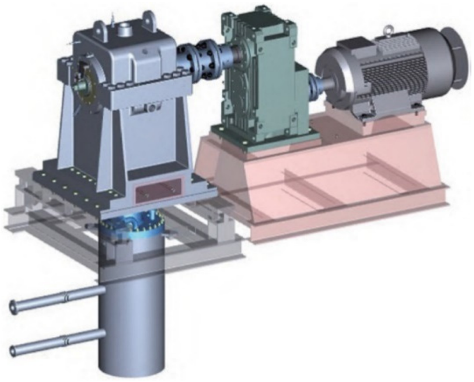
Features of Ultra-high Pressure Liquid Hydrogen Pumps for FCV Hydrogen Refueling Stations



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Toward achieving carbon neutrality, the application of fuel cell technology is not limited to passenger cars. The demand is expected to grow in various settings such as commercial vehicles, ports, and transportation (trains) in the coming years. It is therefore required to increase the capacity of hydrogen stations for fuel cell vehicles and the refueling speed.

This report pertains to hydrogen stations, especially focusing on the hydrogen station system with a liquid hydrogen booster pump, which is suitable for increasing the capacity and refueling speed. The liquid hydrogen booster pump, which we developed for use in hydrogen stations, is also presented in terms of the structure, features and current status in development, in addition to our future challenges.

1. Fuel cell vehicle refueling steps at hydrogen stations with liquid hydrogen booster pump and equipment configuration

To achieve a longer cruising range, hydrogen needs to be refueled at a high pressure (≈70 MPa) at current hydrogen stations. The pressure can be boosted by either pumping liquid hydrogen or compressing gaseous hydrogen. Hydrogen gas is produced at hydrogen manufacturing plants. Conventionally, the compressor is usually used to increase the pressure of hydrogen gas to about 20 MPa for transportation by trailer truck to hydrogen stations where it is further compressed to 70 MPa.

However, the increase in hydrogen demand and widespread use of large mobilities such as Fuel cell (hereinafter referred to as FC) buses and FC trucks can be expected in the future. The hydrogen transportation method, which is likely to be widely adopted, is as follows. The produced gaseous hydrogen is converted into liquid hydrogen, which is of higher density, and is transported in large quantities by tanker truck to the liquid hydrogen storage tanks at hydrogen stations, before boosting the pressure by pumping at a high flow rate. In this way, the energy consumption per unit weight of hydrogen will be halved or even less, while the transportation volume will increase considerably. So, this is expected to be the mainstream method.

Figure 1 gives an example of the equipment configuration of a hydrogen station with a liquid hydrogen booster pump. Having been delivered by tanker truck, liquid hydrogen is stored in a liquid hydrogen storage tank. The pressure is then boosted by the pump, before passing through the vaporizer and kept as high-pressure hydrogen gas in a high-pressure storage vessel. Hydrogen is filled into a fuel cell vehicle (hereinafter referred to as FCV) through a dispenser using differential pressure with a high-pressure reservoir. As rapid refueling of FCVs with gaseous hydrogen can raise the temperature, gaseous hydrogen is cooled by the chiller before being dispensed. If the pressure of the high-pressure storage vessel drops below the predetermined level after dispensing, the pump starts operating to send hydrogen again to the high-pressure storage vessel.

Mitsubishi Heavy Industries, Ltd. (hereinafter referred to as MHI) has acquired cryogenic technologies through the development of space rockets and liquefied natural gas for shipping, and the underlying technologies related to fluid, materials, heat, vibration and such through the product development of equipment for use in nuclear power plants with high safety and reliability requirements. Based on these technologies, we started developing a 90-MPa-class liquid hydrogen booster pump in 2018. The target performance was attained in 2021, which was followed by the durability verification test using the actual liquid hydrogen for enhanced reliability. The test is still in progress at this point in time in 2024.

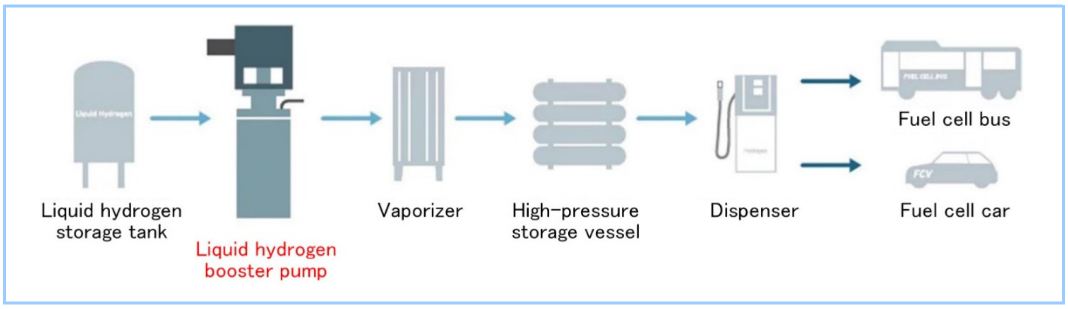

Figure 1　Example of equipment configuration of hydrogen station with liquid hydrogen booster pump

2. Structure and features of our liquid hydrogen booster pump

In developing the pump, we aimed to satisfy tough basic requirements with the specifications that can make the product operable in a cryogenic environment of -253°C at an ultra-high pressure of 90 MPa and, at the same time, meet advanced technical specifications that are expected to be required for future hydrogen stations with a liquid hydrogen booster pump. The product features are listed below, which are our achievements in this development project. The following sections describe each of these features.

- Large volume and advanced flow rate control from high level to low level
- Space-saving compact unit
- High-efficiency performance enabled by preventing liquid hydrogen vaporization
- Long service life design based on element tests
- High reliability backed by durability/performance tests in actual operation system
- Stable operation with MHI’ s own remote monitoring system

2.1 Large volume and advanced flow rate control from high level to low level

Figure 2 is an external view of the liquid hydrogen booster pump. The pump is motor-driven; torque is transmitted to the pump (drive part) through the reduction gear. The motor is explosion-proof, and will not ignite even in a flammable atmosphere.

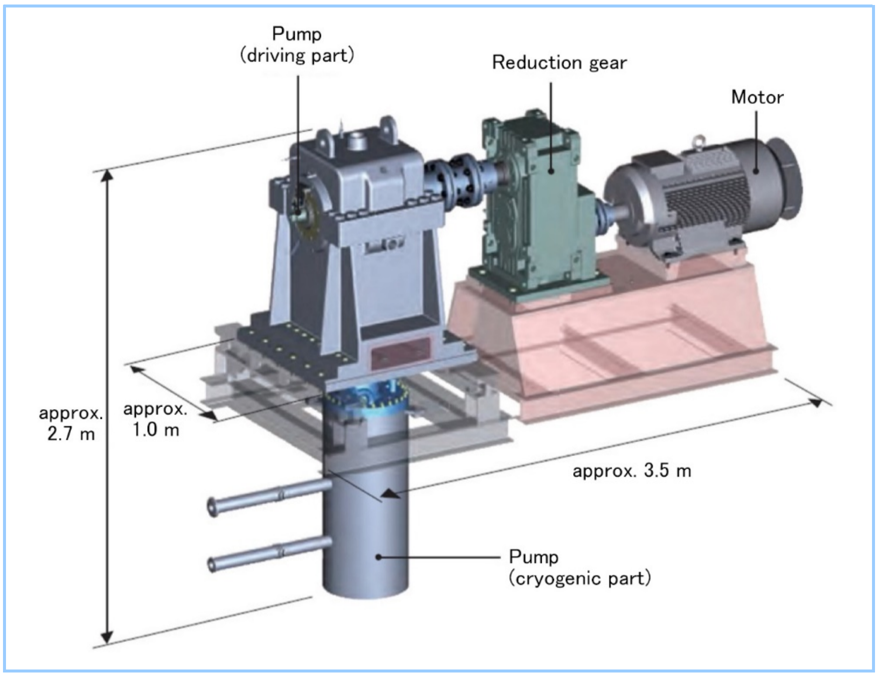

Figure 2　Exterior view of liquid hydrogen booster pump

As the motor is driven by the inverter, the number of pump rotations can be arbitrarily adjusted by controlling the output frequency of the inverter. Depending on the status of the high-pressure storage vessel, the flow rate can be adjusted in a flexible and fine-tuned manner.

Hydrogen stations are required to provide quick refueling regardless of a different residual hydrogen pressure in the tank of each vehicle. On the other, there is a limitation on the speed at which the pressure of gaseous hydrogen can be boosted, because the temperature rise during pressure boosting needs to be prevented. It is therefore necessary to control the boosting speed according to the dispensing conditions. Having achieved a flow rate of nearly five times larger than the conventional compressors, our new pump is suitable for quick refueling (the time required is shortened to about 1/5). It is also easy to change the flow rate to a low level.

2.2 Space-saving compact unit

Driven by the air-cooled motor, the pump does not necessitate the installation of a hydraulic unit, hydraulic piping or utility facility such as cooling water, unlike the hydraulic-driven pumps. This enables the size of the pump unit including the devices to be as compact as approximately 3.5 m long, 1.0 m wide and 2.7 m high, which becomes advantageous when the space for the unit installation is limited whether the refueling station is stationary or mobile (e.g., installed on the trailer).

2.3 High-efficiency performance enabled by preventing liquid hydrogen vaporization

The specifications of the liquid hydrogen booster pump are given in **Table 1**, while the structure diagram is in **Figure 3**. The rotational motion of the motor is converted into the reciprocating motion of the piston by the drive part. As the piston moves upward, liquid hydrogen is drawn into the cylinder from the sump side. During this time, the valve on the suction side is open and the valve on the discharge side is closed. The following downward movement of the piston allows liquid hydrogen to flow toward the discharge side. During this time, the valve on the suction side is closed and the valve on the discharge side is open.

As the compression efficiency of liquids is better than that of gases, the power for compression can be about 1/4 of that of gas compression, which is a considerable reduction. However, liquid hydrogen, which is a cryogenic fluid, has the risk of vaporization even with a little amount of heat from outside or slight heat generation during pressure boosting. Once gaseous hydrogen enters the cylinder, the pressure boosting efficiency markedly drops.

Adopted for this reason is a submerged structure in which the entire cylinder is contained in a liquid-hydrogen sump so that thermal input can be minimized. Moreover, repeated high-load sliding between the piston rings and the cylinder generates heat, facilitating vaporization of liquid hydrogen. In developing the piston rings, therefore, we repeatedly conducted element tests to select superior materials causing low sliding heat and having excellent sealing properties in the given environment. These research activities have enabled our pump to achieve stable, high efficiency while minimizing the vaporization of liquid hydrogen due to thermal input or heat generation.

Table 1 Liquid hydrogen booster pump specifications

Pump system	Reciprocating type
Drive system	Motor (inverter-driven)
Suction part structure	Submerged type
Rated discharge pressure	90 MPa
Rated flow rate	1,800 Nm^3/h* (approx. 160 kg/h)

* Nm^3: Volume at standard conditions (1 atmospheric pressure, 0°C)

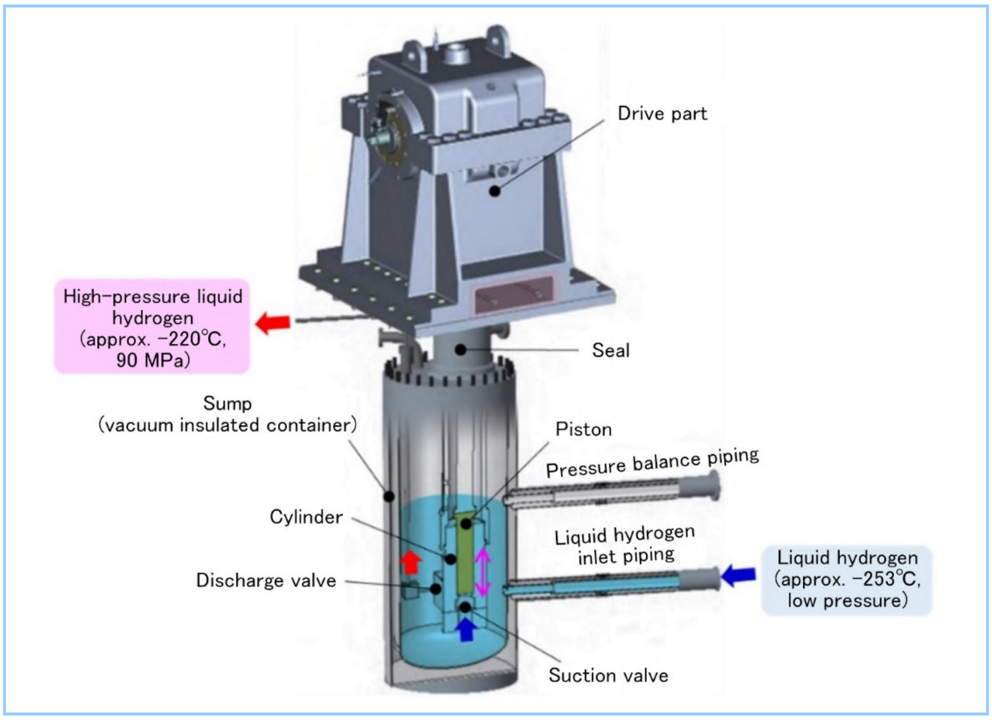

Figure 3 Structural diagram of liquid hydrogen booster pump

2.4 Long service life design based on element tests

While the pump is in operation, the valve and the seal frequently come into contact with the reciprocating piston or are made to slide. How quickly these parts are damaged greatly affects the frequency of maintenance. Therefore, we conducted not only the durability test of the entire pump unit, but also element tests to assess the service lives of consumable parts. In these tests, the operating cycle was accelerated so as to assess the service lives within a short period of time.

Figure 4 shows a valve element test being conducted in a liquid hydrogen environment. In a cryogenic environment of liquid hydrogen, the valve repeatedly opens and closes as the piston goes up and down. The conditions under which it is used are therefore tough. In this element test, the actual load is repeatedly applied to the valve of the same size as the actual valve under the liquid hydrogen environment, and the transition of wear such as wear and deformation is confirmed by detailed observation and shape measurement every fixed evaluation time, and it is reflected in the life extension design.

A seal element test was also conducted. The upper part of the sump is in a gaseous hydrogen environment, because thermal input from outside vaporizes liquid hydrogen. As the piston moves upwards and downwards, the seal repeatedly slides between the piston shaft and the stationary part. **Figure 5** shows the seal element test being conducted in a gaseous hydrogen environment. In this element test, the full-size seal and piston shaft were used. The shaft was reciprocated, while the pressure was applied on the seal with hydrogen gas. Leakage from the seal was continuously measured to assess the sealing function. The seal was also examined/measured at regular intervals to check for signs of damage over time. Based on the results, the seal was designed to achieve a long service life.

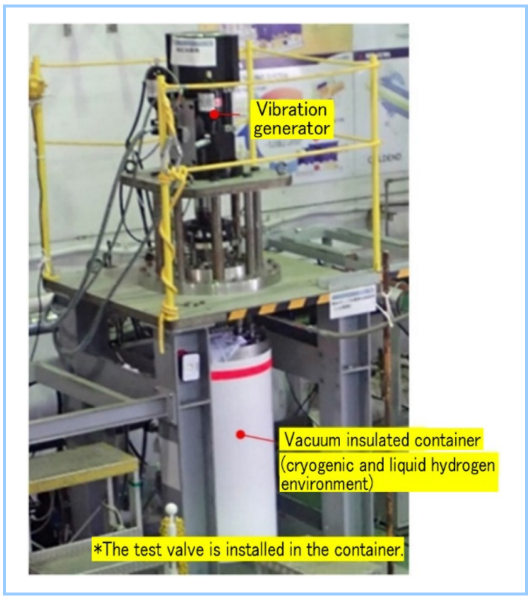

Figure 4 Valve element test apparatus in liquid hydrogen environment

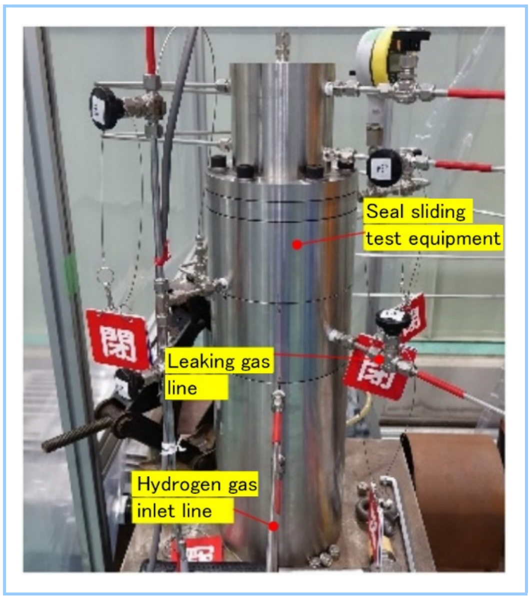

Figure 5 Seal element test apparatus in gaseous hydrogen environment

2.5 High reliability backed by durability and performance tests in actual operation system

As the durability assessment of the entire system, the long-term durability test using the actual liquid hydrogen, which is difficult to carry out in Japan, is under way at the hydrogen supply facility run by FirstElement Fuel (California, USA). A photograph of this facility is in **Figure 6**. It is the hydrogen gas supply hub for hydrogen stations in northern California. In the facility, liquid hydrogen stored in the tank is vaporized by the vaporizer, before the compressor is used to fill the high-pressure storage vessel on the trailer with hydrogen. A vaporization system with our booster pump has been added to the facility, thereby assessing the long-term durability and performance in the process of actual operation.

The total operation time exceeded 1,000 hours, with the total amount of dispensed hydrogen reaching nearly 120 tonnes. This is equivalent to refueling about 4,200 FC buses, when supposing that the fuel tank capacity of each bus is 28 kg. This durability test has demonstrated that our pump is capable of supplying liquid hydrogen at a high flow rate in a stable manner, vaporization of liquid hydrogen during pump operation is extremely low, and no hydrogen gas is released into the air. The data related to the performance were also gathered/accumulated throughout the period of operation. And, the durability of main consumable parts is confirmed by carrying out disassembly inspection every evaluation time.

As the liquid hydrogen booster pump is used in a harsh environment with a cryogenic temperature (-253°C) and ultra-high pressure (90 MPa), the service lives of consumable parts (such as the valve and the seal) are generally short. However, we are working to extend their service lives and therefore extend the maintenance interval of the pump.

Figure 6 Hydrogen supply facility run by FirstElement Fuel

2.6 Stable operation with MHI's own remote monitoring system

Having built its own remote monitoring system, MHI can constantly monitor the pump operation parameters (e.g., flow rate and temperature) from a distant place. This makes it possible to obtain long-term pump operation data, understand the situation when a failure occurs, and have sound discussions about maintenance plans based on predictive detection before the occurrence of a failure. The pump can thus be operated in a stable manner.

3. Future directions

Another initiative in the development of a liquid hydrogen booster pump is the optimization of the entire hydrogen station (including reducing the loss of hydrogen gas, and achieving optimal equipment configuration), while placing the liquid hydrogen booster pump technology at the core. During this process, the technologies cultivated through designing nuclear power plants work to our advantage. **Figure 7** shows an example of such hydrogen station optimization. The capacity of the compressor system is reduced by using it only for limited hydrogen gas recovery applications such as when the pump stops. And enabling even large FCVs such as FC buses and FC trucks to be filled up directly from the pump eliminates the need of high-pressure storage vessels and the like. CAPEX (capital expenditure) and OPEX (operating expenses) can be reduced through such attempts.

Our newly developed liquid hydrogen booster pump and the optimization of the entire hydrogen station serve as new solutions that can help to realize a hydrogen society. Through their applications, we will contribute toward achieving the carbon neutrality of the entire global society.

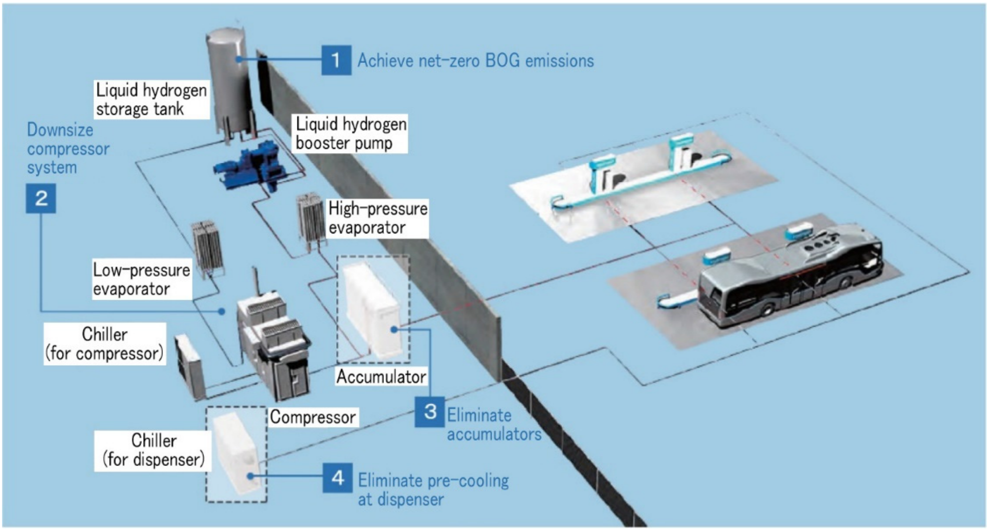

Figure 7 Our initiatives for hydrogen station optimization