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DEVELOPMENT OF A SMALL-SCALE SOLID OXIDE FUEL CELL (SOFC)

S. Kurachi

Y. Mizutani

T. Hiroyama

K. Katsurayama

F. Okada

and

K. Ukai

Fundamental Research Dept.,

Toho Gas Co., Ltd.

JAPAN

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ABSTRACT

Solid Oxide Fuel Cell (SOFC) systems are promising power sources since they provide the highest electrical conversion efficiency of the various kinds of fuel cell systems. Toho Gas has been developed the small-scale SOFC for residential and commercial applications.

In order to verify the possibility of small-scale SOFC systems, a 3kW-class SOFC power generation module was examined. The module consisted of two units of planar stacks, combustor, reformer, vaporizer, heat exchanger for air preheating, and startup burner, surrounded by thermal insulators. When the rated operation for about 200 hours, the module generated stable electric power of 3.1kW (DC) and the electrical conversion efficiency reached 56% (DC, LHV). The results indicated a potential of the small-scale SOFC system and showed that the system is expected to achieve 46% as AC electrical efficiency and 80% as overall efficiency.

For the small-scale SOFC for residential applications, flexibility such as load-following operation and daily start-stop operation is required. But SOFC has technological difficulties such as slow start-up operation because of the weakness to rapid temperature change due to the properties of ceramic cells. In an effort to solve such difficulties, compact and high power density stack through the integration of micro tubular cells as next generation SOFC was developed under the NEDO (the New Energy and Industrial Technology Development Organization of Japan) project called "Advanced Ceramic Reactor Project." One cubic centimeter bundle that was integrated from nine anode supported micro tubular cells which diameter is 2mm could generate electric power of more than 2W at a temperature of 823K. This was the world's highest level as power density at the temperature of less than 873K. And the robustness against rapid thermal cycle was achieved.

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1. Introduction

As the end of the first commitment period (2008 to 2012) of the Kyoto Protocol approaches, Japan is required to reduce CO_2 emissions by about 14% from its current emission level. There is thus a strong need for a multifaceted effort to reduce CO_2 emissions. Cogeneration systems are one of the effective solutions to reduce CO_2 emissions, and the systems with large generating power have been already introduced into the market. Meanwhile, the systems with small generating power for the consumer sector, such as those for residential and commercial applications, have not spread as rapidly because of the low electrical conversion efficiency of the engines and the turbines. However, because CO_2 emissions in the consumer sector have been increasing in recent years, there is a need for the development of high-efficiency systems in this field.

Because fuel cells were expected to achieve high electrical conversion efficiency in the systems with small generating power, the development of fuel cells has been energetically pursued. In particular, following the large-scale field tests under the NEDO (the New Energy and Industrial Technology Development Organization of Japan), the introduction of polymer electrolyte fuel cells (PEFC) into the residential market has been promoted since FY2009. Meanwhile, a demonstrative research project of solid oxide fuel cells (SOFC) expected much higher electrical conversion efficiency begun under the NEDO in 2007, and movements to commercialize them are accelerating.

Under the circumstances, Toho Gas has been developed the small-scale SOFC systems for residential and commercial applications. This paper reports the status of development of a small-scale SOFC system using planar cells for commercial application and the status of development under the NEDO project called "Advanced Ceramic Reactor Project” with the aim at compact and high power density stack.

2. A Small-scale SOFC System Using Planar Cells for Commercial Applications

2-1. Development Background

Toho Gas has been developed cubic scandia-stabilized zirconia (ScSZ) electrolyte (*1, 2) since the 1990s and succeeded in developing tetragonal ScSZ electrolyte of great resistance to fracture (*3, 4) and already put it into practical use. Afterwards, 12 cm-diameter planar electrolyte-supported cell (ESC) with ScSZ electrolyte was successfully developed into practical use (*5).

Since 2003, a small-scale SOFC system based on a planar stack composed of ESC has been developed and the first 1 kW-class SOFC system was demonstrated in Japan. Thin interconnect plates made of ferritic stainless steel were used in the planar stack which was designed as few parts as possible in order to achieve a compact and low-cost system. In the 2005 World Exposition Aichi, Japan (EXPO2005), the 1 kW-class SOFC system was operated continuously as a cogeneration system for half a year. Moreover, with further improvement, the system achieved an electrical conversion efficiency of 55.7% (DC. LHV) in 2006.

These systems verify the possibility of small-scale SOFC systems, but more high efficiency power generation module and perfect process controls in BOP (Balance of Plant) are required for the system for commercial applications. Since 2007, Toho Gas has been developed a several kW class SOFC system with Nippon Telegraph and Telephone Co. (NTT) and Sumitomo Precision Products Co. Ltd,. (SPP). In the development, a 3kW-class SOFC power generation module which is the most important part of a SOFC system was examined.

2-2. 3 kW-class SOFC Power Generation Module

2-2-1. Specifications and Construction of the Module

The specifications of the module are shown in Table 1. The electric power is 3 kW (DC) and two units of 1.5 kW planar stacks are connected in electrical series. The stacks used for the module are consisted by 40 planar cells with a diameter of 120 mm. In the test on the single cell stack, it was confirmed that the stack shows stable performance during over thousands of hours. As fuel, city gas (Natural gas:13A) was supplied by a booster pump, and air was also supplied by an air blower. Regarding the exhaust gas, no heat recovery system was connected, but exhaust gas temperature was measured.

Figure 1 shows the flow diagram of the module. This power generation module consists of a stack, combustor, reformer, vaporizer, heat exchanger for air preheating, and startup burner, surrounded by thermal insulators. City gas is mixed with steam made by the vaporizer in a reformer for steam reforming and supplied to the stack as reformed gas. Moreover, at the time of startup, stack and the reformer can be heated by the startup burner to close the operating temperature instead of electrical heater (The startup burner is omitted in the figure.). In addition, the heat generated by the cell stack and post combustor is used for reforming reaction, generation of steam, and air and fuel preheating.

Figure 2 shows the appearance of the module. The module has a volume of approx. 1m^3, which is miniaturized by approx. 20% per unit output, compared with the previous 1 kW-class module

Table 1 Specifications of a 3kW-class SOFC Power Generation Module

Item	Specifications	Comments
Output	3 kW DC	Not connected to grid
SOFC stack	2 stacks	-
Stack output	1.5 kW/stack	-
Dimension (Volume)	810×680×1825h (1m^3)	The volume is reduced by approx. 20% per unit output, compared with the previous 1 kW-class module
Fuel	City Gas	Connected to a city gas pipeline (Natural gas:13A) Supplied by Fuel compressor
Air	-	Supplied by air blower
Reformer	Steam reforming	Steam/Carbon ratio = 3.0
Startup Burner	10 kW	Used for startup
Exhaust gas	-	No heat recovery system was connected

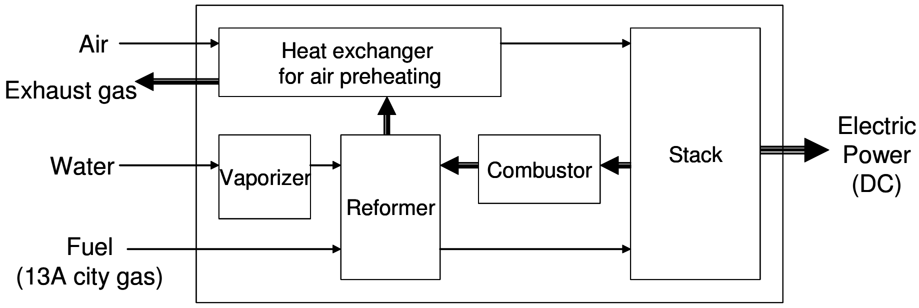

Fig.1 Flow Diagram of a 3 kW-class SOFC Power Generation Module

Fig.2 Appearance of a 3 kW-class SOFC Power Generation Modul

2-2-2. Performance of the Module

Electric Power and Electrical Conversion Efficiency

Figure 3 shows the stack voltage and temperature from the start to rated operation of the power generation module. After the startup burner was stopped, power generation was conducted under constant current conditions with the stack output finally becoming 50 A. The voltage was maintained at a constant level for about 200 hours, and the electric power of 3.1 kW was generated. At this time, the electrical conversion efficiency reached 56% (DC. LHV). Moreover, the temperature difference of stack between the top and bottom was small and kept at approx. 20K.

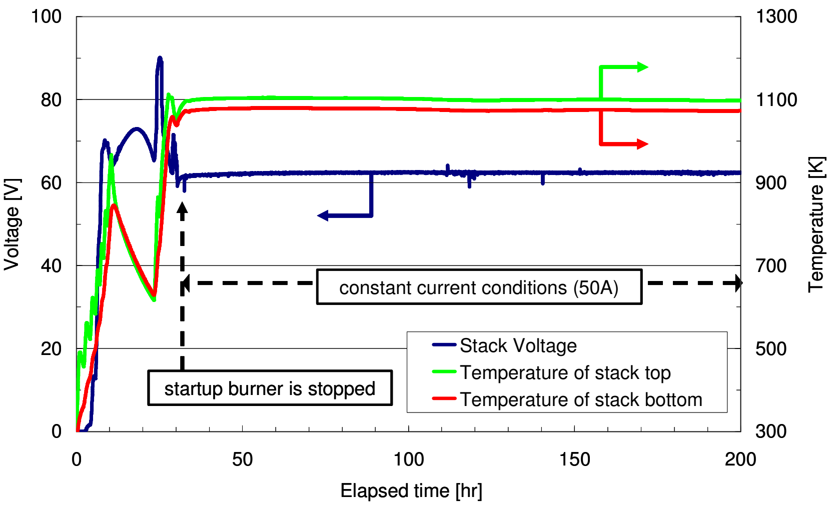

Fig.3 Stack Voltage and Temperature from Start to Rated Operation

The operation under various operating conditions was tested. Thermally self-sustainable operation was confirmed even when the electric power was 50%. Moreover, the maximum electrical conversion efficiency for a short time reached the world's highest level at 59% (DC. LHV). Total operating time of 750 hours were achieved.

Energy Balance

The energy balance of the module in rated electric power is shown in Fig. 4. When the input energy of the supplied city gas was 100%, the percentage of electric power became 56.3%, and the remainder became exhaust gas heat and heat loss. The reason why the heat loss was low at approx. 5% is the high insulator performance. The results show that the AC efficiency is expected to become 46% if the loss of auxiliary machines such as an inverter and air blower is assumed to be 10% of the input. Moreover, when it is assumed that 60% of the exhaust gas heat can be recovered, the recovered heat becomes 24% of the input, and, therefore, there is a possibility that the system with an overall efficiency 80% can be created.

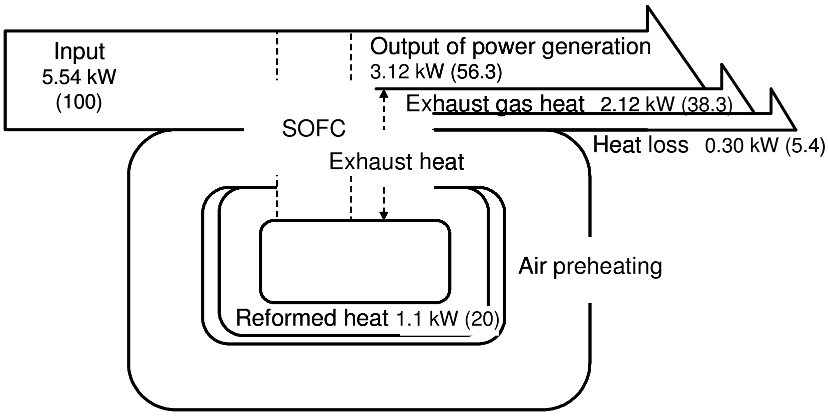

Fig.4 Energy Balance in Rated Operation

2-3. Future Perspectives

It was confirmed that stable and high efficiency operation can be achieved regarding the 3 kW-class power generation module. Therefore, after checking the stability of electric power and efficiency and thermal durability of the module over a long period of 1000 hours, SOFC system based on the combination of module and BOP including an inverter and other auxiliary machines is scheduled to create. In March 2010, a 6 kW-class SOFC system based on this power generation module is scheduled to develop. Moreover, following a study into achieving high performance, high-reliability, and low cost, we will promote the development of a small-scale SOFC system for commercial applications with the aim to put it into practical use.

3. A Compact and High Power Density Stack - Advanced Ceramic Reactor Project

3-1. Development Background

For a cogeneration system with small generating power for the consumer sector, flexibility such as load-following operation and daily start-stop operation is required. It is considered, however, that conducting such flexible operations is normally difficult for SOFC because starting-stopping requires much energy and time due to a high operating temperature that reaches 1073 to 1,273K and the cells, because they consist of ceramics, are brittle to rapid temperature change. Therefore, under a NEDO project entitled the "Advanced Ceramic Reactor Project," the technological difficulties mentioned above are looking to be solved through the development of a compact stack through the integration of micro tubular cells of high power density and the reduction in the operating temperature to 923K or lower. Toho Gas has participated in this project and has been in charge of the evaluation of stacks and studying the applicability of the cogeneration system for residential application.

3-2. Advanced Ceramic Reactor

3-2-1. Concept of Advanced Ceramic Reactor

Anode-supported micro tubular cells are used for the ceramic reactor. This cell, because it is extremely small with a diameter of 2 mm, has an extremely high output of power generation due to large reactive surface area in unit volume and high thermal shock resistance. Moreover, due to the low resistance from the use of thin electrolyte and a material of high conductivity, it is possible to reduce the operating temperature to 973K or lower. The low operating temperature helps increase the capability of quick starts and contributes to the relaxation of heat-resistant conditions of stack components such as the manifold and pipe. It can be considered that, with the integration of the cells in a high power density configuration, the manufacturing of a SOFC module that has a high power density and enables quick starts is possible. Because the small-scale high-power module has low heat capacity, it is suitable for quick starts and can reduce the usage of insulators required for operation in thermal self-sustainability, and, as a result, cost reductions can be ultimately achieved.

3-2-2. Procedures of Development

The ceramic reactor is developed through a process of gradual integration to high density from a tubular cell to a cube bundle with the integration of several tubular cells and then to a module with the integration of several bundles connected via gas manifolds. All of the cells, bundles and modules were fabricated by Fine Ceramics Research Association (FCRA), a partner in this joint research, and were subject to the power generation tests conducted by Toho Gas.

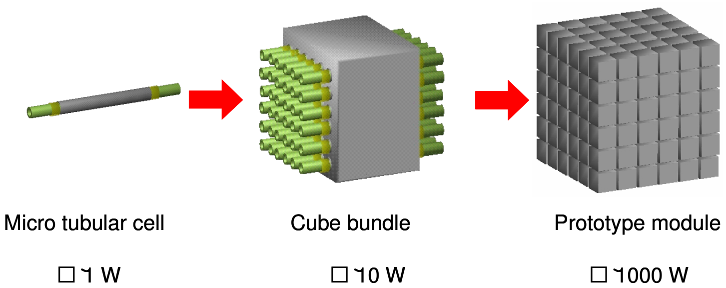

Fig.5 Development Process of Advanced Ceramic Reactor

3-2-3. Performance of the Advanced Ceramic Reactor

Performance of cube bundle

With the integration of nine tubular cells, a 1 cm^3 SOFC cube bundles were created. In this bundle, the cells are fixed by porous matrices, which is the same material as the cell cathode. The porous matrices simultaneously serve as a current collector and airflow path. When the power generation test was conducted with a supply of hydrogen as fuel and with the current collection plate and gas manifold connected to the bundle, electricity of more than 2 W was obtained at a power generation temperature of 823K. This is the world's highest level as power density in operation conducted at a temperature of less than 873K.

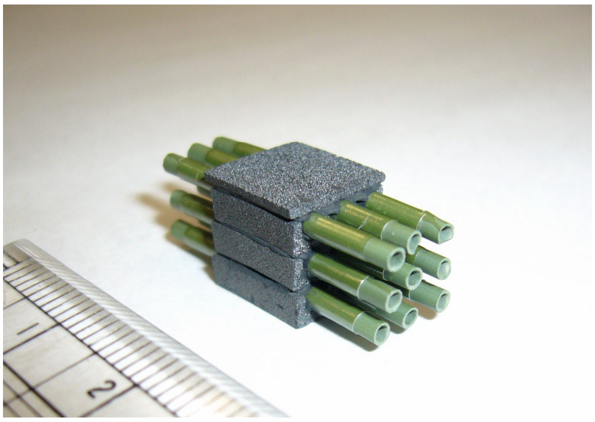

Fig.6 Cube Bundle

Performance of a 30 W-class Module

With the integration of two cube bundles (1 x 3 x 3 cm, equivalent of 15 W) with one cube bundle consisting of 27 tubular cells, a 30 W-class SOFC module was fabricated. In the power generation tests using this module, output power of 30W was confirmed as we planned. And the robustness against rapid thermal cycle was achieved.

3-3. Future Perspectives

In the process of development so far, under the conditions of an extremely low operating temperature of 873K or lower, the ceramic reactor demonstrated superior power generation performance, producing an output of 2 W or more per cm^3. Moreover, fundamental techniques for modularizing were also developed. Demonstration of power generation using a 200 W module as the ultimate goal of the project is tested, and its applicability as a stationary power source is being studied in the future.

4. Conclusion

Toho Gas has been developed the small-scale SOFC for residential and commercial applications.

In order to verify the possibility of small-scale SOFC systems, a 3kW-class SOFC power generation module was examined. When the rated operation for about 200 hours, the module generated stable electric power of 3.1kW (DC) and the electrical conversion efficiency reached 56% (DC, LHV).

In an effort to solve technological difficulties of a small-scale SOFC, compact and high power density stack through the integration of micro tubular cells as next generation SOFC was developed under the NEDO project called "Advanced Ceramic Reactor Project." One cubic centimeter bundle could generate electric power of more than 2W at a temperature of 823K. And the robustness against rapid thermal cycle was achieved.

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6. List of Tables

7. List of Figures

8. Acknowledgement

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