

Development of Lithium Ion Battery System for Fuel Cell Vehicle

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ABSTRACT

A lithium ion battery system was developed for the fuel cell vehicle Honda FCX Clarity.

This system achieves output power better than the ultra-capacitor mounted in the previous Honda FCX, and enhances both starting acceleration and fuel economy performance by increasing the energy recovery rate. In addition, durability and reliability requirements are also satisfied by performing appropriate battery cooling and control.

Regarding mounting in a vehicle, this system is 40% lighter and 50% smaller by volume than the previous Honda FCX system, and mounting the system under the vehicle floor results in expanded cabin space, which increases vehicle appeal. In addition, the new system also realizes increased resistance to environmental factors such as water and dust.

1. Introduction

Increased attention is being placed on environmental measures, and there are high expectations for fuel cell vehicles as eco-friendlier vehicles. As such, energy storage with the same high performance as fuel cells is demanded to enhance the fuel economy and acceleration performance of fuel cell vehicles. The Honda FCX⁽¹⁾, the world's first fuel cell vehicle certified for commercial use by the U.S. government, was delivered to its customers in December 2002. It employed an ultra-capacitor^{(2), (3)} that realized acceleration performance exceeding that of hybrid vehicles. At the same time it was also understood that increasing the energy capacity and energy recovery rate would lead to further enhancements in fuel economy.

The FCX Clarity is the first Honda vehicle to use a lithium ion (hereafter, "Li-ion") battery to enhance fuel economy without impairing the conventional acceleration performance. A Li-ion battery system was mounted in the vehicle including cooling and control that aims to maximize battery performance.

When mounting the battery system in the vehicle, placement under the vehicle floor expanded the cabin and trunk room space, which increased product appeal. On the other hand, it increased its exposure to environmental factors outside the cabin, such that protecting the high voltage parts from water and dust needed to be addressed.

This paper reports the Li-ion battery performance and

durability, and describes the technologies used to address environmental factors outside the cabin, when mounting the Li-ion battery system in an actual vehicle.

2. Adoption of Lithium Ion Batteries

The two main performance features required of the energy storage mounted in the FCX Clarity were output power density, which is related to acceleration performance, and energy density, which is related to fuel economy. Figure 1 shows a chart comparing the energy density and output power density of various energy storage types.

The Li-ion batteries used in consumer products drive those products for long times, so they have a high energy density. On the other hand, ultra-capacitors have low internal resistance, which gives them reliable output power density. This development used a Li-ion battery with low internal resistance that features both reliable output power density and energy density as the energy storage for realizing the required performance. This Li-ion battery uses different positive and negative-electrode materials and a different collector structure than those of Li-ion batteries for consumer products. This achieves an output power density greater than that of an ultra-capacitor and an energy density greater than that of the nickel-metal-hydride batteries used in hybrid vehicles. As a result, the battery output power is approximately three times that of

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a hybrid vehicle. In addition, the new battery has higher energy than the ultra-capacitor used in the previous model, which extends the time that the acceleration state can be maintained, increasing the acceleration time from vehicle launch by 40%. The energy level has been increased and a cooperative regenerative braking system that controls the division between generation and braking is also used, which increases the amount of regenerative energy recovered during deceleration by 13% in 10-15 mode, leading to enhanced fuel economy. Furthermore, the new Li-ion battery has a high rated voltage per battery unit approximately three times that of a nickel-metal-hydrate battery, and approximately 1.5 times that of an ultra-capacitor. This means that fewer Li-ion batteries are needed to produce the same system voltage, which enables a more compact size. In addition, there is no memory accumulation like with a nickel-metal-hydrate battery, and the charging status can be understood from the voltage, so the control system can also be simplified.

For these reasons, a Li-ion battery with both reliable energy density and high output power density was adopted as the energy storage for the FCX Clarity.

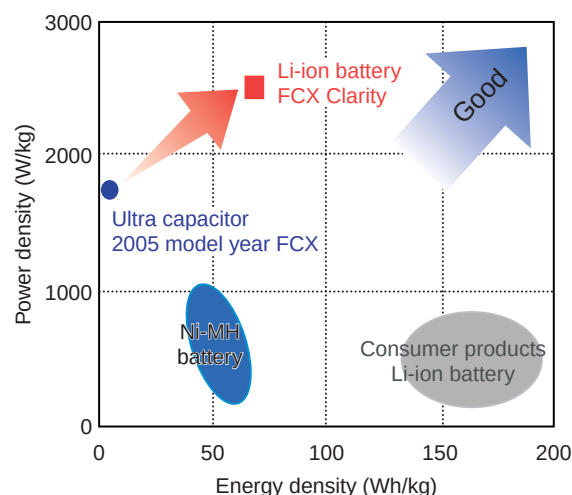


Fig. 1 Battery performance comparison

3. System Goals

Development of the Li-ion battery system focused on the following two goals:

- (1) Establishing battery durability
- (2) Achieving a full-cabin sedan style

Establishing battery durability is important for maintaining vehicle performance over long periods using multiple batteries. This makes it necessary to construct a system that includes cooling so that the multiple batteries are always placed under the same environment in order to increase durability.

In addition, development emphasized a compact and

lightweight Li-ion battery system to enable mounting in a manner that achieved the full-cabin sedan style that is a feature of the FCX Clarity. The goal was to enhance both comfort and mounting performance, so the Li-ion battery system was mounted under the floor of the rear seat, allowing even more cabin and trunk space.

4. Battery Durability

4.1. Factors and Estimation of Drops in Performance

The effects of the state of charge (hereafter, "SOC") and temperature produce a drop in the Li-ion battery capacity and a rise in resistance, leading to a drop in performance. In particular, this drop in performance progresses faster when used continuously under high SOC and high temperature conditions. Figure 2 shows the change in capacity at different environmental temperatures in a charge-discharge cycle test. (The horizontal axes in Figs. 2 through 7 and Fig. 9 hereafter show the time with the durable life of the FCX Clarity defined as "1".) These results show that the drop in capacity increases when the test is performed under high environmental temperature conditions.

Next, Fig. 3 shows the change in capacity in a shelf test. As seen in the charge-discharge cycle test, the drop

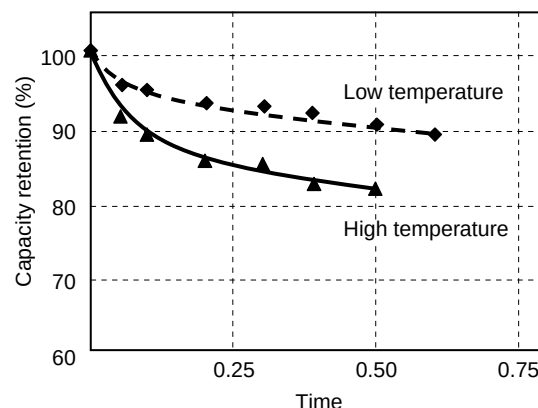


Fig. 2 Capacity retention in charge-discharge test

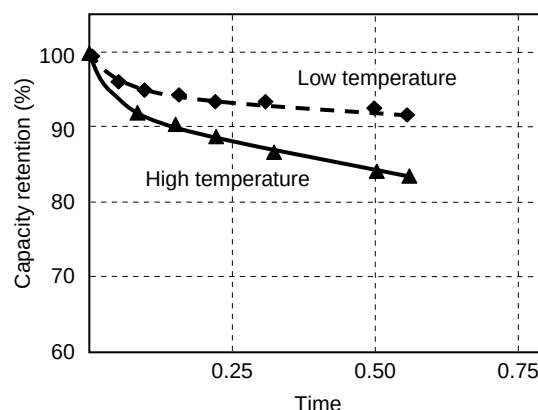


Fig. 3 Capacity retention in shelf test

in capacity increases when left under high environmental temperature conditions. This difference in the progression of performance drop due to differences in the environmental temperature occurs not only for capacity; the same phenomenon also occurs for resistance (Fig. 4). In addition, Fig. 5 shows that even at the same environmental temperature, the resistance changes according to the SOC.

In this manner, the change in Li-ion battery performance is influenced by the battery state, including the temperature and SOC, and the rate of change can be arranged using the 1/2 power-law of time⁽⁴⁾. Figures 6 and 7 show examples of shelf tests. A performance drop coefficient can be calculated from the results of tests performed under different temperature and SOC conditions, and that the coefficient can be used to estimate the change in Li-ion battery performance during the vehicle operation period.

The drop in performance progresses regardless of whether the Li-ion battery is performing charge-discharge or in the shelved state, so acceleration tests can be performed by calculating the performance drop coefficient and setting various conditions. This ability to understand changes in performance occurring over long-term vehicle operation in a short time is useful for development.

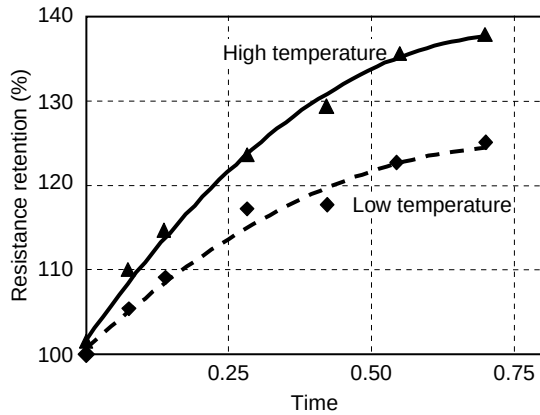


Fig. 4 Resistance retention in charge-discharge test

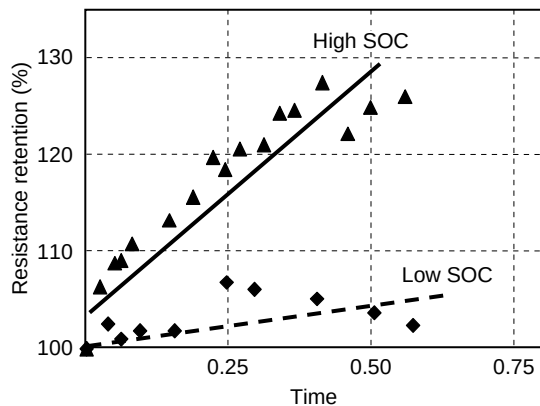


Fig. 5 Resistance retention in shelf test

4.2. Operating Temperature and SOC Range Settings

The battery operating temperature range and SOC operating range should be determined in consideration of various thermal effects, such as the environmental temperature of the region where the vehicle is operated, radiated heat from the road surface, battery heat generation due to current input/output while running. Environmental temperatures were assumed to range from an outside air temperature of 45°C in regions with intense heat to -30°C in regions with extreme cold. Battery heat generation due to current input/output varies according to the running conditions, so past running data for gasoline and hybrid vehicles as well as running data for the predecessor model were taken into account as operational data. These data were combined and evaluation was repeatedly performed to determine the battery operating temperature and SOC ranges over which the required performance could be satisfied for the vehicle operation period.

4.3. Cooling System Structure and Performance

Simulations were repeatedly performed to design a cooling structure that could efficiently cool all the

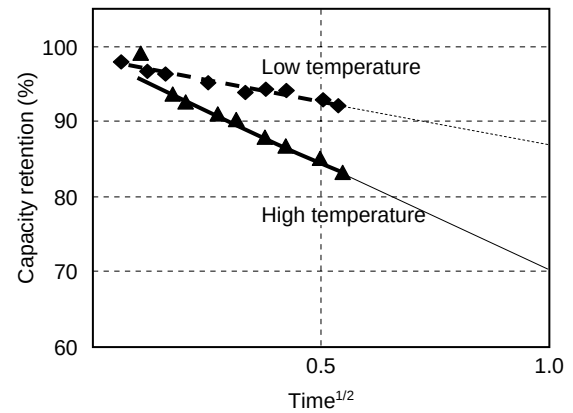


Fig. 6 Capacity retention in shelf test (acceleration test)

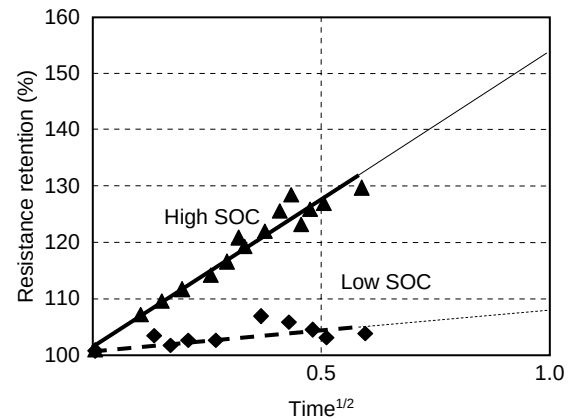


Fig. 7 Resistance retention in shelf test (acceleration test)

batteries. In contrast to the capacitor system of the previous model that was divided into two boxes and performed cooling for each box, the new system places all batteries into a single box for cooling, which enables a more compact size. Figure 8 shows the cooling structure. An air-cooled side flow format was selected, where external air sucked in from the top of the intake duct is divided inside the duct to cool from the right and left sides of the battery box. In addition, an exhaust duct was installed inside the battery frame. Side plates that serve as structural members were installed on the sides of the box, and openings were made in these plates as entrances for outside air. An opening was also set in the center of the battery frame as an exhaust port. Battery temperature variance is reduced by adjusting the area of these openings to adjust the air flow. In addition, the design divided the inside of the box into front and rear

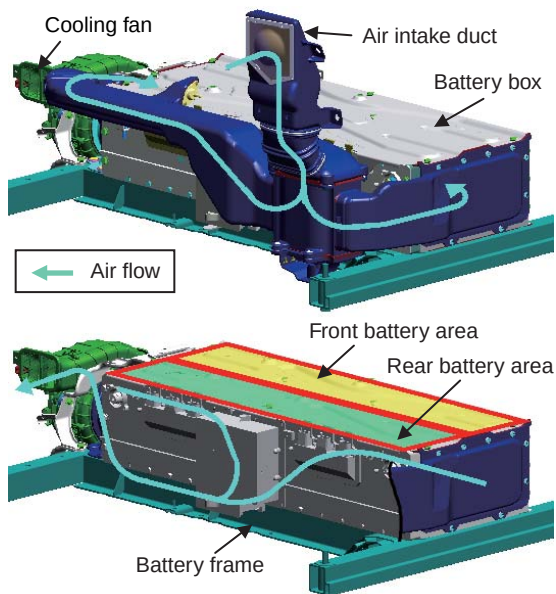


Fig. 8 Battery cooling air flow

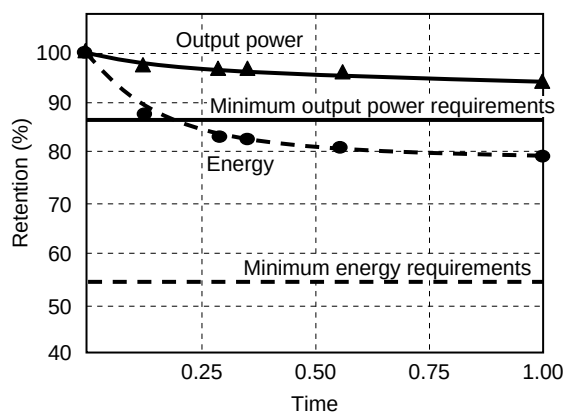


Fig. 9 Life test of Li-ion battery system

portions, and the front battery temperature was set a few degrees higher than the rear battery temperature. This enabled measurement with emphasis on the front battery temperature, which helped to prevent the increase of thermistors for detecting the battery temperature. Figure 9 shows the life test results using the set SOC operating range and new cooling structure. This confirmed that both the energy and output power satisfy the required performance levels for the assumed operation method over the number of operation years.

5. Features of the Vehicle Package

Figure 10 shows the mounting structure of the Li-ion battery system. This system is mounted under the floor of the rear seat, and consists of a box enclosing the battery units in the center, a battery ECU on top, a cooling fan on the side, and a contactor box in the rear.

As mentioned above, air cooling was selected as the cooling method, and a side flow format that reduces the structural height was used to secure a wide cabin space in order to achieve both high performance and light weight. This realized a weight reduction of 40% and a volume reduction of 50% compared to the previous model.

On the other hand, placing the energy storage outside the cabin made it important that consideration be given to external factors such as water and dust, and this became a technical issue in this development.

5.1. Structure with the Battery Module Placed outside the Cabin

An important point for realizing a structure that places the battery module outside the cabin with external air intake and exhaust is measures to help prevent the entry of water. This is because the batteries are constantly high voltage, and water entering may eventually lead to a

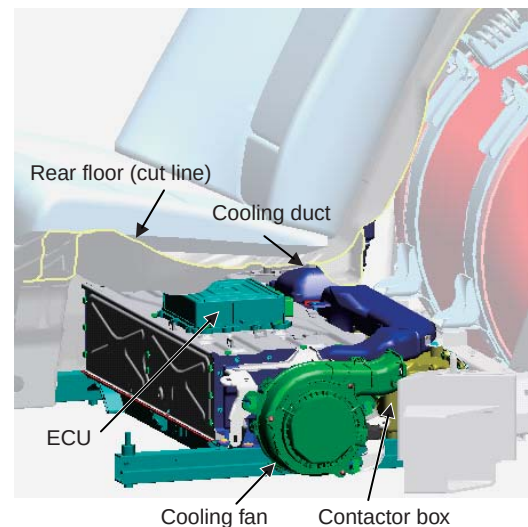


Fig. 10 Battery module placement

battery short circuit. The selection of external air intake and exhaust means that the cooling air itself contains moisture, so each individual battery was waterproofed. In this development, the batteries were protected by a resin covering that not only secured waterproofing and insulation performance, but at the same time enabled direct exposure to the cooling air. The terminal structure combines surface sealing using synthetic rubber with outstanding weather resistance, and adhesive sealing, to secure reliability. The battery ECU and cooling fan electrical parts are waterproofed by applying the adhesive sealing technology used for the ECU of mass production gasoline vehicles. This achieved the high reliability of being able to provide insulation performance even when the entire battery module is submerged. However, for these structures to maintain stable quality over long periods, consideration should be given to foreign matter and dust in addition to water.

Dust and foreign matter countermeasures are basically divided into two parts: a structure that helps prevent the entry of dead leaves and other large foreign matter, and a structure that catches dust and other fine particles. The former uses a mesh over the air intake, and the latter catches and helps prevent the entry of foreign matter and dust using an air filter. The air intake to which the mesh is attached faces the rear, or the direction opposite of vehicle travel, and is located at a position above the battery module. This is approximately the same height as the air intake of mass production vehicles, and helps prevent the entry of foreign matter and water flung up when running.

Figure 11 shows the intake structure.

The air filter catching ability was set in consideration

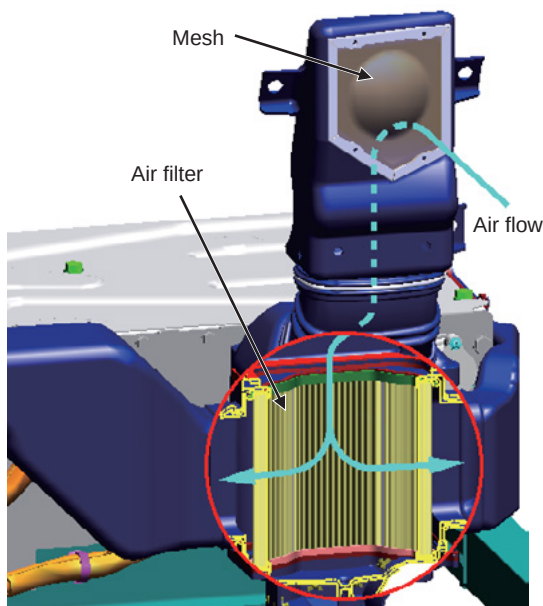


Fig. 11 Cooling duct structure

of the balance with the cooling capacity. As mentioned above, the battery's waterproof structure also gives it a certain degree of dust resistance. However, attention was given to the following three points as the effects of dust.

- (1) Short circuits resulting from potential differences and moisture-laden dust (tracking)
- (2) Structural erosion resulting from collisions between dust and the batteries (erosion)
- (3) Structural corrosion resulting from corrosive products (corrosion)

Figure 12 shows the relationship between dust catching ability and the effects of these three points for various dust particle sizes.

When addressing tracking which may lead to dielectric breakdown, pollution level 3 specified in JIS C0704⁽⁵⁾ – an environment in which conductive pollution exists – was assumed in consideration of placement outside the cabin. Tracking resistance was determined to be a potential difference of 2 000 V or more to take measures against voltage spike noise. In order to achieve this tracking resistance, a minimum distance between terminals of 16.5 mm was provided, and a comparative tracking index, which indicates tracking resistance performance, of 600 or more was maintained by examining resin materials.

Erosion was determined by calculating the impact value from the duct length, wind flow and other factors based on the Kanto loam formation (JIS Z8901 TYPE 8)⁽⁶⁾, and the results showed there to be no problem with a particle diameter of 30 μm or less.

From a broad group of potentially corrosive dusts, ranging from mainly inorganic dusts such as Kanto loam formation to organic dusts such as pollen and spores, emphasis was placed on corrosion due to the effects of organic dust and moisture, and the like.

Pollen, spores and other small particles generally have a diameter of approximately 10 μm , and a particle diameter of 30 μm or less presents no issues in terms of erosion, so an air filter with dust catching ability of approximately 10 μm was selected. Corrosion resistance

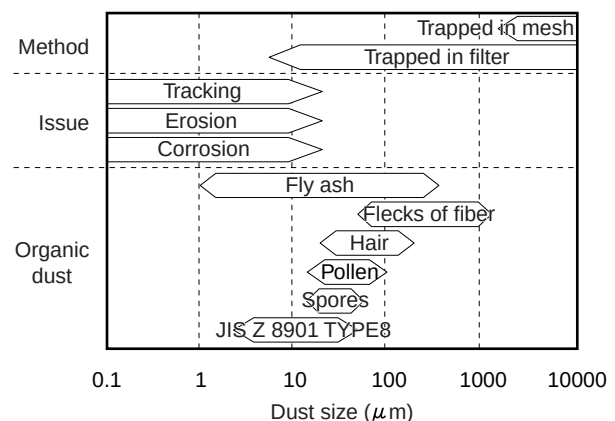


Fig. 12 Dust catching ability and issues

with respect to the entry of dust particles 10 μm and smaller was secured by employing resin materials with outstanding environmental resistance, which are used on the exterior of the vehicle and inside the engine room, in the cooling channel. This waterproof, dustproof structure enabled placement outside the cabin.

6. Conclusion

This paper introduced the Li-ion battery system developed for the FCX Clarity. The conclusions reached as a result of this system development are as follows.

- Li-ion batteries have high energy density and high output power compared to other forms of energy storage.
- Changes in battery performance can be estimated, and it was confirmed that this new system can supply stable energy over the vehicle operation period by setting durability modes and constructing a cooling system based on market usage.
- Addressing environmental factors in consideration of placement outside the cabin gives this Li-ion battery system increased mounting freedom and makes it possible to enhance cabin comfort.

In this manner the Li-ion battery system mounted in the FCX Clarity features outstanding performance and reliability. This contributes to continuously extendable acceleration with powerful torque and a spacious cabin interior, which increases the appeal of the FCX Clarity.

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