LIQUID HYDROGEN EXPERIMENT FACILITY WITH SYSTEM ENABLING OBSERVATION UNDER HORIZONTAL VIBRATION

Takeda, Minoru ; Yagi, Sho ; Matsuno, Yu ; Kodama, Itaru ; Fujikawa, Shizuichi ; Kumakura, Hiroaki ; Kuroda, Tsuneo

(Citation)
AIP Conference Proceedings,1218(1):311-318

(Issue Date)
2010-04-09

(Resource Type)
journal article

(Version)
Version of Record

LIQUID HYDROGEN EXPERIMENT FACILITY WITH SYSTEM ENABLING OBSERVATION UNDER HORIZONTAL VIBRATION

M. Takeda[1], S. Yagi[1], Y. Matsuno[2], I. Kodama[2], S. Fujikawa[2], H. Kumakura[3], and T. Kuroda[3]

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

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

[3]National 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

CP1218, *Advances in Cryogenic Engineering: Transactions of the Cryogenic Engineering Conference - CEC, Vol. 55,* edited by J. G. Weisend II

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 (LH_2) has the advantage of high storage efficiency. The World Energy Network (WE-NET) project has examined a scenario in which large quantities of LH_2, which is generated by electrolysis utilizing sustainable energy sources, is transported using LH_2 tankers (2×10^5 m^3) [1].

Some research on the thermal and mechanical properties of thermal insulating materials suitable for LH_2 tanks [2-4] has been carried out as part of the research and development of basic technologies for dealing with large quantities of LH_2. Recently, superconducting magnesium diboride (MgB_2) level sensors such as self-heating-type MgB_2 level sensors [5-8] and external-heating-type MgB_2 level sensors [9, 10] have been reported as new sensors for detecting the level of LH_2. However, research on their level-detecting characteristics and durability under the vibration conditions of the LH_2 surface has been insufficient. In addition, the behavior of the LH_2 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 LH_2, it is important to develop an LH_2 level gauge with high performance and to clarify the vibrational behavior of the LH_2 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 LH_2 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

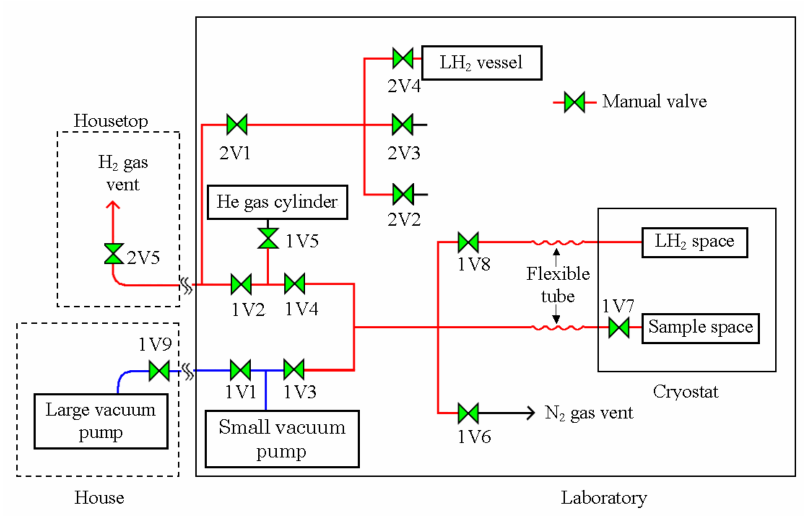

FIGURE 1. Basic layout of liquid hydrogen experiment facility (LHEF).

FIGURE 2. Photograph 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 H_2 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 H_2 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 H_2 gas vent line and for extracting the liquid nitrogen (LN_2) used for precooling the cryostat.

Observation System

FIGURE 3 shows a schematic diagram of the LH_2 optical cryostat (Cryovac). The optical cryostat is composed of a vacuum jacket, an LN_2 space (10.0 liters), an LH_2 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

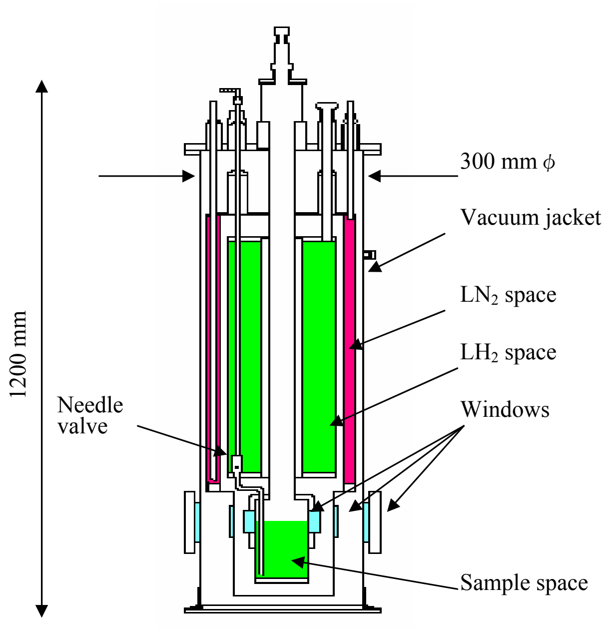

FIGURE 3. Schematic diagram of liquid hydrogen optical cryostat.

(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 ±0.1 G and maximum amplitude of ±100 mm were set upon considering the limitations of the cryostat structure.

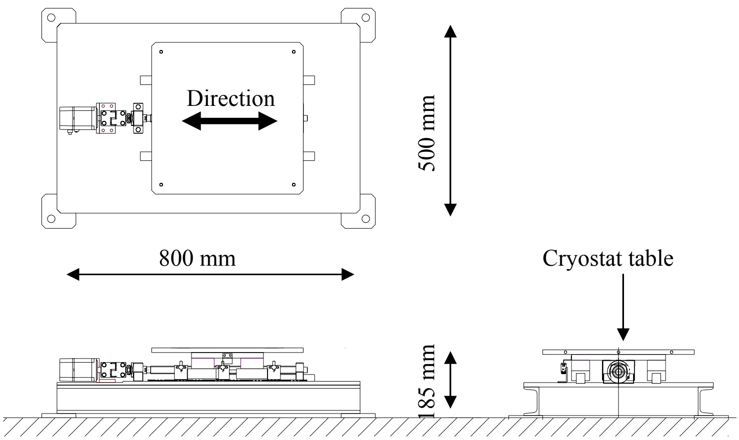

FIGURE 4. Schematic diagram of apparatus for generating horizontal vibrations.

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.

TABLE 1. Measurements results of evaporation rate and heat leak.

Subject	Evaporation rate [L/h]	Heat leak [W]	Heat leak (Cal.) [W]
LN_2 space	0.30	13.6	13.9
LH_2 space	0.05	0.40	0.33

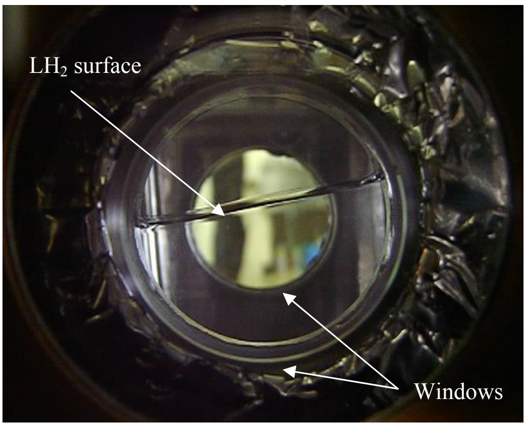

FIGURE 5. Photograph of LH_2 surface (20.3 K) under horizontal vibration.

Damped Oscillation of LH_2 Surface

The damped oscillation of the LH_2 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 LH_2 surface angle at 1 atm. The free surface of LH_2 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 LH_2 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]:

$$\theta(t) = \theta_{\max} \exp(-\gamma t) \cos\sqrt{\omega_0{}^2 - \gamma^2}\, t\,, \tag{1}$$

where θ_{max} is the maximum liquid surface angle at t = 0; γ is the attenuation constant; and ω_0 is the intrinsic angular frequency. The period T of the damped oscillation is

$$T = 2\pi \Big/ \sqrt{\omega_0{}^2 - \gamma^2}\,. \tag{2}$$

Using the experimental values of θ_{max} and T, the attenuation constant γ was obtained by the least-squares method. An approximation curve obtained from equation (1) with γ = 0.215 is shown in FIGURE 7. This curve exhibited good agreement with the experimental data. Details of the response performance of a MgB_2 level sensor under the vibration of the LH_2 surface will be published elsewhere.

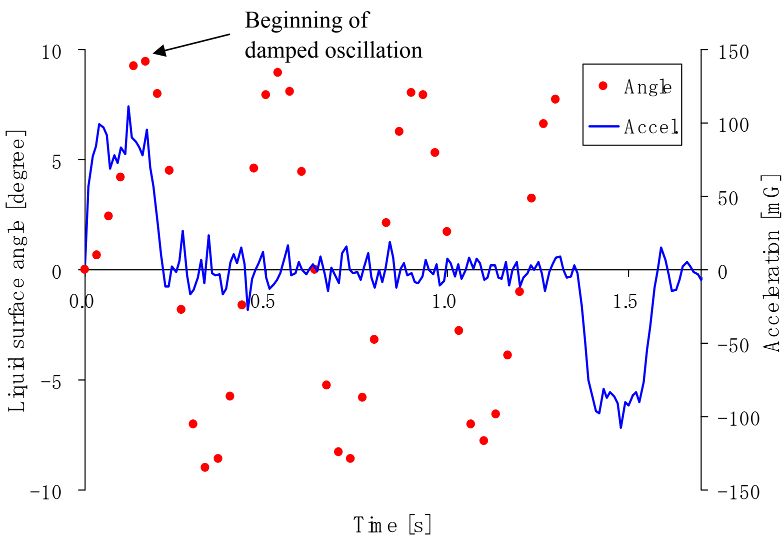

FIGURE 6. Time chart of acceleration and liquid surface angle (LH_2: 20.3 K).

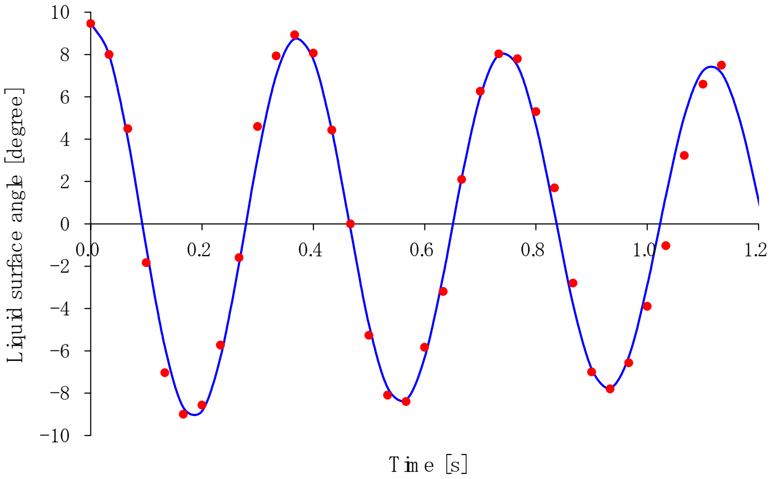

FIGURE 7. Damped oscillation of LH_2 surface (20.3 K).

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.

ACKNOWLEDGMENTS

The authors would like to thank Professor Kenya Sakamoto, Dr. Yuji Iwamoto, Dr. Teruhiko Akazawa, and Mr. Hironobu Iwashita for helpful discussions and technical support, and Mr. Yoshiyuki Okubo, Mr. Chikara Kazama, and Mr. Masanori Maekawa for their assistance in the experiment. This work was supported in part by the Hyogo Prefecture COE Program, NYK-Heyerdahl Projects, and the Mayekawa Houonkai Foundation, Japan.

REFERENCES

1. Seki, N., "Development of the Liquid Hydrogen Tanker," in *Proceedings of WE-NET Hydrogen Energy Symposium*, 1999, pp.131-139, in Japanese.
2. Kamiya, S., Onishi, K., Kawagoe, E. and Nishigaki, K., *Cryogenics* **40**, pp. 35-44 (2000).
3. Kamiya, S., Onishi, K., Konshima, N. and Nishigaki, K., *Cryogenics* **40**, pp. 737-748 (2000).
4. Sakurai, G., Kamiya, S., Horiguchi, K. and Fujii, H., "Cryogenic Strength Characteristics of Thermal Insulators for a Large LH_2 Tank," in *Proceedings of 67th Meeting on Cryogenics and Superconductivity, Japan*, 2002, p. 300, in Japanese.
5. Haberstroh, Ch. and Zick, G., "A Superconductive MgB_2 Level Sensor for Liquid Hydrogen," in *Advances in Cryogenic Engineering* 51A, edited by J. G. Weisend Ⅱ *et al*., AIP, New York, 2006, pp. 679-684.
6. Haberstroh, Ch., Dehn, G. and Kirsten, D., "Liquid Hydrogen Level Sensors Based on MgB_2," in *Proceedings of the 21st International Cryogenic Engineering Conference / International Cryogenic Materials Conference*, 2007, pp. 357-360.
7. Kajikawa, K., Tomachi K., Maema, N., Matsuo, M., Sato, S., Funaki, K., Kumakura, H., Tanaka, K., Okada, M., Nakamachi, K., Kihara, Y., Kamiya, T. and Aoki, I., "Fundamental investigation of a superconducting level sensor for liquid hydrogen with MgB_2 wire," in *Journal of Physics*: *Conference Series* 97, 2008, 012140.
8. Kajikawa, K., Tomachi, K., Tanaka, K., Funaki, K., Kamiya, T., Okada, M. and Kumakura, H., "Numerical simulation of a superconducting level sensor for liquid hydrogen with MgB_2 wire," in *Proceedings of the 22nd International Cryogenic Engineering Conference / International Cryogenic Materials Conference*, 2009, pp. 425-430.
9. Takeda, M., Matsuno, Y., Kodama, I. and Kumakura, H., "Characteristics of MgB_2 Sensor for Detecting Level of Liquid Hydrogen," in *Advances in Cryogenic Engineering* 53B, edited by J. G. Weisend Ⅱ *et al*., AIP, New York, 2008, pp. 933-939.
10. Takeda, M., Matsuno, Y., Kodama, I., Kumakura, H. and Kazama, C., "Application of MgB_2 Wire to Liquid Hydrogen Level Sensor –External-Heating-Type MgB_2 Level Sensor," in *IEEE Transactions on Applied Superconductivity* 19, 2009, pp. 764-767.
11. Himeno, T., Watanabe, T., Nonaka, S., Naruo, Y. and Inatani, Y., "Sloshing Prediction in the Propellant Tanks of VTVL Rocket Vehicle," in *Proceedings of 41st AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit*, 2005, 3931.
12. Kinbara, T., *Fundamental Physics*, Shokabo, Tokyo, 1988, pp. 167-172, in Japanese.