Approach to Hydrogen Related Business by JSW

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—Synopsis—

JSW has been conducting research on hydrogen in steel since before World War II. This led to the entry into nuclear equipment component business and production of large scale petroleum refining reactors. In recent years, there has been significant activity to promote the use of hydrogen energy in order to prevent climate change and decrease dependence on fossil fuels. To prepare for the arrival of "hydrogen society", the JSW approach to hydrogen related business includes development of hydrogen high pressure vessels, systems combining these vessels with compressors, low pressure hydrogen tanks for storing renewable energy utilizing hydrogen absorbing alloy, and power supply systems equipped with hydrogen absorbing alloy tank.

1. Introduction

The Japan Steel Works Ltd. (JSW) was established as a steel mill for producing weapons and high quality steel to support the domestic production of large military equipment. Among the main products prior to World War II, heavy artillery, like the 41-cm cannons mounted on the battleship Mutsu, may be the most widely recognized. Ni-Cr steel, known for its strength and toughness, had long been used as the material for heavy artillery. The weak point of this material is that it becomes brittle and prone to cracking called "hair crack" or "white spot" [(1)]. After a great deal of research, in the 1930's it was confirmed that the main cause was residual hydrogen contained in the steel. JSW devised the world's first quantitative analysis method of hydrogen in steel, which became a standard called the Gakushin Method [(2)]. This led the research on steel and hydrogen throughout the world.

The first reactor at a commercial nuclear power plant in Japan was Tokai No. 1. The material for the reactor pressure vessel was imported from the UK, but many crack-like defects that were thought to be caused by hydrogen were found during the inspection, and everything had to be rejected. JSW offered to produce a replacement. In 1961, using vacuum ingot making, JSW produced and delivered steel plates for the nuclear reactor pressure vessel with no quality problems [(3)]. This was the impetus for JSW entry into the production of components for nuclear power plants, later leading to the manufacture of various materials for nuclear power equipment, making use of the manufacturing technologies for large steel forgings.

The reactors used for refining petroleum are operated in harsh environments, with high temperatures, high pressures and a high hydrogen concentration. Since carbon steel and Ni-steel are sensitive to hydrogen-induced damage when subjected to high temperature and pressure, Cr-Mo steel, which has better resistance to hydrogen, is generally used; but, the production of reactors for petroleum refineries has been a battle against hydrogen. A great deal of research and development has been conducted on materials and manufacturing processes related to resistance to hydrogen damage and hydrogen embrittlement, as well as the hydrogen-induced separation at the boundary between a base material and overlay. This formed the foundation of the technologies for manufacturing various types of large reactors.

In addition to the hydrogen embrittlement due to residual hydrogen within the steel, and the hydrogen damage that arises in a high-temperature, high-pressure environment, there can also be embrittlement resulting from absorbed hydrogen in situations where the material is subjected to stress in a hydrogen environment at normal temperatures. This phenomenon is called hydrogen environment embrittlement, and it is an important process to understand for materials that are used in a hydrogen atmosphere as we progress toward using hydrogen as an energy source in society (the so-called "hydrogen society"). Starting in 2003, JSW participated in a project sponsored by New Energy and Industrial Technology Development

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Organization (NEDO) on the development of a hydrogen high pressure vessel made from steel, making use of JSW knowhow on hydrogen embrittlement. From 2005 development of a pressure vessel for hydrogen refueling at 70 MPa was conducted, and the pressure vessel was installed in the first demonstration hydrogen refueling station at 70 MPa in Japan. Development even more durable, lower-cost steel hydrogen pressure vessels was continued; and steel hydrogen pressure vessels have been adopted for many of the commercial hydrogen refueling stations since 2013.

JSW has been manufacturing and selling reciprocating compressors for industrial applications since 1949, immediately after the end of WWII. We have supplied more than 1,700 compressors, many to customers in the petrochemical industry, earning a reputation for high reliability. These results, and the proprietary technologies related to the hydrogen materials research at Muroran Laboratory, have led to supply many hydrogen compressors to private enterprises that require research and development facilities for hydrogen infrastructure, fuel cell vehicles (FCV) and various hydrogen refueling stations within Japan. With the recent start of commercial sales of FCV, and the progress on the plan for a network of commercial hydrogen refueling stations, we are continuing development on an integrated package of a diaphragm compressor and hydrogen pressure vessels, taking advantage of our unique technology and expertise.

In the late 1960's, it was discovered that certain types of alloys reversibly absorb and desorb large amounts of hydrogen, causing research and development of these metal hydrides (MH) to be started worldwide. JSW has been working on the development of MH and application systems using MH since before 1980. In contrast to the research on the interactions between hydrogen and metals in conventional steel materials, the goal of this work was to incorporate a large amount of hydrogen into the alloy lattice and to develop alloys having properties suitable for various applications. In addition to hydrogen storage tanks, we have developed other applications, including a heat pump system that makes use of the heat of the hydrogenation reaction, and a hydrogen purification system that utilizes a property to absorb hydrogen exclusively. We are also developing an application system of fuel cell power supplies equipped with MH canisters. Fuel cells are devices making use of chemical reactions to convert hydrogen and oxygen into electricity, water and heat. These are expected to be utilized in a variety of fields because of the low environmental impact and high power generation efficiency.

The efforts to achieve a hydrogen society have become more intense in recent years as part of the measures to combat global warming and address the issue of depletion of fossil fuels. Storage of hydrogen from renewable energy sources like solar power and wind power is also being used in demonstration projects. JSW has a long history of experience in the study of hydrogen. This paper introduces some approaches to hydrogen-related business to contribute to the arrival of the hydrogen society of the future.

2. Hydrogen High-pressure Vessels

2.1 Hydrogen pressure vessel materials

For the pressure storage vessels at a hydrogen refueling station, fractures from embrittlement leading to the destruction of the entire vessel cannot be tolerated. The steel material for the high pressure hydrogen vessels must have both the strength and ductility (toughness) to withstand high pressures. JIS SCM435 (SCM435) is used for 45 MPa vessels; but, this cannot be used as the material for 99 MPa vessels because the hardenability of SCM435 is not sufficient for the thickness of the vessel walls that are required at this pressure. This is why a steel type with superior hardenability must be selected. The steel material used must also have the structure and grain size controlled during forging and heat treatment. Furthermore, current understanding indicates that the cleanliness of the steel materials is also important for safe use in the presence of hydrogen gas. Figure 1 shows the results of the slow strain rate testing (SSRT) in a 45 MPa hydrogen gas atmosphere of high and low cleanliness samples of high-strength low-alloy steel (nickel chromium molybdenum steel) produced to have the same strength [4]. The high-cleanliness steel maintains good ductility, even when exposed to hydrogen gas, and fractures at a point greatly exceeding the point of maximum loading (maximum yield). In comparison, the low-cleanliness steel fractured near the maximum load point, and exhibited a noticeable decrease in tensile ductility. It has been confirmed that nonmetallic inclusions in steel containing impurities like P, Si, Mn and S act as the early-stage crack origin sites in a hydrogen gas atmosphere. For this reason, high-cleanliness steel materials should be used in order to improve the safety of the pressure vessels.

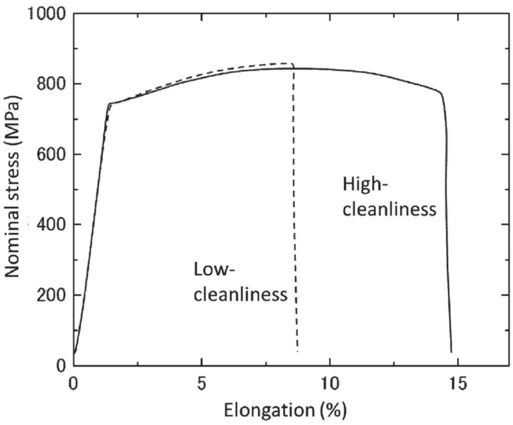

Fig.1 Slow strain rate testing results for high and low cleanliness high-strength low-alloy steel in hydrogen gas

As the material for pressure vessels, JSW uses ASME SA-723M Grade 3 (SA-723M), which has the same strength as SCM435, with superior hardenability. The American Society of Mechanical Engineers (ASME) approves the use of SA-723M in their standards for pressure vessels, and in Japan it has been used for pressure-resistant parts for high-pressure gas equipment. JSW has a wealth of experience manufacturing materials similar to SA-723M for applications like shafts for power generators and ultra-high-pressure vessels, and possesses the technology to produce SA-723M with a systematically-controlled high level of cleanliness. Figure 2 shows the hardness distribution across the entire thickness of a pressure vessel manufactured from SA-723M, with a nearly constant hardness throughout the entire 90 mm thickness, demonstrating the excellent hardenability of SA-723M. Figure 3 shows the relationship between tensile strength and Charpy absorbed energy for SA-723M and JIS-SNCM439 (SNCM439) [(5)]. SA-723M can be hardened even to the interior of a ϕ 1000 mm circular rod, and has sufficiently high toughness for a pressure vessel with a design strength of 930 to 1000 MPa. From this it can be seen that the JSW pressure vessels are made from materials that are highly-reliable, and have an excellent, homogeneous balance of strength and toughness.

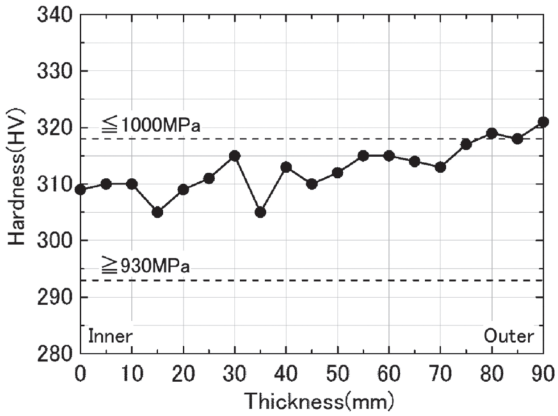

Fig.2 SA-723M pressure vessel hardness distribution for entire thickness

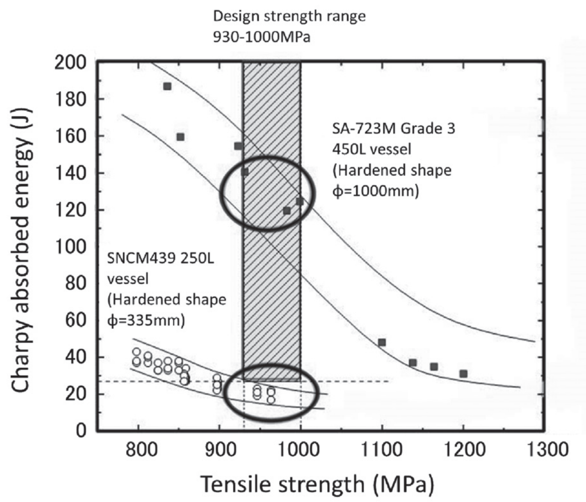

Fig.3 Relationship between tensile strength and Charpy absorbed energy

In addition to the SSRT, fatigue properties are also important for evaluating the safety relative to hydrogen. The pressure vessels at hydrogen refueling stations are repeatedly exposed to pressure cycles as the pressure drops when the hydrogen is dispensed to the FCV, and increases when the vessel is filled, so the fatigue fracture characteristics in hydrogen gas are an important consideration. The results of fatigue tests of SA-723M and SNCM439 in a high-pressure hydrogen gas atmosphere are shown in Figure 4 [(5)]. The results for SA-723M here were obtained with a test specimen that was taken from an actual hydrogen pressure vessel. Since the SA-723M did not fracture even after 2,000,000 cycles at more than twice the stress amplitude applied during normal operation of the vessel, this demonstrates that the fatigue resistance of SA-723M is sufficient, and that it is a material that can be used safely even in the presence of hydrogen gas. The quality of the SA-

723M produced by JSW is controlled to achieve a high degree of cleanliness (with ASTM E45 Type B < 1.5); and it is manufactured using our proprietary, optimized heat treatment conditions in order to ensure superior resistance to hydrogen embrittlement, making it possible to obtain the excellent performance shown in Figure 4.

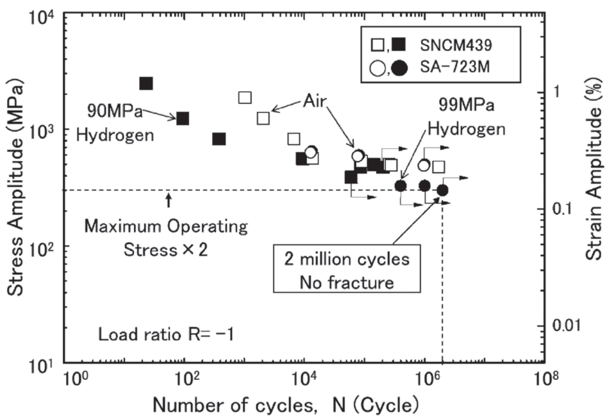

Fig.4 Fatigue test results in a high-pressure hydrogen gas atmosphere

2.2 Manufacture of hydrogen pressure vessels

(1) Manufacturing process control

In addition to the materials assessments required for ordinary pressure vessels, various types of safety assessments in the presence of hydrogen gas are also conducted (testing of mechanical properties and fatigue characteristics, analysis of fatigue crack propagation, etc.) in order produce hydrogen pressure vessels that offer a high level of safety. By understanding the influence of hydrogen on the materials, and conducting our own management and control related to the use of hydrogen in all manufacturing processes involving the materials, design, processing and inspection, pressure vessels that satisfy high standards of safety and durability have been achieved.

(2) Materials with superior resistance to hydrogen embrittlement

The chemical composition, concentration of impurities, structure, strength, grain size, etc. are controlled for the materials used for the pressure vessels, from melting to heat treatment, to produce highly-reliable materials having the same tensile strength and fatigue limits in both ordinary and hydrogen-gas atmospheres.

(3) Highly-reliable pressure vessel structure

A cylindrical structure for the pressure vessel eliminates structural discontinuities and stress concentration point in the sections that are in contact with hydrogen, and also allows the interior surfaces to be carefully examined during production and while in use. The designs of the cover and ground nut structure to maintain the high pressure are based on proven structures for pressure vessels, which have been improved to withstand an even larger number of pressure cycle.

(4) Processing technologies to achieve high durability

Strict standards are set for finishing the surfaces that come into contact with the hydrogen, factors that are susceptible to influence from hydrogen are eliminated as much as possible, and processing to achieve high durability of the interior surfaces is performed in order to suppress the accelerated propagation of fatigue cracks in a high-pressure hydrogen gas atmosphere. As a result, a long service life has been achieved for the pressure vessels, with the permitted number of pressure cycles far exceeding 100,000 repetitions, even for a broad range of operating pressures, from 35 MPa to 87.5 MPa.

(5) Non-destructive inspection techniques to ensure safety

In the inspections conducted during manufacturing, it is necessary to detect any defects on the inner surfaces of the body that come into contact with the hydrogen gas with a high level of accuracy. We have developed a semi-automatic magnetic particle testing (MT) apparatus specifically for pressure vessels, shown in Figure 5. With this MT apparatus it is possible to detect microscopic defects in the inner surfaces, and make a final confirmation that there are no remaining portions that can become a point of origin for crack propagation. Because all parts of a steel pressure vessel can be inspected from the outside using ultrasonic testing, even while the vessel is in use and contains high-pressure hydrogen gas, the safety of the steel pressure vessels can be maintained at a high level by performing periodic inspections, without having to halt the operation of the station.

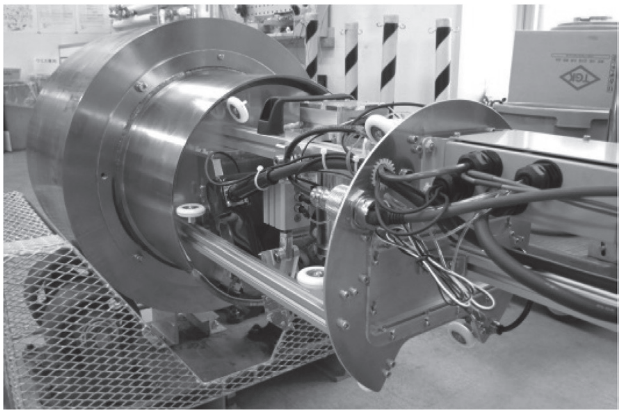

Fig.5 MT apparatus developed specifically for hydrogen pressure vessels

(6) Specifications of steel pressure vessels

Table 1 shows the standard specifications for a 0.3 m^3 capacity hydrogen pressure vessel. Safety can be guaranteed by establishing and applying design standards for steel pressure vessels. JSW has experience producing hydrogen pressure vessels with a design pressure exceeding 100 MPa as well as large pressure vessels with an internal capacity of 0.45 m^3, as shown in Figure 6 [(5)].

Table.1 Specifications for 0.3 m^3 steel pressure vessel for hydrogen

	Japan specifications	Specifications outside Japan	Short model
Outer diameter	Φ420 mm	Φ446 mm	Φ525 mm
Total length	4,890 mm	4,900 mm	3,790 mm
Weight	2,910 kg	3,590 kg	4,020 kg
Design pressure	99 MPa	99 MPa	99 MPa

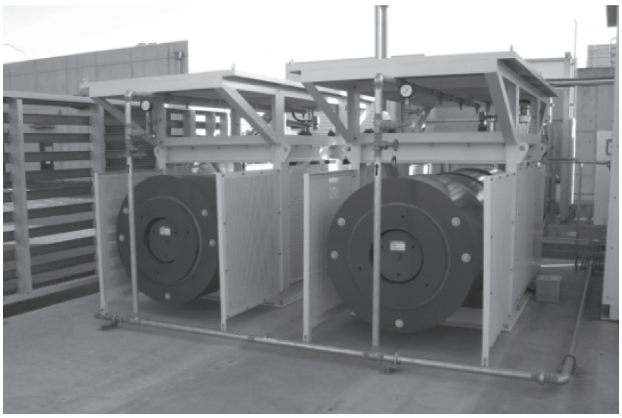

Fig.6 0.45 m^3 hydrogen pressure vessels

3. Hydrogen Compressors

3.1 Piston compressors

JSW activity with compressors designed for hydrogen refueling stations can be traced back to the first hydrogen refueling station demonstrated in Takamatsu City[(6)] by NEDO WE-NET (World Energy Network) Project in 2002. For this project, the required specifications for the compressor capacity was smaller than those in the JSW's own product lineup, so we collaborated with a domestic compressor manufacturer. Since the FCV fuel tanks at that time were filled with hydrogen at the pressure of 35 MPa, the piston compressor with the capacity of 30 Nm^3/h, and discharge pressure of 40 MPa was delivered. A hybrid configuration was adopted, with piston ring method used for the low-pressure stages because of the high efficiency and adoptability for high capacity. To compress the hydrogen up to 40 MPa, the final stage utilized diaphragm method, which has proven performance for high-pressure applications. Subsequently, a total of 5 units were delivered for hydrogen refueling stations as part of the Japan Hydrogen & Fuel Cell (JHFC) Demonstration Project and etc.

In parallel, JSW also developed the 300 Nm^3/h class piston compressor, designed for commercial scale hydrogen refueling stations, in the expectation that FCV would become widely used. By using piston ring method for the low-pressure stages, and plunger method for the high-pressure stages, the oil-free hydrogen compressor was achieved, with discharge pressures of up to 40 MPa. Figure 7 shows the main specifications and outline of the piston compressor manufactured in 2003 for NEDO project on the development of safety technologies for hydrogen infrastructure. This compressor was operated for proof tests for the next 4 years, providing various types of data contributing to the development of safety standards, based on the assumption that such compressors would be used commercially for hydrogen refueling stations [(7)].

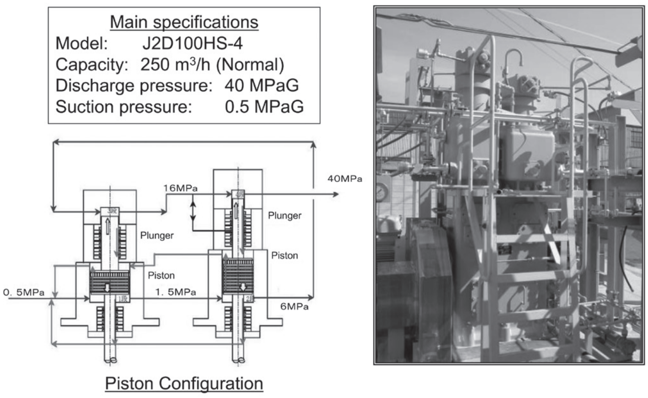

Fig.7 Piston compressor

3.2 Diaphragm compressors

In order to enhance our product lineup to include small compressors suitable for demonstration scale hydrogen refueling station, JSW began collaborating with PDC Machines Inc. (USA) in 2003, and launched a business supplying units combining the small diaphragm compressors and their auxiliary systems. A diaphragm compressor is suitable for a demonstration scale hydrogen refueling station because it is relatively easy to reduce the capacity and increase the operating pressure, there is no contamination or external leakage of the gas because there are no sliding parts like those in a piston compressor, and the structure is simple, with only a few pressure stages (number of cylinders) because it is possible to increase the compression ratio. JSW delivered a total of 15 diaphragm compressor units through 2008 for use in the demonstration scale hydrogen refueling stations of the JHFC project as well as in the private hydrogen refueling stations constructed by companies and research organizations. As mentioned previously, the usual discharge pressure at that time was 40 MPa, with a compression capacity of 30 to 100 Nm^3/h. Currently, the FCV refueling pressure is 70 MPa. Ahead of others, JSW supplied commercial compressor units with a discharge pressure exceeding 80 MPa, and some of these units are currently in operation.

At the same time as the projects above, JSW installed testing facilities for the PDC Machines diaphragm compressors at the Hiroshima Plant, and performed our own research and development on the safe and stable operation of diaphragm compressors, as well as technologies to improve reliability. The main specifications and appearance of the test facilities are shown in Figure 8. Through about 5000 hours of test operation we developed operation technologies including optimized operation logic, such as for compressor start/stop and interlock systems, and optimized maintenance by verifying the service life of various consumable parts. In conjunction with this, JSW also developed long service life diaphragm and optimized design of the hydraulic systems. By combining this with our existing compressor expertise, we established an advanced diaphragm compressor technology [8].

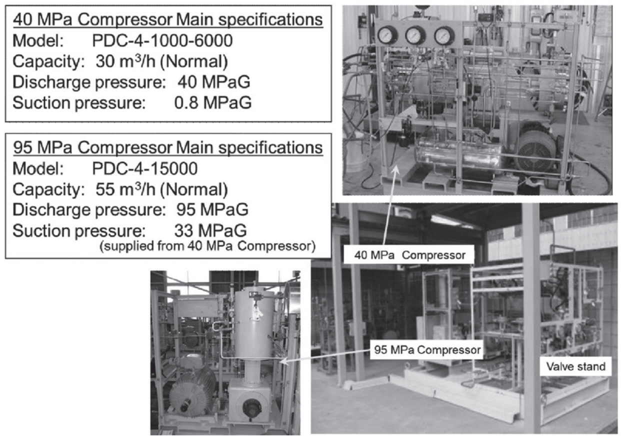

Fig.8 Diaphragm compressor test facilities

As described above, JSW has planned business development by adapting our own piston compressors for use at commercial-scale hydrogen refueling stations, and supplying diaphragm compressors made by PDC Machines [9] to support small-scale hydrogen refueling stations. JSW hydrogen compressors have been used for R&D and many demonstration projects, including the hydrogen refueling station for fuel cell buses operated at the 2005 Aichi World Expo, and supported the dawn of hydrogen refueling stations in Japan.

3.3 FCHP™

The practical development of commercial hydrogen refueling stations in Japan has been progressing with government subsidies since 2013 as part of the national project to prepare the hydrogen supply infrastructure. The pressing issue for promoting widespread development is a reduction in the construction and operating costs. JSW believes that building smaller-scale hydrogen refueling stations will be an effective way to reduce the costs during the transition period to widespread use of FCV. To support this, the package unit designed for small-scale hydrogen refueling stations [10], the Flexible Compact Hydrogen Package (FCHP™) is being marketed. The FCHP™ is an integrated package with a minimal installation footprint, achieved by combining diaphragm compressor and steel storage cylinders with all the auxiliary equipment and safety devices needed for operation at a hydrogen refueling station into a single package. Figure 9 shows the external appearance of the FCHP™, with the main specifications listed in Table 2.

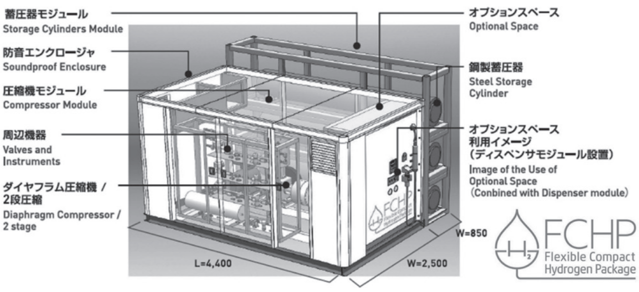

Fig.9 FCHP external appearance and structure

Table.2 FCHP Main Specifications

Compressor	Type	Diaphragm compressor
	Manufacturer	PDC Machines Inc. (USA)
	Configuration	2-stage compression
	Compressor capacity	55 Nm^3/h
	Suction pressure	4 MPa
	Discharge pressure	82 MPa
Storage cylinder	Type	Type I steel storage cylinder
	Manufacturer	JSW
	Volume capacity	300 L × 3 or 4 cylinders
	Bank configuration	3 bank configuration
	Storage pressure	82 MPa
	Refueling performance	Compatible with commercial refueling protocol

The PDC Machines diaphragm compressor has a hydrogen compression capacity of 55 Nm^3/h, which corresponds to the volume of hydrogen needed to fill up 1 FCV produced each hour. By cutting down the capacity of the compressor it is possible to achieve reductions in both capital and operational costs. For example, maintenance costs can be reduced by using a diaphragm compressor that is smaller and has fewer compression stages than the piston compressors operated at existing hydrogen refueling stations. In addition, by incorporating our own technologies described previously, an even higher level of reliability has been obtained.

By utilizing the same bank configuration of the storage cylinders as the existing commercial hydrogen refueling stations, it is possible to achieve rapid refueling expressed as “5 kg in 3 minutes” for FCV with the refueling rate compatible to the commercial refueling protocols such as JPEC-S0003 (2014). This makes commercial operation for the public FCVs feasible. Furthermore, the compressor is housed in a soundproof enclosure along with the auxiliary equipment incorporated into a compact module. When combined with the storage cylinders module, the installation footprint of the smallest type is just 2.9 m × 4.4 m (about 13 m^2), which can be installed even on small sites. There is also an optional space designed in the compressor module, enabling further integration of the equipment for hydrogen refueling stations, such as dispenser. In addition, as illustrated in Figure 10, this design is also expandable. As FCV become more popular, the refueling performance of the hydrogen refueling station can easily be extended by adding and/or replacing the compressor modules and storage cylinders modules.

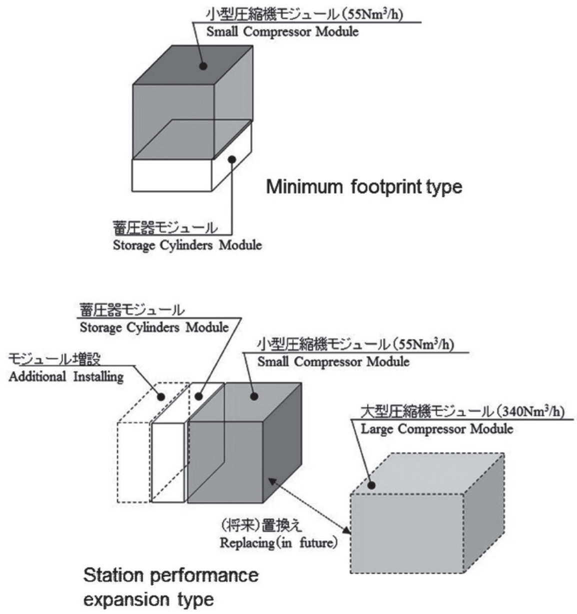

Fig.10 Expandability through modularization

An FCHP™ demonstration facility has been installed at the JSW Hiroshima Plant. The external view of the demo facility is shown in Figure 11. Though the demonstration facility does not refuel FCV with hydrogen, it has been designed, constructed and inspected in accordance with Article 7-3 of the Security Regulation for General High Pressure Gas in the High Pressure Gas Safety Law, technical standard for the stationary commercial hydrogen refueling stations, including the auxiliary equipment (excluding dispenser and pre-cooler) to simulate and demonstrate the actual operation of the compact, small-scale hydrogen refueling station. From FY2017, the scope of the subsidies for the national project to prepare the hydrogen supply infrastructure mentioned above has been expanded from “100 Nm^3/h or more” to “50 Nm^3/h or more” of the hydrogen refueling performance of the station. As a result, the FCHP™ has received increased interest in the market.

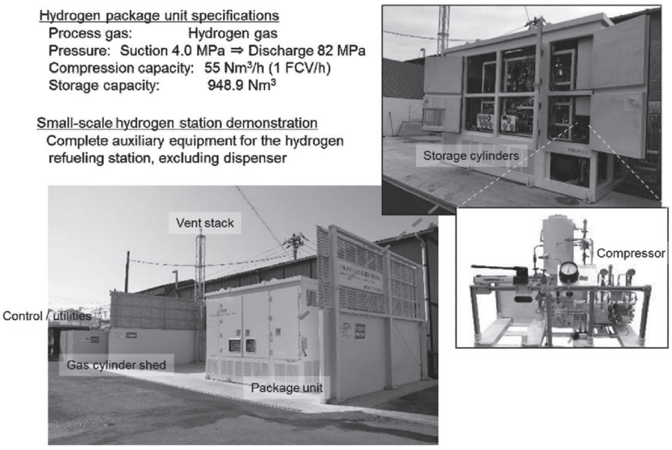

Fig.11 FCHP demo facilities at the Hiroshima Plant

4. Metal Hydrides and Metal Hydride Tanks

4.1 Metal hydrides and application systems

Metal hydrides (MH), which is also called "hydrogen absorbing alloy", can absorb and desorb large amounts of hydrogen at ambient temperature and pressure. In addition to making it possible to safely store hydrogen at low pressures of less than 10 atm, these materials also have a large hydrogen storage density per unit of volume, enabling compact hydrogen storage units to be fabricated (11). Figure 12 shows the relationship between mass storage density and volume storage density for various methods of hydrogen storage. Compared to compressed hydrogen and liquid hydrogen, the mass storage density of hydrogen in MH is low, so MH is not suitable for use on-board vehicles or for material transport applications. On the other hand, MH has the highest volume storage density, so it is ideal for storing a large amount of hydrogen in a limited amount of space. Thus, since hydrogen storage methods making use of MH enable large amounts of hydrogen to be stored safely and compactly at low pressures, it is expected to be used for a variety of purposes as the use of hydrogen continues to be promoted.

JSW started work on MH development in 1978, and have developed AB5 type alloys like $LaNi_5$ (12), (13), AB2 type alloys like $TiCr_2$ and $TiMn_{1.5}$ (14), (15), as well as BCC type alloys like TiCrV (16). In addition to improving the characteristics for practical application, a wide range of data on the properties has been accumulated. Making use of the properties of MH, a variety of MH application systems have also been developed, including actuators (17), heat pump systems (18), hydrogen purity enhancement systems (19), co-generation systems combining a non-fluorocarbon cooling system and micro-gas turbine (20), as well as making improvements to the MH tanks themselves (21). In this way, JSW has acquired MH technologies that can be utilized over a wide range of temperatures, while also accumulating system technologies that make use of the MH technology.

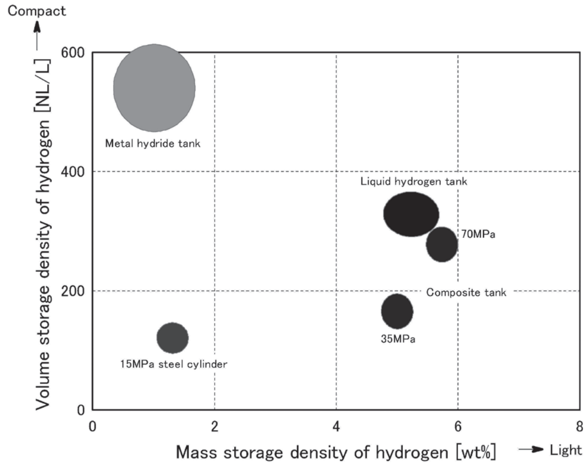

Fig.12 Comparison of hydrogen storage density (including container)

4.2 HYDRAGE™

As the hydrogen is absorbed and desorbed, there is a large variation in the volume of the MH, resulting in pulverization. This leads to a problem when the particles accumulate at the bottom of the vessel and cause strain on the MH tank. In addition, under the Fire Service Act (Japan), MH powders are classified as a Category 2 Hazardous Material (combustible solid), and hydrogenated MH powders are a Category 3 Hazardous Material (spontaneously combustible substances and water-reactive substances). This means that when more than a specified quantity of the material is handled, it is mandatory to have the appropriate facilities (secured open space, fire-fighting equipment, etc.) as stipulated in the Fire Service Act, and the persons handling the materials are obligated to comply with the laws and regulations on operations, monitoring, notification etc. as handlers of hazardous materials. HYDRAGE™ (Trademark registration No. 5899391) by JSW is a new metal hydride combining a conventional MH powder and a polymer material, with no decrease in the rate of hydrogen absorption and release. Using this fabrication technology to immobilize the MH, JSW was successful in reducing the strain occurring in the MH tanks. HYDRAGE™ passes the Fire Service Act tests for determining classification as a hazardous material, including the Category 3 spontaneous combustion test and the Category 2 small gas flame ignition test as well as the flash point measurement test. As a result, HYDRAGE™ is registered in the database (registration No. 2994X014729, etc.) as a non-hazardous material, even when it contains hydrogen in an occluded state. This eliminates the legal restrictions on quantity and required notices for transport and storage. In addition, the HYDRAGE™ technology provides a uniform distribution of the MH alloy, which allows higher density filling of the MH tank than with the conventional MH alloy, thereby achieving a larger hydrogen storage capacity, as shown in Figure 13. The development of the HYDRAGE™ technology makes it possible to use MH not only for small tanks, but also for large hydrogen storage tanks.

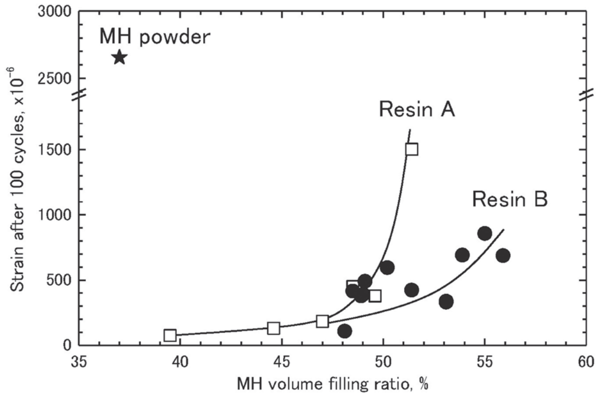

Fig.13 Relationship between filling ratio and strain

4.3 Hydrogen storage tanks

The MH canisters shown in Figure 14 and Table 3 are manufactured and sold as storage for small quantities of hydrogen. Various applications are being studied, such as for portable power supplies, fuel cell (FC) scooters and FC forklifts, and these canisters are also being used in laboratories as easy-to-handle hydrogen sources. Figure 15 shows the hydrogen desorption characteristics at 20 °C with the MHCh-450L as an example of the performance. When desorbing the hydrogen at a constant rate of 2 NL/min, it is possible to release nearly the entire volume of hydrogen. The results shown in Figure 15 are from separate tests performed using 20 different MH canisters. There is no deviation in the results, confirming that the same behavior is exhibited by each of the canisters.

Fig.14 MH canisters (60L, 200L, 450L)

Table.3 Specifications for MH canisters

Type	MHCh-60L	MHCh-200L	MHCh-450L	MHCh-800L
Hydrogen capacity	62～65 NL	217～231 NL	450～474 NL	826～884 NL
Size (mm)	Φ50.0 x L151	Φ54.0 x L270	Φ81.0 x L270	Φ88.9 x 406L
MH alloy	0.43～0.45 kg	1.5～1.6 kg	3.1～3.3 kg	5.7～6.1 kg
Total mass	0.9 kg	2.2 kg	4.5 kg	7.7 kg
Vessel material	Aluminum alloy (A6061-T6)			

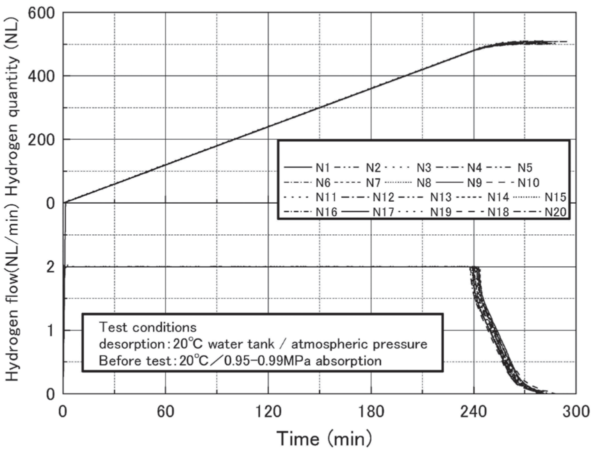

Fig.15 Hydrogen desorption properties of MHCh-450L at 20℃ (Constant rate 2 NL/min)

In recent years hydrogen storage systems using MH have been studied and demonstrated for applications requiring storage of large quantities of hydrogen as well. Since renewable energy, like solar power, has a large variation in the power output, batteries are often used for short-term balancing of supply and demand. To handle medium to long-term fluctuations, instead of the batteries, methods of storing the energy by converting it into hydrogen are also being studied. The number of cases in which MH is being adopted as the storage method is increasing, since it is a storage method that allows the hydrogen to be stored compactly and at low pressures.

In 2014 MH was adopted for the hydrogen storage facilities for a system storing it in the form of electrolytic hydrogen from water [22]. This system was designed to balance the mid- to long-term electricity supply and demand with the electricity generated from a group of solar panels installed on the roof of a building. The water electrolysis device had a maximum hydrogen generation capacity of 40 Nm^3/h. To correspond to this, a hydrogen storage system with a storage capacity of 100 kg of hydrogen was produced by combining 19 units, where 1 unit consisted of 2 MH tanks with the double-tube structure shown in Figure 16.

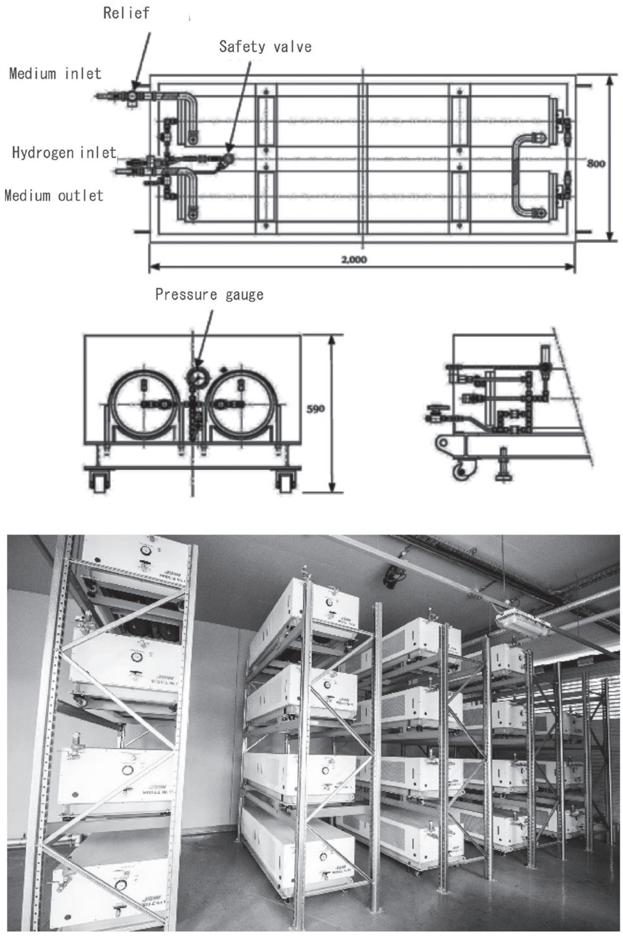

Fig.16 MH tank basic structure and external view of a 2 tank unit

In 2016, MH was used for the hydrogen storage equipment for a system utilizing hydrogen to store electricity generated by solar power generators during the long summer days for consumption during the winter. In this system, since the rate of hydrogen absorption and desorption is relatively slow, the MH tanks had the same double-tube structure as described above, but with a larger hydrogen storage capacity per tank, achieved by increasing the tank diameter. This resulted in a system capable of storing 100 kg of hydrogen in 9 MH tanks. Figure 17 shows an exterior view of the system. The dimensions of this system are width 1.8 m, length 3.1 m and height 2 m. In order to store the same 100 kg of hydrogen as a gas at a pressure of less than 1 MPa, 6 sets of 6 m long gas tanks would be needed, requiring a total length of 36 m of installation space. This illustrates the significant reduction in installation space that can be achieved.

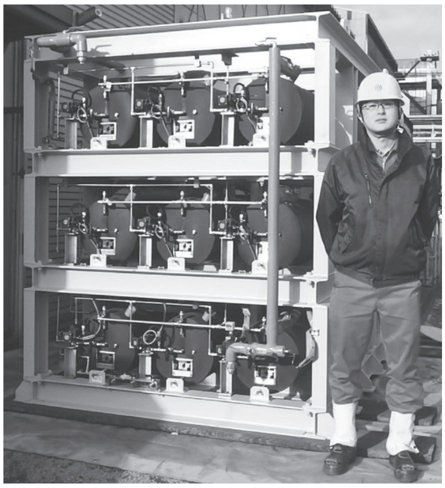

Fig.17 MH tank system with a storage capacity of 100 kg of hydrogen

Recently, the hydrogen absorption and desorption rates demanded from hydrogen storage devices have been increasing, and development of new tanks is required. JSW is developing an aluminum plate fin type MH tank, with a high heat transfer structure, like that of an automobile radiator, as shown in Figure 18. The hydrogen desorption characteristics of a prototype 3 Nm^3 aluminum plate fin MH tank are shown in Figure 19. This tank can desorb the entire volume of hydrogen in about 5 minutes, so there is a high potential for use in a variety of applications. Work is currently underway to develop larger versions of this tank.

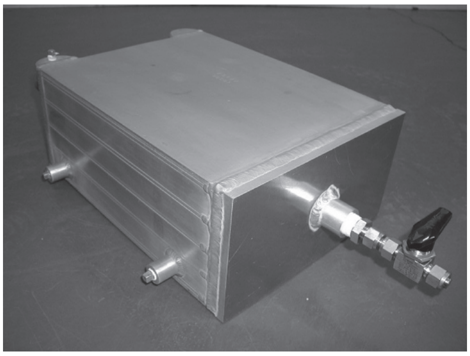

Fig.18 Prototype aluminum plate fin 3 Nm^3 MH tank

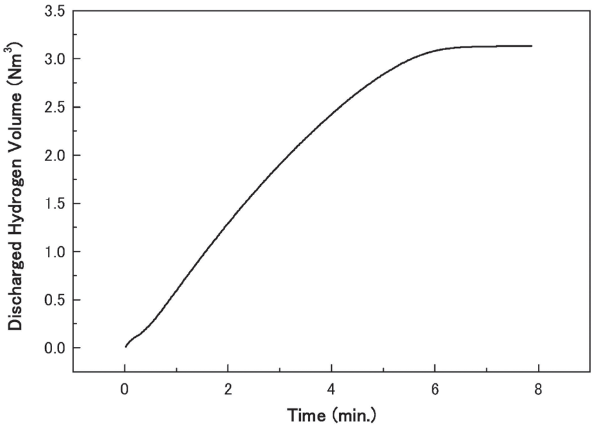

Fig.19 Hydrogen discharge characteristics of the prototype aluminum plate fin 3 Nm^3 MH tank

MH tanks are being considered as the storage tank for applications using hydrogen as a fuel in an increasing number of cases, but, thus far it has been difficult to obtain clear indications of the amount of hydrogen remaining inside a MH tank. A typical method is to use a mass flow meter and calculate the total cumulative flow. Over an extended period of use, however, the cumulative errors become an issue, making this difficult to use for some applications. JSW is working on the development of a remaining hydrogen sensor for MH tanks [(23)]. Figure 20 shows the basic principle of this remaining hydrogen sensor. Making use of the volumetric expansion of the MH when hydrogen is absorbed and the contraction when it is released, the changes in volume accompanying the expansion and contraction of the alloy are transmitted to the C-shaped pipe with high efficiency, and the strain generated in the pipe is measured. In this way, the amount of hydrogen stored in the MH, that is, the amount of hydrogen remaining in the MH tank can be measured. We are currently working on improving the accuracy of the measurements, and are accelerating the development so that this can be put to practical use as soon as possible.

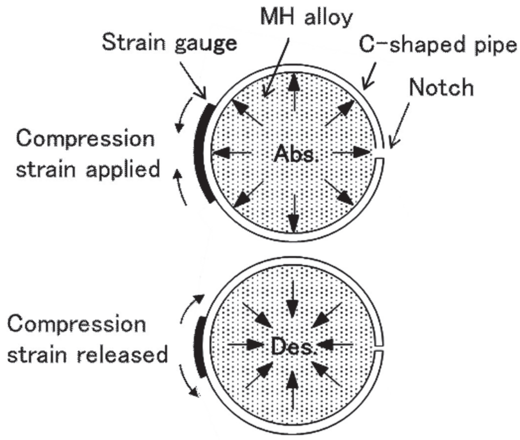

Fig.20 Principle of hydrogen residual sensor

5. Fuel Cell Power Supply

5.1 Portable fuel cell power supply

Portable fuel cell power supply [(24), (25)] is one example of products making good use of the compactness of the MH canisters. In the field of portable power supplies, generators or batteries, like lithium-ion batteries, are typically used. A fuel cell has the advantages of both of these, and has the potential to complement each of these. Figure 21 is a photograph of a portable fuel cell power supply, and Figure 22 shows the system schematic configuration. Air-cooled polymer electrolyte fuel cell (PEFC) was adopted for the fuel cell stack to simplify the system. 450 L MH canister was used for storage/supply of hydrogen. Instant startup and continuous operation became possible by using a secondary battery as an auxiliary power source for system start-up and canister exchange. The rated output is 100 W and the initial generation capacity is 1,000 Wh. In the case of measurement equipment of about 40 W, it is possible to operate about one day without exchanging the canister. Power generation of the fuel cell is an exothermic reaction, and hydrogen discharge from the canister is an endothermic reaction. By directly contacting the canister with the fuel cell stack and exchanging heat, the canister was heated, and the stack was cooled. Furthermore, by building a heater into system, it was possible to operate in a wide temperature range from -20 °C to 40 °C. Durability of the product was confirmed for about 2,000 hours through in-house testing. There was a limit to the weight saving of the canister and the compactness of the product, and the product was only limited sales.

Fig.21 Portable fuel cell power supply

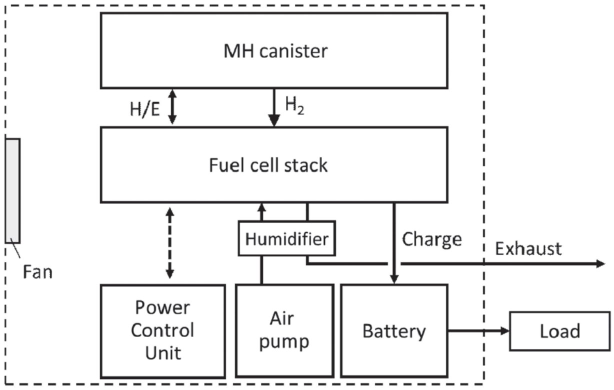

Fig.22 Schematic configuration of portable fuel cell power supply

5.2 Fuel cell backup power for traffic signals

After the Great East Japan Earthquake in March 2011, the backup power facilities for traffic signals were reconsidered. Diesel generators and lithium-ion batteries were being installed as the backup power supply, but the number of installations did not proceed as planned due to issues with the operation time and size/space problems. To address this, JSW developed fuel cell backup power for traffic signals by adapting the portable power supply technology [(26)-(28)]. Figure 23 is a photograph of a fuel cell backup power for traffic signals, and Figure 24 shows the system schematic configuration. The power generation configuration is similar to the portable power supply. The function of the backup power supply was made by adding the charging circuit from the grid power to the secondary battery and the uninterruptible power supply (UPS) function. Since the load of the traffic signal is the signal lamps, and blackouts of several milliseconds can be tolerated, the standby type UPS was adopted from the viewpoint of low conversion loss and long life. By using three 450 L MH canisters, the power generation capacity was about 1,500 Wh, it was possible to operate for about 7.5 hours at a common intersection. In addition, by applying continuous operation method with canister exchange like a portable power supply, it was possible to sufficiently ensure the function as a backup power supply even in the event of a large-scale power failure.

Fig.23 Fuel cell backup power for traffic signals

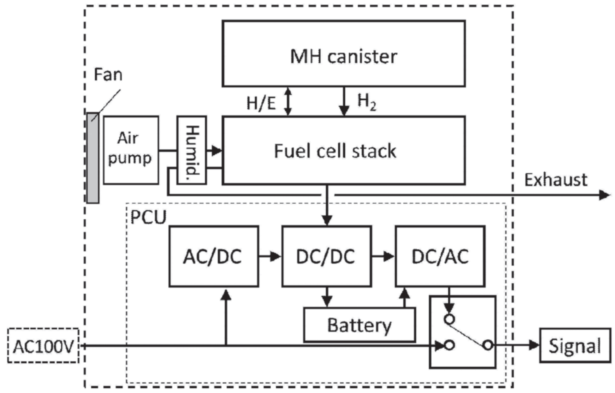

Fig.24 Schematic configuration of fuel cell backup power for traffic signals

For traffic signals, the installation environment is assumed to be -10 °C to 45 °C, and considering direct sunlight, it is expected that the temperature of the stack will become higher than in portable applications. In an air-cooled type fuel cell stack, it is said that when the stack is insufficiently cooled in a high-temperature environment, a dry up phenomenon occurs and the deterioration of the stack is accelerated. In this system, in addition to cooling the stack by heat exchange of the canister and the stack, by returning the exhaust heat of the stack to the supply side of the air gas, the temperature difference at the stack inlet and outlet was reduced and the dry up phenomenon was suppressed. Furthermore, the temperature inside the case was monitored. When the temperature inside the case exceeds the prescribed value, the cooling fan is operated and the outside air is taken in, and the top plate is structured to block the direct sunlight. Dozens of products have been installed so far, and an improved type is currently being developed.

5.3 Fuel cell backup power

Currently, we are developing fuel cell backup power which doubles the specification of the traffic signals, that is, increases the output to 800 W and the capacity to 3,000 Wh. For fuel cell stack of backup power, we used FCgen®-1020ACS manufactured by Ballard Power Systems (BPS) which has been installed worldwide. The power control unit (PCU) that converts the 100 VAC output from the fuel cell stack is manufactured in-house, making use of resonance circuit technologies. Figure 25 is a photograph of a fuel cell backup power, and Figure 26 shows the system schematic configuration. The BPS stack features a dead-end anode side, and an open cathode along with self-humidification. This makes it possible to use fewer system auxiliary devices for stack operation; for example, the same fan can be used for both cooling the stack and supplying oxygen to the stack. For the MH canister, the same as the traffic signals is used, and it can be easily exchanged with a one touch coupler. By using resonance circuit technology, it is possible to reduce harmonic ripple of inverter in PCU, reduce switching loss and downsize PCU. Furthermore, by using inverters bi-directionally, it is possible to charge the secondary battery from the grid power and discharge from the backup power supply to the load with one inverter. It is also possible to handle stable startup and rapid load change by using the fuel cell and the secondary battery together. For backup power, standby type UPS was adopted to reduce standby power during commercial power supply.

Fig.25 Fuel cell backup power

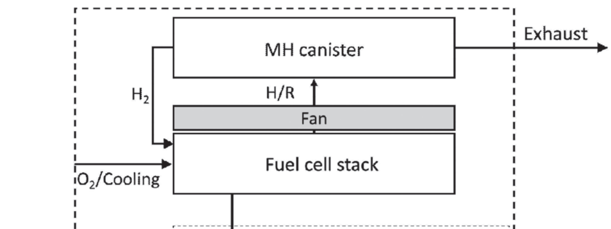

Fig.26 Schematic configuration of fuel cell backup power

6. Conclusion

JSW is working on the development of the facilities for hydrogen refueling stations for fuel cell vehicles and application systems making use of metal hydrides, making use of the material technologies and machinery control technologies that developed over the years. Since hydrogen is a flammable gas with a wide explosive concentration range, it is important to provide highly-reliable equipment systems with safety as the top priority. JSW will continue to advance the technologies related to hydrogen that we have accumulated over many years of effort, and promote technology development to support the realizing of the hydrogen energy society that is in our future.

Acknowledgements

We gratefully acknowledge the support of NEDO for contracted projects in which valuable data was obtained, including data on hydrogen gas during pressure vessel development.

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