

Development of Ultra-high Pressure Liquid Hydrogen Pump for Heavy-duty Hydrogen Refueling Stations



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As efforts to achieve carbon neutrality proceed worldwide, the demand for large-scale hydrogen refueling stations that service commercial fuel cell vehicles (such as trucks and buses) is expected to increase in the future. Since long travel distance and high operating rate are required for commercial vehicles, technology to fill a large amount of hydrogen in a short time is indispensable for the popularization of fuel cell vehicles. Liquid hydrogen booster pumps are equipment that facilitate large-capacity and high-speed hydrogen refueling. However, since any pump failure will directly lead to station downtime, reliability of the equipment is extremely important. Mitsubishi Heavy Industries, Ltd. has developed a large-flow, highly reliable, ultra-high pressure liquid hydrogen booster pump. As a result of long-term endurance tests conducted at a hydrogen transportation terminals in the United States, the pump demonstrated durability of over 1,200 hours and could contribute to the stable operation of a large-scale hydrogen refueling station.

1. Introduction

Efforts in technological development aimed at achieving carbon neutrality have been actively pursued around the world. The transport sector in particular, as represented by automobiles, accounts for approximately 15% of global greenhouse gas emissions⁽¹⁾ and is therefore a critical target for technological development. Among them, for commercial vehicles (such as trucks and buses), which require long driving ranges and high utilization rates, initiatives are underway to develop and promote the introduction of Fuel Cell Vehicles (hereinafter referred to as FCVs) and hydrogen engine vehicles. In parallel with the introduction of these vehicles, the development of a hydrogen supply infrastructure is an urgent issue, and the demand for heavy-duty hydrogen refueling stations to service commercial vehicles is expected to increase in the future⁽²⁾.

Currently, storing hydrogen at ambient temperature and high pressure (70 MPaG or 35 MPaG) in an on-board tank is a common method for FCVs. To refuel an FCV, the hydrogen refueling station equipment must generate hydrogen at a pressure higher than that of the FCV's tank. There are many methods for handling hydrogen, as shown in **Figure 1**. In conventional hydrogen refueling stations for passenger cars, transporting hydrogen gas cylinders at medium pressure (approximately 20 MPaG) from a plant and increasing the pressure to high pressure (over 80 MPaG) using a compressor at the station is mainstream. However, if this hydrogen gas compressor method is applied to heavy-duty hydrogen refueling stations, the following issues would need to be addressed:

- Transportation and storage: Due to high hydrogen consumption at hydrogen stations, frequent deliveries from hydrogen production plants would be required.
- Pressure boosting and refueling: To achieve a high hydrogen supply flow rate to FCV, parallelization of compressors and installation of large number of hydrogen storage cylinders would be necessary.

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Consequently, the necessity of securing a vast site area and expensive equipment introduction and operation costs may become a bottleneck for hydrogen station installation.

On the other hand, method using liquid hydrogen and pump would offer the following advantages:

- Transportation and storage: Liquid hydrogen has a higher density than hydrogen gas and can be handled at low pressures of 1 MPaG or less, enabling mass transportation and large-scale storage.
- Pressure boosting and refueling: Pumps can be made larger in flow rate and more compact than compressors. This would significantly reduce the number of compressors and hydrogen storage cylinders as well as the required installation space.

For heavy-duty hydrogen refueling stations in the United States and South Korea, the liquid hydrogen/boost pump method is already becoming the mainstream.

Mitsubishi Heavy Industries, Ltd. (hereinafter referred to as MHI) has developed an ultra-high pressure liquid hydrogen booster pump, one of the most critical components for the liquid hydrogen/boost pump method. Since failures of the liquid hydrogen booster pump will lead directly to downtime of a heavy-duty hydrogen refueling station and hinder operation of commercial vehicles, reliability and durability of the pump were positioned as the most critical challenges during development. Emphasis was also placed on functionality, such as easy and rapid flow rate control and minimal boil-off loss of liquid hydrogen. This report describes the development process and test results to date, and presents the high reliability and superior functionality of the product developed by MHI.

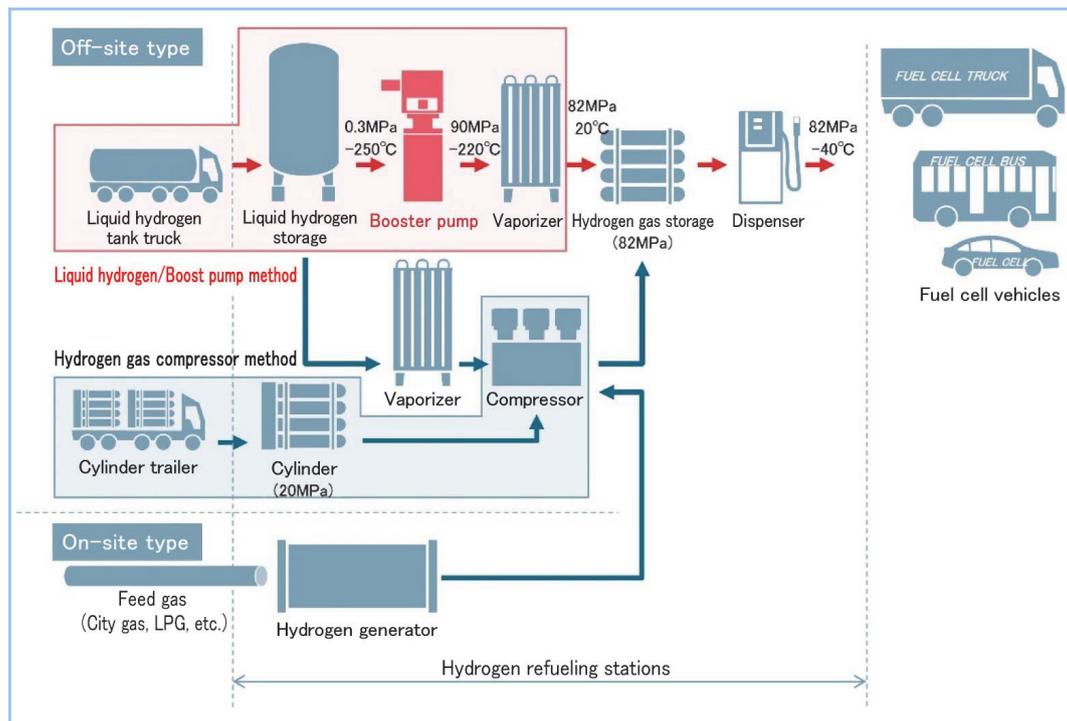


Figure 1 Methods for transport and storage, pressure boosting, and refueling of hydrogen at hydrogen refueling stations

2. Overview of MHI's liquid hydrogen booster pump⁽³⁾

A structural diagram of the ultra-high pressure liquid hydrogen booster pump developed by MHI is shown in **Figure 2**. The pump is a reciprocating piston type driven by a hydrogen-compatible explosion-proof motor. The motor utilizes an inverter control system, which allows the rated flow rate of the pump of 160 kg/h to be controlled to any flow rate within a wide range of 10% to 100%. Responsiveness of the flow rate control is also excellent because of electric control, enabling the pump to quickly adjust to changes in the required flow rate as specified by hydrogen refueling standards (such as SAE J2601⁽⁴⁾).

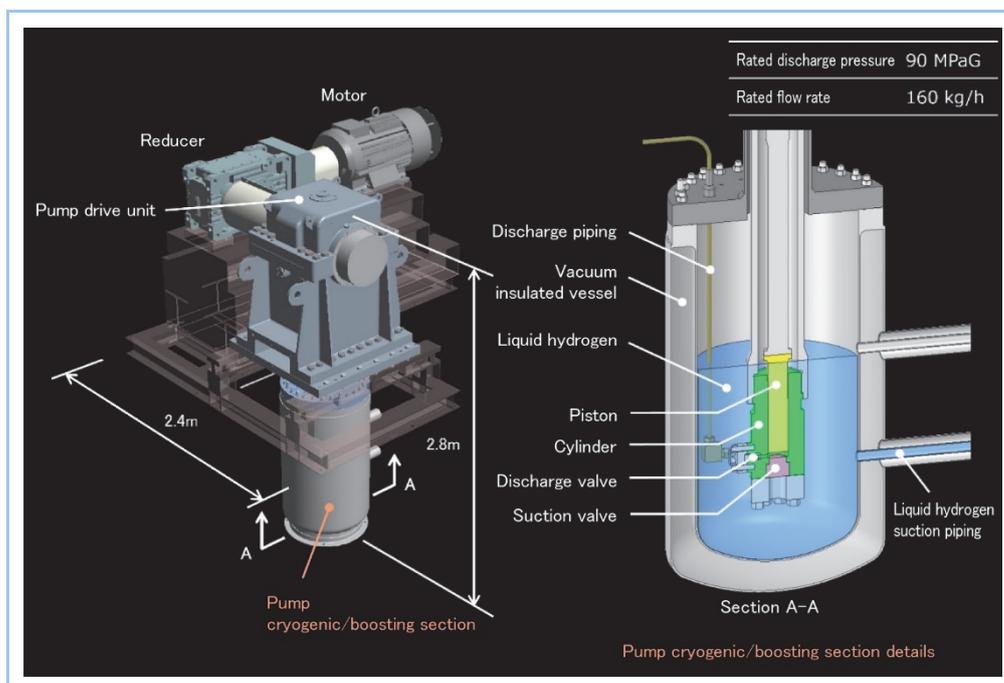


Figure 2 Structural diagram of ultra-high pressure liquid hydrogen booster pump

This pump is equipped with a small sump to store liquid hydrogen temporarily. Components related to the pressure-boosting function, such as the cylinder, piston, suction valve, and discharge valve, are constantly submerged in cryogenic liquid hydrogen (approximately -253°C). The liquid hydrogen booster pump must be able to boost the pressure of low-pressure liquid hydrogen (0 to 1 MPaG) up to a maximum of 90 MPaG and deliver it to the downstream piping. A major challenge in achieving this function is that liquid hydrogen is extremely susceptible to evaporation and vaporization, with a latent heat of vaporization per unit volume (kJ/L) of only about one-fifth that of liquid nitrogen, which is also a cryogenic fluid, at atmospheric pressure. Therefore, temperature change of hydrogen due to pump power supply, even slight heat generated by friction between mechanical parts, heat flow from the atmosphere, etc. can cause the liquid hydrogen to enter a gas-liquid two-phase state. In particular, vaporization of liquid hydrogen may occur in ultra-high pressure liquid hydrogen booster pumps due to compression heat generated during pressure boosting or frictional heat from the sliding of seal rings. Two major problems with pumps caused by vaporization of liquid hydrogen: (1) deterioration of the pump's suction capability, leading to a decrease in flow rate or the inability to boost pressure, and (2) a decrease in the hydrogen utilization rate (boil-off loss) caused by the release of vaporized hydrogen outside the system necessity in order to operate the equipment below the design pressure, which increases supply cost of the hydrogen refueling station.

Regarding issue (1), some existing liquid hydrogen booster pumps utilize a method that boosts the pressure to 90 MPaG in two stages. This equipment configuration aims to stabilize the suction capability. However, this also presents challenges such as:

- The large number of moving and sliding parts can be a factor in the reduction of reliability and durability.
- Depending on the structure, the flow rates of the first and second stages may not match, potentially causing some of the liquid hydrogen delivered from the first stage to return to the pump inlet side, which could increase boil-off loss.

In contrast, focusing on reliability and durability, MHI has adopted a single-stage pressure boosting method instead of a two-stage method. While stable pressure boosting in a single stage can be difficult depending on the pump structure, stable boosting performance has been achieved, even with the single-stage method, by devising and adopting a proprietary structure for the suction section and suction valve of the pump.

Regarding issue (2), boil-off loss reduction, suppressing the amount of heat flow from the atmosphere into the cryogenic sections is crucial. In addition to adopting a vacuum-insulated liquid hydrogen sump, heat flow is suppressed by extending the shaft fully to increase the distance between

the cryogenic and ambient temperature sections. Adopting the single-stage pressure boosting method also contributes to a reduction in boil-off loss during pump operation.

3. Development testing of liquid hydrogen booster pump⁽⁵⁾

3.1 Development process

The development process to date is shown in **Figure 3**. For more than half a century since the early 1970s, MHI has researched and accumulated expertise in liquid hydrogen utilization technologies. As part of these efforts, the development of 40 MPa-class liquid hydrogen booster pump (hereinafter referred to as the 40 MPa model) for hydrogen refueling stations has been completed in 2007. Subsequently, in 2018, as interest in hydrogen utilization began to grow, development of a 90 MPa-class liquid hydrogen booster pump (hereinafter referred to as the 90 MPa model) began. MHI possesses extensive experience in developing a diverse range of products, including liquid-propellant rockets, liquefied natural gas (LNG) equipment, nuclear power-related equipment, and industrial engines. The 90 MPa model was designed utilizing not only the knowledge gained from the 40 MPa model but also technologies such as fluid dynamics, heat transfer, mechanical elements, strength, vibration, and materials in many fields cultivated through various MHI products. Furthermore, component tests and system tests for the 90 MPa model were conducted at MHI's in-house facilities with the company's advanced experimental techniques for handling cryogenic fluids such as liquid nitrogen and liquid hydrogen. Following this, in order to verify reliability, durability, and functionality, a long-term endurance test using actual liquid hydrogen was conducted in collaboration with a U.S. company. The prescribed levels of reliability, durability, and functionality were successfully demonstrated. An overview and results of the tests conducted to date are described in the following sections.

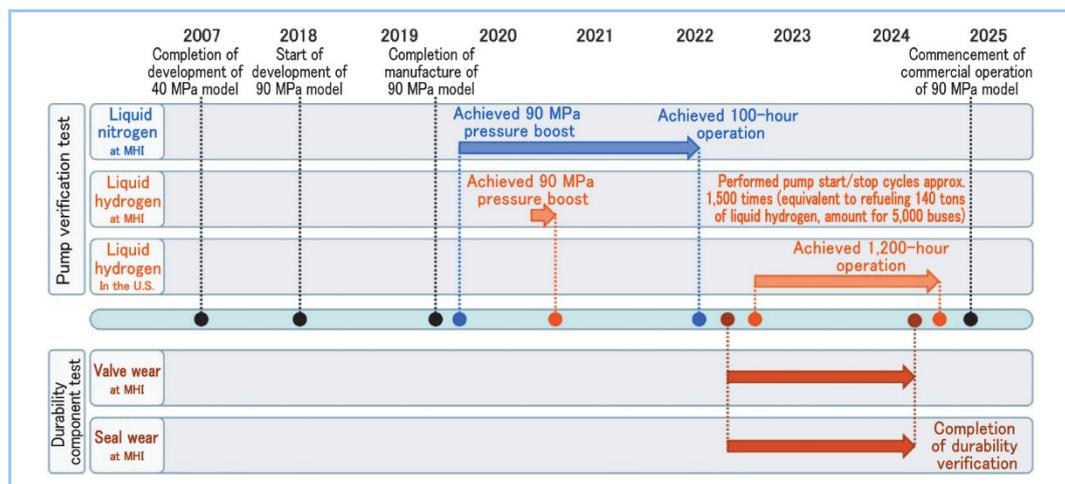


Figure 3 Development process of ultra-high pressure liquid hydrogen booster pump

3.2 In-house testing of the pump

In 2018, a feasibility study for the 90 MPa model was launched, and a prototype pump was manufactured following the basic and detailed design. For pump testing, a functional test using liquid nitrogen was first carried out to confirm that the pump operated normally in a cryogenic environment and possessed a pressure-boosting capability of 90 MPaG. Next, a performance verification test using actual liquid hydrogen was conducted. From the results, stable pressure boosting to 90 MPaG was shown to be possible even with liquid hydrogen, and the pump demonstrated a flow rate of 160 kg/h, which exceeded the target. Subsequently, as a durability test which could be carried out in-house, a 100-hour operation using liquid nitrogen was performed. The setup and results of the 100-hour operation test are shown in **Figure 4**. Liquid nitrogen was supplied from multiple tank trucks, and the pump operated for a total of 100 hours at a discharge pressure of 90 MPaG. A slight difference in the pump's flow rate was observed between the early and final stages of the test, and this was due to conditions upstream side of the pump. Degradation in the performance of the pump itself was not observed. Furthermore, fatigue damage or abnormal wear was not observed in the detailed inspections after the test, and the conclusion that durability of the pump, as predicted during the design phase, was achieved.

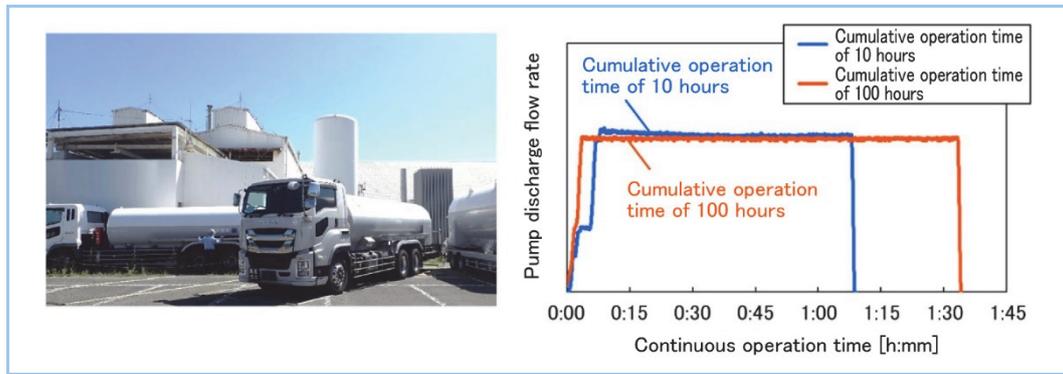


Figure 4 Setup and results of 100-hour operation test using liquid nitrogen

3.3 Component testing⁽⁶⁾

Although the pump durability test was conducted in-house for 100 hours, this test time represents only a fraction of the time interval desired between maintenance events of an actual hydrogen refueling station. Therefore, durability verification tests were performed on individual mechanical components that govern the maintenance interval. Major components targeted for verification were the suction valve, discharge valve, piston rings (seal rings mounted on the outer circumference of the piston), and rod seals (seal rings that isolate the inside of the liquid hydrogen sump from the atmosphere). Since the valve elements of the suction and discharge valves perform reciprocating motion with a differential pressure up to 90 MPa acting upon them during each cycle, generating extremely high contact pressure on their contact surface between valve disc and seat. As wear progresses due to this high contact pressure, the sealing performance, which is a basic function of the valve, is compromised, leading to a decrease in the flow rate of the pump or loss of boost capability. Furthermore, since the piston rings and rod seals also operate in a reciprocating sliding environment, wear progresses due fluid pressure, which may cause a decrease in the flow rate of the pump or leakage of hydrogen gas.

To verify the durability based on these physical phenomena, MHI developed two types of reciprocating sliding test apparatuses that can evaluate each individual component in liquid hydrogen and hydrogen gas environments, respectively. The outer appearance of the test apparatuses is shown in Figure 5. The apparatus for a liquid hydrogen environment is constructed to test any suction valve, discharge valve or piston ring, and can apply the same contact pressure and sliding speed to the test sample as that in the actual operating environment. This apparatus can also perform accelerated testing with a higher reciprocating cycle than that of the actual pump. As a result, durability evaluations equivalent to hundreds or thousands of hours of actual operation in a relatively short period is possible. The apparatus for a hydrogen gas environment is set up to evaluate rod seals. It is also designed for accelerated testing, as well as simultaneous testing of multiple samples, for efficient evaluation of durability.

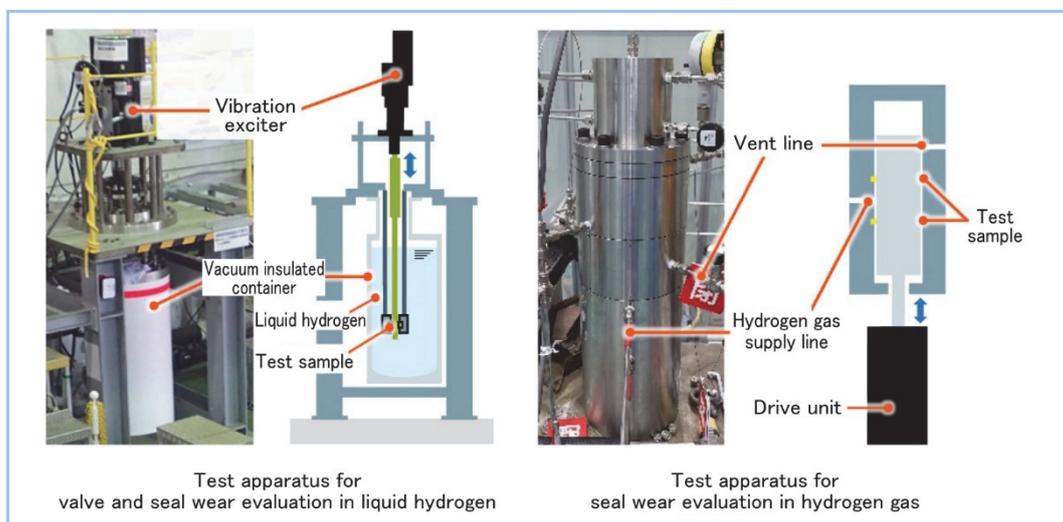


Figure 5 Reciprocating sliding test apparatus

Representative durability test results for the suction valve are shown in **Figure 6**. These results include surface roughness measurements for the valve disc and seat. Although repeated contact caused slight deformation of several μm in the valve disc, almost no surface roughening was observed, and excellent shape of the sliding surface was maintained. To measure the leakage flow rate of the suction valve, fluid pressure was applied to the suction valve before and after the test. Leakage remained under the detection limit, confirming high durability of the suction valve.

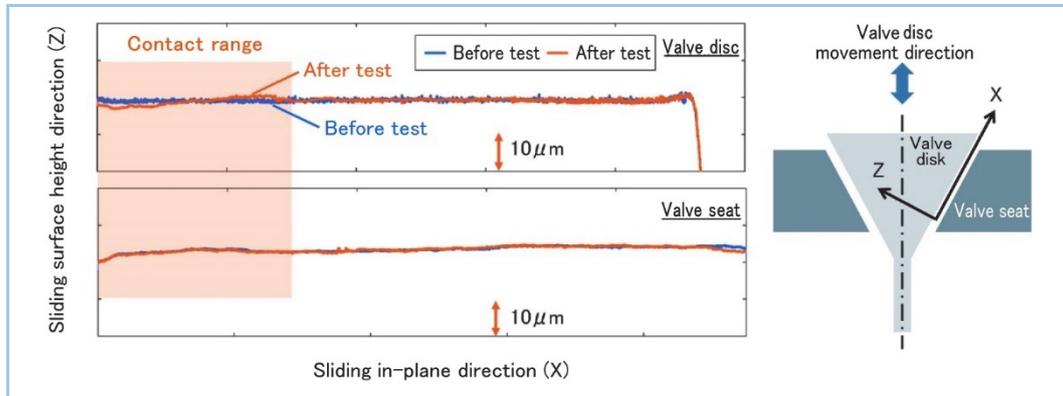


Figure 6 Results of durability test of suction valve

3.4 Long-term durability test in the United States⁽⁷⁾

At present, there was no facility conducting long-term durability tests using actual liquid hydrogen in Japan, including at MHI. Therefore, the United States, where the distribution volume of liquid hydrogen is large, was considered and a long-term durability test was conducted in collaboration with FirstElement Fuel Inc. (hereinafter referred to as FEF). FEF is a developer and operator of hydrogen refueling stations based in California. The installed MHI pump is shown in **Figure 7**. The facility in this figure is a hydrogen gas filling and distribution hub owned by FEF in Northern California, which has a role in providing hydrogen gas to hydrogen refueling stations throughout the Bay Area, centered around San Francisco. Normally, liquid hydrogen from a storage tank is vaporized and then filled into pressure vessels on hydrogen transport trailers using a compressor, after which the trailers distribute the hydrogen gas to each hydrogen refueling station. The MHI's additional pump was installed in this facility, and repeatedly filled the vessels on the trailers.



Figure 7 MHI liquid hydrogen booster pump installed in FEF facility

Discharge pressure of the reciprocating pump depends on the pressure at which hydrogen is charged. Therefore, when the remaining amount of hydrogen and the pressure in the storage cylinder are low at the beginning of the filling process, the discharge pressure of the pump is also low. In response, a pressure-regulating valve was installed downstream from the pump to consistently maintain a discharge pressure of 90 MPaG, which is the most demanding condition from a durability testing standpoint. The valve opening was then automatically controlled based on storage cylinder pressure.

During the long-term durability test, basic indicators such as discharge flow rate of the pump and discharge pressure were constantly measured. Furthermore, to understand the operating state of

the pump in more detail, PV diagram (indicator diagram) described below during the durability test was evaluated. And, for the purpose of durability evaluation of the finite life parts, wear quantity and leakage flow rate of suction valve, discharge valve, and piston ring were measured in the disassembly inspection.

The ideal PV diagrams for reciprocating pumps and reciprocating compressors are shown in **Figure 8**. Three patterns are illustrated: (1) incompressible fluids (such as water), (2) compressible fluids (gases), and (3) liquid hydrogen. P indicates cylinder internal pressure, and V indicates cylinder volume. The PV diagram is rectangular for incompressible fluids and trapezoidal for compressible fluids. On the other hand, the PV diagram for liquid hydrogen has an intermediate shape between those of compressible and incompressible fluids. This is because liquid hydrogen possesses high compressibility, and its PV diagram is characterized by a curved pressure-boosting stroke. The difference between the ideal state and actual state of the PV diagram indicates various effects, such as suction conditions, volumetric efficiency (discharge volume relative to cylinder volume), adiabatic efficiency, response delays of the suction and discharge valves, piston ring leakage, and pressure loss at various points. This is useful to analyze the status of the reciprocating pump.

To plot the PV diagram, measuring in-cylinder pressure fluctuations is needed. The in-cylinder pressure fluctuates between 0 MPaG and 90 MPaG within a single cycle. Therefore, a measuring method with high pressure resistance is required. Furthermore, since the operating speed of reciprocating pumps is generally around several Hz to 10 Hz, a responsiveness of 1 to 10 kHz or higher is needed to measure in-cylinder pressure. While piezoelectric pressure sensors have been used for short-time measurement of in-cylinder pressure fluctuations in high-pressure liquid hydrogen at 10 MPaG in some cases in the past⁽⁸⁾, the durability test in this study requires the pressure sensor to have a lifespan of over 1,000 hours. To meet the above requirements, a proprietary method utilizing strain gauges was developed and applied.

Since durability testing takes over a year, continuous monitoring of the pump's condition in the United States by MHI test personnel was difficult. Therefore, a system was established to allow confirmation of the measurement values related to the operating status from Japan in real-time. This system displays measurements in real-time on a web browser, so any development personnel can confirm the details of operating status of the pump. The system is designed with high security and low cost configuration for safe application to actual large hydrogen stations. In addition, the system can be utilized not only for basic threshold management but also for predictive anomaly detection in consideration of the characteristics of the equipment, significantly contributing to the stable operation of heavy-duty hydrogen refueling stations.

Long-term durability test was conducted for approximately one and a half years, for a cumulative operating time of 1,200 hours. A sample of the operating data is shown in **Figure 9**. These data were obtained in the final stage of the durability test and demonstrate a very stable discharge flow rate even during continuous operation for approximately one and a half hours. The PV diagram of the actual measurement results, comparing the values measured after 300 hours of operation, which represents the early stage of the durability test, with those after 900 hours of operation in the latter half, is shown **Figure 10**. In-cylinder pressure could be stably measured over a long period of time, and it is shown that the operation is near the ideal state. Although there is a slight difference in the peak value of the pressure between 300 and 900 hours because the pressure of the hydrogen gas storage was slightly different, the waveform did not change significantly, and it was judged from the waveform of the in-cylinder pressure that the pump was sound. Based on these in-cylinder pressure waveforms, the pump was determined to be sound. Furthermore, the boil-off loss of liquid hydrogen was extremely low and was less than the design value, and no hydrogen gas was released into the atmosphere during the durability test period.

After completion of the durability test, an inspection of all pump components was conducted. No significant wear, leakage, or degradation was observed in the suction or discharge valves. The amount of wear of the piston rings and rod seal was equivalent to the component test result, confirming the validity of the design. No abnormalities were found in other components, and consumable parts still had a sufficient margin of use before replacement would be required. Based on the above, the MHI pump demonstrated durability for more than 1,200 hours, as well as high

reliability, durability, and functionality. There are no cases of a durability evaluation for more than 1,000 hours in an actual environment during the development stage of a liquid hydrogen booster pump other than that by MHI, demonstrating that customers can use the product with confidence.

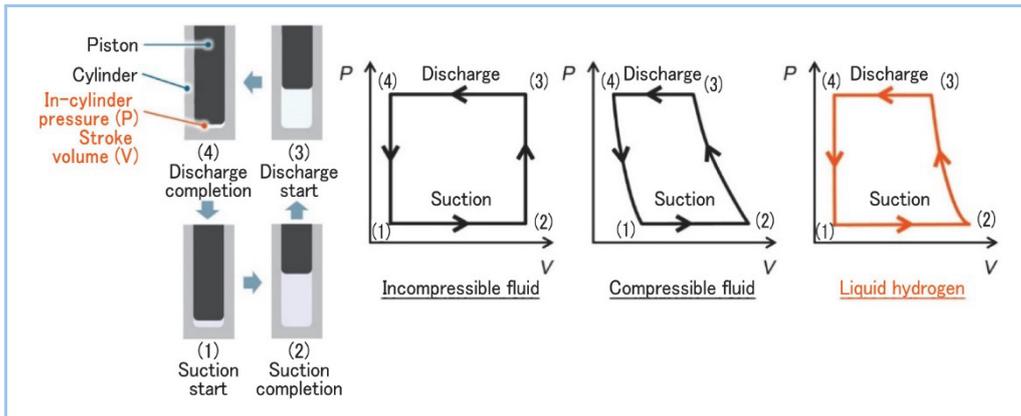


Figure 8 Ideal PV diagram of reciprocating pump/compressor

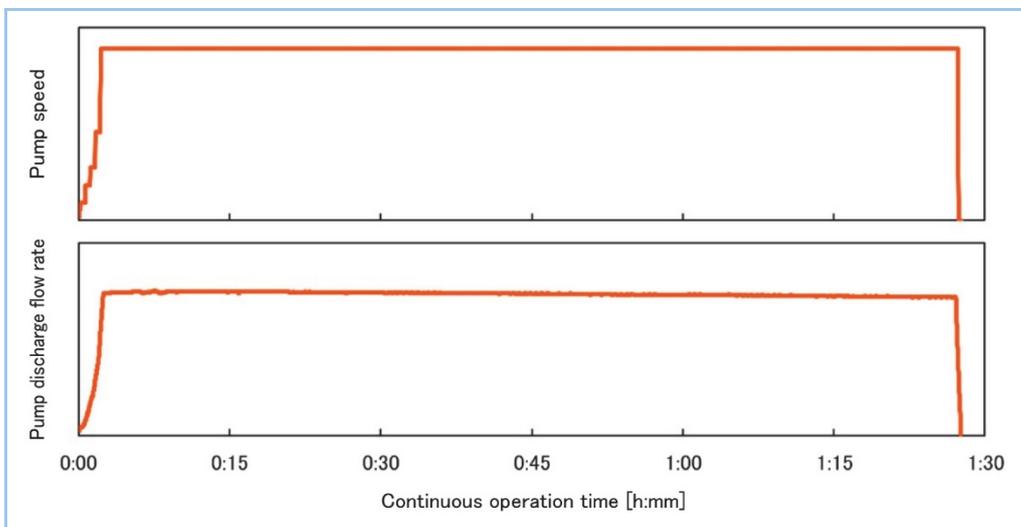


Figure 9 Example of operating data during long-term durability testing

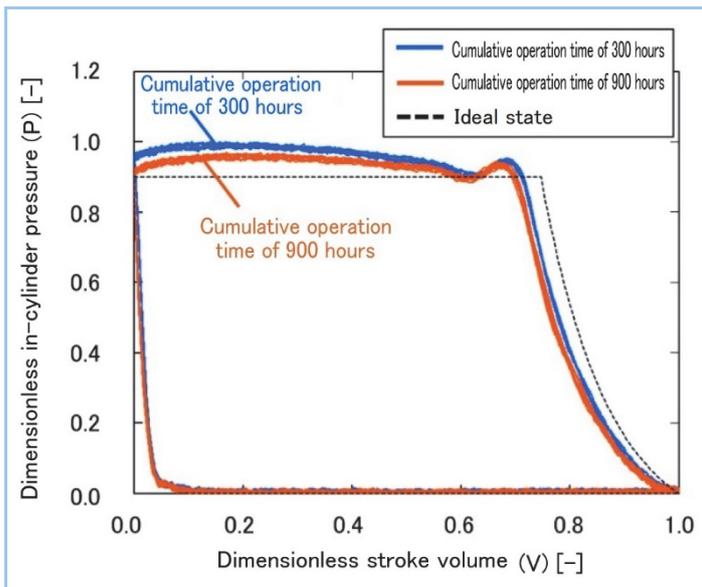


Figure 10 PV diagram of actual measurement results

4. Conclusion

A 90 MPa-class ultra-high pressure liquid hydrogen booster pump has been developed, targeting heavy-duty hydrogen refueling stations for commercial fuel cell vehicles. Development was carried out with pump reliability and durability as the most critical challenges. Following in-house pump testing and component testing, a long-term durability test was conducted at an actual facility in the United States. During the 1,200-hour test period, no significant damage, wear, or leakage was observed, successfully demonstrating high durability. Simultaneously, functionality was also demonstrated, including extremely low boil-off loss of liquid hydrogen.

Development of this pump was completed in fiscal year 2024. In April 2025, the first commercial unit began operation at the Iwatani Cosmo Hydrogen Station Ariake Bus Depot in Tokyo (**Figure 11**) and it is used for hydrogen filling of Tokyo Metropolitan Bus. Despite being the first domestically produced pump, it has continued to operate smoothly without any problems.

Currently, efforts are underway not only to further improve the pump's performance and functionality but also to expand its application to on-board mobile hydrogen refueling stations and to streamline hydrogen refueling station operations. MHI will continue to contribute to the realization of global carbon neutrality through solutions that support customers' businesses.

Finally, the authors would like to express sincere gratitude to FirstElement Fuel Inc. for their cooperation with MHI's development efforts through the collaborative implementation of the long-term durability test.



Figure 11 First commercial unit of liquid hydrogen booster pump

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