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< DEVELOPMENT OF A RESIDENTIAL SOFC CHP SYSTEM>

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1. Abstract

In this study, we developed a residential-use solid oxide fuel cell (SOFC) cogeneration system with the following characteristics.

・ High energy efficiency

The electric power efficiency of the system at the rated power is 46.5% LHV. To the best of our knowledge, this is the highest existing power efficiency for a commercialized residential combined heat and power (CHP) system. The overall energy efficiency amounts to 90% LHV.

・ High CO_2 reduction and lower running costs

Compared with the emissions of a house using conventional grid power, customers using the SOFC CHP can reduce their annual CO_2 emissions associated with household power usage by approximately 1.9 tons. In our trial calculation for a typical household, the SOFC saved 90,000 yen per year.

・ High salability due to compactness

The installation space required is a mere 1.9 m^2, which is industry-leading in terms of space saving. It can be installed in narrow spaces, which is an important advantage in urban areas and apartment buildings with limited space.

・ Development a system with a ten-year operation life

During the development stages, one of our main goals was to improve the durability and reliability of our product. Our aim was to develop a system with a ten-year operation life and a start-to-stop heat cycle tolerability of 360 cycles. To assess our proposed solutions, we performed durability evaluations of the materials, stacks, and SOFC generator units under accelerated conditions. We attempted to clarify the effect of the specification changes of the developed stacks over short time periods. The advanced ceramic coating on the metal current collector was selected from hundreds of potential materials. Over 100 samples were tested simultaneously under varied temperature and current density conditions. In addition, field tests were conducted at more than 100 residential houses. The results demonstrated the required reliability and durability were achieved for commercial products.

・ High reduction of electric power consumption due to high load flattery characteristics

By consecutive running with high load flattery characteristics, the SOFC system can generate 80% of the electricity used by an average Japanese household, thus reducing demand from the power grid. Moreover, we also developed a new function that allows grid-independent operation in the event of a power outage.
The following characteristics are under development now.

・ Increase applicability to the residential market

High power efficiency, compatibility with various fuels, and elimination of the need for expensive and precious metal catalysts are means of increasing applicability to the residential market. Due to the simplicity of the auxiliary machinery composition, there is great potential for cost cutting.

・ Improve suitability for use in small businesses.

High generation efficiency and adaptability to a wide range of power generation scales are both necessary to improve suitability of the SOFC CHP system for use in small businesses with minimal power consumption.

CONTENTS

2. PAPER

2.1. Introduction

In residential homes, highly efficient energy use can be achieved by installing a residential CHP system, as heat produced by power generation can effectively be used to meet hot water demand. Osaka Gas began commercializing gas engine type “Eco Will” system in 2003 and the polymer electrolyte fuel cell (PEFC) type Ene Farm in 2009, through a joint development with manufacturers, achieving a combined total sales of 70,000 units by the end of 2010. Osaka Gas began joint development of the residential solid oxide fuel cell (SOFC) combined head and power (CHP) system with Kyocera in FY2004. In November 2005, we conducted operational testing at a residence and achieved a high power generation efficiency of 49% (net AC, LHV). We demonstrated the highest electric efficiency residential CHP system for actual in-house operation1). Two attractive features of SOFC were also demonstrated; one is its high power efficiency and the other is its compact size and cost reduction potential due to a simplified fuel treatment and cooling system. For the system to fit in a conventional Japanese urban house, we developed and installed a compact SOFC power generation unit in four houses at the end of 2006. From September 2007, Osaka Gas enlisted in the Solid Oxide Fuel Cell Demonstration Project, managed by New Energy and Industrial Technology Development Organization and NEF, installing the SOFC in a home and condominium within the Osaka Gas service area, in order to verify its energy-saving property and long-term reliability2). From 2009, we commenced a new joint development with Osaka Gas, Kyocera, Toyota Motor, and Aisin Seiki.

In April 2012, commercialization of the SOFC-type residential CHP system “Ene Farm type S” (see Figure 2 and Table 1), was launched. Aisin Seiki manufactures the SOFC power generation unit, and the hot water supply and heating unit, which uses waste heat, is manufactured by Chofu Seisakusho.

The most significant technical challenge for commercialization was durability. The Osaka Gas conducted durability verification of a large number of units, as well as longtime testing for stacks, material, and SOFC generation units, in order to establish a ten-year life time. Specification for the residential SOFC CHP system, Ene Farm type S, and durability verification are introduced in this report.

Table 1. Specifications of the residential CHP system

	Gas engine	PEFC	SOFC
Trade name	Eco will	Ene-Farm	Ene-Farm type S
Electrical efficiency	26.3%	39.0%	46.5%
Heat recovery efficiency	65.7%	56.0%	43.5%
Heat/ Power ratio	2.5	1.2-1.3	0.9
Operating mode	SS（Start and Stop）	Continuous, DSS	Continuous
Sales launch time	launched in 2003	launched in 2009	launched in 2012

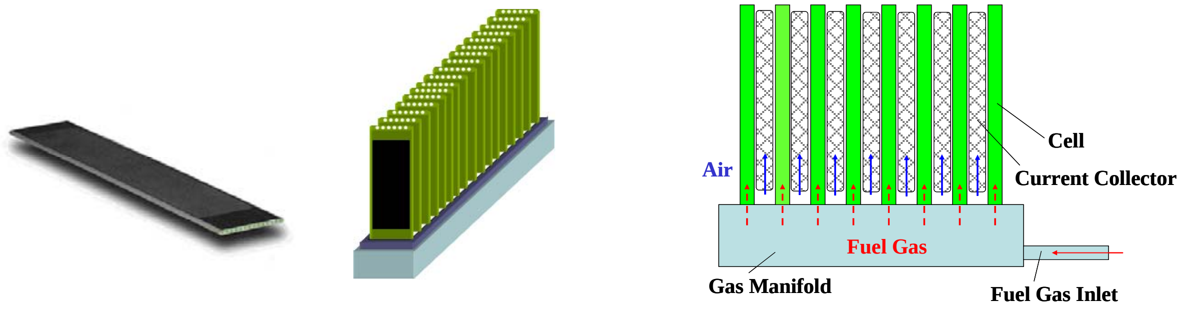
Efficiency: at rated power, LHV basis

2.2. Configuration of a residential SOFC CHP system

2.2.1 Cell, Stack, and Module

Figure 1 shows a SOFC cell stack. The cell type is a flat tube with a ceramic interconnection film. After optimization of the components, the cell delivers high performance at low temperatures (about 750 °C). Fuel gas flows inside the cell and air flows outside. The bottom of cell is sealed and fixed to the manifold. Due to its self-sealing cell and stack structures, such stacks are relatively robust to temperature changes. Such toughness is crucial for small applications, particularly for residential applications.

In a SOFC module, stack, reactor, vaporizer, and heat exchanger are thermally integrated, consisting of both exothermic reaction and heat exchange components. Fuel is partially steam-reformed at the reactor and supplied to each cell. The rest of fuel is combusted with air at the open-ends of the cells. This combustion heat and joule heat of the stack are used for steam generation and reforming, thus providing the SOFC high power efficiency. The side wall of the module is used as a heat exchanger between the air and exhaust gas. The air flows inside after being preheated, thus enabling high thermal efficiency and independent thermal operation.



(a) SOFC cell (b) Stack (c)Schematic of the cell stack

Figure 1. Features of a SOFC cell stack

2.2.2 SOFC generator unit and Heat recovery unit

The residential SOFC CHP system consists of a SOFC generator unit and a heat recovery unit. Figure 2 shows the FY2014-type SOFC CHP system. The SOFC generator and heat recovery units are on the left-hand and right-hand sides, respectively. The SOFC generator unit includes a hot module, auxiliary parts, and a power conditioner. The auxiliary parts include a blower, flow meters, piping, and sensors. Parasitic power consumption is low because of the small pressure drop of the module and recent developments in auxiliary parts technology. Heat recovery in a SOFC generator unit is very simple and is composed of only the heat exchange between the exhaust gas of the SOFC module and water. Improving the heat exchanger in a SOFC generator results in the amount of drain water from the SOFC exhaust gas being sufficient for steam reforming. AC power from a SOFC generator unit is automatically changed between 700 W and 50 W, according to the electric demand of the house, assuming that reverse flow to the grid is prevented. The system operation is conducted in continuity, with few exceptions, and not as a daily start and stop operation. The exhaust heat is collected in the hot water tank of a heat recovery unit. Between the heat recovery unit and the SOFC generating unit, a telecommunication facility is installed. Energy saving information and classified failure information of a SOFC system are displayed at the heat recovery unit’s remote control unit, which is generally located in the kitchen. To enable maintenance from one direction, the internal structure of the SOFC generator unit was reviewed. Thus, the necessary space required for installation and maintenance was minimized for the residential CHP system.

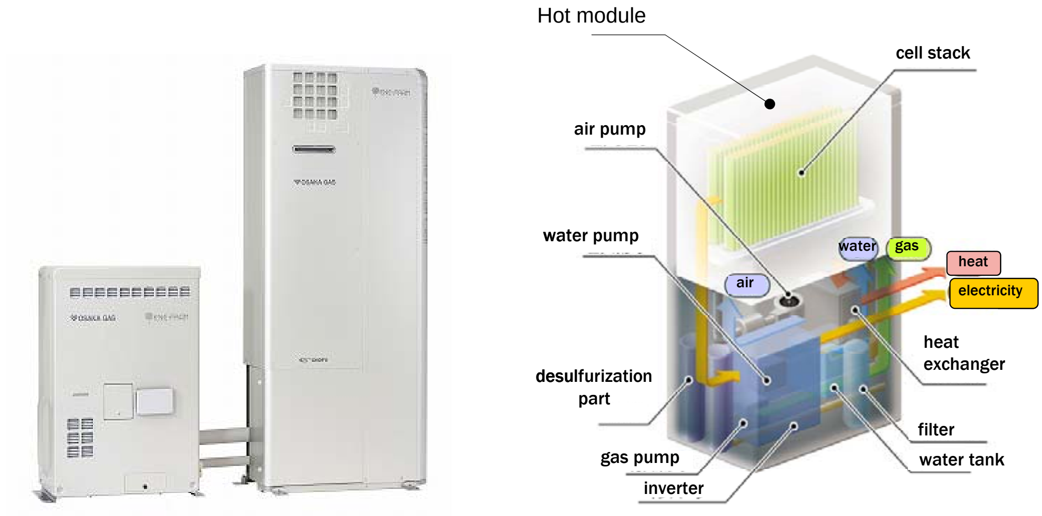


Figure 2. Residential SOFC CHP system
Left: Ene Farm type S, Right: Schematic of the SOFC generator unit

Table 2. Specifications of the Ene Farm type S

Dimensions	935 mm × 600 mm × 335mm
Weight	94 kg
Power Output	700 W (rated)–50W
Electric efficiency (rated)	46.5% (LHV)
Heat recovery efficiency	43.5% (LHV)

2.3 Durability target and verification

2.3.1 Durability target

In the stationary fuel cell system, 40,000 hours is the general criterion for implementation. However, in the small class stationary system—for example, a residential CHP system—a five-year lifetime for the stack less than ideal for a commercial product. Maintenance and overhaul costs must be minimal for a small stationary system. Our target lifetime is ten years. For the SOFC generator unit, operation time for a year is more than 8,000 hours. Factors such as operation time, number of start–stops, and number of shut-offs for fuel gas and grid electricity must also be considered as a precondition of lifetime.

Design of the hot module and control of the power generating unit are important factors affecting product life time. In general, the SOFC system cools its stack by reaction gas, i.e., fuel gas and air. Since no additional parts are required, this may be an advantage in terms of downsizing and lowering cost; however, maintaining appropriate temperature distribution is a problem. Long term measurement of the temperature distribution of stack was effective.

As mentioned previously, the initial performance of the system was successfully demonstrated in FY2005; however, at that time, the gap between the target durability and its actual capability was significant. Osaka Gas has evaluated predominantly long time durability for stacks and SOFC generating units. Because assessing the latest specification-type stacks in real time is difficult, we performed evaluation by 1) long-term testing of former specifications to establish criteria for relatively evaluating the durability of the improved specifications, 2) conducting a large number of evaluations using the accelerated tests available, and 3) adding items that permit engineering, such as temperature control, in the power generating unit.

2.3.2 Component durability test

Accelerated test for the whole SOFC stack is not easy because of the interrelation and restrictions caused by plural factors. However, at a component level, accelerated testing by temperature, among other factors, is available. With regard to current collectors, which are made out of coated stainless steel, we tested resistance over various conditions using approximately 100 samples simultaneously. Using an Arrhenius plot, we evaluated its lifetime at the standard temperature. In addition to oxidation resistance, we also evaluated Cr poisoning degradation using a coated alloy and single cell. We confirmed a lifetime greater than ten years for the current collector.

2.3.3 SOFC stack long-term durability test

Figure 3 shows the stack durability testing units at Osaka Gas. We evaluated the relation between conditions (temperature, current density, and specification) and durability performance using a stack with half the number of cells mounted on the residential 700 W system. In this test, we produced similar fuel gas composition at the stack inlet in the power generating system by desulfurizing city gas to mix it with steam and the reforming catalyst prior to being supplied to the fuel side of the stack. Figure 6 shows the results of cell stack durability test after FY2005. The stacks were set in the electric furnace, and the furnace was controlled at a set cell stack temperature of 750 °C. Pipeline natural gas, with a steam carbon ratio of 2.5, was used as fuel. Improvements on this have been made every fiscal year, and degradation for the FY2010 stack is half that of FY2008 specifications.

Figure 3 Stack durability test units.

2.3.4 Power generating unit durability test

Durability data was obtained using field tests for 121 units in the Solid Oxide Fuel Cell Demonstration Project. Some FY2008 demonstration units are still operating without stack exchange; the longest operation time as of May 2014 was 45,000 hours. The power generation efficiency transition of units is shown in Figure 5. This result extracts the rated power performance data. The data in Figure 4 which shows the durability of the stack voltage also shows the durability of the power generation unit.

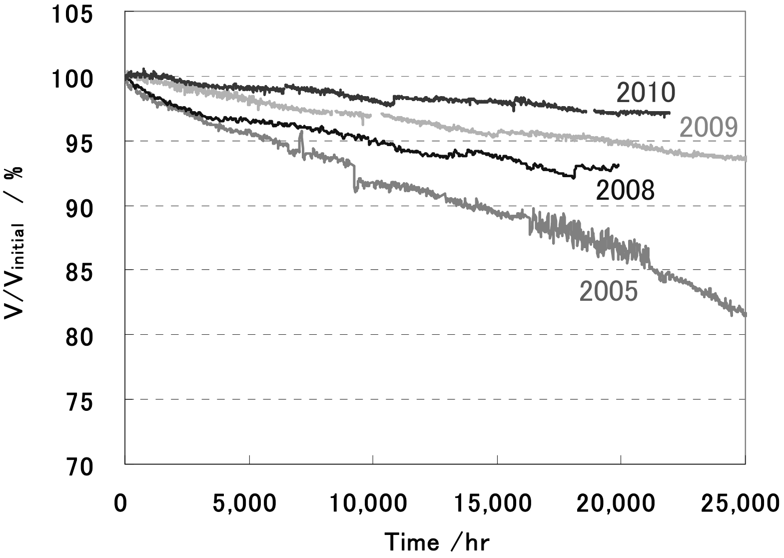


Figure 4 Durability test of SOFC stacks.

From these results, we judged that the durability of the SOFC power generation unit using the latest stack, hot module design, and control reached our durability target.

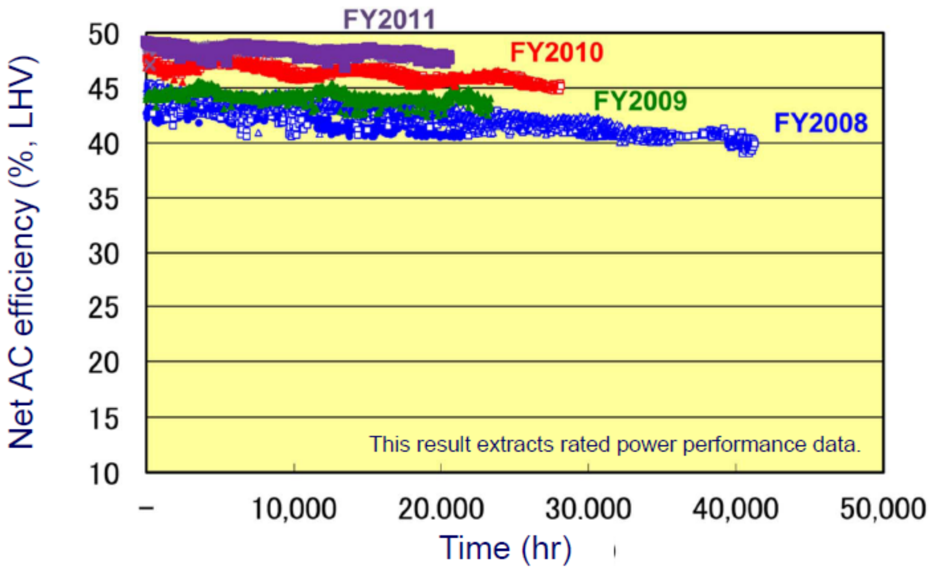


Figure 5 Net AC efficiency trends for residential SOFC CHP systems installed in houses in FY2008-FY2011.

2.4 Recent development trends for Ene Farm type S

2.4.1 Improvement after commercialization

We released the residential SOFC CHP system, Ene Farm type S, in April 2012. In April 2014, we released a cost-reduction model for further promotion, which possessed improved quality, with the additional capability of operation during a blackout.

2012 model	2014 model
Commercialization model	Cost reduction model
	

Figure 6 History of the commercial model

2.4.2 Development of new model (2014 model)

With these field tests, the durability and reliability data enable us to reduce and stretch the lifetime of the periodical replacement components, making it possible to reduce cost.

In addition to the cost reduction of major components such as the SOFC stack, simplification of the device contributed to cost reduction, which have enabled a selling price reduction of 20% in comparison with the conventional model.

We also achieved compatibility with LPG in addition to city gas.

Table 3 Specifications of 2014 and 2012 models

	2014 model	2012 model
Release Date	April 2014	April 2012
Adaptation gas	City gas, LPG	City gas
Maintenance period	5.5 years	3.5 years
Periodical replacement parts	Combustible gas sensor	Ion-exchange resin Combustible gas sensor Combustion catalyst
Suggested Retail Price	2,322,000￥ (8% consumption tax rate)	2,751,000￥ (5% consumption tax rate)

2.5 Conclusions

In an SOFC CHP system, we steadily improved the reliability and durability of the cell stacks, modules, and systems. From field tests at approximately 120 sites, we were able to verify that the system has a high capability for energy savings and can operate for over 45,000 h. We further determined that our SOFC CHP system has enough endurance reliability for ten years of actual usage.

We finished developing the SOFC CHP system and launched our sales campaign on April 2012. In April 2014, we released an improved model for further promotion, with a reduced sales price and an improved salability.

3. References

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