Toyota MIRAI Fuel Cell Vehicle and Progress Toward a Future Hydrogen Society

by Toshihiko Yoshida and Koichi Kojima

In anticipation of the diversification of primary energy resources such as oil, natural gas, coal, electricity, and renewable resources, Toyota launched the Prius Hybrid vehicle in 1997 and has also made available Electric Vehicle (EV) and Plug-in Hybrid Vehicle (PHV) versions to improve fuel consumption efficiency and reduce exhaust gas emissions as compared to conventional combustion-engine vehicles. Moreover, Toyota has developed a Fuel Cell Vehicle (FCV) and regards a sustainable society as the future energy scenario. In such a scenario, the energy supply relies not only on fossil fuels, but also on environment-friendly renewable resources. Electricity and hydrogen are used as energy carriers in a common idealized infrastructure in the sustainable society, as shown in Fig. 1. Toyota believes hydrogen will be a leading energy carrier and has just started sales of the MIRAI FCV, introduced with an affordable price (approximately 7 million Japanese yen or $57,500), in December 2014.

Toyota's FCV development started in 1992, with the Fuel Cell Hybrid Vehicle (FCHV), which was first leased in 2002. Three big technical issues were addressed over several years: the cruising range was increased to more than 500 km, cold start was enabled from −30 °C, and refueling times were lowered to about 3 minutes.[1] This led to the FCHV-adv being leased in 2008, with around 100 cars tested worldwide. A FC bus was developed with Hino Motor Ltd, with field-testing beginning with a Tokyo city route bus in 2003 and subsequent demonstration tests conducted on many routes in Japan. Toyota made use of the customers' experiences of the FCHV-adv and the FC bus to help guide the design of the MIRAI FCV. The MIRAI retains FCHV-adv's excellent qualities of zero emissions, large cruising range, cold start, and short refueling time, with further improvements towards quiet operation and better acceleration. A power supply function is also added for emergency use. Currently, overcoming the cost hurdle to bring FCVs to commercial reality is of paramount importance. This paper presents new technologies introduced to reduce cost and improve performance as steady progress is made towards a hydrogen society.

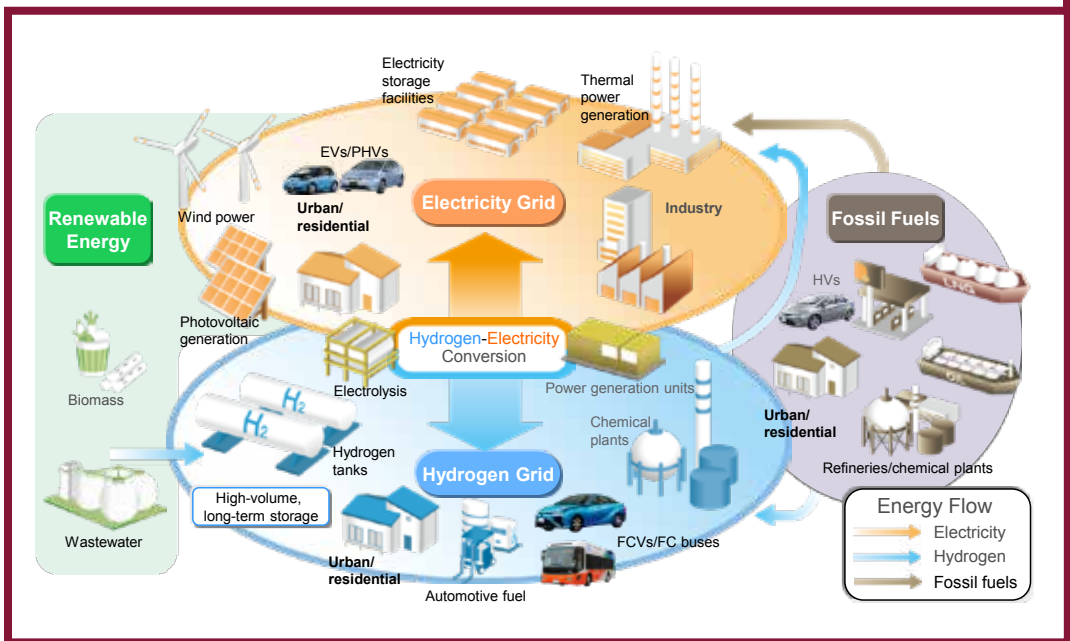

Fig. 1. *Sustainable society, a society that uses diverse energy sources, with electricity and hydrogen infrastructures.*

A New Concept in Flow Field Structure

A conventional flow field is made up of a rib and channel architecture. The rib contacts against and presses into the gas diffusion layer (GDL) on the membrane electrode assembly (MEA) to reduce contact resistance. However, the rib partially covers the GDL and the resultant gas-transport distance become longer than the inter-channel distance. Thus, the width of the rib results in lower V-I performance.[2] The contact pressure between the GDL and the rib also compresses the GDL, making its thickness non-uniform across the rib and channel. This thinner portion of the GDL experiences higher water saturation.[3,4] As a result, the product water remains in the GDL at the rib position. Consequently, oxygen transport is compromised, leading to non-uniform power generation in the FC. Using sintered metal foam as the flow field alleviates the above issues. The contact width with the GDL is now small enough not to impede gas transportation significantly. The product water in the GDL is adsorbed by the hydrophilic metal foam, thus homogenizing the oxygen transport and resulting in power being generated uniformly, with an anticipated higher power output. At the same time however, the metal foam flow field causes a higher pressure drop, retains water, and the material quality distribution results in a higher cost.

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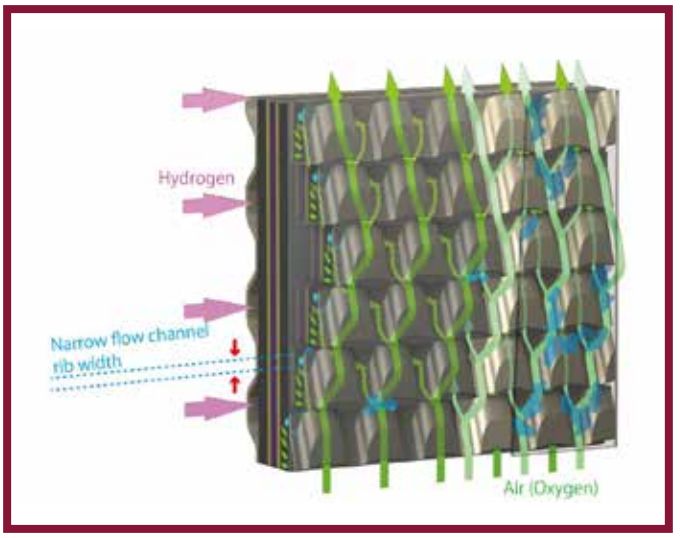


Fig. 2. *MIRAI cell and 3-D fine mesh flow filed.*

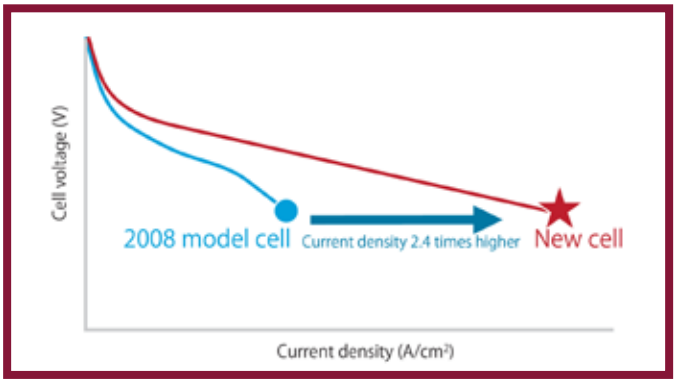


Fig. 3. *Current-Voltage curve of 2008 model and MIRAI.*

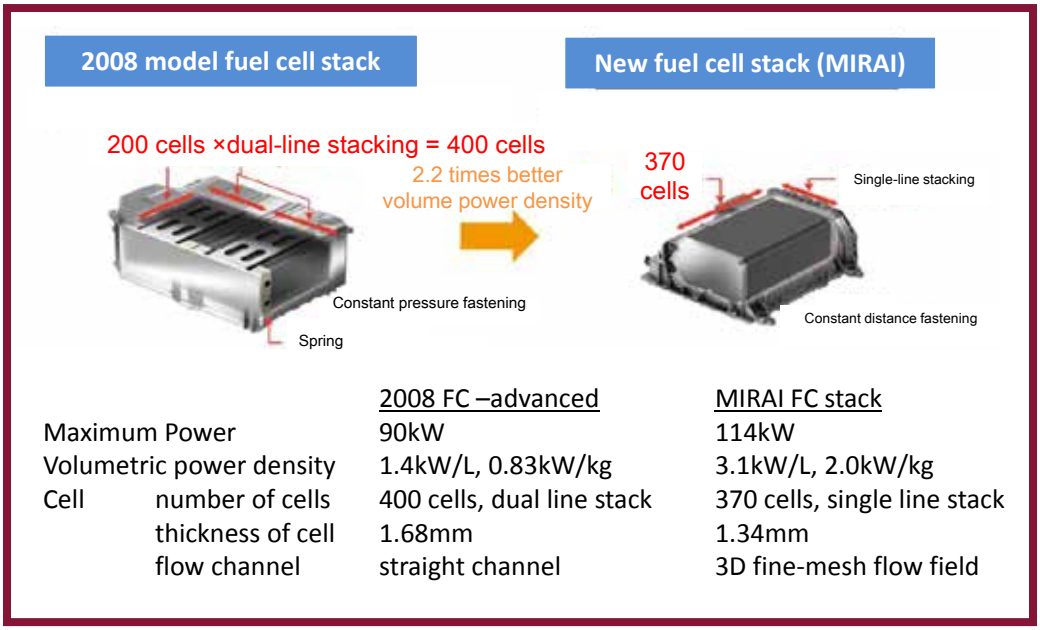
A 3-D fine mesh flow field (shown in Fig. 2) was developed to overcome these issues and this architecture achieves higher V-I behavior and power stability. The metal plate is manufactured in a steric conformation (three-dimensional structure) so as to promote airflow towards the GDL and gas transport to the cathode catalyst layer. Flow-field structures on both sides are optimized and treated to render them hydrophilic. The generated water is quickly drawn out through the flow field, preventing accumulation within the pores. Thus, power generation from this flow field is uniform across the cross-section. The novel flow-field structure provides added pathways for gas flow. The flow-field structure is designed to decrease airflow toward the GDL near the air inlet, and cathode drying is mitigated by the removal of the system humidifier.

A New Catalyst Layer, Separator, and Stack

The oxygen reduction reaction activity in the MIRAI has been enhanced by a factor of 1.8 over the 2008 FCV model via optimization of the composition of the PtCo catalyst. In the previous generation of FCVs, the conventional hollow carbon support did not allow for full utilization of the Pt, as the Pt was often located inside the support pores. Herein, the hollow carbon support was replaced with a solid-core type support, and Pt utilization was thereby improved.

The 3-D fine mesh flow-field, new PtCo catalyst, and a reduction in membrane thickness lowered gas transport, activation, and electronic resistances, respectively, resulting in dramatic improvements in performance. The current density of the MIRAI fuel cell is 2.4 times larger compared to the 2008 model, as shown in Fig. 3. This improvement enabled downsizing of the cell and less usage of expensive materials, resulting in significant cost reduction.

In addition, the original stainless steel, SUS316L, that had been used in the 2008 model as the separator was replaced with titanium. This resulted in a lower amount of metal ion-impurities dissolving from the separator plates and interfering with the performance of the proton exchange membrane (PEM) in the FC stack. This development also removed the need for the gold coating on the plates (required with steel to provide a corrosion-resistant surface and to provide an electrically conductive contact). To reduce the corrosion of Ti and to avoid formation of its highly electrically resistive oxide layer, a carbon coating, π-Conjugated Amorphous Carbon (PAC), was applied. The change from stainless steel to Ti resulted in cost reductions and increased durability. Figure 4 shows the stack configuration and performance. In addition to the above aspects, the stack fastening method was also changed from a constant-pressure fastening that



		2008 FC –advanced	MIRAI FC stack
Maximum Power		90kW	114kW
Volumetric power density		1.4kW/L, 0.83kW/kg	3.1kW/L, 2.0kW/kg
Cell	number of cells	400 cells, dual line stack	370 cells, single line stack
	thickness of cell	1.68mm	1.34mm
	flow channel	straight channel	3D fine-mesh flow field

Fig. 4. *Stacks performance of 2008 model and MIRAI.*

was applied using a spring in the 2008 model to a constant-distance fastening in the MIRAI, to further reduce cost. Such accumulated improvements have made the stack more compact and yielded a volumetric power density of 3.1 kW/L.

The Hydrogen Tank

Carbon fiber accounts for a large portion of a high-pressure hydrogen tank and so a reduction the tank unit price through improved usage of carbon fiber is essential. Expensive high-grade carbon fiber, airplane grade, was adopted in the 2008 model. To reduce cost, the manufacturer has committed to reinforcing the less expensive general-purpose carbon-fiber strength in order to move it closer to airplane grade performance. Figure 5 shows the tank structure and the carbon fiber reinforced plastic (CFRP) winding method. The high-pressure hydrogen tank is made up of a plastic liner, CFRP from the inner to the outer layer, and bosses at the two ends. The plastic liner and innermost layer encapsulate hydrogen gas, and the CFRP inner layer bears the high pressure of 70 MPa. Three kinds of CFRP winding configuration were used in combination: low-angle helical winding is principally applied to the dome section, high-angle helical winding to the boundary section, and hoop winding to the cylindrical section. CFRP was partially wound in a portion of the dome section using a high-angle helical configuration, however, this configuration bore only 1/6th of the stress compared to the boundary section and accounted for 25% of the total amount of CFRP in the 2008 model tank.

In the MIRAI, the tank is newly designed to remove the high-angle helical winding in the boundary section by revising the liner structure in terms of flattening the rounded portion of the boundary section, along with winding the CFRP in a higher-strength hoop configuration. This revision achieved a total reduction of 20% in the amount of CFRP in the tank of the MIRAI, which allowed a hydrogen storage capacity of 5.7 wt-% (hydrogen weight/total weight of tank system). Along with the above development, system control optimization allowed for a hydrogen-fuel-consumption improvement of 20% and a concomitant reduction in the number of tanks from four tanks in the 2008 model to two distinct dimensional tanks in the MIRAI; this ensured that the hydrogen storage tanks did not impact cabin space in the MIRAI sedan.

Streamlining of the FC System

The FC system was streamlined to reduce cost. The humidifier was removed in the MIRAI system as shown in Fig. 6. The retention of an adequate amount of water is required for membrane hydration and good FC performance. The humidifier exchanges the humidity of the inlet air with that of the exhaust. It was thought that the removal of the humidifier would result in dry air and a dehydrated membrane, thus reducing FC performance and deteriorating the membrane's mechanical properties.[5-7] To alleviate this scenario, a design with internal humidification was implemented using a counter flow cell, where the wet gas at the end of the air flow field humidified the dry gas at the inlet to the hydrogen flow field via water transport across the membrane. The humidified hydrogen stream transported the water across the cell, where excess water was again transported through the membrane to humidify the dry air inlet. To realize internal humidification, a 1/3rd thinner membrane relative to the 2008 model was employed to facilitate the diffusion of water. Moreover, the hydrogen gas flow rate was increased, and cooling water was used to lower the temperature at the entrance of the air flow field (making humidification easier).

Leveraging Mass-Produced Parts

While the initial FCV sales are not sufficiently large to reduce the cost of the FCV through mass-production, HV system parts, on the other hand, are already mass produced. Thus, utilization of these parts should be attractive for FCV cost reduction. The Toyota HV system

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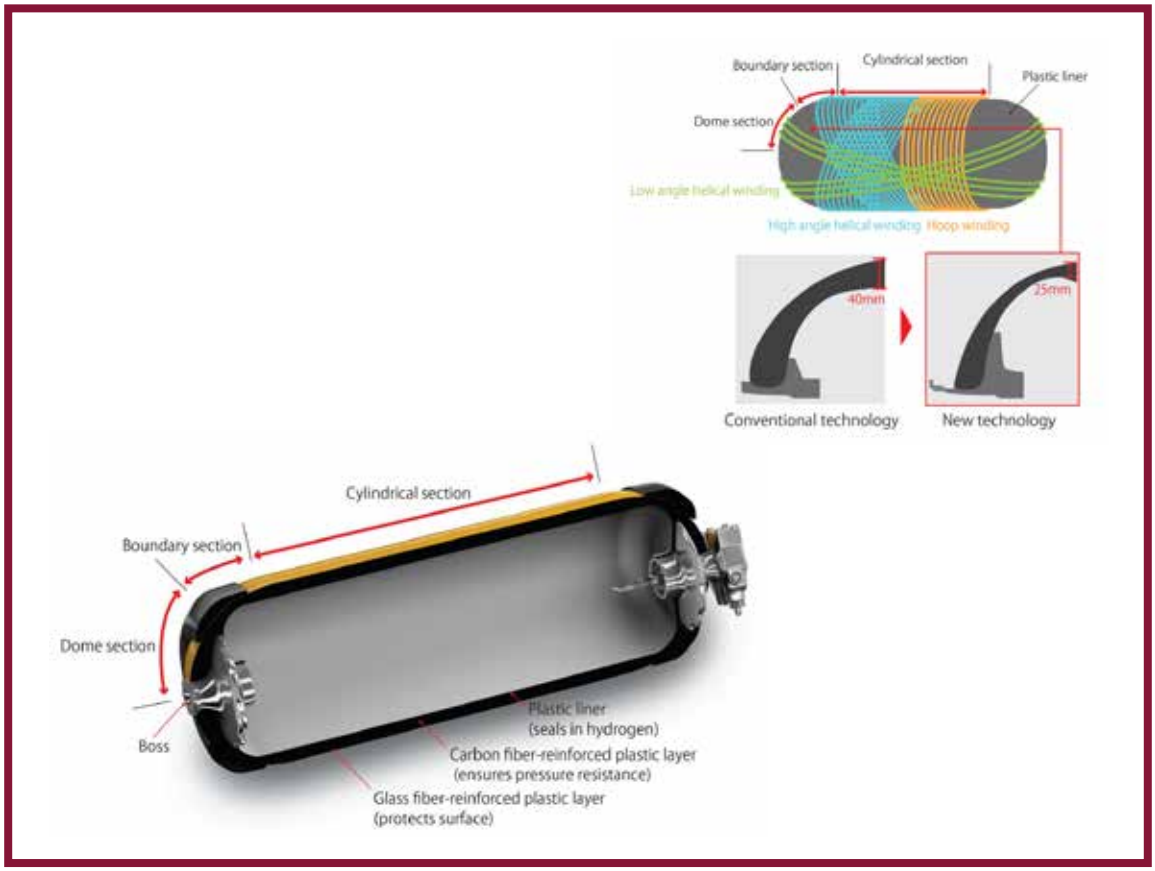

Fig. 5. *Tank structure and CFRP winding method.*

uses a maximum voltage of 650 V, and only becomes applicable to the FCV system on the condition that the FC voltage is boosted to the HV system voltage. Thus, a DC-DC boost converter was newly installed in the MIRAI instead of the direct connection between the motor inverter and FC stack in the 2008 model. This modification now allows mass-produced HV parts to be leveraged in the MIRAI FCV.

Future FCV Technologies and Infrastructure

Even with the above improvements and cost reductions, the MIRAI price is still higher than that of a typical family car; further cost reduction is required for widespread adoption of the FCV. An improved PtCo/C catalyst is applied in the MIRAI, but the amount of Pt in the catalyst is still not low enough. Higher specific activity (SA) and lower electrochemical surface area (ECSA) or higher Pt utilization in the catalyst with roughly equal ECSA and SA compared to existing catalysts are being explored, for example, using Pt nano-frame and core-shell catalysts, respectively.[8,9] Modeling and simulation are expected to improve the associated issues.[10-12] At the same time, non-noble metal catalysts, oxide catalysts, and carbon alloys are being actively researched.[13,14] The Pt loading in the anode catalyst layer is also expected to be reduced after Pt reduction is realized at the cathode. For the perfluorinated membrane and the GDL, the chemistry and processes for manufacturing are nearly fixed, and cost reductions will come with scale.

FC durability has been and will be mitigated by operational optimization. For example, the Pt dissolution that causes the ECSA reduction is minimized through the use of current operation with slow sweep rates and upper and lower voltage limits.[15,16]

Technology for efficient exhaust heat management is still required. The PEMFC is usually operated at around 60 to 80 °C, whereas the conventional ICE vehicle is operated at around 110 °C. This smaller temperature gap between the FC and the ambient air requires a bigger radiator size when the FCV is driven at maximum power. High-temperature operation would increase the rate of heat rejection from the radiator, and so high-temperature operation is a candidate among many solutions to keep radiator size low. Technologies to reduce exhaust heat have not yet received much attention.

In terms of infrastructure, it is imperative to establish and operate hydrogen-fueling stations through the initial market introduction period of the FCV. To help with this aspect, not only have governments made plans to subsidize the establishment and operation of these fueling stations, but also Toyota, Nissan, and Honda have announced partial financial support for the operation of hydrogen stations in Japan.

Toward a Hydrogen Society

Toyota has announced the royalty-free use of approximately 5,680 fuel cell related patents until the end of 2020, including critical technologies developed for the new Toyota MIRAI[17]. Bob Carter, Senior Vice President of Automotive Operations at Toyota Motor Sales, USA Inc., has summarized this initiative, "The first generation hydrogen fuel cell vehicles, launched between 2015 and 2020, will be critical, requiring a concerted effort and unconventional collaboration between automakers, government regulators, academia, and energy providers. By eliminating traditional corporate boundaries, we can speed the development of new technologies and move into the future of mobility more quickly, effectively, and economically."

Such a collaborative approach will certainly hasten the commercialization of FCVs across the world.

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About the Authors

Toshihiko Yoshida is a Project General Manager in the Fuel Cell System Engineering & Development Division, R&D Group at Toyota Motor Corporation and holds Bachelors and Doctorate Degrees in Chemical Engineering from Waseda University, Tokyo, Japan. He has investigated Photo Galvanic Cells, Amorphous Silicon Solar Cells, and Solid Oxide Fuel Cells. He was a principal investigator on a National Project on SOFCs for five years. He has led the

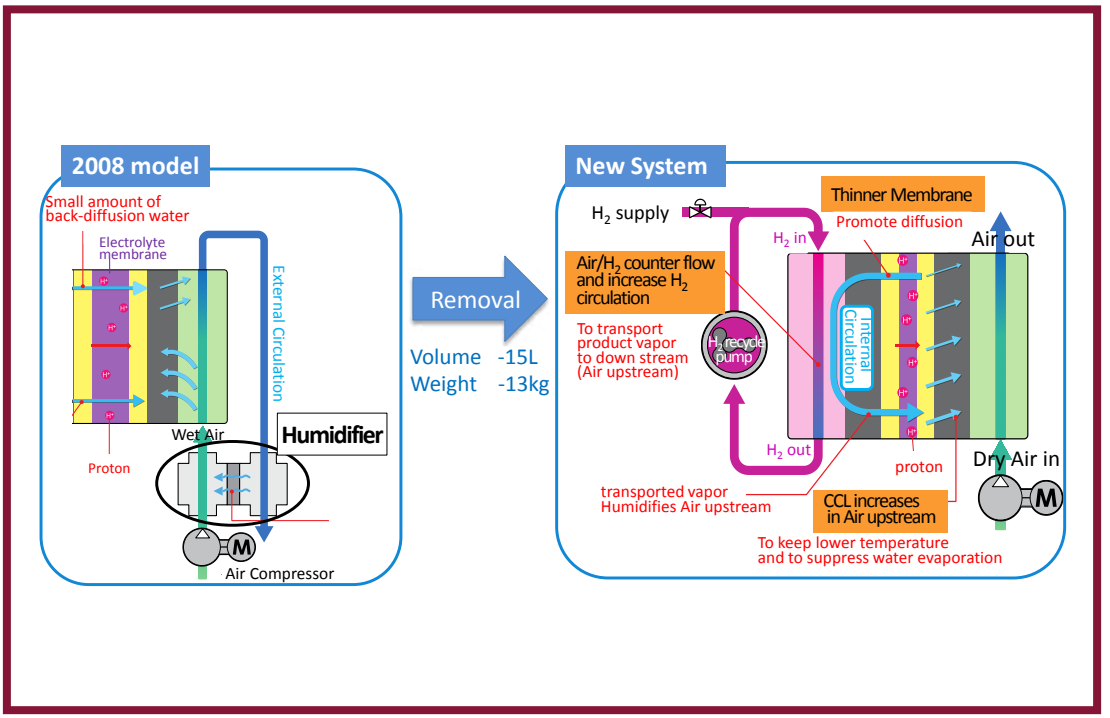

Fig. 6. *Humidifier removal and adoption of internal circulation.*

effort to develop materials, MEAs, and cell configurations for Polymer Electrolyte Membrane Fuel Cells since 2001. His current research focus is on advanced PEMFC technology, including membranes and catalysts.

Koichi Kojima is a Project General Manager in the Fuel Cell System Engineering & Development Division, R&D Group at Toyota Motor Corporation and previously held the position of General Manager in the Fuel Cell System Development Division and Fuel Cell System Engineering Division from 2005 to 2014. He was one of the longest-tenured General Mangers at Toyota Motor Corporation. He holds bachelors and masters degrees from the Department of Crystalline Materials Science, Graduate School of Engineering, Nagoya University, Japan. He joined Toyota Motor Corporation in 1981 and has engaged in material development relating to ceramics, exhaust gas catalysts, batteries, and hydrogen storage.

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