# DEVELOPMENT OF A RESIDENTIAL COMBINED HEAT AND POWER SYSTEM USING SOLID OXIDE FUEL CELLS

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## 1. Introduction

In order to address the causes of global warming, much effort has been made worldwide to utilize fossil fuels in a more efficient way and emit less greenhouse gases. A residential combined heat and power (CHP) system is an effective solution to reduce $CO_2$ emissions. Under these circumstances, Osaka Gas developed and commercialized the gas-engine-type residential CHP system, named “Eco-Will,” in 2003 and also released polymer electrolyte fuel cell (PEFC) systems, named “ENE-FARM,” in 2009.

One advantage of using solid oxide fuel cells (SOFC) in a CHP system is that they provide the highest generation efficiency among the residential CHPs. Another advantage is their simple configuration, which allows for a compact design. These advantages make SOFC-CHP systems a good choice for installation in small residential houses in urban areas, apartment buildings, and condominiums, thereby expanding the residential CHP market.

Osaka Gas has been developing SOFC systems in alliance with Kyocera since 2004, and with Toyota Motor Corporation and Aisin Seiki Co., Ltd. since 2008, aiming for commercialization. In 2005, Osaka Gas and Kyocera conducted the first SOFC demonstration test in Japan at a residential house using a 1kW-class (electric output) SOFC system, and we demonstrated that the system performed excellently in actual operation; for example, the system exhibited a generation efficiency of 49%LHV (net AC) [1]. Since then, Osaka Gas has installed SOFC systems into 121 residential houses from FY2007 to FY2010, under the Demonstrative Research on Solid Oxide Fuel Cells project conducted by New Energy Foundation (NEF) and New Energy and Industrial Technology Development Organization (NEDO), and we have accumulated data about energy savings and have improved the durability and reliability of the systems.

With promising results from tests in the field and in the laboratory, indicating that the target life time of the system is almost 10 years, we have now begun the final stage of developing the system for commercial use. This paper outlines the features of the SOFC-CHP system, the technology that was adopted, and the experimental data regarding energy savings and durability for the latest models.

## 2. Features of SOFC

### 2.1 Construction and specification

Figure 1 shows FY2010 type SOFC-CHP system. The SOFC-CHP system consists of a SOFC power generation unit and a heat recovery hot-water supply and heating unit. These units are connected by a communication link. A remote controller, which is usually installed on the wall of the kitchen, displays information concerning the temperature of the hot water, energy savings, and the current status of the system.

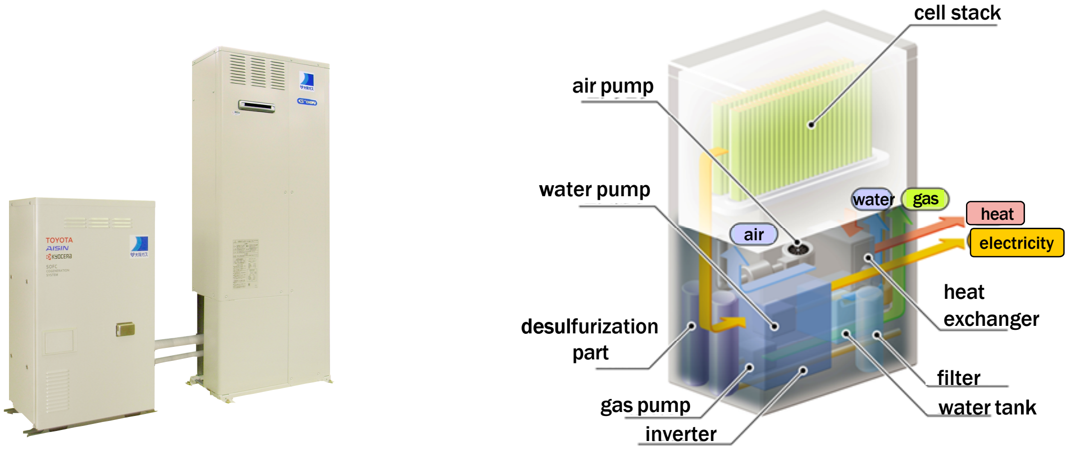

**Figure 1. Appearance of the SOFC-CHP system (left) and the main components in the power generation unit (right)**

The SOFC power generation unit includes an SOFC module, auxiliaries, and a power conditioner. The auxiliaries, which occupy the lower half of the unit, include pumps, blowers, flow meters, piping, sensors and heat exchangers for recovering exhaust heat. Compared with PEFC units, SOFC units have a simpler and more compact structure, because the fuel preprocessing part is compact and the unit contains fewer heat exchangers and needs less piping.

Table 1 shows the specifications of the SOFC-CHP system. The efficiency for power and heat recovery are 46.5% (LHV, net AC) and above 40% (LHV), respectively. The electric output varies between 50 W and 700 W during the load-following operation, which is the most efficient operation for the SOFC-CHP system in view of its partial-load efficiency characteristics. In order to fit Japanese urban houses, this system must be light-weight and have a short depth so that the space required for installation and maintenance can be minimized.

| SOFC power generating unit | |
|---|---|
| Dimensions (HxWxD) | 935 x 600 x 335 mm |
| Mass | 94 kg |
| Power output | 50～700W |
| Electrical efficiency | 46.5%(LHV) |
| Thermal efficiency | 40%(LHV) > |
| Frequency of periodic inspection | approx. 3.5year |

| Hot water supply and central heating system utilizing waste heat | |
|---|---|
| Dimensions (HxWxD) | 1760 x 740 x 310 mm |
| Mass | 94 kg (184kg, in operation) |
| Hot water storage capacity | 90ℓ |
| Hot water storage temperature | 70℃ |
| Supplementary boiler capacity | 41.9 kW |
| Heating capacity | 17.4kW |

**Table 1. Specification**

## 2.2 Cell Stack & Module

The cell stack consists of flat tube cells, metal current collectors, and a gas manifold, as shown in Figure 2. The cells are aligned in a series; one end of the cells is attached to the gas manifold using a glass sealing compound, and the metal current collectors are located between each of the cells and electrically connected. The flat tube cell configuration (Figure 3) has the advantages of low thermal stress and a good gas seal. In addition, because of the flexibility created by fixing one side of the cells and the flexibility of the metal current collectors, this stack structure can tolerate the displacement caused by temperature changes. This enables the electrical load-following operation and the start and stop cycles, which are very important for residential applications [2].

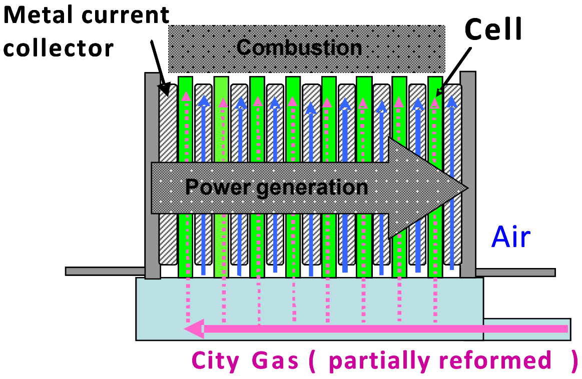

**Figure 2. Schematic drawing of the cell stack**

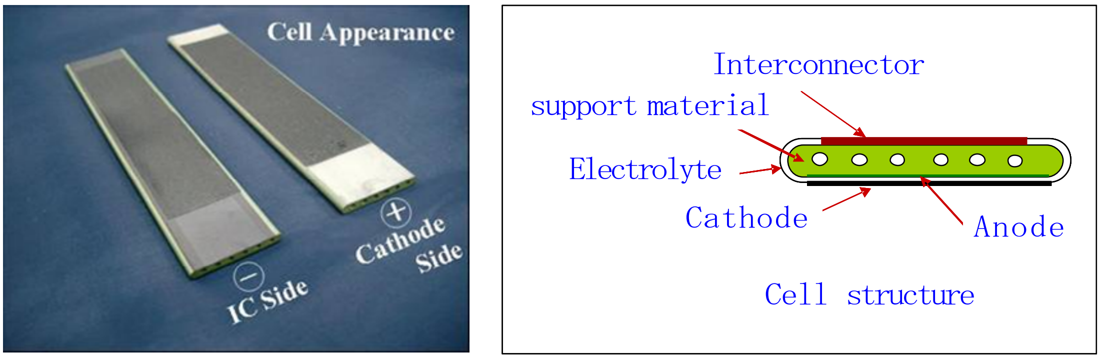

**Figure 3.** Appearance of the SOFC cell and a schematic drawing of the cross section

The SOFC module, which occupies the upper half of the unit, includes a cell stack, a heat exchanger, a water vaporizer, a steam reformer, and heat insulation materials. Air is heated by the exhaust gas with the heat exchanger and introduced to the bottom part of the cells. On the other hand, the fuel gas and the water for steam reforming are introduced to the vaporizer and the reformer, and they are heated by the resulting off-gas combustion. The fuel gas, reformed to hydrogen-rich gas that includes carbon monoxide, is fed to the manifold and distributed to all cells. Although most of the chemical energy of this anode gas is extracted at the rectangular electrodes of each cell as an electric current, the residual energy is consumed at the top of the cell by burning. As previously mentioned, this combustion heat in the exhaust gas is used to vaporize the water, reform the steam and heat the cathode air.

## 3. NEDO SOFC demonstration project and operation results

The purpose of the SOFC Demonstrative Research from FY2007 to FY2010 is to collect operation data under actual load conditions to assess the latest technological developments, identify technological issues, and clarify the future technological challenges. Osaka Gas took part in the project since 2007 and had installed about 120 units (see Table 2).

The installed system that ran the longest during FY2007 operated for 24,470h. Several systems installed in FY2008 ran more than 25,000h and still continue to operate as of December 31, 2011.

Table 2. Description of SOFC systems that Osaka Gas tested as part of the SOFC Demonstrative Research project.

| Year | FY2007 | FY2008 | FY2009 | | FY2010 |
|---|---|---|---|---|---|
| Manufacturer of power generating unit | Kyocera | Kyocera | Kyocera | Toyota & Aisin | Toyota & Aisin |
| Tested units at starting year | 20 | 25 | 12 | 23 | 41 |
| Longest run time* without stack exchange | 24, 700h<br>(finished) | 27, 500h<br>(continuing) | 19, 300h<br>(continuing) | 15, 900h<br>(continuing) | 10, 300h<br>(continuing) |

＊at the end of 2011

Figure 4 shows an example of the daily operation data of a SOFC system installed at a site that required a relatively small load. The data includes the house's demand load, the system's electric output, and the amount of heat stored in the hot water tank. As shown in this example, the power generation of SOFC can respond to the change of electrical load and cover a large portion of the electrical load. Even in this prolonged partial-load operation, the primary energy saving ratio and $CO_2$ emission reduction ratio per generated power were 20% and 38%, respectively.

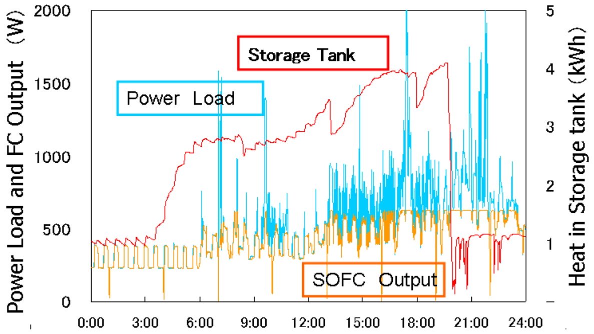

Figure 4. Daily power generation and heat utilization pattern (example)

Figure 5 shows the relationship between the $CO_2$ reduction efficiency and the power load at the demonstration sites installed in FY2008, FY2009 and FY2010. Each dot is the monthly average value at each site measured from November to December 2010. As shown in this figure, even under a relatively small power load (ex. 10kWh/day) conditions, the SOFC-CHP demonstrated good performance with respect to $CO_2$ reduction. These results demonstrate that the system substantially reduces $CO_2$ emissions even when operating under a relatively small load [3].

The comparison between the FY2009 and FY2010 prototypes reveals how the power efficiency of the FY2010 prototypes was improved. One reason for this improvement was the enhanced power generation efficiency, such as an enhancement in heat insulation and homogenization in the temperature around the cell stacks. The other reason is thought to be effect of enlarging the hot water storage tank from 70 L to 90 L, which enhanced the system's efficiency of storing heat.

Figure 6 illustrates the representative trends of power generation efficiency at rated power for each prototype installed from 2007 to 2010. As shown in this figure, although the electric efficiency of the FY2007 prototype dropped under 37% LHV at its end-of-life (24,700 h), the efficiency of FY2008 prototypes remained around 41% LHV even at 27,500 h. Therefore, durability was significantly improved from FY2007 to FY2008. Other prototypes installed after FY2008 also exhibited a good transition. A remarkable advancement is shown in the initial high electric efficiency of FY2010, more than 46% LHV, due to the previously mentioned improvement in SOFC modules.

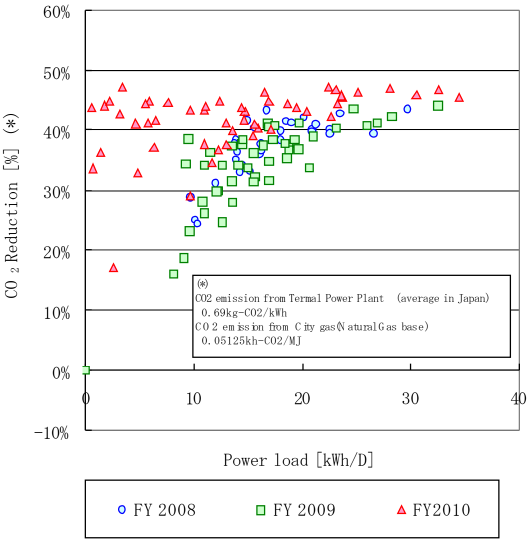

**Figure 5. Relation between CO$_2$ reduction efficiency and the power**

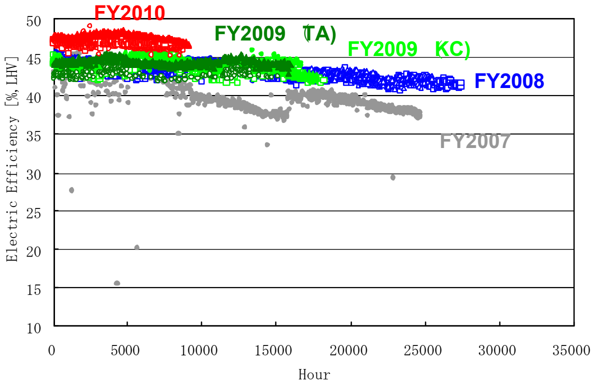

**Figure 6. Representative trends of electric efficiency at rated power for each prototype.**

## 4. Durability Test

Similar to other commercialized gas appliances in Japan, we have set the goal to develop systems that have an operation life of 10 years. In addition to the above field tests, Osaka Gas has executed in our laboratory durability evaluations of the materials, the stacks, and the SOFC generator units. Additionally, we have tested cell stacks under accelerated conditions using electric furnaces (Figure. 7). We have tried to clarify the effect of the change in specification of the developed stacks in a short period of time.

**Figure 7. Experimental facilities (Osaka Gas)**

Figure 8 shows the representative degradation of cell stacks developed in each year. The FY2008-type stack has less than half the degradation rate of the FY2005-type stacks. As shown in this figure, the degradation rate has been improved steadily year after year. Significantly, the degradation of the FY2010 stack was only 2% of its initial voltage at 5000 hours, and currently it has levelled out. This transition is well above the prediction curve, which was calculated from the degradation rate of the components, in view of the operating temperature. We estimated that the durability of the stacks has nearly reached our target for operational life.

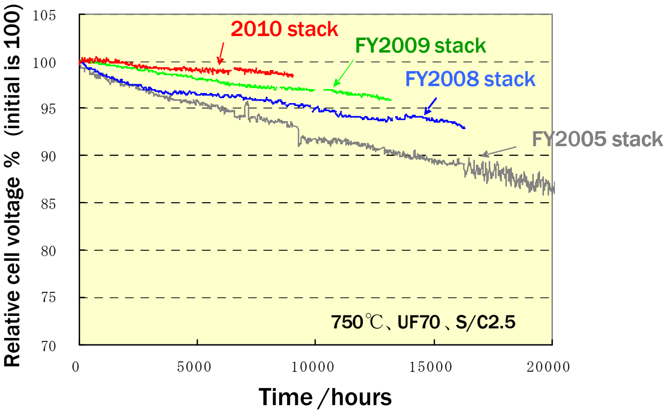

**Figure 8. Degradation of cell stacks fabricated in each fisical year.**

As for the SOFC power generation unit, in addition to field tests, we executed start- and stop-cycle tests and detailed internal measurement for the unit at our laboratory. After stopping and starting 360 times, the system exhibited no degradation either on the power generation efficiency or on the adjusted cell voltage, which was calculated from the stack temperature and the DC current.

With the promising results in the field tests and in our laboratory, as previously described, we recognized that we have nearly achieved the reliability and durability required for commercial products.

## 5. Conclusions

Since the first SOFC demonstration test in Japan, installed at an occupied residence in 2005, we have steadily improved the reliability and durability of cell stacks, modules, and systems, and we conducted many verification tests for our prototypes at many field test sites and at our laboratory. From the field tests at approximately 120 sites, we were able to verify that the system is capable of high energy-savings and operates more than 25000 hours. We have obtained positive results in the performance data during field tests as well as the data from test in our laboratory. Thus, we have become convinced that our SOFC-CHP system has enough endurance reliability for 10 years of actual usage. We will be able to commercially launch SOFC products in the very near future.

## 6. Acknowledgement

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## 7. Reference

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