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Toyota Fuel Cell System (TFCS)

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Abstract

In December, 2014, Toyota Motor Corporation started public sale of FCV "MIRAI" ahead of the world. Toyota Fuel Cell System (TFCS) was aimed to realize the world's first truly practical FCV, which would be capable of demonstrating the potential of FCVs. TFCS was adopted in MIRAI, enhanced the excellence of FCV, which had the reputation remarkably so far and Toyota drastically reduced the cost of the FC system, which is one of the largest obstacles to the commercialization of FCVs. This paper describes the development of the TFCS and its components, focusing on the approaches taken to accomplish this reduction in cost.

Keywords: EV・HV system, Fuel Cell, Hydrogen Tank, System Technology

1 Introduction

The use of electricity and hydrogen (H_2) is regarded as a promising way of helping to resolve environmental and energy related issues. For this reason, H_2-powered fuel cell vehicles (FCVs) are attracting attention as a type of alternative energy vehicle with strong market appeal. In addition to clean and highly efficient environmental performance, FCVs also combine driving enjoyment and user-friendliness through smooth and quiet dynamic performance using motors and a similar cruising range and refuelling time as conventional gasoline vehicles.

Toyota Motor Corporation began the development of FC systems in 1992 and was the first automaker in the world to start sales of an FCV on a limited lease basis in December 2002. Subsequently, after incorporating a number of incremental advances and making progress toward the resolution of the main technical issues of cruising range and cold start capability, lease sales of the FCHV-adv (Figure 1) began in 2008. The FCHV-adv demonstrated the high potential of an FCV as a viable alternative energy vehicle.

Figure 1: Toyota FCHV-adv

2 Development of the Toyota Fuel Cell System (TFCS)

In December 2014, Toyota began general sales of the world's first mass-production FCV, the Mirai (Figure 2). Development of the TFCS for the Mirai aimed to realize the world's first truly practical FCV, which would be capable of demonstrating the potential of FCVs and encouraging full-scale popularization in the future. In addition to further refining the dynamic performance and silent operation established by previous FCVs, the TFCS also features a fully updated FC system and components. The development drastically reduced the cost of the FC system, which is one of the largest obstacles to the commercialization of FCVs. This paper describes the development of the TFCS and its components, focusing on the approaches taken to accomplish this reduction in cost.

Figure 2: Mirai FCV

3 Developmental Approaches for Low-Cost FC System

Table 1 lists the main cost factors for an FCV and the adopted countermeasures. These factors can be broadly categorized as the small production scale, the complexity of dedicated FCV systems (i.e., the large numbers of parts), and the high cost of special materials for FCVs. These factors are discussed in more detail below.

Table 1: FCV cost analysis

Factor	Countermeasures
1. Small production scale	Carry over mass-production parts from other vehicles Carry over the production line from other vehicles Unify mass-production specifications between automakers
2. Complexity dedicated FCV systems	Consolidate parts Optimize part requirement specifications (market feedback, regulations, etc.) Revise part configurations
3. High cost of FCV materials	Reduce material amounts Use or develop alternative materials

3.1 Effect of mass-production

Although there may be a certain cost reduction effect from mass-production at the initial stage of FCV introduction, the establishment of hydrogen stations is likely to proceed only gradually in accordance with the spread of FCVs. For this reason, in the initial period, FCVS are unlikely to achieve the same cost reduction effect as the mass-production of conventional gasoline vehicles.

Therefore, it will be important to carry over mass-production parts from other vehicles. The main mass-production parts that can be carried over from other vehicles are in the motor system and the systems for operating the FC. The scope of part carryover can have a major cost reduction effect from the standpoints of both components and the production line.

Part carryovers require changing system specifications to match those of the original vehicle. Figure 3 shows the configurations of the motor systems used in Toyota's FCVs. In the previous model (left), the FC and inverter were directly connected and used the same voltage. Therefore, dedicated designs were required for both the motor and inverter to match the unique characteristics of an FC (i.e., low voltage and high current).

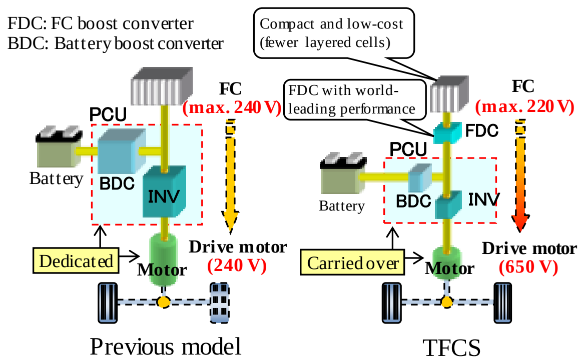


Figure 3: Motor system configurations

An FC voltage transformer called the FDC was newly adopted in the TFCS (right side of Figure 4). This enabled the adoption of a motor and inverter (high voltage and low current) already used in mass-produced hybrid vehicles (HV), thereby reducing the size and cost of the motor system. The FDC was also designed to incorporate other mass-production HV components, such as the intelligent power module (IPM) and reactor, further reducing the system cost.

3.2 FCV system simplification

Eliminating or consolidating parts is the most effective way of simplifying a system. Figure 4 and 5 show system diagrams of the previous system and the TFCS, respectively. Figure 5 also illustrates the progress that was achieved in carrying over (yellow) and consolidating (blue) component parts.

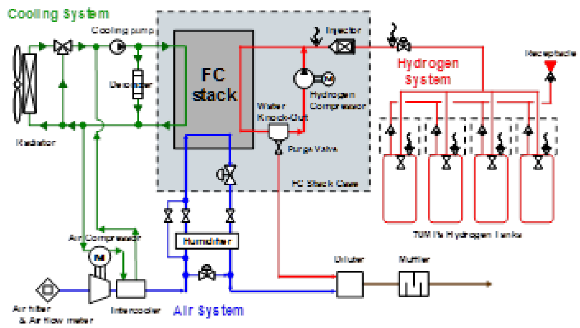


Figure 4: Diagram of previous system

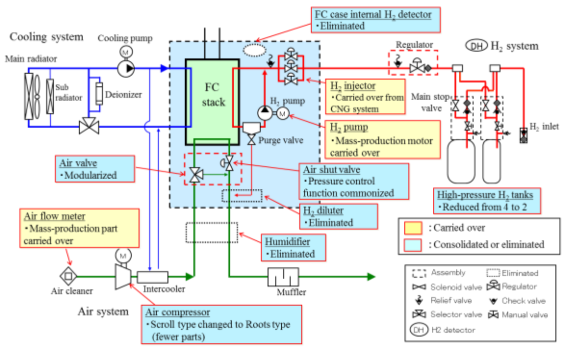


Figure 5: Diagram of TFCS

The TFCS is the first FC system in the world without an external humidifier. The FC stack and system control were refined so that water generated downstream of the cathode is returned upstream of the cathode by internal circulation via the anode. This humidifier-less concept is illustrated in Figure 6. The details of this concept are described in Section 4 (stack development) below.

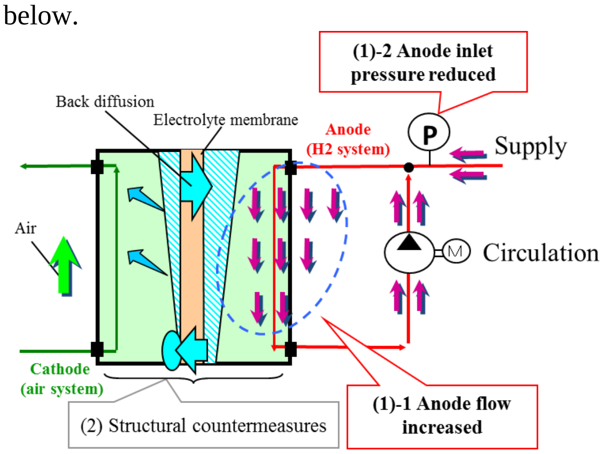


Figure 6: Outline of self-humidification concept by water content control

The previous model used four high-pressure H_2 tanks installed under the floor. Due to the high-cost of this design, it was important to reduce the number of tanks. Four tanks would also be an impediment to installing the system in a sedan package.

To reduce the number of tanks, it was important to improve the fuel efficiency of the vehicle and to design an efficient way of packaging the high-pressure tanks to maximize the H_2 capacity within a limited space. The TFCS improved fuel efficiency by approximately 20% compared to the previous model, and efficient packaging reduced the number of tanks in the Mirai to two. Section 5 (tank development) describes the details of these efforts.

3.3 Special FCV materials

An FC uses large amounts of high-cost materials, such as platinum (Pt) catalyst and carbon fiber high-pressure tanks. As shown in Figure 7, the FC system in the Toyota FCHV-adv used a high proportion of special materials.

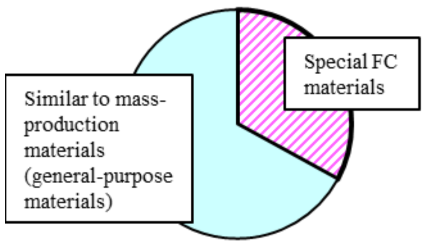


Figure 7: Cost breakdown

Material amounts in the TFCS were reduced by adopting smaller and lighter high-performance components. Cost reductions were also achieved by switching from high-cost to general-purpose materials. The details of these efforts are described below in the sections about the FC stack and tanks.

4 Development of New FC Stack

The TFCS is the world's first FC system without an external humidifier. This design was adopted to reduce cost through simplification and to improve reliability. Eliminating the humidifier means that water management in the cells of the FC stack is even more important for improving stack performance than in the previous system. Innovative technology was developed for the cell flow field structure and electrode in the new stack.

As a result, a power density of 3.1 kW/L was achieved, more than twice that of the previous stack (Figure 8).

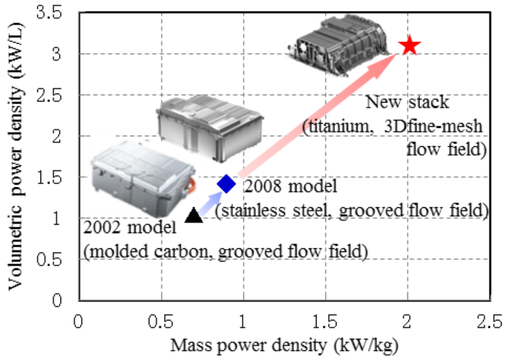


Figure 8: Stack volumetric and mass power density

The maximum power of the new stack was increased by 27% from 90 to 114 kW (a per cell increase of 36%). At the same time, the volume of the cells was reduced by 24% as a result of higher current density (increased by a factor of 2.4) and the use of thinner cells (thickness reduced by 20%). Furthermore, changing the separator flow field material from stainless steel to titanium, which has a lower specific gravity, also reduced cell weight by 39%.

4.1 Innovative cell flow field structure

Conventional cell flow field structures in FC stacks generally use straight grooves. This structure is susceptible to water accumulation underneath the flow field ribs that contact the electrode, which adversely affects oxygen (O_2) diffusion and causes non-uniform power generation (Figure 9). In contrast, porous metal flow fields such as foamed sintered compacts that remove the generated water from the electrode by capillary force through minute holes have been studied as a way of ensuring O_2 diffusion and enhancing performance. However, issues with porous metal flow fields include high pressure loss, large amounts of residual water left inside the pores, product quality, and cost.

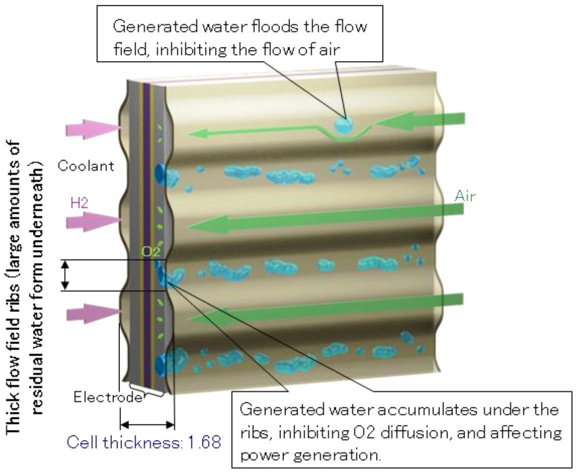


Figure 9: Conventional grooved cell flow field structure

To increase the current density and ensure the voltage stability of the new stack, an innovative three-dimensional (3D) fine-mesh air flow field was developed. This 3D fine-mesh flow field is a 3D micro-lattice that promotes O_2 diffusion to the catalyst layer by flowing turbulent air toward the electrode. The front and back shapes and surface wettability of the flow field were also optimized to quickly draw water generated from the electrode to the back surface of the flow field. These measures help to prevent the inhibition of gas flows due to flooding of the flow field, enable uniform power generation within each cell surface, and reduce voltage variations between stack cells. Furthermore, the 3D fine-mesh flow field pattern within each cell surface can be modified to alleviate turbulence at the air inlet and help to restrict drying of the electrode by dry air (Figure 10).

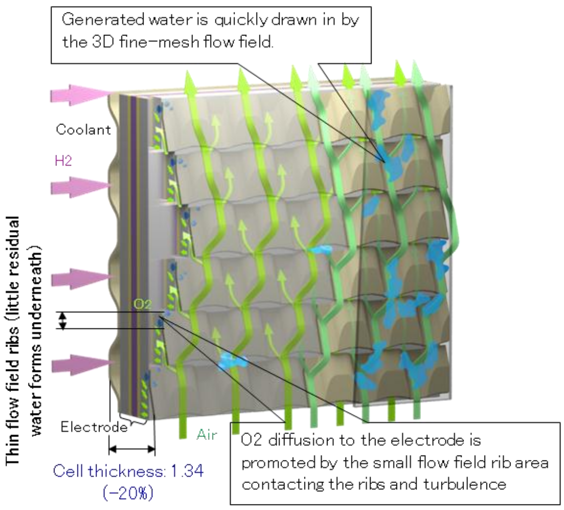


Figure 10: New 3D fine-mesh cell flow field structure

In addition, the H_2 flow field is grooved and integrated with the coolant flow field at the back and front. This creates a 2-turn, 3-step cascade microstructure in which the H_2 and air flow in counter directions on either side of the electrode. This structure uses the water generated at the air outlet by back diffusion to humidify the inlet H_2. An H_2 circulation pump then transports water vapor to the H_2 outlet and humidifies the flow field at the air inlet, which is susceptible to the drying action of the electrode. Therefore, this configuration enables self-humidification by circulating generated water within each cell, thereby maintaining high temperature performance even without a humidifier (Figure 11).

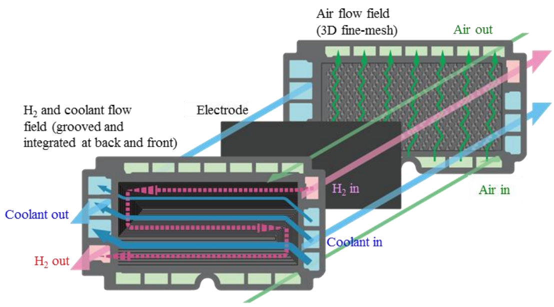


Figure 11: New cell flow field structure

4.2 Innovative electrode

To enhance performance without a humidifier, the electrolyte membrane thickness was reduced by two-thirds, thereby promoting the generation of water by back diffusion and increasing proton conductivity by a factor of at least 3. The activity of the catalyst was boosted by a factor of 1.8 by optimizing the Pt/cobalt (Co) alloy ratio. The carbon support was changed from a hollow to a solid type. This measure allowed the Pt catalyst to be supported on the carbon surface, increasing the effective utilization rate of the Pt that contributes to the reaction by a factor of approximately 2.

The innovative cell flow field and electrode structures described above had the following effects: lower concentration overvoltage due to improved gas diffusion, lower resistance overvoltage due to improved proton conductivity, and lower active overvoltage due to improved catalytic activity. As a result, the maximum per unit area sweep current of the electrode improved substantially, increasing the current density by a factor of 2.4 compared to the previous structures (Figure 12).

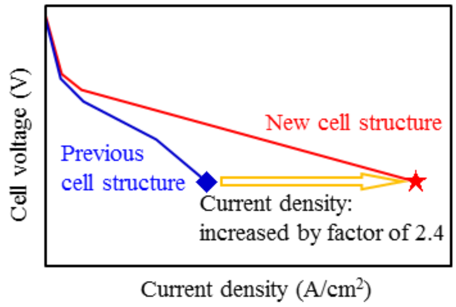


Figure 12: Current-voltage (I-V) characteristics of new cell structure (current density)

4.3 Size and cost reduction of FC stack

The high cost of the FC stack is mainly due to the electrolyte membrane in the electrode, which is a special FC material, the Pt in the catalyst, and the gold (Au) plating separator surface treatment (to reduce contact resistance and provide corrosion resistance), which cannot be reduced by economies of scale through mass-production.

The area of the electrode per unit power in the new FC stack was reduced by 59%. This was accomplished by improving performance with the innovative cell flow field and electrode structures described above (current density was increased by a factor of 2.4). Furthermore, the development also lowered the material cost of the electrode per unit area. This was accomplished by reducing the electrolyte membrane thickness by two-thirds (thereby decreasing the required amount of high-cost electrolyte polymer) and by reducing the amount of Pt by two-thirds through increasing the Pt utilization rate (Figure 13).

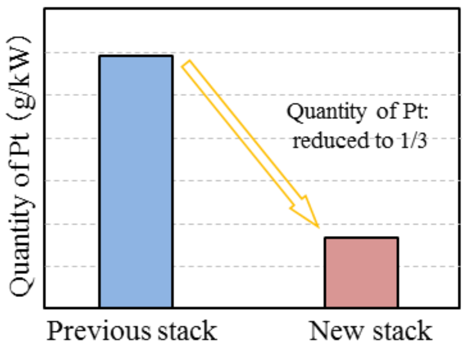
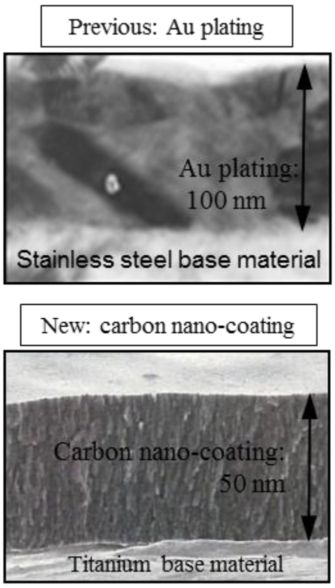


Figure 13: Amount of catalytic Pt per unit power

In addition, the base material of the separator flow field was changed from stainless steel (SUS 316L) to corrosion-resistant titanium, thereby allowing the function of the surface treatment to be restricted to the reduction of contact resistance. As a result, the previous Au plating treatment was replaced by a newly developed carbon nanocoating called Pi conjugated amorphous carbon (PAC). Eliminating the precious metal usage in the design enabled substantial cost reductions (Photograph 1).



Photograph 1: Separator surface treatment

In addition, simplifying the stack tightening structure by integrating the functions of the structure reduced the number of tightening parts and helped to lower size and cost.

5 Development of Low-Cost H_2 tanks

Tanks with two different shapes were newly developed to ensure sufficient H_2 storage capacity without sacrificing interior space in the Mirai sedan. Refinements to the carbon fiber reinforced plastic (CFRP) lamination enabled a world-leading H_2 storage capacity of 5.7 wt% (Figure 14).

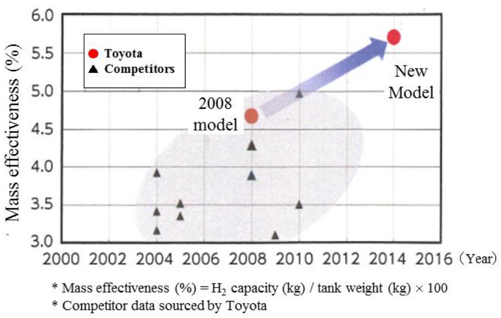


Figure 14: H_2 storage capacity of high-pressure H_2 tanks

5.1 Newly developed low-cost carbon fiber

Since carbon fiber makes up most of the cost of the H_2 tanks, it is important to reduce both the cost and the usage amount of the fiber. Therefore, the TFCS adopted a general-purpose carbon fiber instead of the high-grade aviation carbon fiber used in the previous model. With the cooperation of carbon fiber manufacturers, the carbon fiber properties were strengthened to the same level as aviation-grade carbon fiber, thereby reducing the carbon fiber cost.

5.2 CFRP lamination pattern

Figure 15 shows the structure of the high-pressure H_2 tanks. The tanks are composed of a resin liner at the innermost layer to seal in the H_2 gas, surrounded by a strong CFRP layer. Aluminum bosses are provided at both ends of the resin liner for valve fitting. Cost and weight were reduced mainly by improving the CFRP layer and greatly reducing the amount of CFRP used.

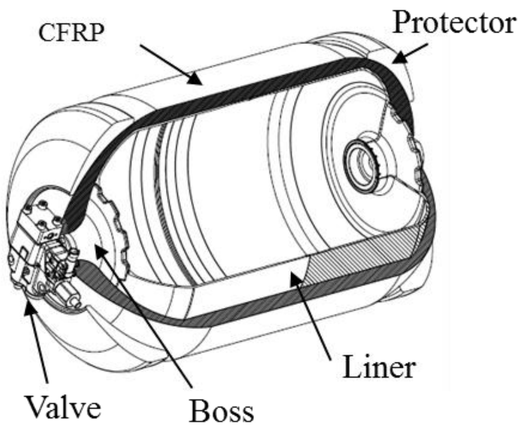


Figure 15: High-pressure hydrogen tank structure

The CFRP lamination pattern of tanks generally combines the following three types of winding methods: hoop winding (in the circumferential direction) to strengthen the central region of the tank, helical winding (in the axial direction) to strengthen the dome regions, and high-angle helical winding to reinforce the boundaries of these regions (Figure 16).

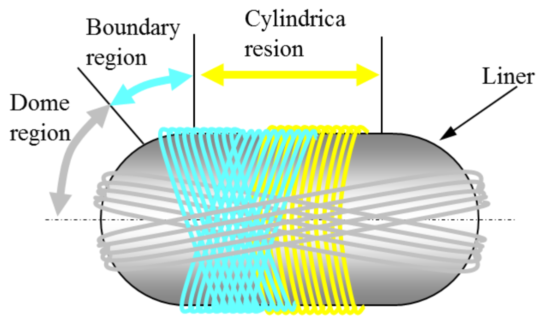


Figure 16: Lamination pattern of high-pressure tanks

The high-angle helical winding is carried out at an angle of approximately 70° to the axis. However, since the high-angle helical winding is also, by necessity, wound over the dome regions, stress in the circumferential direction is low (Figure 17). This arrangement is not an effective way of ensuring the tank strength.

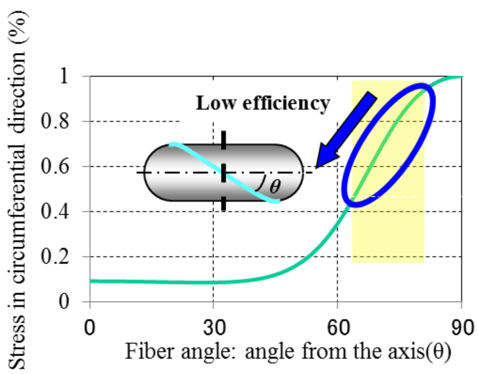


Figure 17: Relationship between fiber angle and strength efficiency

5.3 Reduction of CFRP by adopting new laminated structure

In the previous model, the high-angle helical winding accounted for approximately 25% of the total laminated structure. A new lamination method was developed that does not require high-angle helical winding to strengthen the boundary regions (Figure 18).

Specifically, the following three changes were made to the lamination method.

(1) The shape of the liner was changed to flatten the boundary regions and enable lamination by hoop winding.

(2) The boundary regions were strengthened while forming the conventional liner shape by hoop winding over the flat portions.

(3) Hoop winding lamination was concentrated in the inner layers.

These changes had the following effects. First, the high-angle helical winding was eliminated. Second, hoop winding, which is a highly effective way of strengthening in the circumferential direction, was concentrated in the inner layers where the generated stress is highest. These two effects reduced the amount of CFRP by 20wt% compared to the conventional lamination method. Combined with the reduction in CFRP achieved by optimizing the shapes of the bosses, a world-leading H_2 storage capacity of 5.7 wt% was achieved, which made a major contribution to reducing the cost of the H_2 tanks.

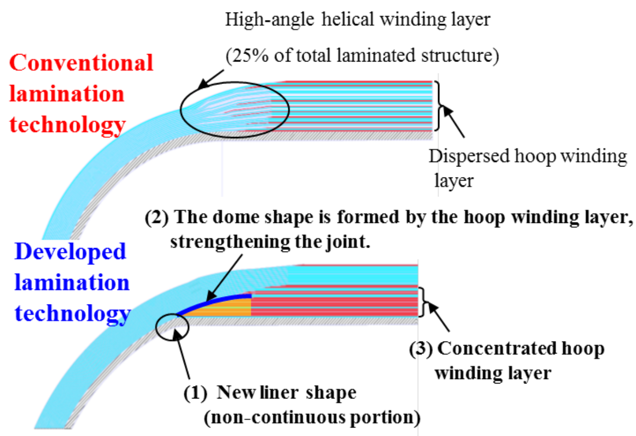


Figure 18: Comparison of conventional and new lamination methods

6 Conclusions

The mass-production and commercialization of this FCV is the result of a long and arduous journey by a large number of people at Toyota and its partner companies.

Furthermore, the launch of this FCV signals the start of a lengthy struggle toward achieving widespread popularization.

The name Mirai was chosen since it is means “future” in the Japanese language and it was decided to adopt this name in every country around the world. The name symbolizes the Mirai as a car that will lead the way into the future for the next generations.

Toyota is continuing the development of FCVs as one of the most promising technologies for achieving sustainable mobility and energy diversification. At the same time, it will carry on actively working with governments and related fields toward the realization of a hydrogen-based society, for the sake of the Earth, future generations, and society.

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