

Downsizing Technology for FC Cooling System Installation under Front Hood

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ABSTRACT

Technology for downsizing the fuel cell cooling system was developed in order to realize installation of the fuel cell power plant under the front hood of the CLARITY FUEL CELL. The fuel cell stack was downsized by accurately estimating the amount of corrosion current by using technology for predicting corrosion of the metal separator, decreasing the conductivity of the coolant, and removing the insulation rubber from the cell. For the fuel cell cooling device, the conductivity of the coolant was set within a range that would enable piping to be shorter and not necessitate the large-scale coolant pump used when a pressure drop increase occurred. In the fuel cell cooling system, the conductivity of the coolant was decreased within the range that would make a large contribution to downsizing the fuel cell stack and the fuel cell cooling device. In order to decrease the conductivity of the coolant, a fuel cell cooling system was built that would decrease ion dissolution from parts, inhibit degradation of the coolant, and constantly remove dissolved ions. These measures achieved a fuel cell cooling system that was downsized 20% over the previous model and succeeded in realizing the world's first five-passenger fuel cell vehicle in a sedan package.

1. Introduction

The CLARITY FUEL CELL, a new model fuel cell vehicle (FCV) introduced in 2016, was developed with the aim of achieving the first five-passenger FCV in the world to offer a sedan package identical to vehicles with an internal combustion engine (ICE). For that purpose, the fuel cell (FC) power plant was downsized from the 2009 model year (09MY) so that it could be relocated from under the floor to under the front hood⁽¹⁾ (Fig. 1). That advantage enabled realization of a five-passenger vehicle in the same way as ICE vehicles, and also eliminated the necessity



Fig. 1 Schematic drawing of FC power plant for new CLARITY FUEL CELL

for development of a dedicated FCV car body. Achieving this necessitated downsizing the FC power plant while enhancing the shock resistance to a level four times greater than in the 09MY. This was highly challenging in terms of technical difficulty⁽¹⁾.

This paper introduces the downsizing of the FC cooling system as one of the technologies applied in downsizing the 2016 model year (16MY) FC power plant.

2. FC Cooling System Downsizing Target and Issues

2.1. FC Cooling System Configuration

Figure 2 shows a diagram of the FC cooling system, including the FC stack installed in the CLARITY FUEL CELL.

The FC cooling system is made up of FC stack and FC cooling devices for radiating the heat generated in the FC stack to the outside.

2.1.1. FC stack

Figure 3 shows the configuration of the FC stack examined in this paper.

The FC stack shown in (a) was constructed with

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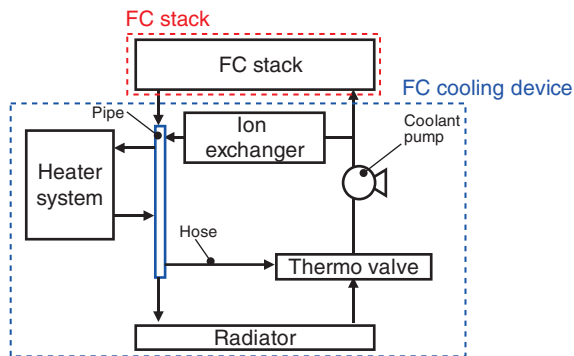


Fig. 2 Schematic diagram of FC cooling system

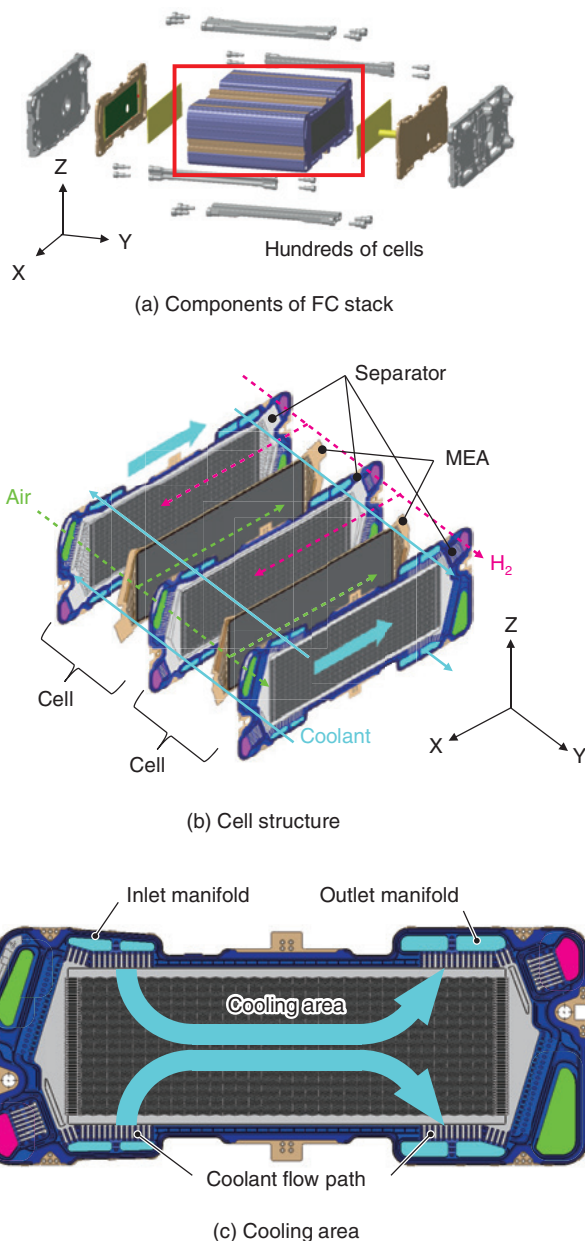


Fig. 3 Inside of FC stack, cell component, and cooling area

hundreds of cells stacked in layers in order to supply the electric power needed to assure the vehicle's dynamic performance. The cell structure shown in (b) has two membrane electrode assemblies (MEA) held in place by three metal separators⁽²⁾. A structure that has coolant flowing through every pair of cells was adopted.

The polymer electrolyte fuel cells adopted in the FCV form a system that uses electrolyte membranes to cause an electrochemical reaction between the hydrogen from the fuel and oxygen from the air, and converts the resulting chemical energy directly into electrical energy. The heat generated during the electrochemical reaction is exchanged with the coolant that is circulated in the cooling device by means of the metal separators and the heat is discharged. As shown in (c), the coolant passes from the coolant manifold on the inlet side through the coolant flow path, is supplied to the cooling area, then passes through the coolant flow path to the coolant manifold on the outlet side and is discharged.

2.1.2. FC cooling device

As shown in Fig. 2, the FC cooling device was configured with a coolant pump that circulates coolant, a radiator that radiates heat to the outside, and a thermo valve that switches the circuit between the radiator and a radiator bypass circuit. An ion exchanger has been adopted from before to help assure electrical safety in the vehicle and help prevent corrosion of the FC stack by removing ions that are in the coolant. It is a device that is widely adopted in fuel cell cooling systems. The exhaust heat recovery circuit is installed for the purpose of raising fuel economy at lower temperatures by recovering heat from the FC stack through the coolant and supplying it to the heater system circuit.

2.2. Target and Means of Accomplishment of FC Cooling System Downsizing

In order to make it possible to install the FC power plant under the front hood, the aim of making the FC power plant volume the same as that of a V6 engine was adopted⁽¹⁾. Therefore the work of downsizing the FC cooling system was examined in terms of approach both from structure and from function. The aim of decreasing the volume of the FC stack by 20 percentage points from the 09MY by revising the coolant flow path structure while maintaining the functionality of the FC cooling system was adopted.

The FC stack is made up of hundreds of cells. Decreasing the cell thickness contributes greatly to downsizing. Therefore, attention was focused on removing the rubber insulation covering that is a component of cell thickness.

Figure 4 shows the coolant flow path structure in the 09MY and 16MY FC stack. A front view of the 09MY and 16MY cooling area is shown first. The change in the height of the cooling flow structure and the change in the coolant flow path distance from the manifold due to the rubber insulation covering are shown next.

The 09MY coolant flow path was built to help prevent

corrosion of the metal separator by covering the left and right sides and top and bottom of the coolant flow path with insulation rubber. The structure of the 16MY coolant flow path, by contrast, has reduced the insulation rubber placed on the top and bottom. The height h_{16MY} of the coolant flow path was also set to be the same as the height h_{09MY} . As a result, cell thickness has been decreased by two layers of rubber covering without increasing the pressure drop in the coolant flow path.

With regard to cell area, too, the length l_{16MY} from the manifold to the metal surface that is covered by insulation rubber in 16MY is shorter than the length l_{09MY} in 09MY. This reduced the cell area.

These revisions of structure realized a 20% downsizing of the FC stack volume.

2.3. FC Cooling System Function

Table 1 shows the three functions demanded of the FC cooling system together with parameters influencing those functions and the issues involved in downsizing.

FC stack cooling performance is determined by the coolant flow rate into the FC stack and radiator and by the amount of heat radiated to the outside, which is determined by the heat exchange efficiency of the various parts. When downsizing measures are taken with the coolant pump and radiator, the coolant flow rate and the amount of heat

Table 1 Three functions for FC cooling system

Function	Parameters	Issues of downsizing
Stack cooling	• Coolant flow • Heat exchanger rate	Decrease in cooling performance
Insulation	• Insulation resistance • Coolant conductivity	Decrease in insulation resistance
Corrosion resistance	• Cell thickness • Insulation distance • Coolant conductivity	Increase in metal corrosion

radiated to the outside are reduced, which lowers cooling performance. Therefore it was decided not to implement downsizing at the component level, but rather to achieve it by shortening the piping length.

The FC cooling system needs to have insulating properties that maintain the electrical safety of the vehicle. These depend on the length of the piping that connects the FC stack and the ground and on the conductivity of the coolant. As noted above, downsizing shortens the piping length and this lowers the insulation resistance value. In order to assure the needed insulation resistance value, therefore, the coolant conductivity has to be made still lower than in the previous model.

The oxidation-reduction reaction that occurs in the coolant flow path on the metal separator, shown in Fig.

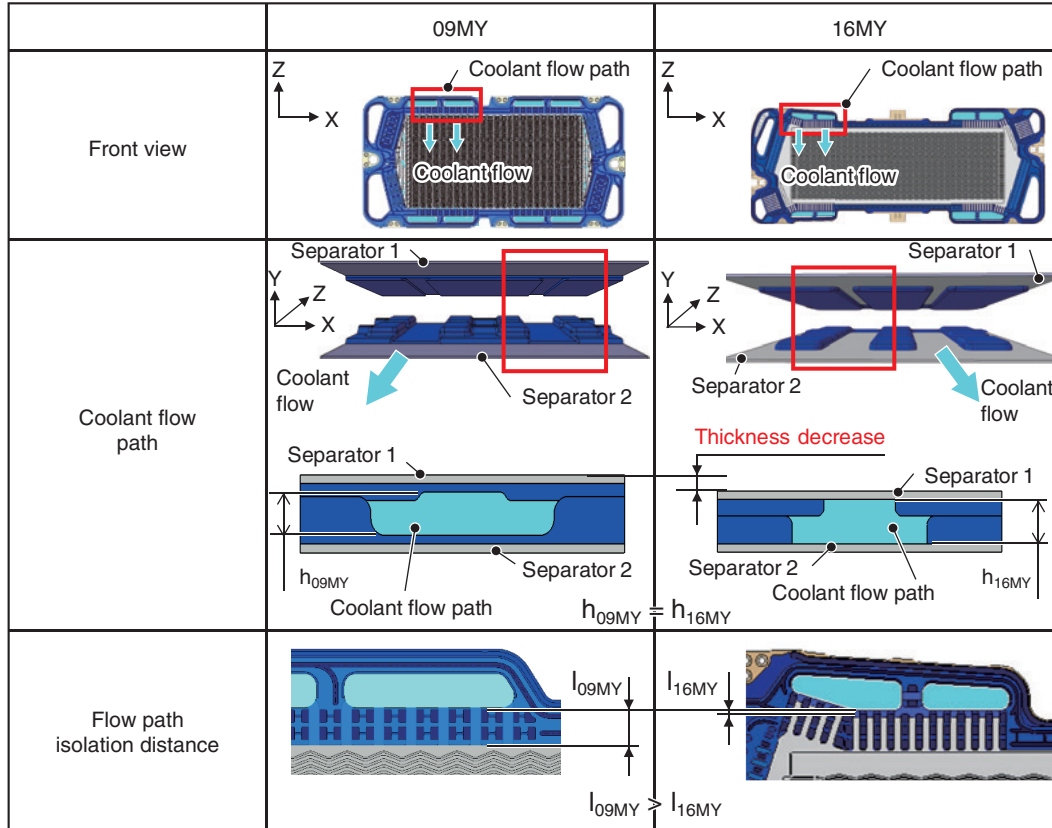


Fig. 4 Detail of coolant flow path

5(a), causes corrosion of the metal separator. The corrosion resistance of the FC separator inhibits that corrosion, and this is needed to maintain the strength of the separator.

The coolant flow path, shown in Fig. 3(c), contains coolant, which is an electrical conductor. It is, therefore, not possible to help prevent the formation of a circuit by structural means.

As shown in Fig. 5(b), corrosion of the metal separator occurs where there are exposed stainless steel portions along the coolant flow path. The main reaction is to cause dissolution of steel, which is the principal component of stainless steel, on the high potential side (1), while hydrogen is generated by the oxidation-reduction reaction on the low potential side (2).

Reaction formula on high potential side: $\text{Fe} \rightarrow \text{Fe}^{2+} + 2\text{e}^-$ (1)

Reaction formula on low potential side: $2\text{H}^+ + 2\text{e}^- \rightarrow \text{H}_2$ (2)

As dissolution occurs in the stainless steel material in the coolant flow path, the strength of the material is diminished so that deformation may occur due to the pressure differential and pitting corrosion may occur.

When cell thickness and insulation distance are decreased for the purpose of downsizing the FC cooling system, the electrical resistance in each part is reduced so

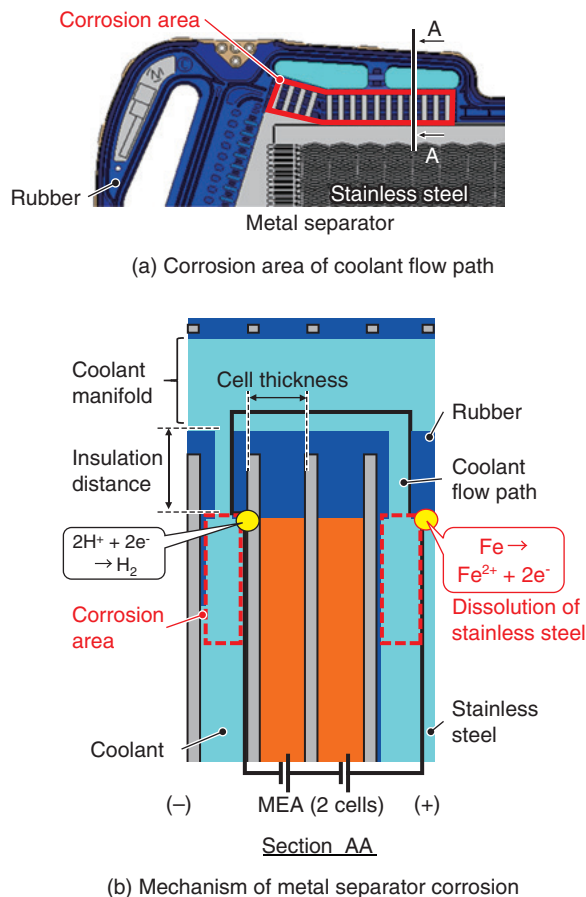


Fig. 5 Outline of metal corrosion

that the amount of corrosion current flowing in the coolant flow path is increased. This accelerates corrosion of the metal separator. Lowering the coolant conductivity would be useful for realizing downsizing and effective corrosion resistance in the metal separator.

Figure 6 shows an equivalent circuit diagram that was considered for the purpose of accurately calculating the amount of corrosion current in this FC stack.

The current flowing in the coolant manifold is designated I_A , the current flowing in the coolant flow path I_B , the resistance of the coolant manifold R_A , and the resistance of the coolant flow path R_B .

This equivalent circuit was used to calculate the largest corrosion current, $I_{B(n+1)}$ ⁽³⁾. Figures 7, 8, and 9 show the cell thickness ratio, insulation distance ratio, and coolant conductivity ratio on the horizontal axis, and the corrosion current ratio on the vertical axis, to show the influence of the former on the latter when 09MY is taken as 100%. Figure 7 indicates that when the cell thickness that is subject to downsizing in the Y direction, shown in Figs. 3 and 4, is decreased 20 points, the resistance R_A becomes smaller so that the corrosion current $I_{B(n+1)}$ increases 14 points. Figure 8 indicates that when the insulation rubber is removed so that downsizing can take place in the Z direction shown in Figs. 3 and 4, and the insulation distance is decreased 79 points, then the amount of corrosion current will increase 113 points. The increase in the corrosion current is brought about by these decreases in cell thickness and insulation distance. The influence of the number of layers in the FC

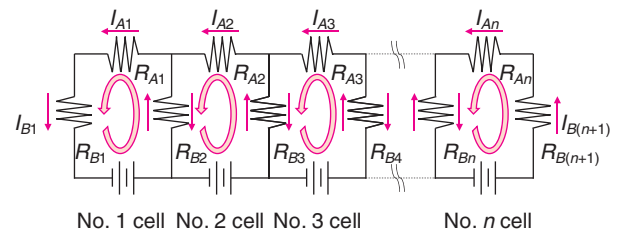


Fig. 6 FC stack circuit diagram

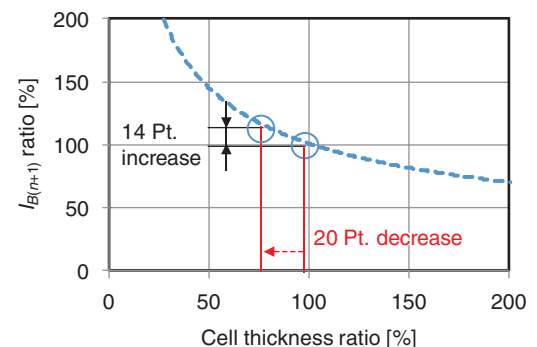


Fig. 7 Influence of cell thickness ratio on $I_{B(n+1)}$ ratio

stack, the sectional area of the coolant manifold, and the operating environment also cause the amount of corrosion current to increase. In order to bring about these decreases, it will be effective, as shown in Fig. 9, to lower the conductivity of the coolant, which contributes greatly to the corrosion current. Therefore the 16MY target was set as a reduction of 59 points in coolant conductivity ratio relative to the 09MY where the corrosion current was increased by the decrease in cell thickness and insulation distance, and a reduction of 37 points in coolant conductivity ratio relative

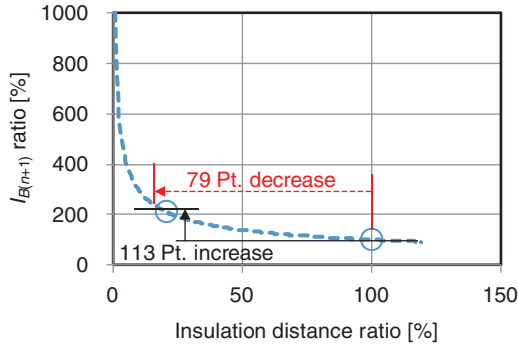


Fig. 8 Influence of insulation distance ratio on $I_{B(n+1)}$ ratio

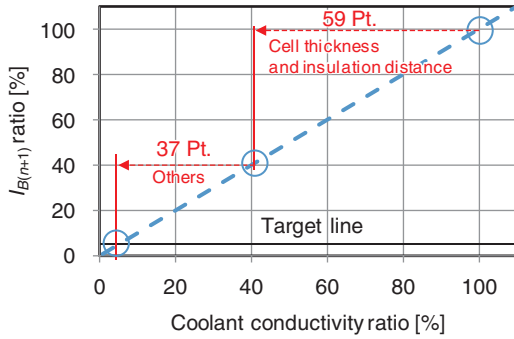


Fig. 9 Influence of coolant conductivity ratio on $I_{B(n+1)}$ ratio

to the 09MY in order to reduce the other amount of increase in the corrosion current.

It was ascertained from the above that the conductivity of the coolant, which influences the volume of the FC stack and the FC cooling device, is a crucial parameter for the purpose of meeting the functional requirement from the FC cooling system. Figure 10 shows the coolant conductivity ratio with respect to 09MY on the horizontal axis while the vertical axis on part (a) has the FC cooling device volume ratio and the vertical axis on part (b) has the FC stack volume ratio. The 09MY is taken as 100% for both the horizontal and vertical axes, and graphs express the contribution that the decrease in coolant conductivity makes to the downsizing of the FC cooling device and FC stack.

As shown by range (1) in Fig. 10(a) for the FC cooling device, when the conductivity ratio is reduced from 100%, the insulation resistance value increases so that the piping length can be shortened, and the volume decreases at a gentle rate. In order to construct an FC cooling system with a coolant conductivity ratio of less than 4% as shown in range (2), it is necessary to place an ion exchanger at the FC stack inlet to remove the ions in the coolant immediately before it flows in. However, placing an ion exchanger at that location causes the pressure drop to increase so that a large coolant pump becomes necessary and, as shown in range (2), the volume of the FC cooling device increases.

Similarly with the FC stack, as shown in range (3) of Fig. 10(b), when the coolant conductivity ratio is reduced from 100% to 4%, the insulation resistance value of the parts where cell thickness and insulation distance are major factors can be decreased. This means that the amount covered by insulation rubber can be reduced and the volume of the FC stack becomes smaller. In range (4), where the coolant conductivity ratio is 4% or less, only the corrosion of the metal separator is decreased and the contribution to downsizing is slight.

Therefore it was decided to achieve the downsizing target for the FC cooling system by setting the coolant conductivity within the range where the contribution to downsizing would be greater.

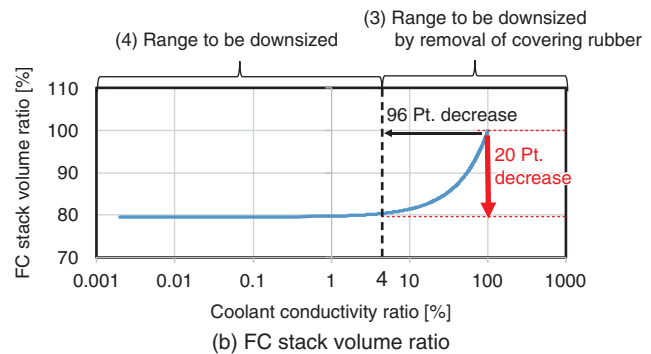
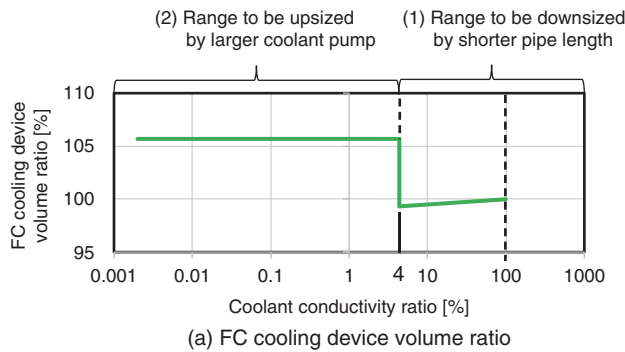


Fig. 10 Volume ratios of FC cooling device

3. Construction of an FC Cooling System with Low Conductivity

The main cause of ion dissolution in coolant is from cooling system parts and heater system parts and generation of ions by degradation of the coolant. Even if measures were taken to decrease the amount of ion dissolution, the dissolution of ions from parts and the generation of ions by degradation of the coolant would occur constantly. In order to maintain the low conductivity of coolant in the FC cooling system, therefore, it will be necessary to address two issues simultaneously.

- (1) Decrease ion dissolution from parts and limit the degradation of coolant
- (2) Build the FC cooling system to constantly remove dissolved ions

3.1. Limit Ion Dissolution Amount

Measures to limit the ion dissolution amount from parts used in the FC cooling circuit were already being implemented in 09MY. The methods are shown in Table 2. Manufacturing methods that involves less ion dissolution were adopted for the radiator. Materials that are subject to less ion dissolution were selected and adopted for the piping and other resin parts and rubber hose. For the coolant, oxidation inhibitor was added in order to limit ion dissolution caused by thermal decomposition.

In contradistinction to the 09MY, the 16MY added a system to take waste heat from the FC stack and make effective use of it for heating. Measures to reduce conductivity thus also became needed for heater system parts. The methods used are shown in Table 3. Here, in contradistinction to ICE specification vehicles, the heater core has low ion dissolution measures taken by means of manufacturing methods while materials that experience less ion dissolution were selected for the piping and other resin parts and rubber hose and adopted as in those other FC cooling parts.

By means of these measures, items that are subject to ion dissolution were successfully reduced by 75 points in the 16MY relative to cases where heater system parts from ICE specification vehicles were adopted. The ion dissolution amount for the FC cooling system as a whole was held down to the same level as the 09MY (Fig. 11).

3.2. Constant Removal of Dissolved Ion Material

When only the measures described above for limiting dissolved ion material are used, maintaining conductivity at a low level is no simple matter. This is particularly the case when a vehicle is left unused for a long time, since dissolved ions build up inside every part. Then when the vehicle is started, coolant with a temporarily high conductivity flows into the FC stack. The necessity to remove ions promptly and lower the conductivity still remains even in such cases. A bypass system configured to keep the coolant constantly flowing through an ion exchanger was adopted as the means

Table 2 Electric conductivity reduction method of FC coolant system

Parts	Method
FC radiator	Adopt flux reduction
Resin parts	Adopt low ion dissolution material
Hose	Adopt low ion dissolution material
Coolant	Add oxidation inhibitor

Table 3 Electric conductivity reduction method for heater system parts

Parts	Method
Heater core	Adopt flux reduction
Resin parts	Adopt low ion dissolution material
Hose	Adopt low ion dissolution material

for accomplishing this aim.

When an ion exchanger is arranged in series with the FC stack, the pressure drop increases in the system as a whole. However, when the ion exchanger is arranged in parallel with the FC stack, as shown in Fig. 2, the pressure drop is reduced so that a smaller coolant pump can be selected. This approach successfully decreased the coolant pump volume by 40 points.

One advantage of configuring a system for constant ion removal is that when the vehicle is warming up, the ions

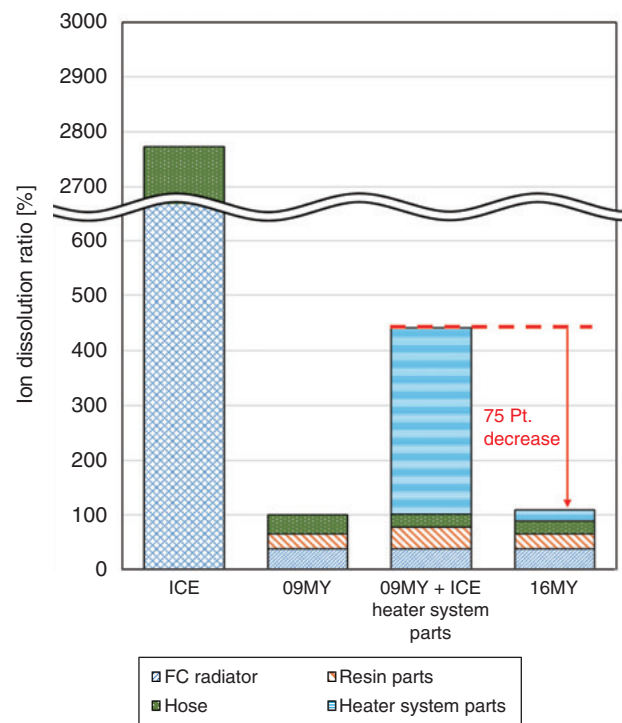


Fig. 11 Ion dissolution ratio in FC cooling system

already inside the radiator bypass circuit can be removed. This means that even if there is an inflow of ions from the radiator circuit after warming up, that inflow can be mixed in so that the range of the increase will be limited.

3.3. Performance in Maintaining Low Conductivity

Figure 12 shows how the FC cooling system incorporating the measures described above performs in maintaining low conductivity. Even in cases where the conductivity rises temporarily, the system quickly restores the lower conductivity again and can maintain that state.

During warming up (Fig. 13), the dissolved ion material that has built up inside the radiator bypass circuit flows into the system immediately after the vehicle is started. This causes the conductivity to rise temporarily. However, the conductivity can be lowered quickly because the coolant is kept constantly flowing to the ion exchanger, and that lower level can be maintained.

After warming up (Fig. 13), the dissolved ion material that has built up inside the radiator circuit flows into the system so that the conductivity rises again. Since the dissolved ion material is constantly removed after that, low conductivity is quickly restored and that lower level can be maintained.

The system is configured to switch between the radiator

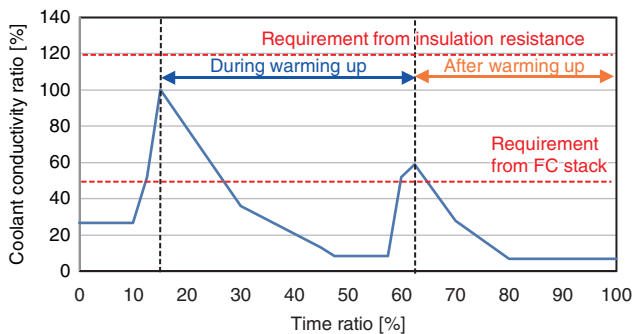


Fig. 12 Performance of keeping low coolant conductivity

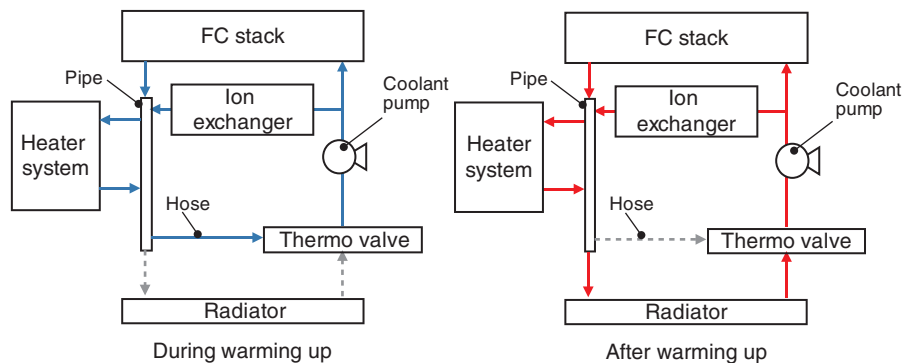


Fig. 13 Diagram of FC cooling system

bypass circuit and the radiator circuit by a thermo valve when the vehicle is warming up and after it has finished warming up. Therefore the dissolved ion material inside the radiator bypass circuit can be removed before the vehicle finishes warming up. Consequently, even if dissolved ion material flows into the system from the radiator circuit after warming up is finished, that material mixes with the coolant, which has a low level of dissolved ion material, so that the range of the increase in conductivity can be limited.

4. Conclusion

- (1) Technology for predicting corrosion of the metal separator was used to accurately estimate the amount of corrosion current and the FC stack was downsized by lowering the conductivity of the coolant and removing insulation rubber from the cells.
- (2) Downsizing of the FC cooling device was achieved by shortening the length of pipes and by setting the coolant conductivity within the range where the pressure drop increase does not necessitate use of a larger coolant pump.
- (3) An FC cooling system was developed to decrease the conductivity of the coolant within the range that would make a large contribution in downsizing the above FC stack and FC cooling device, to decrease ion dissolution from parts, to inhibit degradation of the coolant, and to constantly remove dissolved ions.

The above measures achieved downsizing of the CLARITY FUEL CELL FC cooling system by 20% over the previous model. This made it possible to install the FC power plant under the front hood and thereby to realize the world's first five-passenger FCV in a sedan package.

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