IOP Conf. Series: Materials Science and Engineering **1344** (2026) 012044 doi:10.1088/1757-899X/1344/1/012044

Study on zero boil-off of liquid hydrogen using a single stage GM cryocooler

Yutaro Koike[1*], Takehisa Tsurudome[1], Yoshihiko Arakawa[1], Takashi Hirayama[1], Jun Kondo[1] and Takaaki Morie[1]

[1] Technology Research Center, Sumitomo Heavy Industries, Ltd.

[*]yutaro.koike@shi-g.com

Abstract. Hydrogen is expected to become one of the major energy sources as an environment-friendly fuel since it emits no carbon dioxide when used. Rather than as a gas, hydrogen will be transported and stored as liquid hydrogen (LH_2) owing to its higher density, which enables more efficient utilization of container capacity. However, LH_2 has a very low boiling point of 20 K. Therefore, a small amount of heat generates boil-off gas. For long-term storage of LH_2, a system for cooling and recondensing the boil-off gas is required, with cooling system such as cryocoolers. We demonstrated zero boil-off of LH_2 by cooling and recondensing boil-off gas using a single stage Gifford-McMahon (GM) cryocooler. In this paper, we report the results of the demonstration experiment for zero boil-off gas.

1. Introduction

Hydrogen is widely recognized as a clean energy carrier, with its only combustion byproduct being water vapor. In order to realize a hydrogen society in the future, efficient storage and transportation of hydrogen is crucial. Liquid hydrogen (LH_2) is expected to be a future energy carrier owing to its high storage density. However, at atmospheric pressure, LH_2 must be stored at about 20 K. Also, even tiny heat leaks lead to vaporization and boil-off gas (BOG) will be generated. Therefore, the BOG needs to be removed by cooling and recondensing it using a cooling system such as a cryocooler. So far, it has been calculated that the efficiency of the zero boil-off (ZBO) system is crucial for economic viability [1]. In addition, ZBO of LH_2 have been researched using cooling systems, such as a two-stage GM cryocooler [2]. To date, there is no reports of direct measurements of the efficiency of a ZBO system. Therefore, these findings highlight the need for further research on ZBO systems employing high-efficiency cooling systems and studies on their efficiency.

The efficiency of cryocoolers is commonly expressed using the coefficient of performance (COP) and is given by equation (1). Here, COP is the ratio of cooling capacity Q to power consumption P.

$$COP\ (\%) = \frac{Q}{P} \times 100 \tag{1}$$

The ratio of the power energy cost to the cost of BOG suppressed by the ZBO system, as used in the study [2], can be rewritten using COP as given by equation (2).

$$Cost\ Ratio = \frac{h_{fg}(\mathrm{kJ/kg})}{COP(\%)} \times \frac{Electric\ rate(\$\ /\mathrm{kWh})}{Hydrogen\ cost(\$\ /\mathrm{kg}) \times 3600(\mathrm{s})}, \tag{2}$$

where h_{fg} represents the latent heat of vaporization of hydrogen, and $Cost\ Ratio$ represents the ratio between electricity cost and the price of hydrogen. Equation (2) describes that when the cost ratio equals 1, the cost of boil-off hydrogen is equal to the electricity cost of the ZBO system. If the cost ratio is less than 1, it indicates that the electricity cost of the ZBO system with a cryocooler is lower than the cost of BOG. This showing that the ZBO system is economically viable. Using this equation (2), the required COP for the cost ratio to equal 1 can be estimated. Figure 1 shows the required COP of the ZBO system to balance the two costs, assuming two different electricity rates and hydrogen costs. The electricity rates were calculated using the maximum and minimum industrial electricity rates in the United States over the past 20 years [4]. Considering that the target hydrogen price in the U.S. in 2026 is $2 per kilogram [5], it is shown that a COP of 0.6% is required to achieve a cost ratio of 1. A COP higher than 0.6% will be necessary for the cost ratio to be less than 1. As a result, a COP of 0.6% or higher indicates that the ZBO system is sufficiently economically viable under current conditions. This calculation takes only operational expenditure into account and excludes capital expenditure.

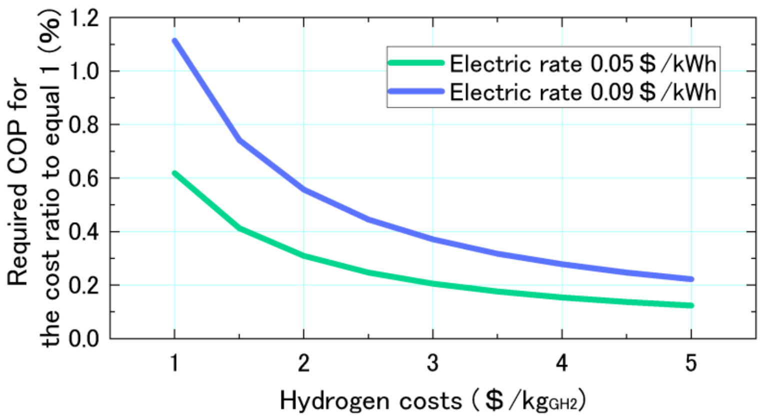

Figure 1. The COP of the ZBO system when the cost ratio equals 1. The blue line represents the calculation results with an electricity rate of $0.09/kWh, and the green line represents the calculation results with an electricity rate of $0.05/kWh.

Unlike the two-stage GM cryocooler used in prior study in [2], the single-stage GM cryocooler may offer higher cooling capacity and COP around the hydrogen boiling point of 20 K.

In this study, a ZBO measurement system was constructed using a GM cryocooler whose efficiency is enhanced from RDK-500B2. RDK-500B2 cryocooler is released in 2024 from Sumitomo Heavy Industries, Ltd., and is coupled with an F-70 compressor. For this test, we optimized the internal components of the RDK-500B2 cryocooler and used a more energy-efficient compressor compared to the F-70. This paper reports the demonstration of ZBO and the system efficiency obtained using the measurement system.

2. Measurement system and method

Figure 2 shows a schematic overview of the ZBO measurement system designed in this study. The system consists of a single stage GM cryocooler, a heat exchanger, an LH_2 storage tank, and a vacuum chamber.

The recondensation heat exchanger is a key component. It is designed to be thermally and mechanically connected with the stage of the GM cryocooler, which allows it to be cooled directly by the cryocooler. It is made of high-purity copper. It features multiple fins to increase the surface area for effective vapor condensation. The LH_2 storage vessel used in this study is a 3-liter stainless-steel tank, surrounded by multilayer insulation (MLI) (Not shown in Figure 2) and vacuum chamber to minimize radiation heat, enabling reliable evaluation of ZBO performance. The LH_2 storage tank and the heat exchanger are hermetically sealed to ensure that hydrogen gas does not leak into the vacuum chamber. Two pipelines are connected to the LH_2 storage tank, allowing hydrogen to be introduced into and exhausted from the system. A pressure sensor is installed on a pipe directly connected to the LH_2 storage tank to continuously monitor the internal pressure. In addition, a vent valve is installed on the pipeline to discharge hydrogen gas from the LH_2 storage tank. Three temperature sensors T1, T2, T3 are installed to the system. The temperature sensor T1 is positioned at the heat exchanger, T2 is placed in the middle of the gas space and T3 is located at the bottom of the gas space inside the LH_2 storage tank. The bottom sensor T3 measures the temperature of the liquid phase, while the middle sensor T2 measures the temperature of the vapor phase. A heater is installed around the LH_2 storage tank to apply thermal loads to the LH_2. The heater is positioned to ensure that the thermal load is applied only to the LH_2. The heat input from the heater was continuously measured.

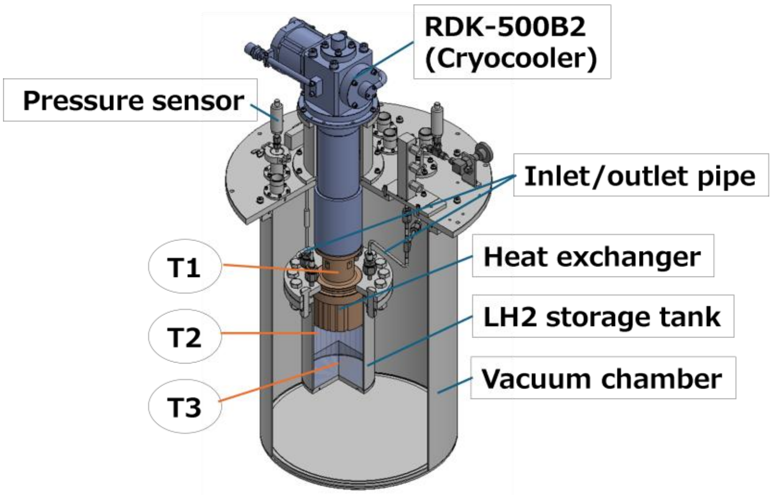

Figure 2. 3D model of the ZBO system. The system consists of a cryocooler, a heat exchanger, an LH_2 storage tank, and a vacuum chamber. T1, T2, and T3 represent the positions of the temperature sensors.

In this experiment, we used a GM cryocooler whose efficiency is enhanced from RDK-500B2. We selected a dual-inverter type compressor, not the officially combined compressor, F-70. This configuration allows independent control of the operating frequencies of both the cold head and the compressor. The use of inverter-driven control improves the ability to tune both cooling power and energy efficiency. This also enables temperature regulation under varying heat loads through selective control of cooling performance.

The operating pressure of the gas space in LH_2 storage tanks at hydrogen stations is set to approximately 0.2 MPaG, which corresponds to a saturation temperature of hydrogen around 25 K [3]. Therefore, this paper primarily reports on recondensation experiments conducted at the saturation pressure of 0.2 MPaG. This temperature is higher than its normal boiling point. At this temperature, cryocooler efficiency improves. Before conducting the ZBO experiment, efficiency of the cryocooler itself was measured. When operating at a cryocooler frequency of 60 Hz and at 25 K, the cryocooler provided 60 W of cooling with a COP of 1.02%.

This measurement evaluates both liquefying hydrogen gas and recondensation LH_2 in the LH_2 storage tank. Hydrogen gas was continuously supplied through the inlet line and condensed into LH_2 by the heat exchanger. After liquefaction, a heater was used to apply a thermal load to the LH_2 to generate BOG, and the system ability to maintain ZBO was evaluated. If ZBO is successfully achieved, the internal pressure of the LH_2 storage tank remains stable, indicating effective suppression of BOG. The COP of the ZBO system was evaluated by measuring the electrical power consumption of the system using a power meter.

3. Experimental Result and Discussion

First, we describe the result of liquefaction of hydrogen from its 300 K gas. Figure 3 shows the result of the hydrogen liquefaction experiment. Room-temperature hydrogen gas was continuously introduced into the system at a pressure of 0.2 MPaG. The experiment was conducted with the vent valve closed, preventing any venting of the introduced hydrogen gas. One and a half hours after the start of gas introduction, the gas temperature reached approximately 25 K, near the liquefaction point at 0.2 MPaG. The amount of LH_2 calculated from the residual pressure of the supply cylinder began to increase from the timing. This indicates that liquefaction had occurred. Accordingly, the volume of LH_2 stored in the LH_2 storage tank was increased. Finally, approximately 2-liters of LH_2, which is equivalent to about 65% of the LH_2 storage tank volume, were successfully generated and stored.

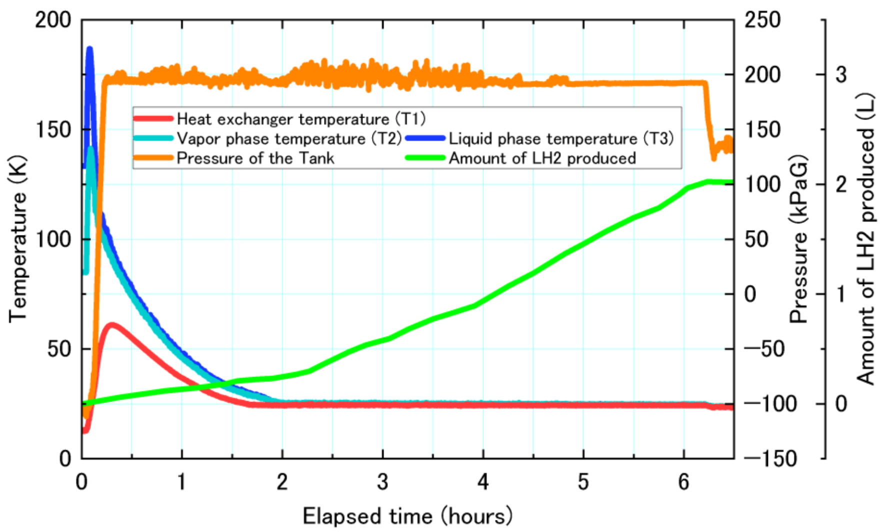

Figure 3. The results of the hydrogen gas liquefaction test. The red line represents the temperature of the heat exchanger (T1), the light blue line represents the vapor phase temperature of the LH_2 (T2), the blue line represents the liquid phase temperature of the LH_2 (T3), the orange line represents the LH_2 storage tank pressure, and the green line shows the amount of LH_2 produced, calculated from the gas injection volume. The liquefaction test was conducted with the cooling capacity limited to 25 W due to Japanese regulations. This limited the liquefaction rate.

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Next, we describe the result of recondensation. Figure 4 presents the results of the ZBO test conducted using the stored LH_2. In this test, both the hydrogen inlet and vent valves were kept closed to ensure no gas could escape from the system. The figure shows the pressure and temperature of the LH_2 in the LH_2 storage tank over a 10-hour period under a constant heat load of 60 W. The heat load was applied using a heater, which generated BOG. The BOG was successfully recondensed by the cryocooler. The cryocooler prevented any pressure build-up. The pressure rise in the LH_2 storage tank was suppressed throughout the 10-hour period during which the cryocooler was operating. Additionally, the light red line in Figure 4 represents the saturated vapor pressure calculated from the temperature of the LH_2, which closely matches the measured pressure in the LH_2 storage tank, that recondensation is occurring under saturated conditions. From these results, we confirmed the system's ability to maintain ZBO. Throughout the test, there was no venting observed, and the temperature remained tightly regulated near the saturation point of hydrogen, 25 K. Additionally, the recondensation rate during this period was estimated to be 7.9 L/h.

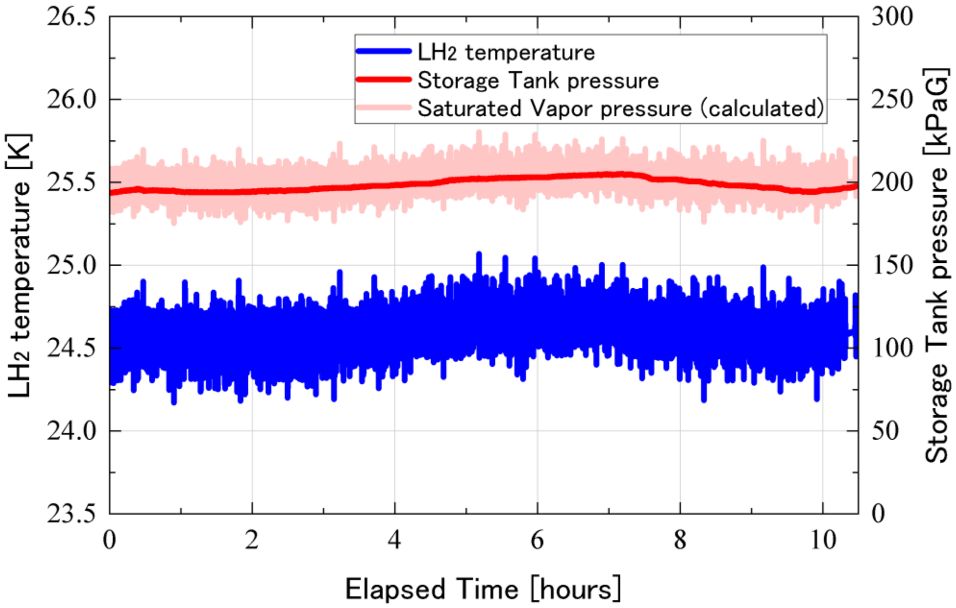

Figure 4. ZBO test result under a heat load condition of 60 W. The blue line represents the liquid phase temperature of the LH_2 (T3), the red line represents the LH_2 storage tank pressure, and the light red line shows the saturation vapor pressure calculated from the temperature of the LH_2.

The COP of the ZBO system was measured as the ratio of the applied heat load to the electrical power consumed by the cryocooler system with several heat inputs. Figure 5 shows the COP results across a range of applied heat loads from 40 W to 60 W. In this experiment, the cryocooler frequency was adjusted at each heat load condition to maintain the LH_2 storage tank pressure at 0.2 MPaG, and efficiency was measured accordingly. Across all tested conditions, the system consistently achieved a COP higher than 0.9%, reaching a maximum value of 0.99% at a 60 W heat load. These results confirm the high energy efficiency of the cryocooler under realistic operational conditions. Furthermore, the ability to selectively regulate LH_2 tank pressure through dynamic adjustment of the cryocooler frequency, enabled by the dual-inverter system, was clearly demonstrated.

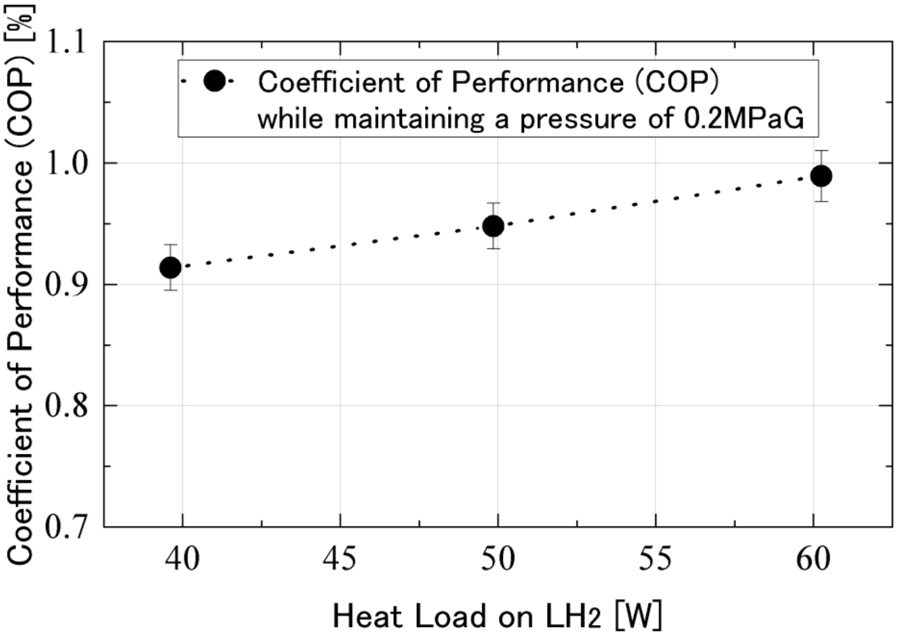

Figure 5. Measurement result of efficiency of the system. The system efficiency (COP) was measured under pressure conditions of 0.2 MPaG, with heat load conditions ranging from 40 W to 60 W.

4. Conclusion

In this study, we successfully constructed and demonstrated energy-efficient ZBO system for LH_2 using a single-stage GM cryocooler. The experimental evaluation confirmed the system ability to maintain stable pressure and temperature under a sustained thermal load of 60 W for more than a period of 10 hours, achieving ZBO operation without venting. Across the tested heat load range between 40 W to 60 W, the system with the single stage GM cryocooler can consistently achieved COP greater than 0.9%, with a maximum value of 0.99% measured at 60 W. These results indicate that our system can be operated with high energy efficiency, making the ZBO system economically viable for industrial applications. Additionally, the inverter control of the cryocooler enabled flexible adjustment of its cooling capacity, allowing stable control at the desired BOG pressure even under varying thermal conditions. These advancements will significantly contribute to enabling safe, cost-effective, and sustainable hydrogen energy utilization.

Acknowledgments
The authors would like to express their gratitude to the members of the Technology Research Center and the Cryogenics Division, Precision Equipment Group at Sumitomo Heavy Industries, Ltd., for their invaluable support throughout the development and testing of the ZBO measurement system.

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