mg/sec** (3.6 NmL/min), the resultant allowable rate of bubble generation is approximately 2,030 bubbles per minute for a typical bubble diameter of 1.5 mm. Even if much larger bubbles are formed, the leak should be readily detectable. For an unusually large bubble with a diameter of 6 mm, the allowable bubble rate is approximately 32 bubbles per minute.

These regulations are continuously updated. Unlike the domestic and international regulations, they do not have the nature of mandatory regulations but can be viewed as recommended for actual trade transactions of hydrogen electric vehicles.

3.2 Test Method for Leak Evaluation

To derive a test method for evaluating the Leak Test of the hydrogen storage system, the domestic and foreign standards for composite vessels were compared and analyzed. According to the comparative standards shown in Table 1, dry air or nitrogen containing detectable gas such as hydrogen or helium is used and pressurized for at least 3 min to the working pressure. Furthermore, the ISO 11119-3 standard specifies that the amount of gas leakage should be 6 cc/hr or less. High-purity hydrogen gas was used in harsh conditions by considering the following acceptance criteria. The pressure was maintained as 1.25 times the working pressure; 87.5 MPa for 5 min, and the leaked hydrogen was allowed within 5 cc/hr to reinforce safety. As a result, the test method in Section 3.2.1 was derived.

The Type 4 composite vessel used was not tested for Leak Test because the vessel had been previously certified. This test examined whether gas leaked from the part where the piping and valve were connected when the composite vessel was mounted on the frame.

3.2.1 Test method

1. Dry the vessel completely without moisture.
2. Pressurize the hydrogen gas to 87.5 MPa at room temperature (25℃ or less) and maintain the pressure for 5 min.
3. Check the Leak of the gas.
   (1) Check whether bubbles are generated by spraying soapy water on the places where gas leaks may occur.

Fig. 5 Hydrogen Buster and Hydrogen Cylinder

Fig. 6 Hydrogen Leak Detector

(2) Measure the amount of leaked hydrogen after blocking the inflow of external air by installing a diaphragm any place where gas leaks may occur.

4. Suitable when the amount of hydrogen leaked without bubbles is 5 cc/hr or less.

4. Hydrogen Storage System Leak Evaluation

4.1 Equipment for Leak Evaluation in Hydrogen Storage System

The hydrogen booster shown in Fig. 5 is pressurized to a maximum of 150 MPa; is composed of a pressure sensor, a pressure gauge, and a two-stage booster; and is manufactured by itself. 99.999% high-purity hydrogen was used as the applicable gas. The hydrogen leak detector shown in Fig. 6 was INFICON ISH2000, which can measure a minimum of 1×10^{-7} cc/s of leaked hydrogen with 5% H_2.

4.2 Appearance of Bubbles from Hydrogen Storage System

To determine the leak of hydrogen storage system, this study has checked whether bubbles were generated with the naked eye. The hydrogen storage system is composed of twelve Type 4 composite vessels, valves, pipes, and frames according to the frame structure. As shown in Fig. 8, it was classified into three categories: Adapter, 1/2 inch Tee, and 1/4 inch Tee. According to the test method derived in Section 3.2.1, after pressurizing to 87.5 MPa using hydrogen gas at room temperature and maintaining the pressure for 5 min, as shown in Fig. 7, it was confirmed that bubbles did not appear by spraying soapy water on the connection part where gas leaks could occur.

4.3 Amount of Hydrogen Leaked from Hydrogen Storage System

it was confirmed that bubbles did not appear. and To measure more precisely, according to the test method derived in Section 3.2.1, as this was similar to the test to check whether bubbles would occur, after installing a diaphragm to block the inflow of external air, as shown in Fig. 9, and pressurizing the hydrogen gas to 87.5 MPa at room temperature, the pressure was maintained for 5 min, as shown in Fig. 7 The amount of leaked hydrogen was measured with a hydrogen leak detector for the part where gas leaks could occur, and Table 2 shows the measured values. The average amount of leaked hydrogen was 0.0477 cc/hr, which achieved 5 cc/hr or less, according to the standard presented in Section 3.2.1.

5. Conclusion

This study has evaluated structural safety to check

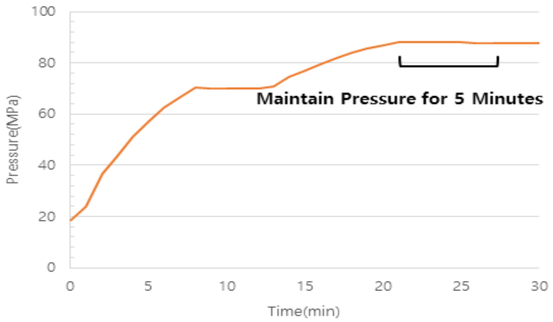
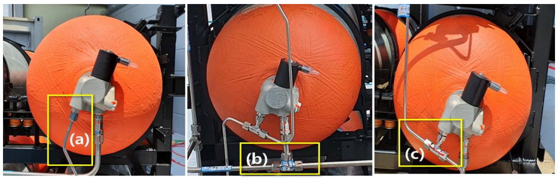


Fig. 7 Pressurize to 87.5 MPa of hydrogen gas and maintain pressure for 5 minutes



(a) Adapter (b) 1/2 inch Tee (c) 1/4 inch Tee

Fig. 8 Type of Connecting part

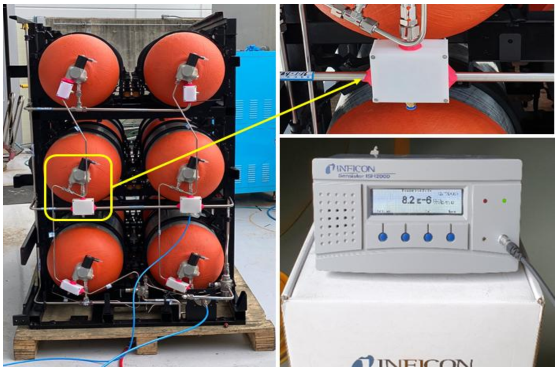


Fig. 9 The preparation and measurement of Leak Test

Table 2 The result of Leak test

	1st	2nd	3rd	Average
①	0.0828	0.2880	0.0202	0.1303
②	0.0328	0.0335	0.0320	0.0328
③	0.0346	0.0335	0.0313	0.0331
④	0.0335	0.0320	0.0295	0.0317
⑤	0.0295	0.0324	0.0298	0.0306
⑥	0.0313	0.0194	0.0320	0.0276
Total Average				0.0477

※ Adapter(①,②), 1/2 inch Tee(③,④), 1/4 inch Tee(⑤,⑥)

whether interference occurs during the expansion of the hydrogen storage system mounted on the hydrogen truck and further conducted the Leak evaluation by using the experimental method derived through the standard comparative analysis. The following conclusions were obtained.

1. Through structural analysis, when the composite vessel was theoretically pressurized to 87.5 MPa, a maximum of 8 mm deformation occurred from the summation of the left and right sides in the longitudinal direction of the vessel, and a maximum of 0.8 mm distortion occurred in the horizontal direction of the vessel.
2. The Leak evaluation method to be applied to the hydrogen storage system was derived by comparing and analyzing the Leak test items based on the Attached Table 4, Ministry of Land, Infrastructure, and Transport Regulation on the Safety of Pressure-Resistant Vessels for Automobiles, ISO 11119-3, and GTR 13.
3. According to the derived method, when checking whether bubbles would appear after pressurizing the hydrogen gas to 87.5 MPa, no bubbles appeared. n average, which achieved 5 cc/hr or lessAs a more precise test, the amount of leaked hydrogen measured by a hydrogen leak detector was 0.0477 cc/hr o according to the presented standards.

Based on these results that the free space was 86 mm when the optimal layout was fabricated in the hydrogen storage system, mutual interference would not occur because smaller vessel deformation occurred to a lesser degree than that of the free space. Therefore, safety was confirmed through the structural analysis and Leak evaluation of the hydrogen storage system. In the future, the results of this study will be used as a pilot test for the safety evaluation of leading systems for commercial vehicles, such as hydrogen trucks and cargoes using hydrogen fuel.

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REFERENCES

1. Jang, G. J., Choi, Y. M., Ahn, B. K., Lim, T. W., "The Evaluation of Reliability for the High pressure hydrogen Storage System," The Korean Hydrogen and New Energy Society, Vol. 19, No. 4 , pp. 266-275, 2008.
2. Kim, C. K., Kim, D. H., "Strength Safety Study on the Stress Characteristics of a Composite Pressure Cylinder for 35MPa Hydrogen Gas Vehicle," Journal of Korean Institute of Gas, Vol. 16, No. 2, pp. 25-30, 2012.
3. Kim, C. K., Kim, D. H., "A Safety Study on the Stress Characteristics of a Composite Pressure Cylinder for a Use of 70MPa Hydrogen Gas Vehicle," Journal of Korean Institute of Gas, Vol. 21, No. 1, pp. 1-6, 2012.
4. Cho, S. M., Lee, S. k., Cho, M. S., Lyu, S. K., "Development of Type 4 Composite Pressure Vessel by using PET Liner for Self-contained Breathing Apparatus," Journal of the Korean Society of Manufacturing Process Engineers, Vol. 17, No. 6, pp. 164-169, 2018.
5. Cho, S. M., Kim, C. J., Kim, Y. G., "A Study on the Behavior of Ambient Hydraulic Cycling Test for 70 MPa Type3 Hydrogen Composite Cylinder," Journal of the Korean Institute of Gas, Vol. 16, No. 1, pp. 46-50, 2012.
6. Son, D. S., Chang, S. H., "Evaluation of modeling techniques for a type III hydrogen pressure vessel (70MPa) made of an aluminum liner and a thick carbon/epoxy composite for fuel cell vehicles," International Journal of Hydrogen Energy, pp. 2353-2369, 2012.
7. Cho, S. M., Kim, D. E., Seong, H. J., Choi, S. J., Ko, Y. K., Lyu, S. K., "Development of a Type 4 Composite Cylinder for Self-contained Breathing Apparatus," Journal of the Korean Society of Manufacturing Process Engineers, Vol. 10, No. 2, pp. 1-6, 2019.
8. Cho, S. M., Cho, M. S., Jung, G. S., Lee, S. K., Lee, S. K., Park, G. D., Lyu, S. K., "A Study on the Development of a Hybrid Fiber Reinforced Composite for a Type 4 CNG Vessel," Journal of the Korean Society of Manufacturing Process Engineers, Vol. 16, No. 4, pp. 97-103, 2017.
9. Kim, G. H., "Optimal Shape Design of ANG Fuel Cell Vessel Applied to Composite Carbon Fiber," Journal of the Korean Society of Manufacturing Process Engineers, Vol. 18, No. 1, pp. 65-71, 2019.