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LIQUID HYDROGEN EXPERIMENT FACILITY
WITH SYSTEM ENABLING OBSERVATION
UNDER HORIZONTAL VIBRATION

M. Takeda¹, S. Yagi¹, Y. Matsuno², I. Kodama², S. Fujikawa², H. Kumakura³, and T. Kuroda³

¹Graduate School of Maritime Sciences, Kobe University
Kobe, Hyogo 658-0022, Japan

²Iwatani Industrial Gases Corporation
Moriyama, Shiga 524-0041, Japan

³National Institute for Materials Science
Tsukuba, Ibaraki 305-0047, Japan

ABSTRACT

To develop basic technologies for the maritime transport of hydrogen energy, a liquid hydrogen experiment facility (LHEF) with system enabling observation under horizontal vibration has been designed and constructed. The LHEF consists of a liquid hydrogen optical cryostat, a gas-handling system, vacuum pumps, and apparatus for generating horizontal vibrations. The liquid hydrogen optical cryostat, which is 1200 mm in height and 300 mm in diameter, includes a vacuum jacket, a liquid nitrogen space (10.0 liters), a liquid hydrogen space (13.6 liters), a sample space (3.8 liters), optical windows, and a needle valve. The results of performance tests show that the heat leak in the liquid hydrogen space is sufficiently small. Using the LHEF under horizontal vibration, the damped oscillation of the liquid hydrogen surface is successfully observed and analyzed on the basis of a simple model.

KEYWORDS: liquid hydrogen, experiment facility, optical observation, horizontal vibration, damped oscillation

INTRODUCTION

Hydrogen is expected to be the ultimate clean energy source, because only water is produced by the chemical reaction of hydrogen and oxygen. The use of fuel-cell vehicles and internal-combustion-engine vehicles utilizing hydrogen gas has become widespread. In
addition, power generators and hot water supply system for household use and small fuel cells for electric equipment are now commercially available. In the near future, a society consuming a large amount of hydrogen energy is expected to come into existence. In the storage and transport of large quantities of hydrogen, liquid hydrogen (LH₂) has the advantage of high storage efficiency. The World Energy Network (WE-NET) project has examined a scenario in which large quantities of LH₂, which is generated by electrolysis utilizing sustainable energy sources, is transported using LH₂ tankers \( (2 \times 10^5 \text{ m}^3) \) [1].

Some research on the thermal and mechanical properties of thermal insulating materials suitable for LH₂ tanks [2-4] has been carried out as part of the research and development of basic technologies for dealing with large quantities of LH₂. Recently, superconducting magnesium diboride (MgB₂) level sensors such as self-heating-type MgB₂ level sensors [5-8] and external-heating-type MgB₂ level sensors [9, 10] have been reported as new sensors for detecting the level of LH₂. However, research on their level-detecting characteristics and durability under the vibration conditions of the LH₂ surface has been insufficient. In addition, the behavior of the LH₂ surface in the tank under vibration conditions has not yet been sufficiently clarified experimentally, although it has been estimated numerically [11]. To establish a storage and transport system for large quantities of LH₂, it is important to develop an LH₂ level gauge with high performance and to clarify the vibrational behavior of the LH₂ surface. The purpose of the present work is to construct a liquid hydrogen experiment facility (LHEF) that enables optical observation under horizontal vibration. In this paper, the details of the constructed LHEF and experimental results on the damped oscillation of the LH₂ surface are reported.

**EXPERIMENTAL**

**Liquid Hydrogen Experiment Facility**

FIGURE 1 shows the basic layout of the LHEF. A photograph of the LHEF installed in our laboratory is shown in FIGURE 2. The LHEF consists of a liquid hydrogen optical cryostat, a gas-handling system, a large vacuum pump, a small vacuum pump, and

![Diagram of the LHEF](http://example.com/diagram.jpg)

**FIGURE 1.** Basic layout of liquid hydrogen experiment facility (LHEF).
apparatus for generating horizontal vibrations. The gas-handling system is separated into a vacuum line (54.0 mm in outer diameter) and a H₂ gas vent line (41.3 mm in outer diameter). The vacuum line is connected to the small vacuum pump (Diavac, DS-312N) inside the laboratory and the large vacuum pump (Diavac, KRP-3000) outside the laboratory. The H₂ gas vent line is connected to a vent stack on the roof. Helium gas stored in a cylinder is used for flushing the cryostat and the H₂ gas vent line and for extracting the liquid nitrogen (LN₂) used for precooling the cryostat.

Observation System

FIGURE 3 shows a schematic diagram of the LH₂ optical cryostat (Cryovac). The optical cryostat is composed of a vacuum jacket, an LN₂ space (10.0 liters), an LH₂ space (13.6 liters), a sample space (3.8 liters), optical windows, and a needle valve. The optical cryostat, which is made of SUS304, has a height of 1200 mm and an outer diameter of 300 mm. Optical windows made of Pyrex glass are set at four locations (in the x and y directions) and are 50 mm in effective diameter and 10 mm in thickness. The Pyrex windows are sealed with O-rings at ambient temperature and with indium wires at a low temperature to render them vacuum-tight and pressure-tight. Thus, the sample space can withstand pressures of up to 0.5 MPaG (set value). A digital camera (Sanyo, DSC-MZ3) and the digital video camera (Toshiba Teri, CS3960DCL) are mounted on the window area.

Vibration System

A schematic diagram of apparatus for generating horizontal vibrations is shown in FIGURE 4. The apparatus has a base with dimensions of 500 mm by 800 mm and a height of 185 mm, and is composed of a servo motor (Oriental Motor, DX220AD), a ball screw
(THK, BNK2010-2.5), linear rails (THK, SSR25XWY), and a cryostat table (Cryovac). An acceleration sensor (Analog Devices, ADXL202) is mounted on the cryostat table. PC software (Oriental Motor, PC Loader for DX) is used for setting the horizontal vibration conditions. A maximum acceleration of $\pm 0.1$ G and maximum amplitude of $\pm 100$ mm were set upon considering the limitations of the cryostat structure.

**FIGURE 3.** Schematic diagram of liquid hydrogen optical cryostat.

**FIGURE 4.** Schematic diagram of apparatus for generating horizontal vibrations.
EXPERIMENTAL RESULTS

Evaporation Rates of LN$_2$ and LH$_2$

To test the performance of the LHEF, the evaporation rates of the cryogens in the LN$_2$ space and LH$_2$ space of the optical cryostat were measured. The evaporation rate was determined as follows. In the case of LN$_2$, the change in liquid level per hour was measured. In the case of LH$_2$, the flow rate of evaporated H$_2$ gas was measured at ambient temperature and converted to the evaporation rate of LH$_2$.

TABLE 1 shows the measured evaporation rate and the heat leak (experimental and calculated values). The calculated values were obtained by considering thermal conduction and radiation except for the effect of sensible heat of the boiling cryogens. As shown in TABLE 1, the experimental values are in good agreement with the calculated values. The heat leak in the LH$_2$ space was sufficiently small; thus, experiments can be performed over two days with only one LH$_2$ transfer.

Free Surface of LH$_2$

The free surface of LH$_2$ in the sample space was observed through the optical windows. First, LH$_2$ was transferred from the LH$_2$ space to the sample space by opening the needle valve at a low pressure. Next, after the surface condition of LH$_2$ had settled, the surface was observed. The surface under horizontal vibration was recorded continuously using the digital camera. FIGURE 5 shows a photograph of the free surface of LH$_2$ at 1 atm under horizontal vibration. The sloshing of LH$_2$ was also observed using the digital video camera. There were no problems associated with the optical observation under horizontal vibration.

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<td>LN$_2$ space</td>
<td>0.30</td>
<td>13.6</td>
<td>13.9</td>
</tr>
<tr>
<td>LH$_2$ space</td>
<td>0.05</td>
<td>0.40</td>
<td>0.33</td>
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FIGURE 5. Photograph of LH$_2$ surface (20.3 K) under horizontal vibration.
Damped Oscillation of LH₂ Surface

The damped oscillation of the LH₂ surface was recorded by the digital video camera after generating horizontal vibrations with an acceleration of 0.1 G. The liquid surface angle θ, which was defined as zero under a static condition, was analyzed as a function of time during uniform motion. FIGURE 6 shows a time chart of acceleration and the LH₂ surface angle at 1 atm. The free surface of LH₂ was damped with a constant period T after exhibiting a maximum angle θ_max of 9.5 deg. at T = 0.372 s, which was the average value of five measurements obtained under the same conditions.

On the basis of a damped oscillation model, the time dependence of the LH₂ surface angle was calculated. Assuming that the liquid surface angle θ is minute and that the effect of the braking force is less than that of the restoring force, the slowly damped liquid surface oscillation can be expressed by the following equation [12]:

\[ \theta(t) = \theta_{\text{max}} \exp(-\gamma t) \cos \left( \sqrt{\frac{\omega_0^2}{\gamma^2}} t \right), \]  

where \( \theta_{\text{max}} \) is the maximum liquid surface angle at \( t = 0 \); \( \gamma \) is the attenuation constant; and \( \omega_0 \) is the intrinsic angular frequency. The period \( T \) of the damped oscillation is

\[ T = \frac{2\pi}{\sqrt{\frac{\omega_0^2}{\gamma^2}}}. \]  

Using the experimental values of \( \theta_{\text{max}} \) and \( T \), the attenuation constant \( \gamma \) was obtained by the least-squares method. An approximation curve obtained from equation (1) with \( \gamma = 0.215 \) is shown in FIGURE 7. This curve exhibited good agreement with the experimental data. Details of the response performance of a MgB₂ level sensor under the vibration of the LH₂ surface will be published elsewhere.

FIGURE 6. Time chart of acceleration and liquid surface angle (LH₂: 20.3 K).
By means of the LHEF under horizontal vibration, the effect of attenuation plates of sloshing of LH$_2$ surface can be tested. In addition, the difference in damped oscillation between cryogens, e.g., LN$_2$, LH$_2$, LHe, and He II, can be elucidated.

**SUMMARY**

To develop the basic technologies for the maritime transport of hydrogen energy, a liquid hydrogen experiment facility (LHEF) with a system enabling observation under horizontal vibration was designed and constructed. To test the LHEF performance, the evaporation rates of cryogens in the LN$_2$ space and LH$_2$ space of the optical cryostat were measured. Test results show that the heat leak in the LH$_2$ space was sufficiently small. Using the LHEF under horizontal vibration with an acceleration of 0.1 G, observations of the free surface of LH$_2$ and the surface under damped oscillation were carried out successfully. The calculated values of the liquid surface angle based on a damped oscillation model were in good agreement with the experimental values.

Some subjects for future research are as follows: (1) the development of a flowmeter for LH$_2$, (2) the sloshing of the free surface of LH$_2$, (3) the cavitation of LH$_2$, (4) the thermal oscillation of LH$_2$, (5) the rollover of LH$_2$, (6) the boiling heat transfer of LH$_2$, (7) the hydraulic loss of LH$_2$, and (8) the development of an LH$_2$ pump for transport.

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