

Development of High-power Electric Double-layer Capacitor for Fuel Cell Vehicle

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ABSTRACT

An electric double-layer capacitor has been developed as an energy storage device for a fuel cell vehicle. This capacitor was utilized in the Honda FCX fuel cell vehicle marketed in December 2002. The capacitor features a rolled electrode housed in a cylindrical case. The aluminum foil at the sides of the electrodes is welded to collector plates with radial U-shaped grooves; the structure is welded together after alignment of the terminals at the center of the collector plates with the holes in the center of the case and case cover. This configuration has enabled the achievement of a fill density of 86% in the electrode and a connection resistance of less than 0.05 m Ω . Due to this packaging the unit displays the highest level of performance for a capacitor cell known to date, with a specific power density of more than 1,500 W/kg and a specific energy density of 3.9 Wh/kg. Tests show that the longevity of the capacitor is equivalent to or greater than that of the vehicle in which it is fitted.

1. Introduction

Honda's continuing commitment to the environment has resulted in the marketing of the Insight⁽¹⁾ hybrid vehicle, provided with Integrated Motor Assist (IMA), in 1999, followed in 2002 by the Civic Hybrid⁽²⁾. Both of these vehicles employed nickel metal-hydride (Ni-MH) batteries as energy storage devices.

In a new innovation, electric double-layer capacitors were utilized as the energy storage system in the Honda FCX fuel cell vehicle. The FCX was first produced in December 2002, and is a zero-emission vehicle with considerable future potential.

This paper will discuss the structure and performance of the capacitor cells utilized in the FCX.

2. Principle and Characteristics of Electric Double-layer Capacitors

An electric double layer is a distribution of positive and negative charges separated by extremely small distances at the interface of a solid and an electrolyte. In an electric double layer, the charge of the electrode is balanced by ions in the electrolyte; for example, a positively charged electrode is balanced by negative ions in the electrolyte.

Figure 1 shows a schematic of charge and discharge for an electric double layer capacitor. One of the characteristics of these capacitors is that the phenomenon of physical adsorption of positive (or negative) ions by the activated carbon in the electrode gives the units lower internal resistance and higher durability under repeated use than chemical batteries. Because no chemical reaction is involved,

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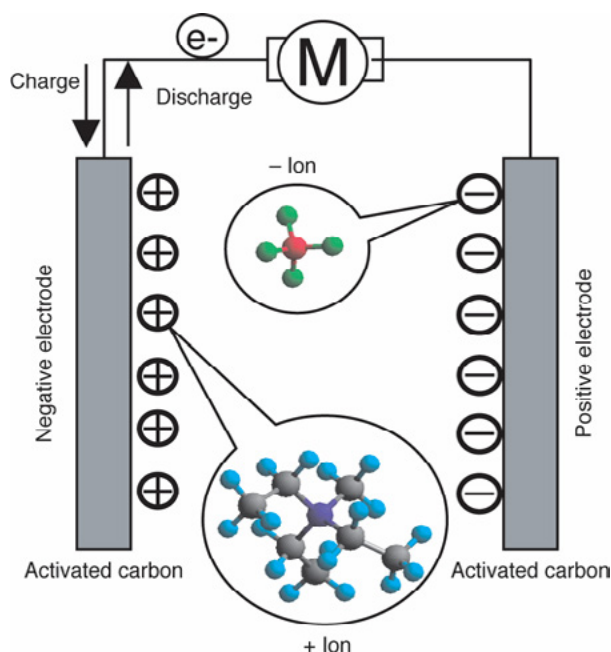


Fig. 1 Schematic illustration of electric double-layer capacitor

they can operate in a wide range of temperatures, from low to high. In addition, they employ no environmentally harmful materials requiring special treatment, such as heavy metals, acids and alkalis.

However, the significantly lower energy storage capacity of current electric double-layer capacitors makes them inferior to chemical batteries from the perspective of practical use.

Figure 2 shows the discharge curve of the new Honda capacitor at a fixed current. Cell voltage drops linearly at discharge. This characteristic indicates that the capacitor can be charged and discharged at a wide range of voltage, and is capable of synchronizing with fuel cell voltage without a voltage regulator.

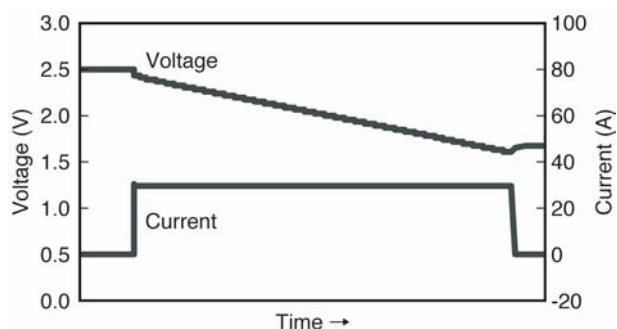


Fig. 2 Discharge curve of Honda Ultra capacitor

3. Development Aims

Targets of 2.5 mΩ for DC resistance and 1,350 F for capacitance were established for the new capacitor cells on the basis of targets for the capacitor system to be employed in the fuel cell vehicle.

The following goals were established to enable these targets to be achieved and to ensure reliability (vibration resistance, etc.):

- (1) To achieve a resistance of less than 0.05 mΩ in the conductive connections from the electrode to the

terminals (a section not involved in energy storage) in order to ensure that the low resistance characteristic of the capacitor was also displayed by the internal connection structure.

- (2) To maximize the ratio of the size of the energy-storing electrode to the interior volume of the cell and minimize the volume required for the connection structure of the collector, which plays no part in storage. This enabled the energy density to be maximized, which was low in comparison to that of chemical batteries (The increase in electrode fill density was more than 80%).

4. Development Concept

4.1. Cell Shape Concept

Excluding small coin-type units, conventional capacitors can be broadly divided into two types. Figure 3 shows one of these, with a rectangular case and a layered electrode. The other type is shown in Fig. 4, and has a cylindrical case and a rolled electrode.

Increasing the width of the collector lead has been considered as a method of reducing resistance in the rectangular type, but because its width must not exceed half the width of the electrode, it is not possible to achieve a target of less than 0.05 mΩ for resistance in the collector section. The further requirement to provide clearance in the direction of the plane to insulate the collector lead from the four sides of the case limits the fill density to 56%, and significant improvements cannot be expected. These considerations led to the selection of a cylindrical case for the new capacitor.

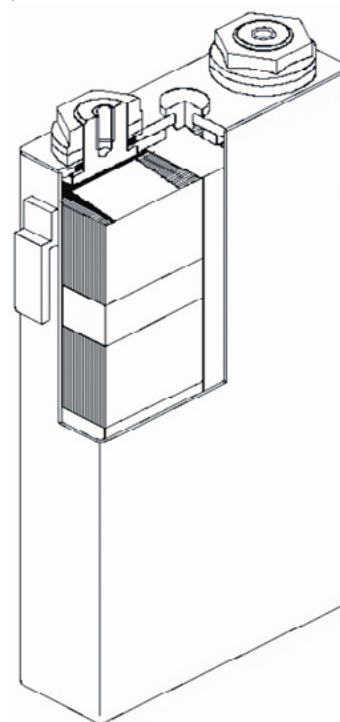


Fig. 3 Rectangular type

4.2. Collection Structure Concept

Various types of collection structures are also possible in a cylindrical cell. The difficulty of significantly reducing the length of the tab connecting the terminal and the rolled electrode in the type with a collector lead made it necessary to reexamine the collector structure to lower resistance and increase the fill density.

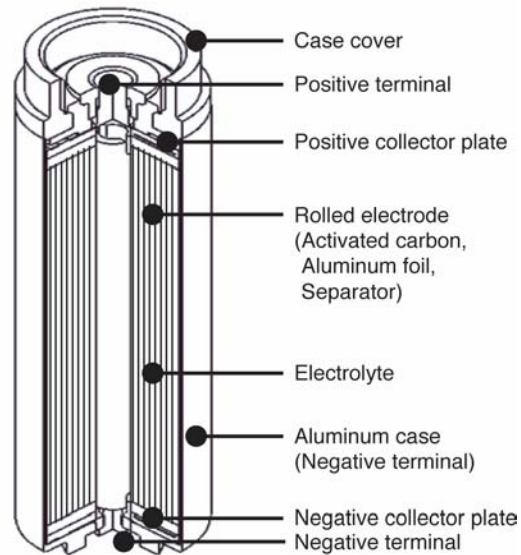


Fig. 4 Photograph and cutaway view of Honda Ultra capacitor

4.3. Concept behind Improvement of Fill Density

This development project focused on the use of the space inside the case, and defined electrode fill density as a function of cell structure as the ratio of the width of the rolled electrode to the internal length of the case. Reduction of the necessary dimensions of the collector structure was the key to increasing the electrode fill density as a function of the ratio of electrode width to available space in the case shown in Fig. 4. The design of the collector structure was studied to enable the establishment of a direct connection between the collector plates and the case and terminals and the minimization of the volume of the collector structure.

5. Study of Structural Design

5.1. Cell Structure

Figure 4 shows an external and a cutaway view of the newly developed cell. The cylindrical rolled electrode is made up of alternately rolled positive and negative poles interleaved with separators. It is immersed in an electrolyte containing positive and negative ions. In consideration of safety during production and normal operation of the cell and in the event of accident, a quaternary ammonium salt dissolved in propylene carbonate was selected as the electrolyte. Collector plates are attached to both ends of the electrode, and the terminals formed by the collector plates are directly connected to the terminal sections of the case and the case cover. To fit the cells to the coupling module in which they are installed in the vehicle, the case cover has the twin functions of sealing the electrolyte and fixing and insulating the positive and negative terminals and is provided with holding screws to fix the cell in place. The case is welded to the case cover, the bottom of which is formed to receive a tightening tool.

5.2. Design and Coupling Method of Collector Section

5.2.1. Shape of collector plates

Connection resistance between the collector plate and the rolled electrode is basically determined by the surface area of the connection between the collector plates and the electrode collector that protrudes from the ends of the rolled electrode. It is possible to establish contact by utilizing a flat collector

plate and pressing it onto the ends of the electrode collector. However, if this method is used, the ends of the electrode collector must be formed extremely accurately to ensure uniform contact. In practice, it is difficult to ensure sufficient flatness in the ends of the electrode collector to enable uniform contact with the collector plate, and it is very difficult to achieve the required connection in the welded sections without modification.

To ensure sufficient contact between the electrode collector and the collector plate, U-shaped grooves are formed on the plate, as shown in Fig. 5, and it is pressed onto the electrode to make the grooves bite into the ends of the electrode collector (Fig. 6). The relationship between the flatness of the ends of the electrode collector and the depth of the grooves on the sides of the collector plate is the important factor in achieving this connection.



Fig. 5 Collector plate



Fig. 6 Detail of welded area on electrical contact points

The accuracy of the formation of the ends of the electrode collector is related to the degree of misalignment in the rolling of the electrode and separators, which constitute it. If there is a large rolling misalignment in the electrode, the positive and negative poles will overlap the separators and the electrode will short itself. If the width of the separators is increased to prevent shorting, the flatness of the ends of the electrode collector is reduced, and the quality of the collector weld connection inevitably declines. Figures of less than 1 mm for deviations in the flatness of the ends of the electrode collector and 1.5 mm for the depth of the U-shaped grooves formed in the collector plate were established as enabling a connection between the plate and the electrode collector (1 mm in width) using a method in which the plates are pressed onto the collector as far as the depth of the grooves.

By positioning weld points at the bottom of the grooves, it was possible to expand the welds from points to surfaces, creating a reliable and low-resistance weld connection. In addition, by making the grooves in the collector plate flat rather than curved, control of variation in the focal point of the YAG laser was achieved, even allowing for some deviation of the welding trajectory from the U-shaped axis, resulting in a consistent weld quality.

Efficient collection is dependent on establishing a sufficient number of collection points at uniform intervals on the electrode collector (collection pitch), but it is difficult to establish collection points at a uniform pitch on a cylindrical rolled electrode. However, by making the grooves on the collector plate radiate out from the center, it is possible to form viable collection points on the inner circumference if the required weld points are ensured at the outermost periphery. Because collection pitch is determined by the number of divisions of the peripheral length, the collection pitch becomes shorter on the inner circumference, and a sufficient connection can be ensured. The relationship between collector connection resistance and weld lines is shown in Fig. 7. Cell resistance reaches a fixed value with three or more weld lines. However, six weld lines have been utilized in the new cells, from considerations of variation in connection quality and to improve safety.

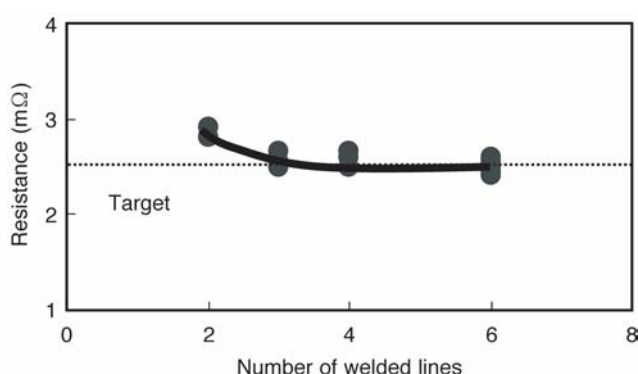


Fig. 7 Relationship between number of welded lines and resistance

5.2.2. Welding in the connector

The operating voltage of the new capacitor necessitated the use of aluminum in the sections in contact with the electrolyte, such as the collector foil and terminals. Brazing and welding (MIG, TIG, spot, YAG, electron beam, etc.) were studied as methods of connecting the aluminum collector foil and collector plates.

The difficulty of controlling the energy of MIG, TIG and

spot welding and brazing made it impractical to apply these techniques to welding 40 μm collector foil and collector plates formed from aluminum rolled into thin sheets. While electron beam welding utilizes a high-energy beam, it was not applied because welding must be conducted in a vacuum, making heat dissipation difficult. Production of the new capacitor employs YAG laser welding to generate heat energy on the surface of the collector plate, producing a weld connection with the collector foil.

5.3. Structure of Collector Terminal

A hole is formed in the bottom of the case and case cover of the newly developed cells. The terminal of the collector plates fits over this hole, and a weld connection can be established with the positive and negative poles at the minimum distance. This does away with the need for any structure leading from the collector plate to the outside, and the space required for electrical connection is effectively zero. In addition, because the collector plate is directly exposed and a conducting surface area is therefore guaranteed, this layout is effective in minimizing connection resistance.

5.4. Establishing Collector Width

Reducing the width of the electrode collector enables the distance required for collection to be reduced, increasing the fill density against the internal space available in the case. However, it is not possible to simply reduce the width of the collector in isolation; the width of the separator must be reduced proportionally, which reduces the amount of coverage of the separators on the electrode. As discussed in 5.2.1 (Shape of collector plates), rolling misalignments occur in the separators and the positive and negative poles, and if these misalignments cause the poles to extend beyond the separators, shorting between positive and negative poles will occur. Paying special attention to the accuracy of the formation of the ends of the rolled electrode has enabled the width of the electrode collector to be minimized, resulting in the achievement of an electrode fill density (ratio of electrode width to internal length of case) of 86%.

6. Cell Performance

As Fig. 8 shows, the new capacitor composition and structure discussed in this paper have enabled the achievement of both high specific power density and high specific energy density (Figures shown are based on in-house measurements, and include variations in cell useable voltage).

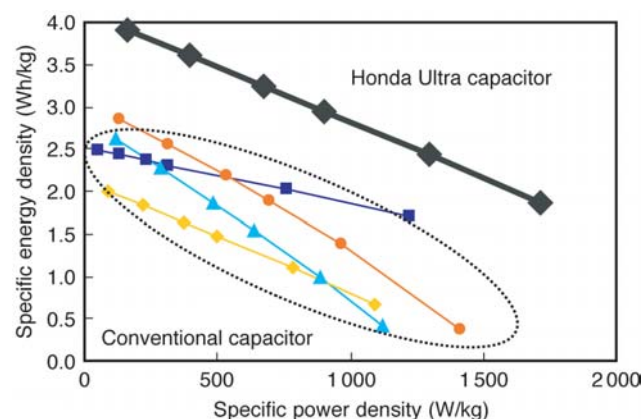


Fig. 8 Ragone plots for conventional capacitors and Honda Ultra capacitor

7. Reliability

7.1. Internal Pressure of the Cell and Reliability

This section will discuss the thinking of the development team with regard to the internal pressure of the cell. The essential structural components of the capacitor are an electrode with positive and negative poles, separators, and an electrolyte. A tightly enclosed space is essential to ensuring adequate performance and durability in a capacitor cell. When the temperature of the cell changes, the various substances sealed in the case (electrode, separators, electrolyte, gases enclosed during production, gases produced in use) expand and contract, causing the internal pressure of the cell to vary. The quality of the weld connections between the case and the cover, the cover and the positive terminal, and the end of the case and the negative terminal are particularly important to ensuring reliability with regard to pressure. The case and case cover have been verified as units to be resistant to pressures of more than 4 MPa and 5 MPa respectively. The welded sections have a margin of mechanical strength, and the strength of the seal is verified during the production process.

The bottom of the cell has been provided with a pressure release valve to guarantee safety when unexpected increases in pressure occur, such as might occur if the cell were thrown into a fire. The pressure resistance of the cell is dependent on the strength of the structural materials in the case and case cover and the strength of the welds. Consideration of the behavior of the valve when opened led to the establishment of the production conditions described below. The maximum internal pressure is determined by the volume of gas produced in the cell until the end of its life and the amount of space initially provided in the cell. Therefore, control of the amount of gas produced in the cell is the key to maintaining internal pressure within a fixed range. To reduce the amount of gas produced in the life of the new cell, impurities have been controlled in the electrode and electrolyte materials and conditions in the production process (temperature and moisture) have been strictly controlled.

7.2. Cell Durability

As Fig. 9 shows, the newly developed capacitor demonstrates excellent durability with little decline in performance in life tests based on hypothetical environmental conditions for actual automotive use. This characteristic is due to the principle of electric double layer capacitor, as described in section 2 of this paper.

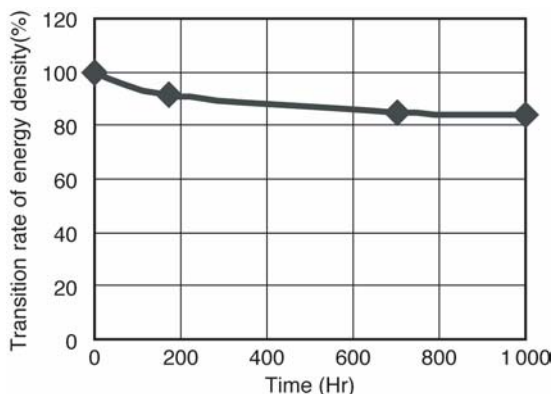


Fig. 9 Life test of Honda Ultra capacitor cell

7.3. Vibration Resistance

Vibration resistance is one of the mechanical characteristics demanded of an automotive energy storage device. During operation of the vehicle, the energy storage device is subjected to amplified and attenuated vibration and shocks, and the load on the unit increases in proportion to its own mass. Sufficient vibration resistance is attained when the device is stably fixed to withstand increased loads, and possesses sufficient resistance to inconsistencies in the mechanical structure (such as issues in electrical conduction or shorting) from occurring. The new capacitors feature collector plates welded onto the electrode collectors. The storage elements are fixed in place by the inner case and the case cover through the intermediary of the welded sections of the electrode collector and the collector plates. The load on these connections is hypothesized as the total mass of the electrolyte and electrode elements multiplied by the acceleration occurring in the holding structures.

The capacitor cells were subjected to vibration tests to verify the mechanical strength of the connection structure. Acceleration settings in vibration tests vary according to the type of vehicle and position of installation of the unit. In the tests of the new cell, the cells were subjected to accelerations in excess of twice those actually measured in the position in which the unit is installed in the FCX. No change in resistance or capacitance was recorded after the tests, verifying the applicability of the cell structure to automotive use.

8. Summary

The development project for the capacitor cell for the Honda FCX established the achievement of low resistance and high energy as its aims. Optimization of the collector structure and the method of connection with the terminals have resulted in the achievement of an internal collector connection resistance of less than 0.05 mΩ and an electrode fill density of 86%.

Individually, the capacitor cells demonstrate the highest specific power density (1,500 W/kg) and specific energy density (3.9 Wh/kg) known to date.

9. Conclusion

The newly developed capacitor cells were installed in the FCX, which has already been produced for the market. Using the new low resistance internal cell structure and electrode fill density design as a base, future development will attempt to respond to demands for increased capacitance, and expand the potential range of application of the cell as an energy storage device to a greater number of vehicles.

In conclusion, the authors would like to express their sincere thanks to the many individuals, in Honda and other companies, who generously offered their assistance during the course of the development project.

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