Current Development Status of Key Technologies for Solid Oxide Electrolysis Cell

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As the global energy transition to realize a carbon-neutral society is accelerating, hydrogen has come under the spotlight as a fuel, as well as the energy or feedstock for chemical synthesis and other industrial applications. Mitsubishi Heavy Industries, Ltd. is also working to develop various types of hydrogen production equipment. We are developing high-temperature steam electrolysis, which is the most efficient method to produce green hydrogen by electrolysis of water and steam using green electric power, aiming at commercialization in the latter half of 2020s.This report presents the current development status of key technologies, focusing on the results of cell stack test.

1. Introduction

Solving global warming problems is critical to humanity. In October 2020, along with the growing momentum of international climate action such as the Conference of the Parties (COP) to the United Nations Framework Convention on Climate Change, the Japanese Government declared its intention to achieve “carbon neutrality” by reducing greenhouse gas emissions to net zero by 2050. Mitsubishi Heavy Industries, Ltd. (hereinafter referred to as MHI) aims to achieve a carbon-neutral society in a realistic and speedy way, while minimizing social costs by promoting energy transition of existing thermal power generation facilities.

The promotion of renewable energy use alone does not realize the achievement of a carbon-neutral society. Energy storage technologies also have to be introduced to balance power output fluctuations. In general, lithium batteries are advantageous for storing energy for a short period of time, but for a relatively long period of time, such as days or weeks, it is considered necessary to convert it into chemical energy such as hydrogen, which can be stored and transported.

Since the 1980s, MHI has been engaged in developing products based on chemical energy conversion technology such as solid oxide fuel cell (hereinafter referred to as SOFC), polymer electrolyte fuel cell (PEFC), and hydrogen production by water electrolysis using proton exchange membrane (PEM). One of our strategies under these circumstances is to further advance SOFC technology to enable its Solid Oxide Electrolysis Cell (hereinafter referred to as SOEC) application, which efficiency is incomparably higher than other electrolytic hydrogen production systems. Commercialization should be realized in the late 2020s, matching the time when the demand for hydrogen is expected to start increasing sometime around 2030.

Moreover, with SOEC, carbon dioxide and steam can be simultaneously decomposed to produce hydrogen and carbon monoxide (co-electrolysis). This means that it is possible to produce feedstock gases for the synthesis of sustainable aviation fuel (hereinafter referred to as SAF) and e-fuel. We are also working on the development of this co-electrolysis technology.

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This report describes our current development status of key technologies for SOEC. The electrolytic hydrogen production technology and the synthetic fuel production technology are indispensable for achieving a decarbonized society, and can be realized by the application of SOEC.

2. Outline of SOEC

Having worked on the development of SOFC since the 1980s, MHI commercialized a 250kW class SOFC-MGT (Micro Gas Turbine) hybrid system and delivered to customers. Our current focus is on further development of this SOFC technology to enable its SOEC application as soon as possible.

In SOEC, part of the energy necessary for steam electrolysis can be supplied as heat. Therefore, electrolysis efficiency, which is expressed by the heating value of hydrogen produced divided by the amount of electric energy input, is advantageously higher than low-temperature water electrolysis.

MHI's original tubular type SOFC/SOEC cell stack has a structure that is generally considered to have less leakage compared to the stacked flat plate type that is widely adopted around the world. This is because the seal part which isolates the flow path of hydrogen and steam from the flow path of air, is only circumference of the cell stack at both ends. Moreover, it has the robustness to withstand the temperature distribution of several hundreds °C in the longitudinal direction of the cell stack. Taking advantage of this temperature distribution, the current density (current per unit area of electrolysis element) can be greatly increased and the output density can be increased.

Figure 1 shows the structure of a tubular type cell stack, which is the most important component of SOEC. Cells are formed on the surface of a gas-permeable ceramic substrate tube, which is a structural member. While electrolysis occurs in each cell (which consists of layers of hydrogen electrodes, electrolytes and air electrodes), an electron-conductive ceramic interconnector is positioned between the cells to connect them in series. Several hundred of such cell stacks are then bundled together to form a cartridge. Cartridges placed in a container is called a module. As illustrated by its conceptual diagram (**Figure 2**), the SOEC hydrogen production system is comprised of the SOEC module and the auxiliary equipment such as the recirculation blower.

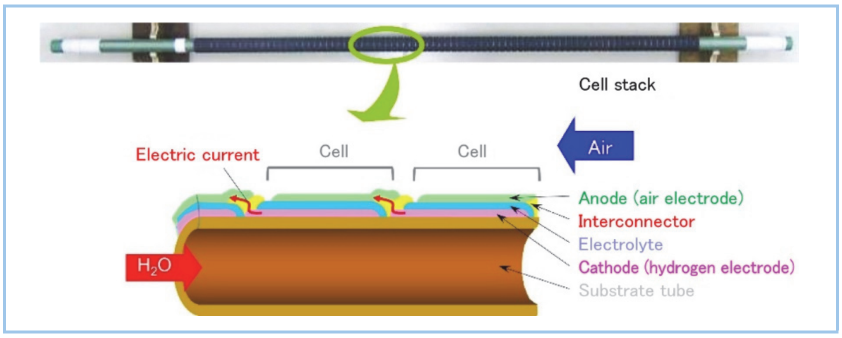


Figure 1 Cell stack structure

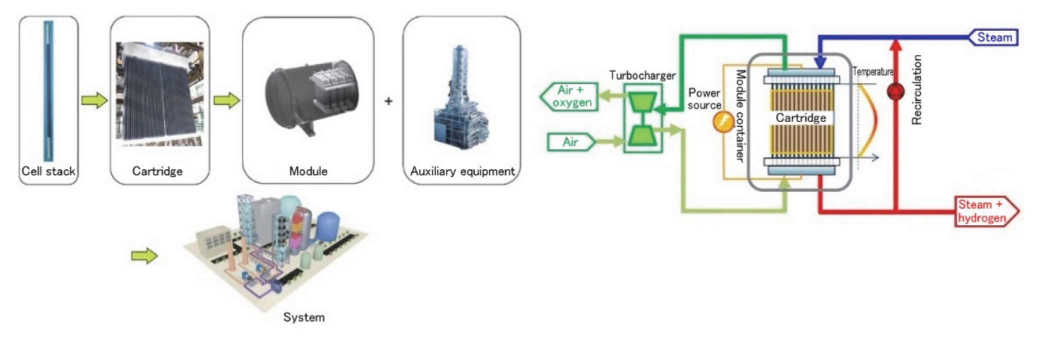


Figure 2 SOEC system configuration

At present, the SOEC demonstration equipment which remodeled the cell stack and cartridge basic structure of SOFC, has already been in operation at Takasago Hydrogen Park since March 2024. To enhance the marketability of SOEC with an increased output density, we are conducting the essential test of system elements, numerical analysis, improvement of system configuration, and development of a new SOEC cell stack. This report mainly presents the cell stack and cartridge test results of SOEC hydrogen production, and the results of co-electrolysis system cell stack test.

3. Current development status of key technologies

Figure 3 shows the element testing equipment, which is currently in use for electrolytic performance test, durability test and co-electrolysis test. The cell stack, when bundled as a cartridge, can compensate for its heat loss because of the heat received by the surrounding cells. When the single cell stack is tested alone, it does not compensate the heat loss to the surroundings. Therefore, in this testing unit, the cell stack is heated by the electric heater from the outside. Described below are some examples of the test results and our up coming development plan.

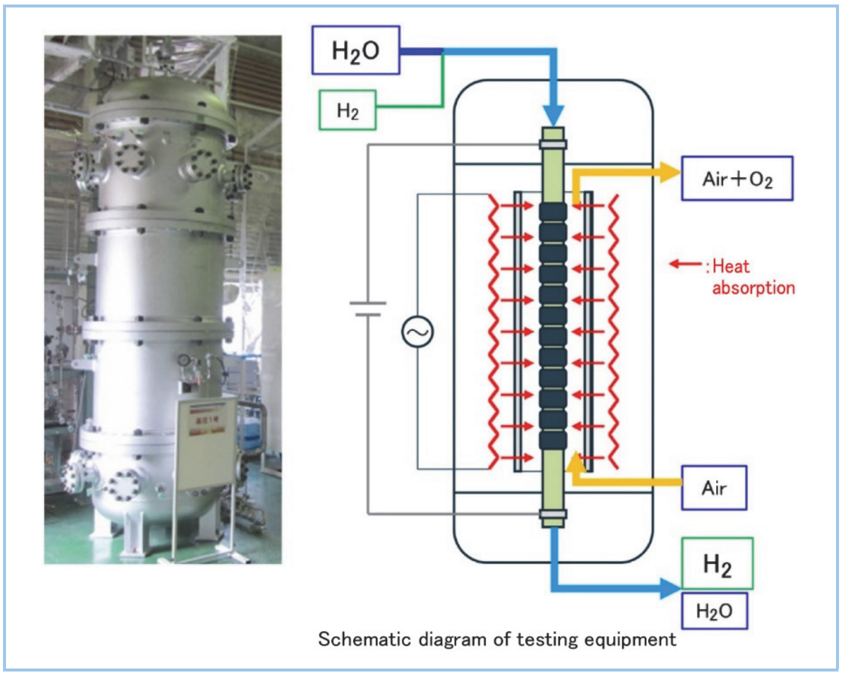


Figure 3 SOEC system element testing equipment

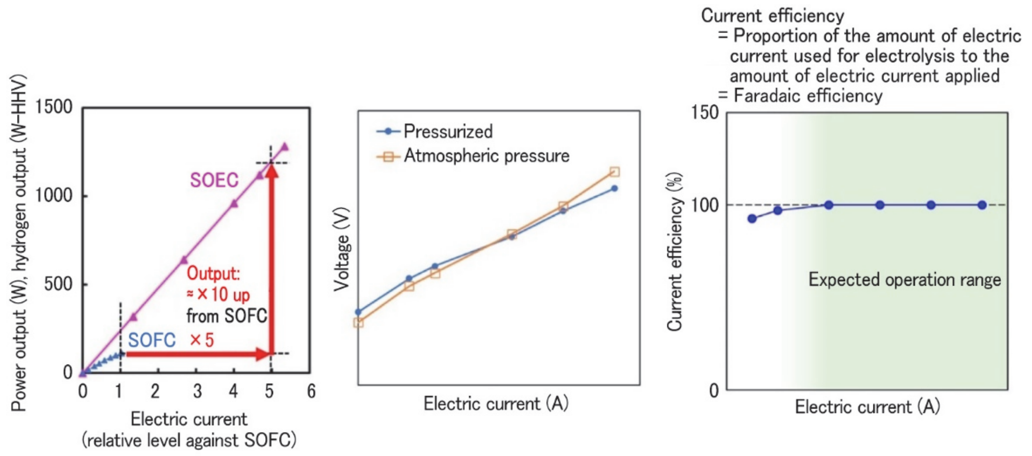
3.1 Hydrogen production (high-temperature steam electrolysis)

(1) Results of electrolytic performance test using single cell stack

Figure 4 shows the comparison of the SOEC electrolysis test and SOFC power generation test using the latest SOFC cell. In the SOEC system, the current density can be increased by about five times compared to the SOFC system. The hydrogen output based on higher heating value (HHV) at this increased current density is expected to be approximately 10 times greater than the power output of the SOFC system, as shown in Figure 4(a).

The pressure dependence was also tested (Figure 4(b)) and the impact of pressure on the performance (I-V characteristics) was investigated. Based on these test results, we are studying the appropriate electrolysis operating pressure that will be suitable for marketable pressure requirement by combination with hydrogen compressor.

Figure 4(c) gives the results of current efficiency measurement. Current efficiency is an indicator of how effectively the charge (current) input to SOEC is used to produce hydrogen. It is expressed by the ratio of the amount of actual and theoretical generation of hydrogen. In our tubular type SOEC, as the hydrogen/steam is isolated from the air/oxygen by a dense membrane, almost no hydrogen leaks into the air side. Since the applied current is used for electrolysis with little loss (a tiny portion is lost as leakage current), the current efficiency is nearly 100%. As indicated by the test results, the impact of leakage current and/or hydrogen crossover can be observed at low current levels when the amount of electrolysis is small. However, as the current increases, leakage ratio diminishes and the current efficiency approaches 100%.



(a) Comparison with SOFC (b) Pressure dependence (c) Current efficiency

Figure 4 Steam electrolysis – element test results

(2) Results of durability test using single cell stack

Figure 5 shows the results of the durability test at the same current level as the SOFC system. After 15,000 hours of electrolysis, the voltage rise rate (= degradation rate) was confirmed to be within the acceptable limits, and the result showing the high durability was obtained. A total of 10 heating cycles were conducted during the 15,000-hours durability test period and no noticeable degradation related to the heating cycles were observed.

Figure 6(b) is a photograph of the cell stack appearance after 15,000 hours of test. According to the visual inspection, no changes are observed before and after the test. There is no detachment or cracking of electrodes, nor any increase in the amount of hydrogen/air cross-leakage. Microstructure observation of the functional membrane will be carried out on the cell stack after 15,000 hours, and the existence of the change from the initial state will be analyzed.

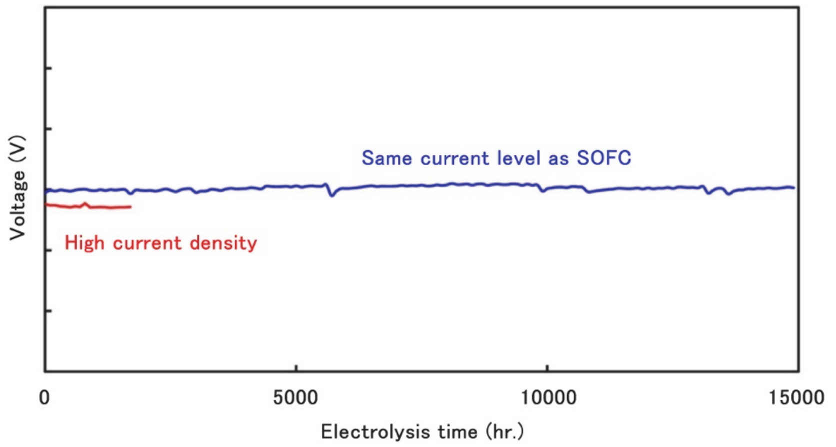
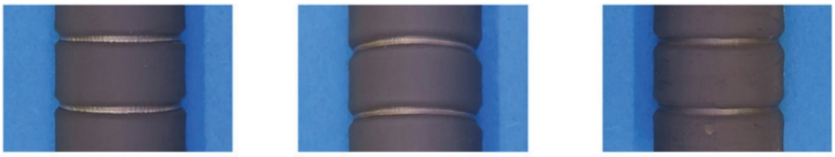


Figure 5 Durability test results



(a) Before testing (b) After 15,000 hours (with same current density as SOFC) (c) After 1,800 hours (with high current density)

Figure 6 Cell stack appearance photographs

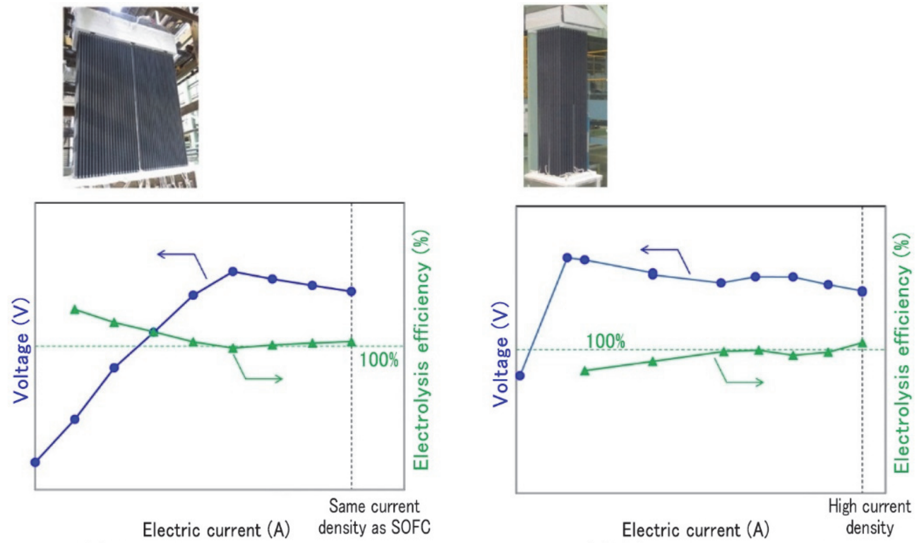
The durability test with high current density was also conducted. In this test, the current efficiency dropped after about 1,800 hours, although the electrolysis was stably continuing. As there was a possibility of leakage or cell stack damage, the test was terminated to investigate the situation and is currently under examination. Figure 6(c) is a photograph of the cell stack's appearance after 1,800 hours of test. No abnormalities are observed in the cell stack by visual inspection. Micro defects are suspected to have occurred somewhere in the cell stack, and the microstructure is under examination. The cause of current efficiency drop is hypothesized such as, increase of electrolytic reaction and/or higher temperature due to the increased self-heating, which are collateral effect of high current density. We have just started further durability test under the conditions in which the temperature can be kept at the appropriate level. The results will be reported accordingly.

(3) Cartridge test

Two types of cartridge test were also conducted.

Figure 7(a) shows the results of electrolysis at the same current density level as the SOFC system using a cartridge with the same structure as SOFC. It has been confirmed that the electrolysis efficiency, which is the ratio of the heating value of hydrogen produced to the power applied to the cell stack, exceeds 100% on a HHV basis.

Another cartridge test with a high current density was also conducted. In this test, the number of cell stacks constituting the cartridge is reduced to 1/4, due to the constraints of the testing equipment. It has also been confirmed, as expected, that the hydrogen output is about 10 times greater than the SOFC power output, and the electrolysis efficiency exceeds 100% (Figure 7(b)) .



(a) Full cartridge test results
(same current density as SOFC)

(b) 1/4 cartridge test results
(high current density)

Figure 7 Cartridge test results

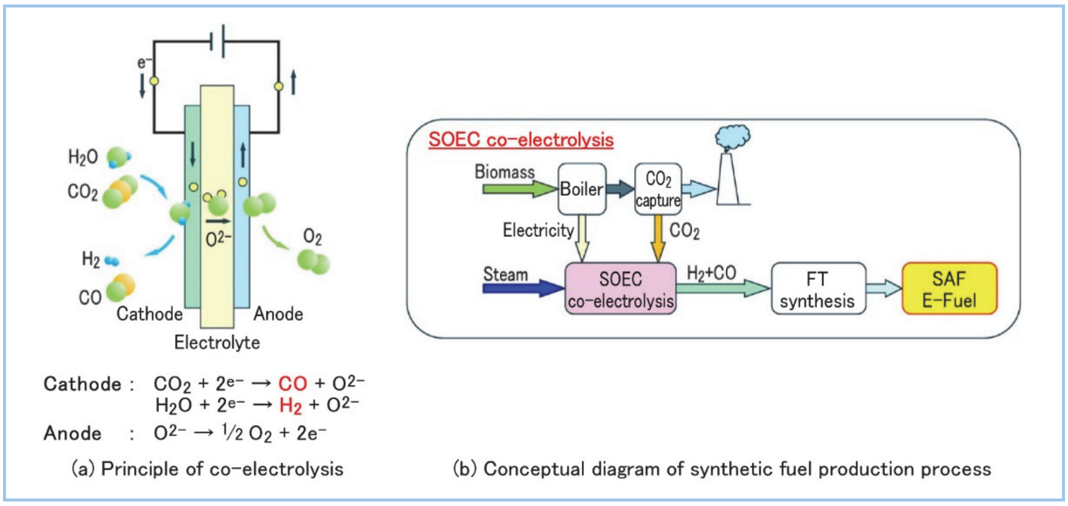
3.2 Co-electrolysis

In the SOEC system, hydrogen is produced by electrolyzing steam. It also can produce hydrogen and carbon monoxide, which are feedstock for synthetic fuel, by electrolyzing a mixture of steam and carbon dioxide (co-electrolysis). **Figure 8** shows the operating principle of co-electrolysis and a conceptual diagram of the synthetic fuel production process. As shown therein, the process is simplified because the feedstock can be produced by a single piece of equipment. It is considered that the high yield synthetic fuel production by the utilization of high-efficient SOEC becomes possible. Therefore, we are working on the development of both co-electrolysis in conjunction with hydrogen production.

In this co-electrolysis system, the internal reforming function, which is a key feature of our tubular cell stacks, is successfully functioning. Our cell stack developed for the SOFC system, natural gas or city gas can be supplied as fuel directly without using a reformer. That is to say, the catalyst component contained in top/bottom part of the cell stack materials and the recirculated steam are utilized to internally reform fuel gas into hydrogen and carbon monoxide, which are then used for power generation. This internal reforming function is utilized to perform co-electrolysis efficiently.

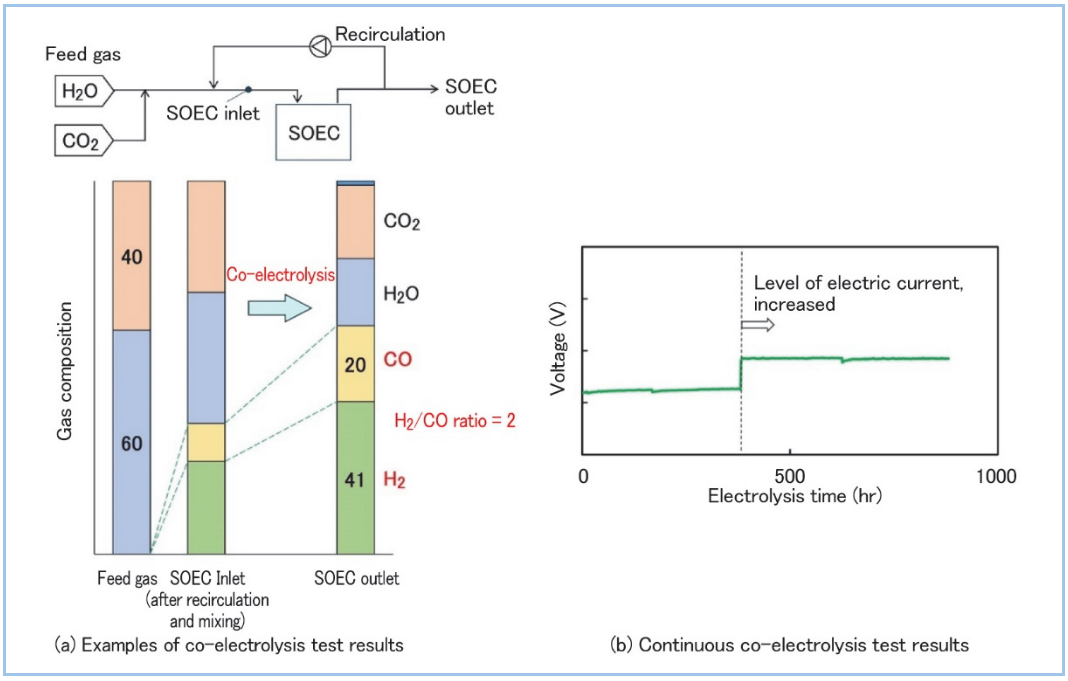
The gas produced by co-electrolysis shall satisfy the required proportion of hydrogen to carbon monoxide for the suitability to undergo Fischer-Tropsch (FT) synthesis. In general, the 2:1 ratio of hydrogen to carbon monoxide is considered suitable. In SOEC co-electrolysis, it was confirmed by the element test that the ratio can be adjusted for FT synthesis by the appropriately control of the parameters such as the feed gas composition and recirculation ratio (**Figure 9**(a)).

The continuous co-electrolysis test was conducted for a relatively short time period of about 900 hours (Figure 9(b)). No noticeable degradation was observed in the cell stack, during this test period. We will further drive the development forward with element test, simulation, and process improvement.



(a) Principle of co-electrolysis (b) Conceptual diagram of synthetic fuel production process

Figure 8 Operating principle of co-electrolysis and conceptual diagram of SAF synthesis process



(a) Examples of co-electrolysis test results (b) Continuous co-electrolysis test results

Figure 9 Co-electrolysis test results

4. Conclusion

This report presents our current development status of key technologies of high-efficiency SOEC system, which pertains to the development of hydrogen production and synthetic fuel production systems, for the carbon neutrality.

In view of the advent of a full-fledged hydrogen society, we will further drive the development, for early commercialization and contribute to the achievement of carbon neutrality in our company and the world.

“Hydrogen Is Not the Future, This Is Real.”

References

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