

Development of In-tank Solenoid Valve Compatible with 70 MPa High-pressure Hydrogen Storage and Supply System for FCV

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ABSTRACT

In order to increase fuel cell vehicle mileage per filling, technologies have been developed to reduce the weight of the in-tank solenoid valve and boost hydrogen seal performance, both issues in increasing the pressure of a hydrogen storage and supply system.

It was necessary for the in-tank solenoid valve for use at 70 MPa to display twice the pressure resistance of the previous model (for 35 MPa use). However, realizing the necessary increase in pressure resistance would increase the size and weight of the valve. The in-tank solenoid valve is provided with a check valve on the hydrogen filling side and a shut-off valve on the hydrogen supply side; these valves connect to the high-pressure hydrogen tank and supply and shut off hydrogen. As a means of reducing weight in the developed in-tank solenoid valve, the functions of these valves were integrated, making it possible to share the flow channels for hydrogen filling and hydrogen supply. The temperature sensor was built into the tank, and aluminum alloy was employed as the material for the valve body. These measures reduced the weight of the developed in-tank solenoid valve by 41% against the previous 35 MPa model.

For the hydrogen seal, a structure that helps to ensure that the seal material is not damaged at a pressure of 70 MPa was adopted, and a high-strength seal material was employed. These measures made it possible to realize a high level of pressure resistance in the hydrogen seal.

1. Introduction

As part of efforts to address global warming and energy issues, fuel cell vehicles (FCV), which employ hydrogen as fuel, are considered to possess outstanding potential as environmentally conscious vehicles. Mileage per filling is an important element of FCV performance. It is necessary to increase hydrogen storage capacity in order to increase mileage per filling.

The high-pressure hydrogen storage and supply system employed in Honda's 2009 model FCV (35 MPa system) used 35 MPa as the pressure for hydrogen storage in the high-pressure fuel tank⁽¹⁾. In the 2016 model, the hydrogen storage pressure in the high-pressure hydrogen storage and supply system (70 MPa system) has been increased to 70 MPa as an effective means of increasing mileage per filling. However, in order to produce a 70 MPa in-tank solenoid valve to take over the function of the previous 35 MPa

technology, it would be necessary to increase thickness to help ensure body strength, and this would result in increased size and weight. In addition, because a pressure of 70 MPa would damage the previous 35 MPa hydrogen seal configuration, it would not be possible to ensure seal performance. Given this, the research discussed in this paper set out to address the issues presented by increased hydrogen storage pressure and develop a valve weight reduction technology and a hydrogen seal technology, making it possible to increase mileage per filling.

2. Development Goals

The following two main aims were set for the development of the 70 MPa system:

- (1) Reduction of weight of high pressure-resistant in-tank solenoid valve
- (2) Increase in pressure resistance of hydrogen seal

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3. System Configuration

Figure 1 shows the high-pressure hydrogen tanks employed in the 2016 model FCV. In order to reconcile the space necessary for fitting the hydrogen tanks with passenger space, two tanks of differing external diameters were employed. The tanks were positioned under the rear seat and behind the rear seat.

Figure 2 shows a transparent view of the 70 MPa system. After passing through the receptacle [Fig. 2(a)] and the check valve [Fig. 2(b)], the hydrogen supplied by the hydrogen station diverges, and passes through the in-tank solenoid valve [Fig. 2(c)] before filling the two high-pressure hydrogen tanks [Fig. 2(d)]. The hydrogen stored in high-pressure hydrogen tanks passes through the in-tank solenoid valve and its pressure is reduced by the regulator [Fig. 2(e)] before being supplied to the fuel cell stack.

Figure 3 shows the amount of hydrogen stored per

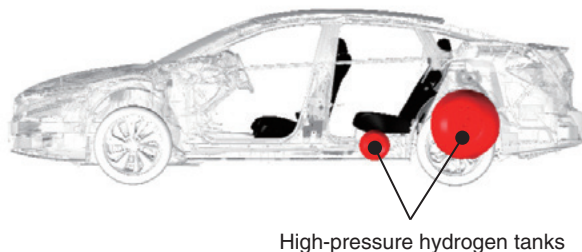


Fig. 1 High-pressure hydrogen tank installation layout

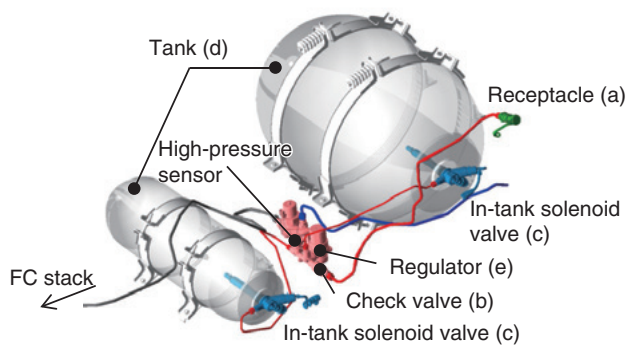


Fig. 2 Hydrogen storage and supply system for 2016 model year FCV

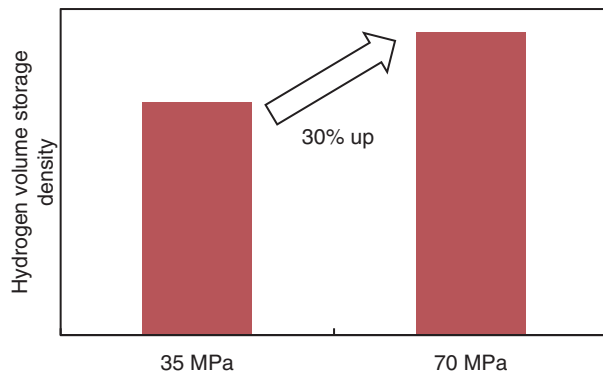


Fig. 3 Hydrogen volume storage density

exterior volume (the hydrogen volume storage density) for the 35 and 70 MPa high-pressure hydrogen tanks. Increasing the hydrogen storage pressure from 35 to 70 MPa increases the hydrogen volume storage density by 30%.

4. Reduction of Weight of In-tank Solenoid Valve

4.1. Integration of Functions of Check Valve and Shut-off Valve

Figure 4 shows the configurations of the 35 and 70 MPa systems. In the 35 MPa system [Fig. 4(a)], separate gas flow channels were used for filling the tank with hydrogen and supplying hydrogen; this was appropriate for a configuration using a single high-pressure hydrogen tank. However, the development of a multiple-tank system based on the same concept [Fig. 4(b)] would necessitate the use of multiple gas flow channels for filling and supply, increasing the overall size of the system. For the 70 MPa system [Fig. 4(c)], the weight of the system was therefore reduced through the development of an in-tank solenoid valve that integrated the functions of the check valve and the shut-off valve and used a common flow channel for

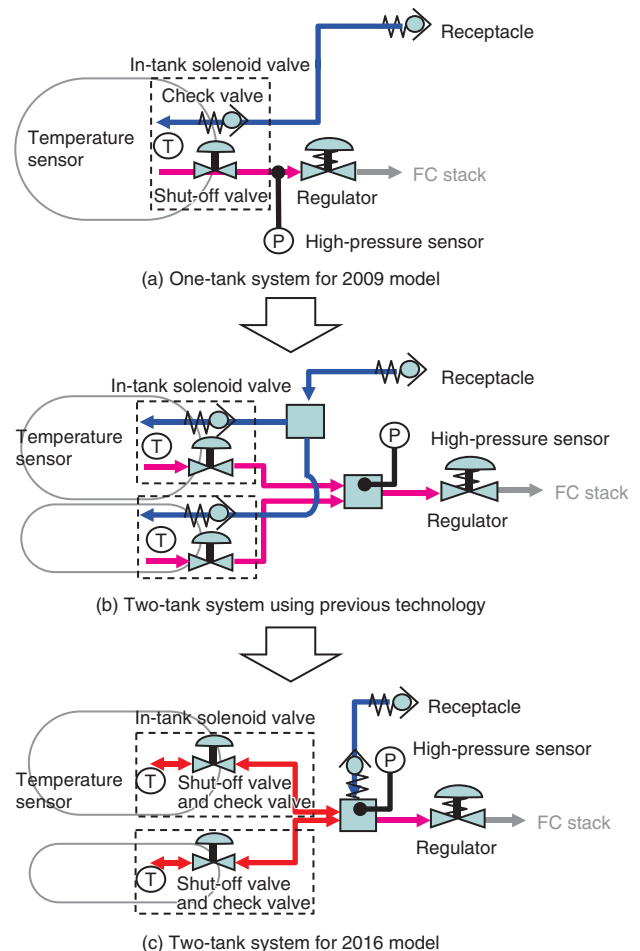


Fig. 4 Configuration of high-pressure hydrogen storage and supply system

filling and supply.

Figure 5 shows the structure of the in-tank solenoid valve and the hydrogen seal specifications for the 2009 model [Fig. 4(a)] and the 2016 model [Fig. 4(c)]. The use of a single gas flow channel for filling and supply in the 2016 model in-tank solenoid valve, which integrates the previous check valve and shut-off valve, reduced the number of parts by 6%.

4.2. Temperature Sensor Built Into Tank

The in-tank solenoid valve was provided with a temperature sensor to make it possible to monitor the temperature of the hydrogen in the high-pressure hydrogen tank during vehicle filling and operation. Figure 6 shows the layout and structure of the temperature sensors used in the 2009 and 2016 models. The thermistor elements used in the temperature sensor are transition metal oxides, mainly of Mn, Co, and Ni. When they come into contact with hydrogen, they are reduced and their properties change. Because of this, the thermistor elements employed in the temperature sensor used in the 2009 model were covered by a stainless steel (SUS) case and isolated from the hydrogen by O-ring

seals (body and temperature sensor). However, in order to make the sensor compatible with a pressure of 70 MPa using a conventional O-ring seal configuration, it would be necessary to increase the thickness of the SUS case to help ensure strength, and this would increase the diameter of the opening of the in-tank solenoid valve in which the temperature sensor is fitted. In order to make the in-tank solenoid valve compatible with a pressure of 70 MPa at the same time as reducing its weight, the temperature sensor for the 2016 model was built into the tank.

The temperature sensor employed in the 2016 model does not employ an O-ring seal (body and temperature sensor) configuration of the type shown in Fig. 6 in order to isolate it from hydrogen. The temperature sensor is isolated from the hydrogen through the application of a hermetic seal technology, making it possible to build the sensor into the tank and realize a lower-diameter opening in the in-tank solenoid valve. A hermetic seal is realized by positioning glass and a lead wire in a metal tube; during slow cooling of the glass following melting, the difference between the rate of thermal expansion of the lead wire, glass, and metal tube induces compressive

	2009 model		2016 model	
Nominal working pressure	35 MPa		70 MPa	
Weight	1.85 kg		1.09 kg	
Structure				
Seal Structure	(1) O-ring seal	(2) Valve seat	(3) O-ring seal	(4) Valve seat

Fig. 5 Structure and specifications of in-tank solenoid valve

stress in the glass, increasing the sticking force between the lead wire and the glass and forming a seal.

4.3. Use of Aluminum Alloy as Body Material

In order to reduce the weight of the in-tank solenoid valve, aluminum alloy was employed as the body material, replacing the SUS used in the 2009 model. Because non-ferrous materials such as aluminum alloys do not have fatigue limits, fatigue life design taking the degree and frequency of pressure fluctuations expected in an actual vehicle into consideration was applied in order to realize high pressure resistance in the body.

In addition, because aluminum alloys are more prone than SUS to corrosion in contact with alkaline chemicals, a non-electrolytic Ni plating treatment was applied to the surface of the alloy to help ensure chemical resistance. Global Technical Regulation (GTR) No. 13⁽²⁾ specifies tests simulating a vehicle environment (Table 1) to verify the external appearance, airtightness, and pressure resistance of the valve following immersion in an aqueous sodium hydroxide solution and other solutions as tests for verification of the chemical resistance of in-tank solenoid valves. The results of these tests showed no corrosion on the valve body.

The application of the three measures discussed above (the integration of the functions of the check valve and the shut-off valve, the building of the temperature sensor into the tank, and the use of aluminum alloy as the sensor body material) reduced the weight of the sensor by 41% against the previous model while realizing compatibility with a pressure of 70 MPa.

Table 1 Tests stipulated by GTR No. 13

Component	Test items
Shut-off valve and check valve	Hydrostatic strength test Leak test Extreme temperature and pressure cycling test Salt corrosion resistance test Vehicle environment test Atmospheric exposure test Electrical test Vibration test Pre-cooled hydrogen exposure test
TPRD	Pressure cycling test Accelerated life test Temperature cycling test Salt corrosion resistance test Vehicle environment test Drop and vibration test Leak test Bench top activation test Flow rate test

5. 70 MPa Hydrogen Seal Technology

5.1. Development of O-ring Seal for 70 MPa Use

5.1.1. Concept of seal

When a seal is created using an O-ring at a joint (an O-ring seal), if the O-ring does not possess sufficient rigidity when subjected to pressure, the pressure can cause the O-ring to protrude into the gap between the body and the connector, damaging the O-ring and reducing the tightness

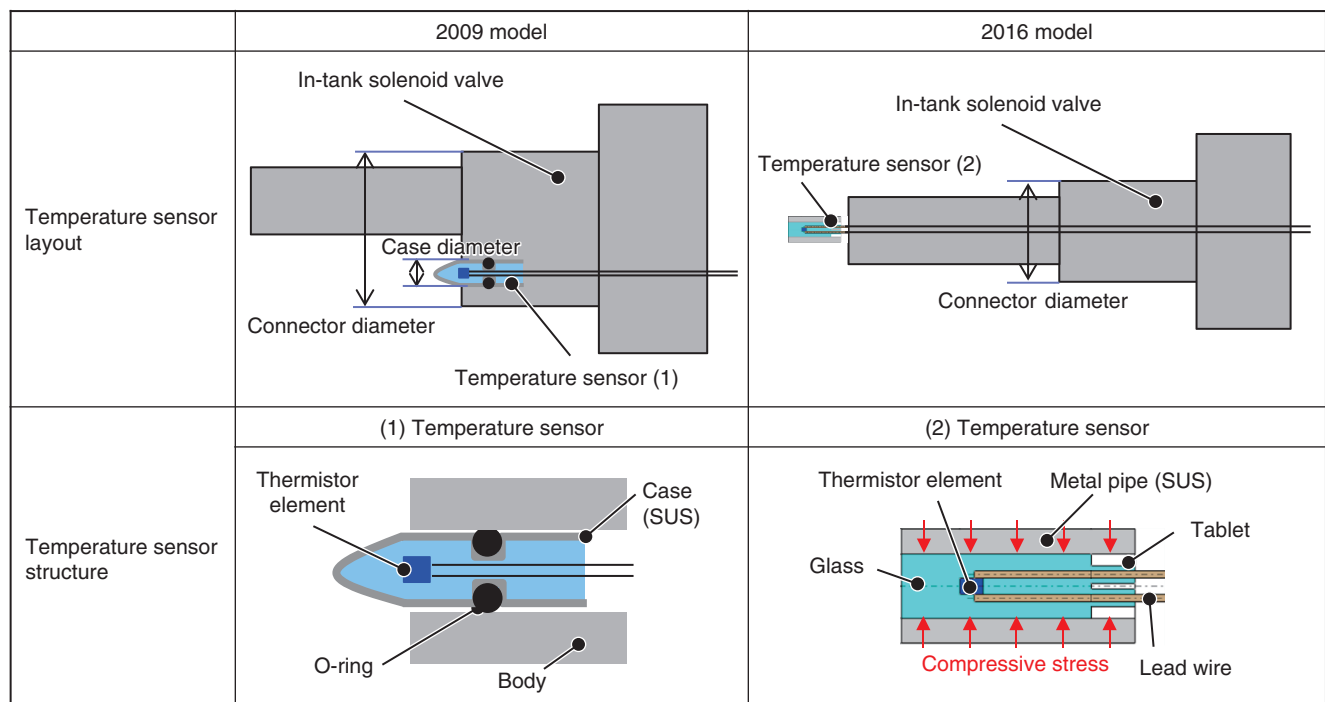


Fig. 6 Layout and structure of temperature sensor

of the seal (Fig. 7). It is essential, therefore, to design the O-ring to help ensure that it does not exceed the allowable gap (the run-over limit) at the pressure being used.

Figure 7 shows the 35 MPa O-ring seal structure employed in the 2009 model. In order to fill the gap into which the O-ring might protrude under pressure, a rubber back-up ring was positioned on the air side of the O-ring. This back-up ring filled the 0.09 mm gap. Figure 8 shows the allowable gap for the back-up ring under pressure (the run-over limit)⁽³⁾. The horizontal axis shows the diameter gap, and the vertical axis shows pressure. The red line shows the back-up ring run-over limit. When the red line is passed (upper right), the back-up ring protrudes into the gap. At a pressure of 35 MPa, the gap does not exceed the protrusion limit. At 70 MPa, however, the gap exceeds the run-over limit, and the back-up ring protrudes into the gap and is damaged. This indicated that the O-ring seal structure employed in the 2009 model was not suited to hydrogen storage at 70 MPa.

Research was therefore conducted in order to develop an O-ring seal structure for 70 MPa use.

5.1.2. Seal structure

Figure 9 shows the developed O-ring structure for use at 70 MPa. In the 2016 model, the material for the back-up ring was changed from rubber to resin to help ensure strength, and a tapered shape was employed to make it

possible for the ring to deform under pressure and fill the gap⁽⁴⁾.

Figure 10 shows CAE results showing the back-up ring deforming under pressure and filling the gap. From its initial state, the gap is gradually filled [in the order (a), (b), and (c) in Fig. 10] as pressure increases, until the gap becomes zero at the predetermined pressure in (c). Figure 11 shows the relationship between the O-ring run-over limit and the gap. The red line shows the O-ring run-over limit, and the blue line shows the relationship between the gap between the back-up ring (which is deformed by pressure) and the body

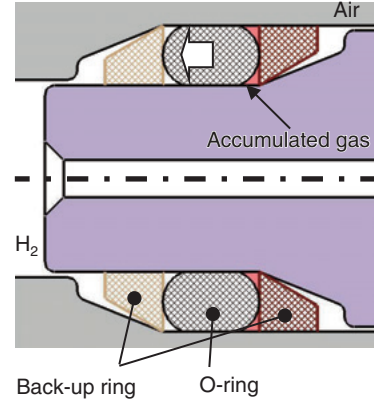


Fig. 9 O-ring seal structure for 70 MPa

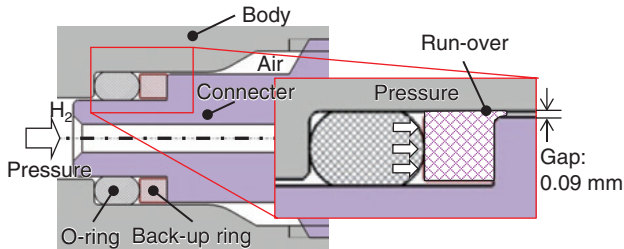


Fig. 7 O-ring seal structure for 35 MPa

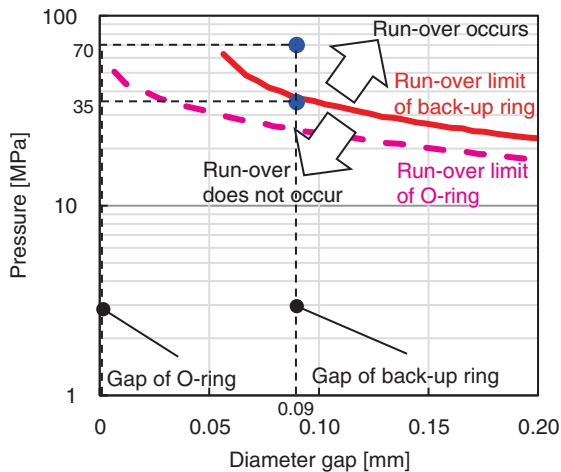


Fig. 8 Relationship of run-over and gap of back-up ring

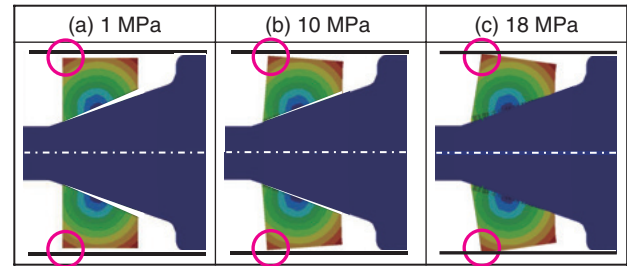


Fig. 10 CAE Results for run-over gap under pressure

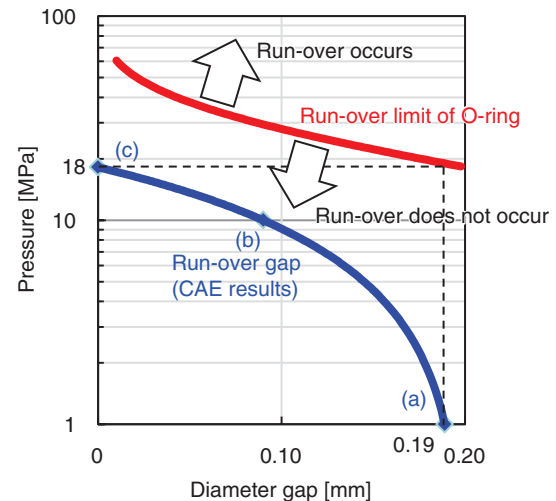


Fig. 11 Relationship between run-over and O-ring gap

and pressure. At a pressure of 18 MPa, the allowable gap for the O-ring is 0.19 mm and below. Because the gap at this time becomes zero (<0.19 mm) due to the deformation of the tapered back-up ring, the O-ring is not damaged by run-over into the gap. The gap calculated by CAE (the blue line) is lower than the run-over limit for the O-ring (the red line), and the O-ring is therefore undamaged.

Because the rubber O-ring is more hydrogen-permeable than the resin back-up ring, gas passes through the O-ring and accumulates between the O-ring and the back-up ring. When pressure decreases, this creates the possibility that the O-ring will be pushed to the hydrogen side and damaged by run-over into the gap. In addition, when the O-ring is exposed to a 70 MPa hydrogen environment for an extended period, the hydrogen penetrates inside the O-ring, resulting in swelling when pressure decreases. Taking this factor into consideration as well, a tapered back-up ring of the same type as used on the air side was also used on the hydrogen side of the O-ring.

5.2. Development of 70 MPa Valve Seat

5.2.1. Concept of seal

In addition to an O-ring seal, a valve seat structure of the type shown in Fig. 5 (2) and (4) is a necessary element of an in-tank solenoid valve that supplies and shuts off hydrogen. It is necessary for this valve seat to operate under conditions of pressure difference between upstream and downstream. In the 2009 model, the valve seat was manufactured from rubber, and a configuration in which a protruding valve pressed against a flat valve seat was adopted. However, if the 35 MPa valve seat employed in the 2009 model were operated under conditions of a 70 MPa pressure difference, the tensile stress generated in the rubber seat by the pressure would exceed the tensile strength of the seat material, with the result that the seat would enter the downstream flow channel and be damaged, and it would no longer be possible to ensure seal performance (Fig. 12).

A study of the seal material and seal structure to be employed for the 70 MPa valve seat was therefore conducted based on this consideration.

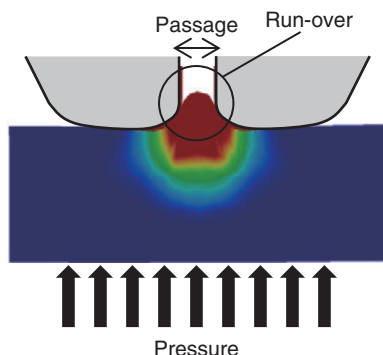


Fig. 12 Seat damage by run-over

5.2.2. Seal material

It was necessary to change the seal material to resin, which possesses a high level of mechanical strength, in order to adapt the seal to use at a hydrogen storage pressure of 70 MPa. However, when force increases, resins generally display elasticity, a property that causes them to rebound like a spring, and viscosity, a property that causes them to flow like a fluid. Because of this, when resins are soaked for long periods under high temperatures and high pressures, they undergo creep deformation and permanent deformation occurs. Figure 13 shows an image of creep deformation of a valve seat. When permanent deformation of the valve seat progresses, the deformation results in an increase in the contact area between the resin and the metal. As a result, the surface pressure of the valve seat declines, and leaks from the seal can occur.

Because of this, a polyamide-imide possessing a high level of mechanical strength and good creep resistance was selected as the resin material for the valve seat for use at a hydrogen storage pressure of 70 MPa. The use of the polyamide-imide material for the resin valve seat made it possible to realize durability in relation to operation under a pressure differential and heat aging. However, if the polyamide-imide material did not compress under comparatively high force, it would not be possible to fill the minute concavities and convexities on the surface of the valve, and seal performance could not be ensured. A study was therefore conducted to determine a structure making it possible to realize the valve seat surface pressure necessary for hydrogen seal performance.

5.2.3. Seal structure

Figure 14 shows the developed resin valve seat structure for use at 70 MPa.

Because force would act in the direction of alignment when the valve was closed and in contact with the valve seat in the case of a tapered resin seat structure, an appropriate relationship between the positions of the valve and the valve seat would be maintained. In addition, a tapered shape would disperse the load on the seat due to surface pressure, reducing stress on the seat.

Figure 15 shows the results of CAE analysis of the surface pressure generated on the valve seat under pressure. A 45° taper was selected for the resin valve seat structure because the stress generated in the valve seat when the

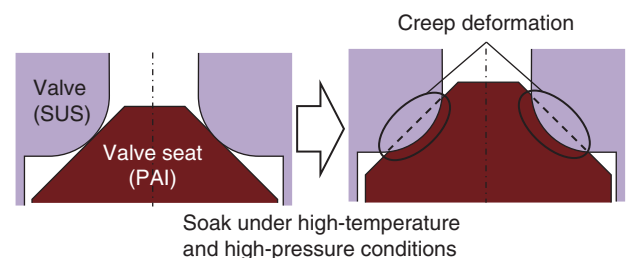


Fig. 13 Creep deformation of valve seat

pressure differential was high remained below the allowable surface pressure for the seat, and the necessary surface pressure for hydrogen seal performance was realized when the pressure differential was low.

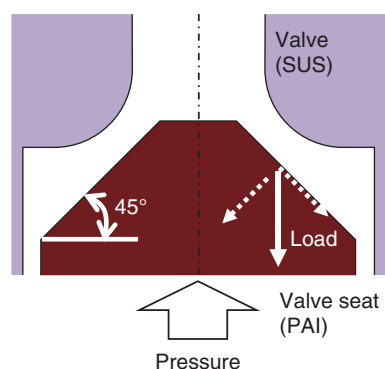


Fig. 14 Valve seat structure for 70 MPa

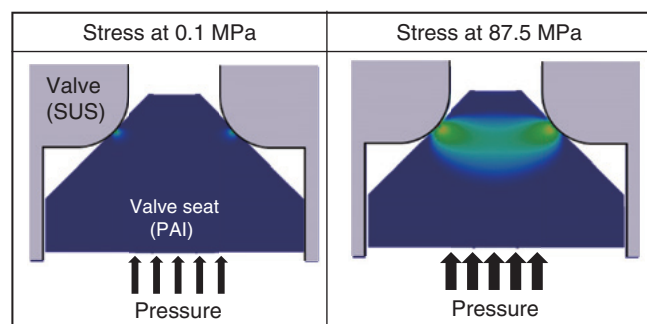


Fig. 15 CAE results for surface pressure

6. Conclusion

The weight of an in-tank solenoid valve was reduced and hydrogen seal performance was enhanced in order to realize the high pressure resistance necessary for a 70 MPa system.

- (1) In order to reduce the weight of the in-tank solenoid valve, the check valve and the shut-off valve were integrated, and a shared gas flow channel inside the valve was employed for hydrogen filling and supply, reducing the number of parts by 6%. In addition, aluminum alloy was employed as the valve body material rather than SUS, and the temperature sensor was built into the tank, making it possible to reduce the diameter of the valve opening. Despite the fact that the developed valve was suitable for use at a pressure of 70 MPa, it was 41% lighter in weight than the previous model.
- (2) For the hydrogen seal, a structure was adopted in which tapered back-up rings were positioned on the hydrogen and air sides of the O-ring in a 70 MPa O-ring seal structure. A resin valve seat structure with a 45° taper

able to operate under a pressure differential of 70 MPa was also employed. These measures made it possible to realize a high level of pressure resistance in the hydrogen seal. As a result, it was possible to realize a 30% increase in the hydrogen volume storage density of the tanks against the 35 MPa model.

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