

Development of New Fuel Cell System

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ABSTRACT

In order to provide fuel cell durability, it is important to reduce iron (Fe) contamination to the polymer electrolyte membrane of the fuel cell stack and to control the humidity to an appropriate level. The new fuel cell system developed jointly with General Motors Company adopts a double-layer coating of titanium and carbon on the stainless steel bipolar plates of the fuel cell stack that reduces Fe elution to 1/10 the previous amount. In addition, the humidification level is increased by estimating the amount of water vapor with a highly accurate humidification model and using a high-efficiency water vapor transfer unit and an electric coolant mixing valve to perform active humidity control. The amount of water contained in the membrane was increased by lowering the coolant temperature and supplying air controlled to high humidity with a high degree of accuracy. As a result, the durability is more than double that of the previous system.

In addition, the start-up time in a low-temperature environment of -20°C was shortened to 1/9 that of the previous system by performing humidity conditioning control when the system is stopped and rapid warm-up control at start-up.

The fuel cell system cost was also reduced to 1/3 that of the previous system by reducing the cost of the fuel cell stack and simplifying the system.

1. Introduction

The utilization of hydrogen energy is attracting attention as a key technology for achieving a carbon-neutral society. Honda has engaged in research and development of fuel cells that extract electrical energy directly from hydrogen and the oxygen in the air. In 2002, the company released the FCX, the first fuel cell passenger vehicle, simultaneously in Japan and the U.S.^{(1), (2)} This was followed in 2003 by development of an FCX equipped with a fuel cell system capable of start-up in sub-zero environments, which enabled use in cold regions⁽³⁾. In 2008, the FCX CLARITY was launched, considered the first sedan type to adopt a dedicated platform for fuel cell vehicles⁽⁴⁾. In anticipation of full-scale mass production, productivity was enhanced, and a downsized fuel cell system was developed in 2016 and positioned as the first generation. This first-generation fuel cell system (hereinafter, the previous system) was installed in the engine room to achieve release of the CLARITY FUEL CELL, considered the first fuel cell vehicle to seat five people, which increased practicality as a daily car⁽⁵⁾. In 2024, the CR-V e:FCEV was announced, which is equipped with the new second-generation fuel cell system introduced in this paper⁽⁶⁾.

In order to help realize a carbon-neutral society, Honda will promote the expanded deployment of fuel cell systems not only in passenger vehicles but also in various applications. Hydrogen features a higher energy density compared to batteries, easy transport in various formats, and quick filling. Efforts will be made to expand use to applications that can take advantage of those characteristics, such as commercial use vehicles, construction machinery, and stationary power sources (Fig. 1). This paper introduces a new fuel cell system that features even greater durability, shorter start-up time at ultra-low temperatures, and further cost reduction with the goal of expanding adoption of fuel cell systems.

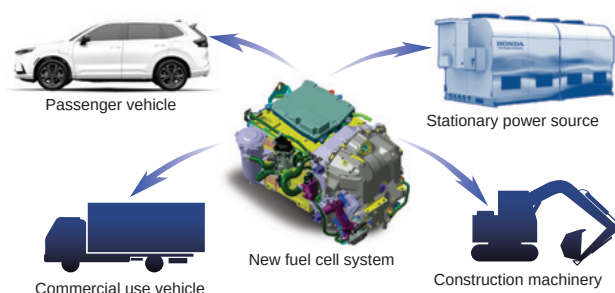


Fig. 1 New fuel cell system and various applications

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Table 1 Main specifications of fuel cell systems

Major specifications	Fuel cell type	Previous fuel cell system Proton exchange membrane	New fuel cell system Proton exchange membrane
	Fuel cell power	103 kW	92.2 kW
	Fuel cell stack size	33 liters	33.8 liters
Main system configuration for durability	FC coolant temperature control	Thermostat valve	Electric coolant mixing valve
	Humidity control	Water vapor transfer bypass valve	
	Provide air circulation	EGR pump	— (Substitution by control)
	Provide H ₂ circulation	Hydrogen pump	

2. Overview of Development

Figure 2(a) shows the previous fuel cell system, and Fig. 2(b) shows the new fuel cell system. It was considered important that the new system have even greater durability, better low-temperature environmental performance, and lower cost compared to the previous system, so the development goals were as follows. Table 1 shows the main specifications of the new and previous fuel cell systems.

(1) Further enhancement of fuel cell stack durability

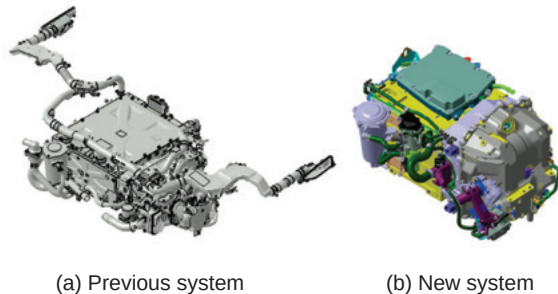
In order to promote compatibility with various applications, the target durability time was set to double that of the previous system. This was achieved by enhancing the amount of water contained in the polymer electrolyte membrane of the fuel cell stack, lowering the coolant temperature, and reducing the amount of Fe elution from the bipolar plates that comprise the fuel cell stack.

(2) Shorter warm-up time in low-temperature environments

In order to further enhance marketability in low-temperature environments, the target warm-up time at -20°C was set to 1/9 that of the previous system. This was achieved by adopting humidity conditioning control when the system is stopped and rapid warm-up control at start-up.

(3) Enhanced productivity and further cost reduction of fuel cell system

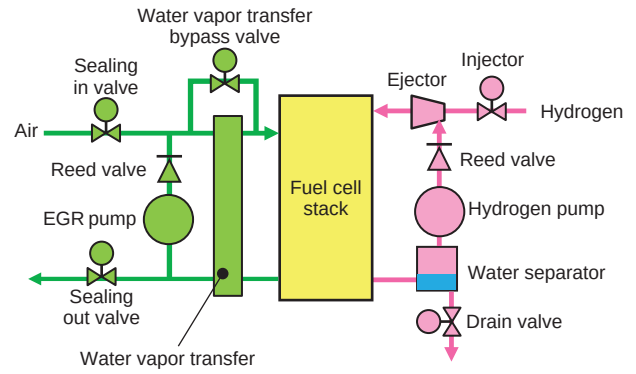
The target cost was set to 1/3 that of the previous system. This was achieved by simplifying the fuel cell stack structure as shown in Fig. 3(b), enhancing productivity, reducing the amount of precious metals used, and simplifying the system components.



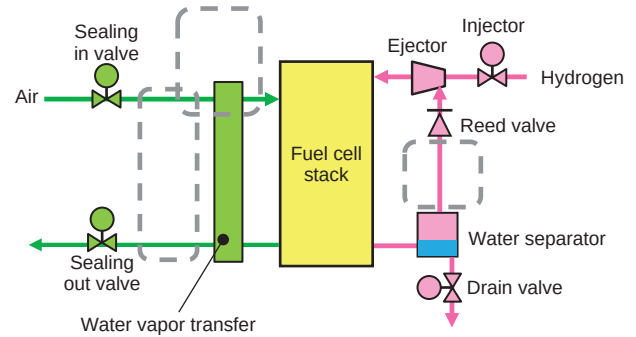
(a) Previous system

(b) New system

Fig. 2 Appearance of fuel cell systems



(a) Previous system



(b) New system

Fig. 3 Comparison of system configuration

3. Further Enhancement of Fuel Cell Stack Durability

The polymer electrolyte fuel cells that are generally used for automobiles directly extract electrical energy externally by transferring hydrogen ions H^+ through polymer electrolyte membranes located in the center part. The fuel cell stack structure consists of a membrane electrode assembly (MEA) with catalyst layers and gas diffusion layers sandwiched around polymer electrolyte membranes, and bipolar plates in which flow channels for gas supplied as fuel and flow channels for coolant to cool the power generation parts are formed. The fuel cell stack humidification control system adopted in the new system like the previous system is described next. Figure 4 shows a diagram of the humidification system of the fuel cell stack. As the exhaust air from the fuel cell stack contains water produced by power generation, it is in the highly humid state. This highly humid exhaust air is passed through a water vapor transfer unit installed in the air supply system. As a result, the water vapor contained in the exhaust air is transferred to the air that is supplied to the fuel cell stack, thereby humidifying the supply air.

A key to enhancing the durability of the fuel cell stack is how to suppress changes over time, especially in the polymer electrolyte membrane that is responsible for the

transfer of hydrogen ions. It is known that the chemical stability of the polymer electrolyte membrane decreases when the amount of water contained in the membrane is insufficient and under high-temperature conditions^{(7), (8)}, and that changes over time are accelerated by contamination of the membrane by Fe eluted from components such as the bipolar plates⁽⁹⁾. However, if the fuel cell stack contains an excessive amount of water, the gas supply will be hindered, leading to changes in the electrodes over time, and thus it is necessary to adjust the amount of water contained to the appropriate range.

To address the decrease in the chemical stability of the membrane and changes in the electrodes over time, it is necessary to increase the amount of water contained in the membrane and lower the temperature within the appropriate ranges during power generation. The amount of water contained in the membrane and the relative humidity of the air supplied to the fuel cell stack are closely related, so the amount of water contained in the membrane was increased by lowering the coolant temperature and supplying air controlled to a highly humid state. This was achieved by the following three methods.

- (1) Enhance the heat exchange performance of the fuel cell stack
- (2) Enhance the accuracy of estimating the amount of water vapor in the air supplied
- (3) Lower the coolant temperature

The heat exchange performance was enhanced by changing the cooling structure from the previous structure that provides one cooling layer for every two cells to a cell-by-cell cooling structure that provides one cooling layer for each cell⁽¹⁰⁾. Figure 5(a) shows the air and coolant flows inside the flow channels formed in the bipolar plates. The effect of the coolant on the relative humidity of the air is as follows. In the fuel cell stack, power generation produces water on the cathode, and the relative humidity of the air inside fuel cell stack increases toward the outlet. For this reason, a flow channel structure is adopted in which the air and coolant flow in parallel in the same direction in order to reduce condensation of the water vapor. In this flow channel structure, the humidified air entering the fuel cell stack undergoes heat exchange with the coolant supplied to the fuel cell stack before being supplied to the MEA, which is the power-generating part, in order to adjust

the temperature of the air supplied to the MEA. The amount of saturated water vapor changes according to the temperature of this air, and thus the relative humidity of the air changes even though the amount of water vapor contained in the air remains the same. That is to say, the relative humidity of the air supplied to the MEA can be adjusted by controlling the coolant temperature at the stack inlet. Adoption of a cell-by-cell cooling structure as shown in Fig. 5(b) enhanced the heat exchange performance and reduced variation between cells compared to the previous system. This enabled performance of precise humidification control.

Enhancement of the accuracy of estimating the amount of water vapor in the air supplied is described next. The previous system applied the method of measuring the average impedance of the fuel cell stack to understand the state of the water contained in the membrane. A valve installed on piping that bypasses the water vapor transfer unit shown in Fig. 3(a) was operated based on that impedance information to control the relative humidity of the supplied air, thereby controlling the amount of water contained in the membrane⁽¹¹⁾. However, there was the issue that the impedance measurement sensitivity is low in the high humidity environment that is the target of the new system, making it a challenge to accurately assess the amount of water contained in the membrane. Therefore, a new model was constructed that mathematically expresses the water vapor transfer principle in the water vapor transfer unit⁽¹²⁾, and this mathematical model was then converted to an approximation function to create a control model with a low calculation load that can be implemented in system control. Use of this control model enabled onboard estimation of the amount of water vapor transfer in the high humidity region where high-precision control was not easy

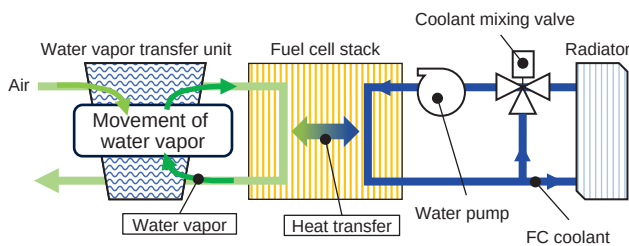
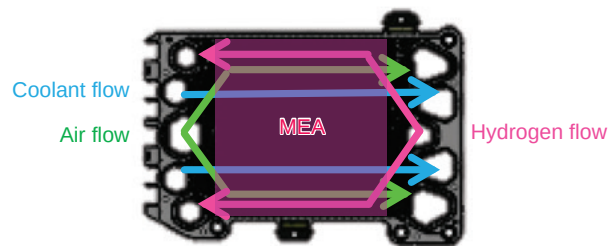
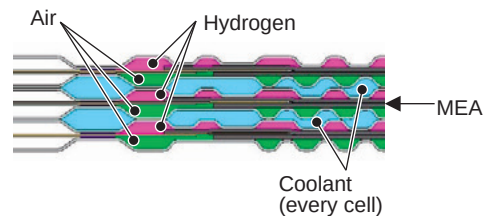


Fig. 4 Humidification system



(a) Fluid flow in stack



(b) Cross-sectional structure of stack (cell-by-cell cooling)

Fig. 5 Structure of flow channels

with the impedance-based method. Figure 6 compares the calculation times of both models, and shows the actual measurement results and model calculation results of the amount of water vapor transfer of the water vapor transfer unit under various power generation conditions of the fuel cell stack. The control model obtained equivalent estimation results while shortening the calculation time to approximately 1/5 that of the mathematical model, thus realizing both accuracy and a low calculation load.

In order to lower the coolant temperature, the cooling performance of the radiator was enhanced and a coolant mixing valve was applied that can electrically control the amount of coolant flowing to the radiator (Fig. 4). The previous system applied a thermostat valve that was passively opened and closed to achieve a constant target coolant temperature. By contrast, the opening of the coolant mixing valve can be adjusted at an arbitrary timing to achieve an arbitrary target coolant temperature. The amount of coolant flowing to the radiator is controlled by adjusting the opening of this valve, enabling the free mixing of coolant with a low water temperature that has been cooled by the radiator and coolant with a high water temperature that does not pass through the radiator. This enabled control at an arbitrary target coolant temperature calculated by the control model, and achieved the target relative humidity of the air supplied to the fuel cell stack.

Figure 7 shows an example of the behavior of the relative humidity of the air with or without this humidification control in constant current power generation. When the temperature of the air rises, as shown in Fig. 7(b), the humidification control model estimates a decrease

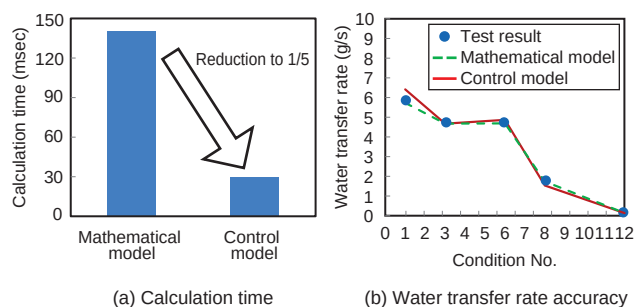


Fig. 6 Performance of control model

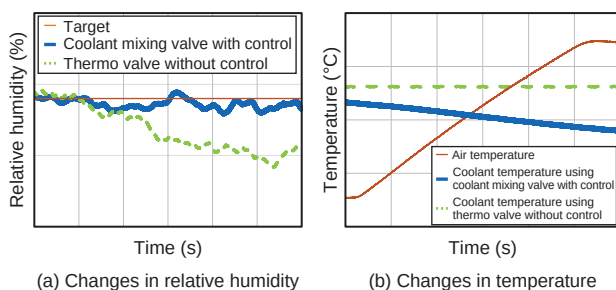


Fig. 7 Behavior of relative humidity

in the relative humidity and lowers the coolant temperature. As a result, the relative humidity can be stably controlled to around the target value as shown in Fig. 7(a). Figures 8(a) and 8(b) show the respective frequency distributions of the coolant temperature and the relative humidity of the air during the evaluation power generation mode used in development. As shown in these figures, a higher amount of water contained in the membrane and a lower temperature could be achieved compared to the previous system.

Acceleration of changes in the membrane over time due to Fe was addressed by coating the stainless steel base bipolar plates in the fuel cell stack with a double layer of titanium and carbon. This reduced the amount of Fe elution to 1/10 that of the previous system⁽¹⁰⁾.

These initiatives to increase the amount of water contained in the membrane, lower the temperature, and reduce the amount of Fe elution from the bipolar plates more than doubled the durability of the fuel cell stack compared to the previous system.

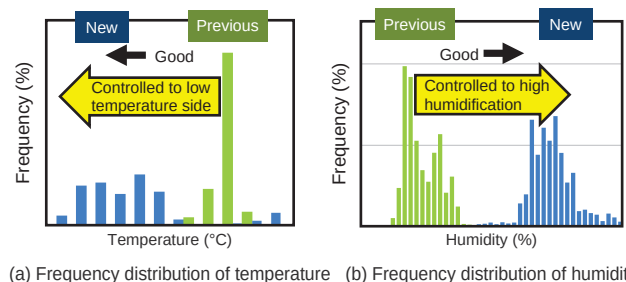


Fig. 8 Operating temperature and humidity

4. Shorter Start-up Time in Low-Temperature Environments

In low-temperature and especially sub-zero environments, the power generation performance of the fuel cell stack decreases for reasons such as lower activity of the catalyst used in the fuel cell stack, and there is the issue that the fuel cell system is unable to supply the power output needed for vehicle operation at some temperatures. Therefore, in addition to warming up the fuel cell system after start-up until it can supply the required power output like the previous system, a goal for the new system was to shorten the start-up time in anticipation of expanding use to a wide range of applications.

First, a rapid warm-up method was applied to actively warm up the fuel cell stack by using the power generation loss (heat generation) that can occur when the amount of air supplied to the fuel cell stack in power generation is reduced compared to that in regular power generation⁽¹³⁾. Figure 9 shows the mechanism of this increase in the amount of heat generated. The more current that flows through a fuel cell, the larger the resistance component, and thus the voltage decreases and the resistance component becomes

heat, as shown in Fig. 9(a). In addition, when the amount of air is decreased, the resistance component increases and the voltage decreases even at the same current value, and thus the heat generation increases commensurately with the increase in resistance, as shown in Fig. 9(b). Figure 9(c) expresses these relationships in terms of energy and power generation efficiency. Power generation energy is the product of the flowing current value and the voltage value at that time, and heat generation energy is the heat due to the resistance component as described above. By increasing the current value and decreasing the amount of supplied air, the voltage decreases and the power generation efficiency drops. The heat generation energy increases due to the drop in power generation efficiency, and thus the start-up time can be shortened by making use of this increase in heat generation.

From the above, the fuel cell system would generate power at a high current in sub-zero environments for warm-up. However, due to the balance between the amount of water produced by power generation and the temperature of the fuel cell stack, the produced water may freeze and hinder the supply of gas, resulting in the issue that power generation cannot be continued. Therefore, by taking advantage of the fact that the dried polymer electrolyte membrane can absorb the produced water, the total amount of water produced in the time until the fuel cell temperature exceeds the freezing point was set to the amount that can be contained by the membrane or less, which realized the continuation of power generation⁽¹⁴⁾. As described in Chapter 3, the membrane in the new system is in a high water content state during regular power generation, making it necessary to dry the membrane for it to absorb

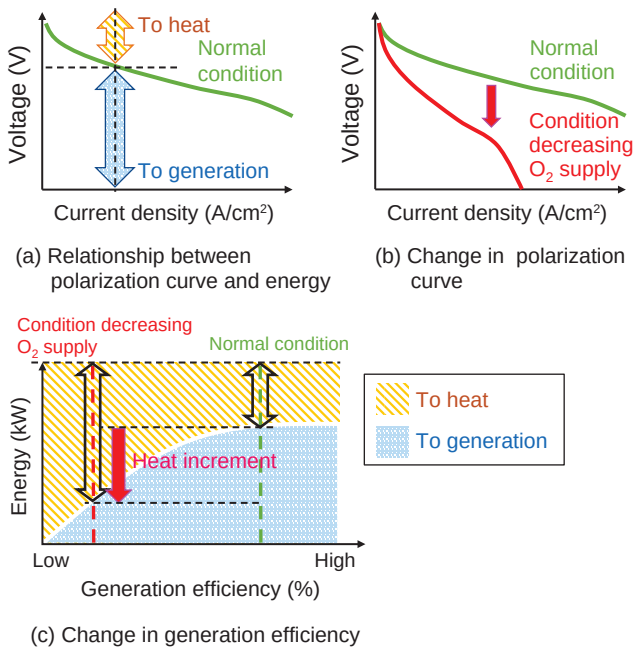


Fig. 9 Mechanism for heat increment

the produced water. However, excessive drying leads to changes in the membrane over time, and thus drying is performed while controlling the relative humidity by performing humidity conditioning with power generation in advance. As the fuel cell temperature can be raised by power generation, the humidity conditioning time can be shortened at the same time.

Application of the above rapid warm-up control and humidity conditioning control achieved shorter start-up time at low temperatures. Figure 10 shows the start-up time in the low-temperature environment of -20°C . The start-up time is shortened to approximately 1/9 that of the previous model.

In addition, as shown in Fig. 11, this humidity conditioning is not performed immediately after fuel cell system stop. After fuel cell system stop is complete, the system is cooled in accordance with the ambient temperature, and humidity conditioning is automatically performed at the timing when the system temperature approaches the freezing point. As described previously, the fuel cell temperature rises due to power generation during humidity conditioning, and thus the period until the fuel cell temperature becomes equal to the ambient temperature can be extended compared to the case without

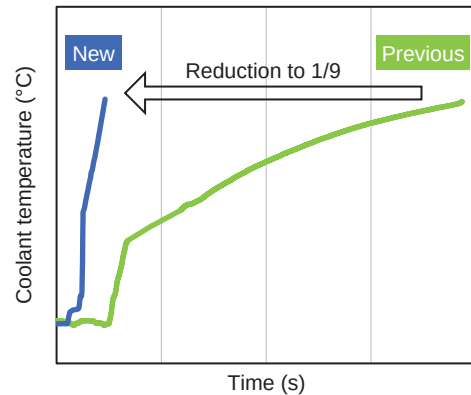


Fig. 10 Start-up time in low-temperature environment

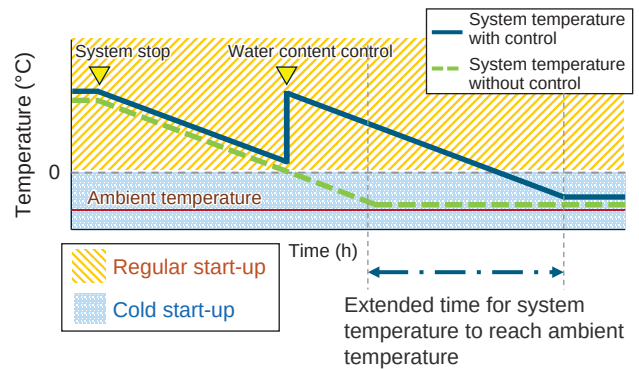


Fig. 11 Schematic diagram of system temperature changes

humidity conditioning. As a result, when performing start-up next under sub-zero ambient temperature conditions, the frequency of regular start-up can be increased in accordance with the amount by which the period that the fuel cell temperature is the freezing point or higher is extended. That is to say, the frequency of sub-zero start-up with a long warm-up time can be reduced.

5. Enhanced Productivity and Further Cost Reduction of Fuel Cell System

Cost reduction measures were implemented in various aspects of the fuel cell stack from materials to production while providing the same or better performance than the previous system⁽¹⁰⁾. The parts composition was reviewed in accordance with the cell-by-cell cooling structure, enabling a reduction in the number of parts from 5 parts/2 cells⁽¹⁵⁾ to 4 parts/2 cells. The surface coating of the bipolar plates was changed from gold plating to a double-layer coating of titanium and carbon. Regarding the seal structure between the bipolar plates of the fuel cell, in addition to the welded seal, a metal bead seal structure that combines metal bead and micro seals was newly developed, as shown in Fig. 12.

A 40% reduction in film thickness from conventional stacks was achieved by adopting novel, proprietary MEA coating processes and formulations⁽¹⁰⁾. In addition, equivalent performance is provided even with 80% less platinum in the MEA electrode parts compared with the previous stack⁽¹⁰⁾. Continuous production was achieved by fully automating fuel cell stack manufacture, as shown in Fig. 13⁽¹⁰⁾. This was realized with a joint venture plant of Honda and General Motors.

Figures 3(a) and 3(b) show the main auxiliary device configurations of the new and previous systems. As described in Chapter 3, the new fuel cell system achieved even greater stack durability by adopting an electric coolant mixing valve to control the humidification amount. This enabled a reduction in the number of auxiliary devices such as the hydrogen pump, EGR pump, reed valve, and

water vapor transfer unit bypass valve that were installed as measures to enhance stack durability in the previous system, leading to a reduction in system cost.

When considering expansion of use to various applications, as shown in Fig. 1, the previous hydrogen ventilation system required specially designed ventilation ducts for each application, as shown in Fig. 14(a). The new hydrogen ventilation structure shown in Fig. 14(b)⁽¹⁶⁾ is a forced ventilation system that constantly ventilates to achieve a safe concentration regardless of differences in installation conditions. This enabled a reduction in the number of specially designed parts and the construction of a system that is advantageous for multi-purpose deployment. Fewer parts also realized further cost reductions.

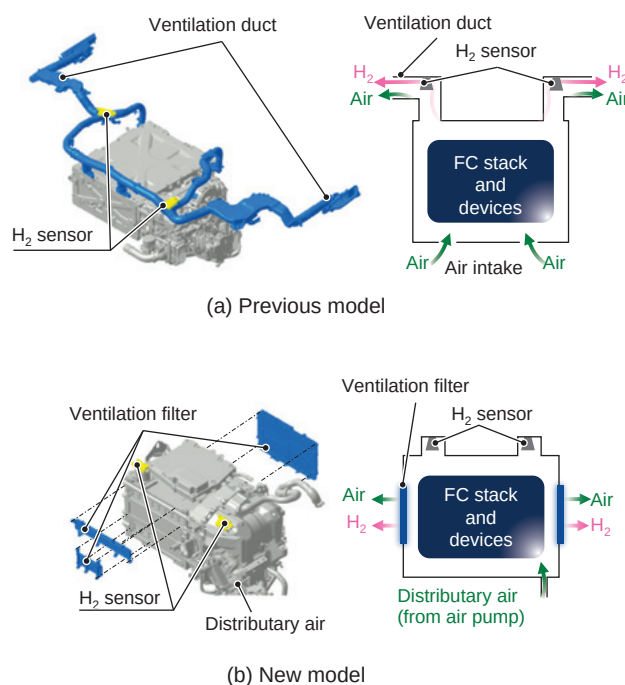


Fig. 14 Hydrogen ventilation systems

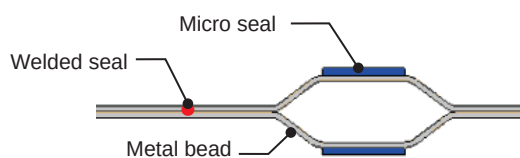


Fig. 12 New bipolar plate structure

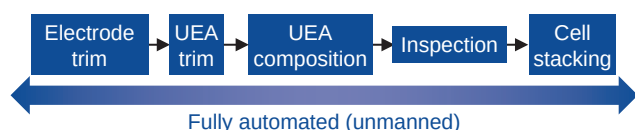


Fig. 13 Fuel cell stack manufacturing process

6. Conclusion

A fuel cell system that achieves enhanced durability and low-temperature environmental performance while reducing the cost was developed to realize deployment not only to passenger cars but also to various applications, with the goal of expanding adoption of fuel cell systems.

(1) Operating conditions with a lower temperature and higher humidification are used, the amount of humidification of the air input to the fuel cell is estimated onboard, and active control is performed with a water vapor transfer unit and a coolant mixing valve. In addition, coating the surface of the bipolar plates of the fuel cell with a double layer of titanium and carbon enabled a reduction in Fe elution to 1/10 the previous level. As a result, the

durability of the fuel cell achieved the target of double or more than the previous system.

- (2) Regarding start-up in low-temperature environments, the start-up time at -20°C was reduced to the target of 1/9 the previous time by combining rapid warm-up control that controls the amount of input air and control that conditions the humidity of the polymer electrolyte membrane in advance before start-up.
- (3) The number of parts comprising the fuel cell stack was reduced, a metal bead and micro seal structure was developed in addition to the welded seal of the bipolar plates, and the parts configuration was simplified. In addition, the amount of precious metals used was reduced and a new MEA manufacturing method and fuel cell assembly process were developed. Together with a simplified system configuration, the cost of the new fuel cell system achieved the target of 1/3 the previous system.

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