First experiment on liquid hydrogen transportation by ship inside Osaka bay

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Abstract. A project to import a large amount of liquid hydrogen (LH₂) from Australia by a cargo carrier, which is equipped with two 1250 m³ tanks, is underway in Japan. It is important to understand sloshing and boil-off characteristics inside the LH₂ tank during marine transportation. However, the LH₂ sloshing and boil-off characteristics on the sea have not yet been clarified. First experiment on the LH₂ transportation of 20 liter with magnesium diboride (MgB₂) level sensors by the training ship “Fukae-maru”, which has 50 m long and 449 ton gross weight, was carried out successfully inside Osaka bay on February 2, 2017. In the experiment, synchronous measurements of liquid level, temperature, pressure, ship motions, and accelerations as well as the rapid depressurization test were done. The increase rate of the temperature and the pressure inside the LH₂ tank were discussed under the rolling and the pitching conditions.

1. Introduction

Renewable energy such as solar energy, wind energy, and tidal energy is very attractive to produce hydrogen, which is expected to be the ultimate energy medium for worldwide storage and transportation. In Japan, a white paper on the energy, especially in the task of “Strategic Road Map for Hydrogen and Fuel Cells” expressed that CO₂ free hydrogen will be imported commercially in the 2020s to 2030s. A CO₂-free Hydrogen Energy Supply-chain Technology Research Association Commences (HySTRA) [1] will demonstrate marine transportation of large quantity of liquid hydrogen (LH₂: 20 K) which is made from brown coal as unutilized energy using two 1250 m³ tanks, from Australia to Kobe, Japan until 2020 [2].

In the case of LH₂, the amount of LH₂ evaporation is 10 times higher than that of liquified natural gas (LNG: 112 K) because the amount of boil-off gas (BOG) increases as heat is exchanged with the inner wall of the pressurized type LH₂ tank when sloshing occurs inside the tank [2]. However, the LH₂ sloshing and boil-off characteristics on the sea have not yet been clarified. Furthermore, the limit of BOG and depressurization period to reduce the pressure to atmosphere before unloading LH₂ to the stationary LH₂ tank on land has not yet been decided.

A magnesium diboride (MgB₂) level sensor for LH₂ has been developed [3-15]. We are currently developing an external-heating-type MgB₂ level sensor [5-15]. So far, 500-mm-long external-heating-type MgB₂ level sensors with a high linearity, a high resolution, good reproducibility, and good dynamic level-detecting characteristics have been made. Thus, the external-heating-type MgB₂ level sensor can
be expected to be applied to sloshing measurement at an optimal heater input of 9 W [14, 15]. This paper describes the first experiment on the LH₂ transportation by ship, using an optical cryostat (a small LH₂ tank) with the external-heating-type MgB₂ level sensors; experimental results of liquid level, temperature, pressure, ship motions, and accelerations as well as the rapid depressurization test are discussed.

2. Experimental apparatus and methods

Figure 1 shows a measurement system. This system consists of an optical cryostat (a small LH₂ tank), five MgB₂ level sensors, two carbon ceramic temperature sensors (CCS sensors), a digital pressure sensor, current sources for the level sensors and the CCS sensors, a power supply for the external heater of level sensor, a data logger (KEYENCE; NR-600), a GPS-aided mems inertial system (MEMSIC; NAV440), and a PC. The optical cryostat having a height of 1327 mm is composed of a vacuum jacket, an LH₂ space (20 L), an LN₂ space (15 L) and a 77 K typical aluminum radiation shield [14], and five optical windows having an effective diameter of 60 mm. The layout of five 500-mm-long MgB₂ level sensors of A1, A2, B1, B2, and C is shown in Figure 1. The CCS sensors A and B were attached on the level sensor support with distance of 250 mm and 125 mm from the bottom of the level sensor, respectively. The data of liquid level, temperature, and pressure inside the cryostat was obtained by NR-600, and the data of ship motions with accelerations of X, Y, and Z direction was obtained by NAV440 through a shipboard LAN. All data was synchronously collected by a PC with the GPS clock. Figure 2 shows a photograph of the experimental setup on afterdeck of the training ship “Fukae-maru”, which has 50 m long and 449 ton gross weight. All electronic equipment was placed in another room on board to make them explosion-proof.

Table 1 shows a time chart of experimental processes inside Osaka bay on February 2, 2017, and also Figure 3 shows a track chart of “Fukae-maru” inside Osaka bay. In the table, test numbers ①-⑥ refer to experimental processes in the transportation test by ship; ①-③ denote rapid depressurizations with a release valve, ④ denotes drifting after stopping engine under the influence of natural wind and wave, ⑤ denotes zig-zag maneuver test after sharp turning maneuver, ⑥ denotes sharp turn at 360-degree circle as shown in Figure 3. The liquid level detected by five 500-mm-long MgB₂ level sensors at a heater input of 9 W, temperature, and pressure inside the cryostat were measured synchronously during ①-⑤. Finally, the temperature and pressure without the liquid level at a heater input of zero

![Figure 1. Measurement system.](image-url)
under natural heat input conditions were measured synchronously during ⑥. Details of the sloshing measurements using five MgB₂ level sensors during ②–⑤ will be published elsewhere.

![Figure 2. Photograph of experimental setup on afterdeck.](image)

**Table 1.** Time chart of experimental processes inside Osaka bay.

| Time   | Process                                           | Test number |
|--------|---------------------------------------------------|-------------|
| 12:53  | Leave port                                       |             |
| 13:02  | Release valve close                              | ①           |
| 13:22  | Release valve open (rapid depressurization)       |             |
| 13:25  | Release valve close                              |             |
| 13:42  | Release valve open (rapid depressurization)       | ②           |
| 13:45  | Release valve close                              |             |
| 14:02  | Release valve open (rapid depressurization)       | ③           |
| 14:10  | Release valve close                              |             |
| 14:10  | Start drifting after stopping engine             | ④           |
| 14:17  | Finish, Release valve open (rapid depressurization) |             |
| 14:30  | Release valve close, A sharp turning maneuver    |             |
| 14:35  | Zig-zag maneuver test                            | ⑤           |
| 14:42  | Finish                                           |             |
| 14:45  | A sharp turn at 360-degree circle                |             |
| 14:49  | A ninety degrees sharp turn to the left           |             |
| 14:51  | Finish                                           |             |
| 14:55  | A sharp turn at 360-degree circle                | ⑥           |
| 14:58  | Finish                                           |             |
| 15:58  | A sharp turn at 360-degree circle                |             |
| 16:17  | Enter port                                       |             |
3. Experimental results
Experimental results of test numbers ① and ⑥ were paid main attention for data analysis. Figures 4-6 show experimental results of liquid level, temperature, pressure, ship motions, and accelerations during ①, using every 1 s data. As shown in Figure 4, the temperature of CCS sensor A upward the liquid level

![Figure 3. Track chart of “Fukae-maru” inside Osaka bay.](image1)

![Figure 4. Time chart of liquid level and pressure inside the cryostat during marine transportation test ① from 12:53pm to 1:22pm.](image2)
increased from 12:57pm to 12:58pm. At the same time, rolling of the ship motions occurred as seen in Figure 6. This is thought to be caused by temperature increase of gaseous phase due to heat exchange between inner wall and hydrogen gas after sloshing inside the cryostat. As shown in Figure 5, the temperature of CCS sensor B downward the liquid level increased with increasing the pressure inside the cryostat after closing the release valve at 1:02pm. This is believed to be caused by an increase of saturated temperature of liquid phase due to an increase of the pressure.

Figure 5. Time chart of temperature and pressure inside the cryostat during marine transportation test ① from 12:53pm to 1:22pm.

Figure 6. Time chart of angle and acceleration during marine transportation test ① from 12:53pm to 1:22pm.
Rapid depressurization tests were done with opening the release valve after achieving the pressure of 0.2 MPaG at 1:22pm. Figures 7 and 8 show the details during 170 s after 1:21pm, using every 0.01 s data. As seen in Figure 7, maximum increase of 30 mm liquid level due to significant boiling was observed, just after rapid depressurization. In addition, the average liquid level decreased with decreasing the pressure under rapid depressurization. As seen in Figure 8, it was found that the temperature of CCS sensor A decreased rapidly and the temperature of CSS sensor B decreased gradually, just after rapid depressurization. In addition, the temperature of CCS sensor A increased gradually under the low stable pressure.

![Figure 7](image7.png)

**Figure 7.** Time chart of liquid level and pressure inside the cryostat under rapid depressurization.

![Figure 8](image8.png)

**Figure 8.** Time chart of temperature and pressure inside the cryostat under rapid depressurization.
The details of test number ⑥ without the liquid level measurement is shown in Figures 9 and 10. As shown in Figure 9, the temperature of CCS sensor A increased immediately just after a sharp turn at 360-degree circle. This is thought to be caused by sloshing inside the cryostat due to a sharp turn. At the same time, the ship rolled greatly with a maximum rolling angle of six degree, and a maximum pitching

**Figure 9.** Time chart of temperature and pressure inside the cryostat during marine transportation test ⑥ from 2:45pm to 4:30pm.

**Figure 10.** Time chart of angle and acceleration inside the cryostat during marine transportation test ⑥ from 2:45pm to 4:30pm.
angle of two degrees and a maximum acceleration of 0.1 g, where g is gravitational acceleration. In this experiment, the rolling angle and pitching angle are small because the experimental sea area is an inland sea in Osaka bay. Therefore, the effect of the tidal current is very small and the rolling and pitching of the training ship in this experiment are generated by such as the turning maneuver and the wind and waves. In addition, the maximum rolling angle is about 25 degrees and the pitching angle is about 20 degrees of the training ship on the open sea. In order to clarify the influence of sloshing inside the LH$_2$ tank in rough seas, we plan to perform an experiment on the open sea and compare with theoretical analysis.

4. Summary
First experiment on the LH$_2$ transportation of 20 liter including rapid depressurization tests with five 500-mm-long MgB$_2$ level sensors by the training ship “Fukae-maru” was carried out successfully inside Osaka bay on February 2, 2017. It was found that the increase rate of the temperature and the pressure inside the LH$_2$ tank was large when the rolling angle of the ship was six degrees without liquid level measurement.

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