Development of Next-Generation Large-Scale SOFC toward Realization of a Hydrogen Society

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Mitsubishi Hitachi Power Systems, Ltd. (MHPS) is developing a combined power generation system by combining a solid oxide fuel cell (SOFC), which is a fuel cell that can operate at high temperature, with other power generation systems including gas turbines. For commercial application of the hybrid system, MHI has been conducting demonstration tests at Tokyo Gas Co., Ltd.'s Senju Techno Station and the operation was started in March 2013. The pressurized-type SOFC-MGT hybrid system brought about by combining the 200-kW-class SOFC with a micro gas turbine (MGT) achieved 4,100 hours of continuous operation for the first time in the world, and exhibited a stable operation state even during the heavy-load season in summer. Based on this accomplishment, a new compact-type demonstration system was designed and set up at national university corporation Kyushu University in March 2015. It is planned to be used in demonstration studies and basic research in the future.

1. Introduction

In order to solve global warming problems, energy problems and economic problems at the same time, it is indispensable to reduce carbon emissions from energy sources and to increase efficiency in energy use. Therefore, to reduce emissions of CO_2, one of the major greenhouse effect gases, it is necessary to combine decentralized power sources rationally according to location and capacity on the basis of the present state of an electric power base infrastructure established with a centralized power source of high efficiency thermal power generation, etc., and then, to introduce new energies including renewable energies in the most economical and rational way possible. And, partly for global preservation of energy resources, it is indispensably and urgently required to use fossil fuel as effectively as possible by developing and quickly diffusing a high efficiency power generation system.

This article introduces the current development status of MHPS's SOFC, the status of the demonstrations of the SOFC-MGT hybrid system, which is a combined power generation system of the SOFC and a MGT, being conducted through the project of the National Research and Development Agency New Energy and Industrial Technology Development Organization (NEDO), and future developments.

2. Composition of SOFC combined power generation system

2.1 Cell stack

Figure 1 illustrates the structure of a cell stack of MHPS's tubular type SOFC. On the outer surface of the substrate tube, which is a structural member, a cell (anode, electrolyte, and cathode) reacting to generate power is formed and an electron-conductive ceramic used as an interconnector connects these cells in series. By selecting components with similar thermal expansion coefficients and the adoption of integral sintering through the improvement of manufacturing technology, the production cost has been reduced, the bonding strength of components has been increased, and the performance and durability have been improved.

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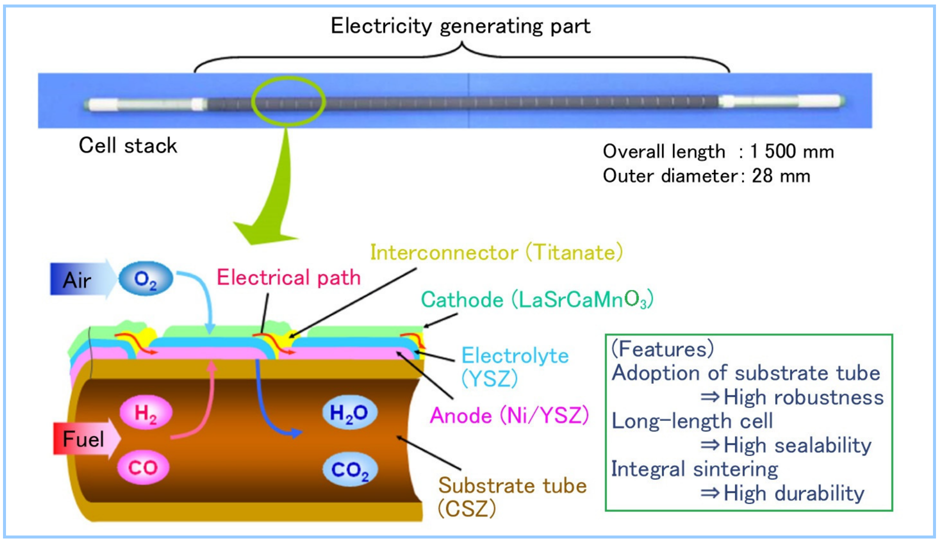

Figure 1 Structure of cell stack

MHPS has been developing our own high performance cell stacks. The Model 10 cell stack raised the number of cells to 85, and at the same time, the power output per cell stack has been enhanced by 30% by optimizing the interconnector composition, adjusting the cathode, etc. In the Model 15 cell stack, with which we have been attempting to further improve efficiency, the interface between the electrodes and the electrolyte has been improved to further increase the output density by 50% compared with Model 10 (**Figure 2**).

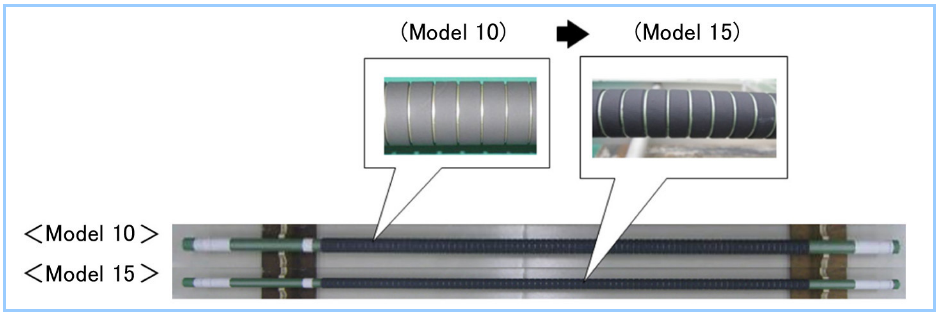

Figure 2 Tubular cell stack for SOFC

2.2 Cartridge

A cartridge that outputs electricity of several tens of kW by binding the cell stacks is formed and a set of cartridges with the necessary capacity, which is collectively contained in a pressure vessel, constitutes a module (**Figure 3**).

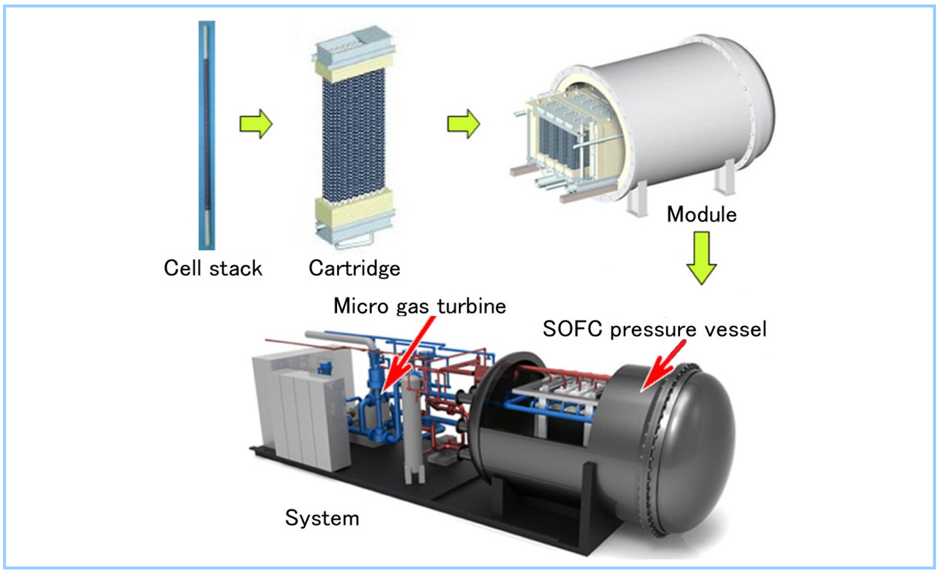

Figure 3 Composition of SOFC-MGT hybrid system

The adoption of such a layered structure seeks systematization by taking installation and even maintainability into consideration. In addition, since the electric output can be adjusted by the number of cartridges or the number of modules, a required wide range of electric output can be covered.

For the cartridge, higher per unit volume output density is aimed at. The higher packing density is accompanied by a higher heating density, but the heat transfer/cooling design of cartridges controls the heat transfer characteristics, ensuring the conventional level of heat transfer in the power generating area as well as in the heat exchange area across the power generation area. In Model 15, the reduction of the diameter and increase of the length of a cell stack enable an increase in the output density per unit volume and reduction of the system installation area (**Figure 4**).

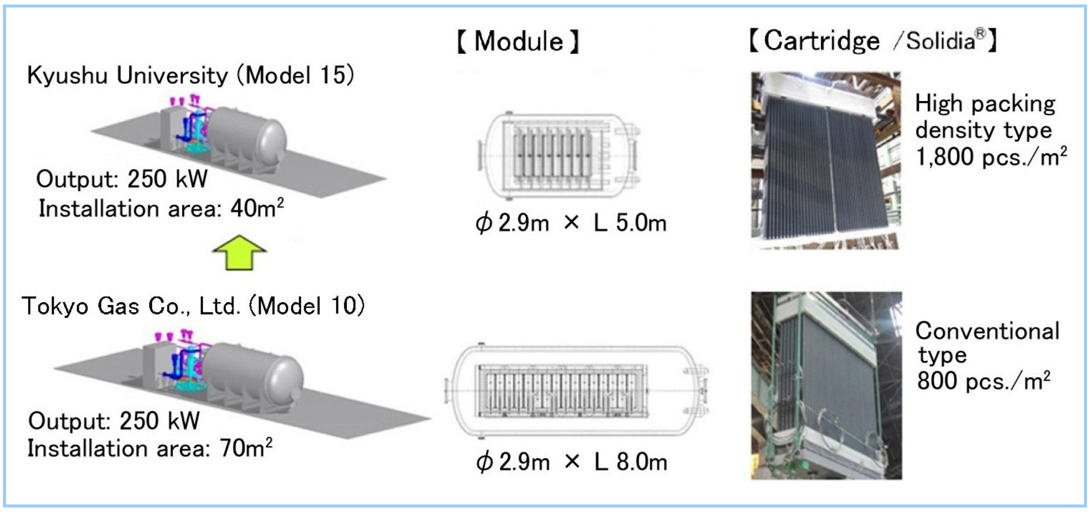

Figure 4 Development of cell stack/cartridge for low-cost mass production

2.3 System

The hybrid system shown in **Figure 5** generates electric power by the SOFC and the MGT in two steps. By installing waste heat recovery equipment on the exhaust gas line, it can function as a co-generation system that supplies steam and hot water at the same time.

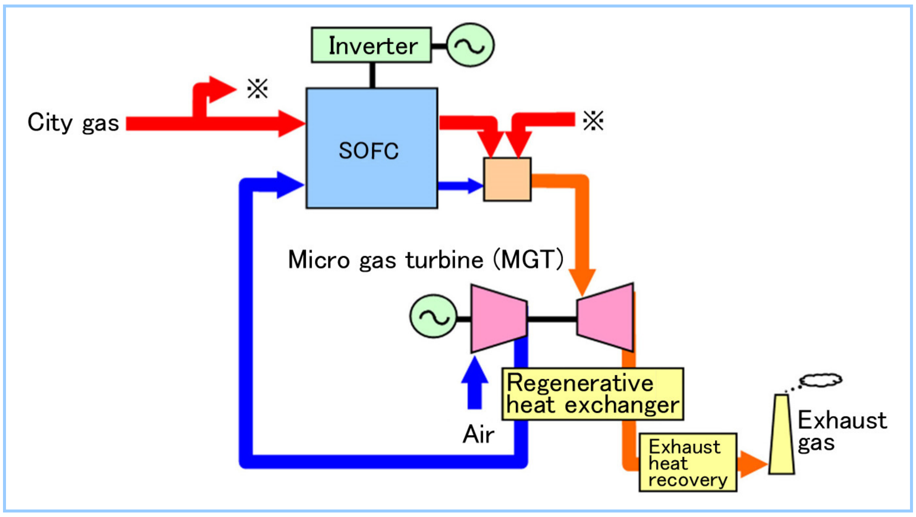

Figure 5 SOFC-MGT hybrid system

3. Market introduction plan for the hybrid system

3.1 Demonstration at Tokyo Gas Co., Ltd. (Model 10 demonstration system)

Based on the achievements thus far, from fiscal 2011 to 2014, we conducted the development and evaluation of the Model 10 250 kW-class SOFC-MGT hybrid demonstration system, under the NEDO project at Tokyo Gas Co., Ltd.'s Senju Techno Station. An MGT made by Toyota Turbine and Systems Inc. was adopted (**Figure 6**).

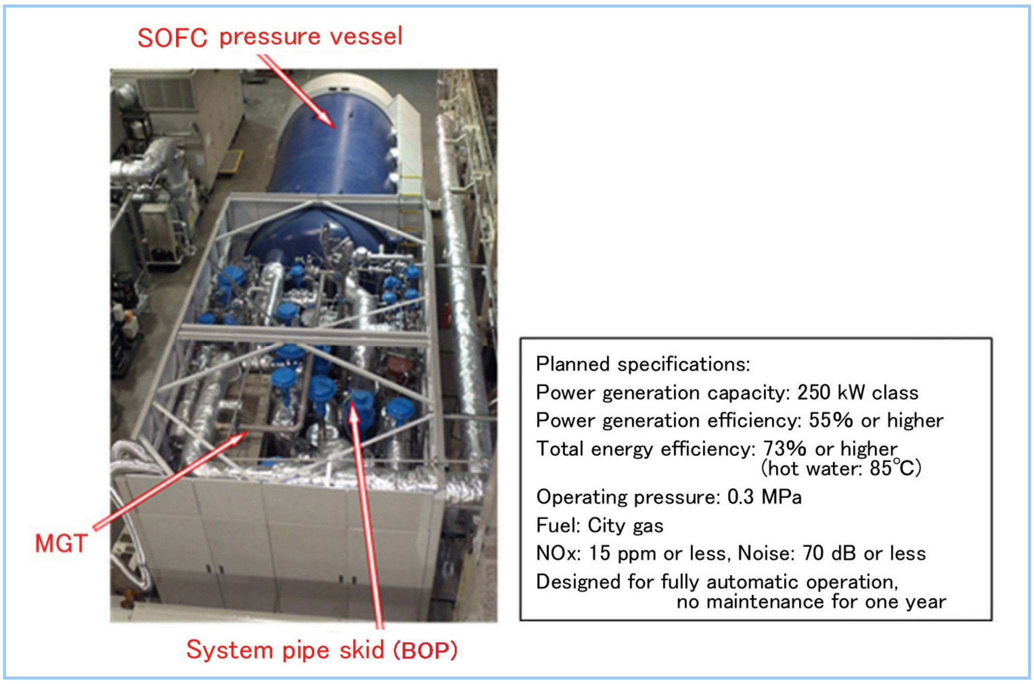

Figure 6 Model 10 SOFC-MGT hybrid system for demonstration

With this demonstration system, we pinpointed problems toward promotion of initial introduction of the SOFC-MGT hybrid system and the examination of deregulation for promotion of its introduction. At present, in particular, because the SOFC-MGT hybrid system is a pressurized system with a fuel gas pressure of 100 kPa or more and is rated as a power generation system that has to be monitored at all times, we are targeting the necessary reconsideration of the regulation requirements for continuous monitoring so that the system would be diffused in earnest. Therefore, we obtained the technical data necessary for deregulation including the grounds for system safety design and the system long-term durability test data, as well as the operation data such as emergency measures on assumed starting and stopping, load change and system problems and verified the system's reliability and safety.

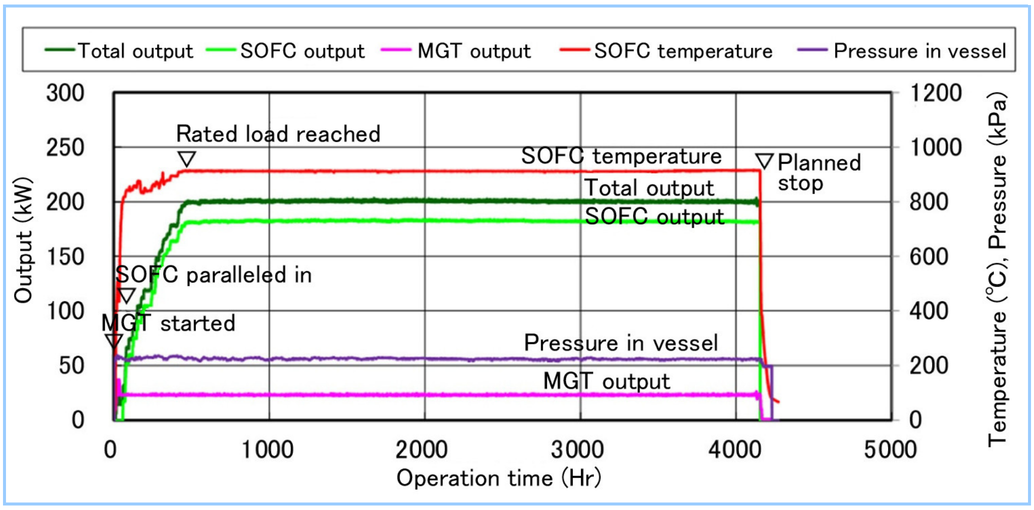

Figure 7 Result of durability test for SOFC-MGT hybrid system

We conducted the evaluations of various kinds of examinations and test data and the deregulation activities, receiving cooperation from the Fuel Cell Commercialization Conference of Japan, Japan Gas Association and Japan Electrical Manufacturers' Association and other entities.

For the system's long-term durability, continuous operation for over 4,100 hours was conducted till the planned shutdown. As a result, no time deterioration was observed under the condition of a constant rated load, and the voltage degradation rate was stable at 0% in 1,000 hours (**Figure 7**).

3.2 Model 15 demonstration system at Kyushu University

Based on the achievements of the Model 10 demonstration system, we designed a Model 15 demonstration system, and it was set up at the Ito Campus of Kyushu University (Nishi-ku, Fukuoka City) in March 2015. In the future, it is planned that the Model 15 demonstration system will be used in verification studies and related basic research for improvement of performance, durability and reliability of SOFC at the Green Asia International Strategic Comprehensive Special Zone "Verification of a Smart Fuel Cell Society" in the "Next-Generation Fuel Cell Research Center (NEXT-FC)*" (**Figure 8**).

* Next-Generation Fuel Cell Research Center (NEXT-FC): The institution established with the objective of promoting industry-academia collaboration toward earnest diffusion of SOFC.

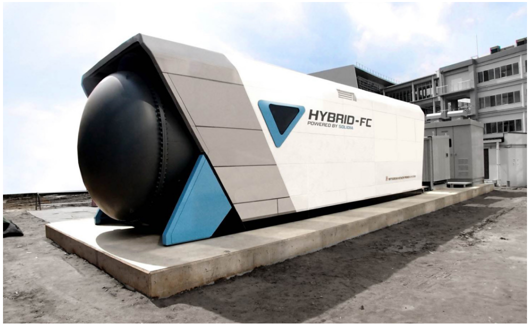

Figure 8 SOFC-MGT hybrid system for demonstration delivered to Kyushu University

Table 1 Specifications of the system

		250 kW SOFC-MGT hybrid system
Appearance		
Rated output	(kW)	250
Net efficiency	(%-LHV)	55
Total heat efficiency	(%-LHV)	73 (hot water), 65 (steam)
Dimensions of the unit	(m)	12.0 x 3.2 x 3.2
Operation		For cogeneration

These specifications indicate planned values.

3.3 SOFC market introduction plan

Taking advantage of the high efficiency, co-generation, quietness, environmental feasibility and other outstanding characteristics of the SOFC-MGT hybrid system, we henceforth intend to introduce it to distributed power sources for business purposes and industrial applications to hospitals, hotels, banks, data centers, etc. The specifications of the system are shown in **Table 1**. In fiscal 2015, we are going to proactively introduce the SOFC-MGT hybrid system as a sample machine on the market for customers' evaluation. Toward the start of its full-fledged introduction on the market in 2017, we are going to make efforts to improve durability, transportability, etc., based on evaluations and findings obtained with the sample machine, improve the system specifications to increase marketability, and bring down costs.

4. Approaches to a hydrogen society

4.1 Multi-energy station (Quatrogen®)

Toward a future low-carbon society/hydrogen society, operations using a hybrid system as noted below are under examination. The SOFC generates electricity and heat using hydrogen and carbon monoxide that are produced by internal reforming of city gas as shown in **Figure 9** (a). In addition, as shown in Figure 9 (b), some of the hydrogen produced by internal reforming may be directly extracted and used without being used for electricity generation. Therefore, electricity, heat and hydrogen can be simultaneously supplied, making it possible to realize Quatrogen, which also supplies city gas as fuel. By applying this mechanism to hydrogen stations, fuel can be simultaneously supplied not only to FCVs (fuel cell electric vehicles), but also to low carbon vehicles such as EVs (electric vehicles) and CNGVs (compressed natural gas vehicles). As a result, an increase in station profitability can be expected (Figure 9 (c)).

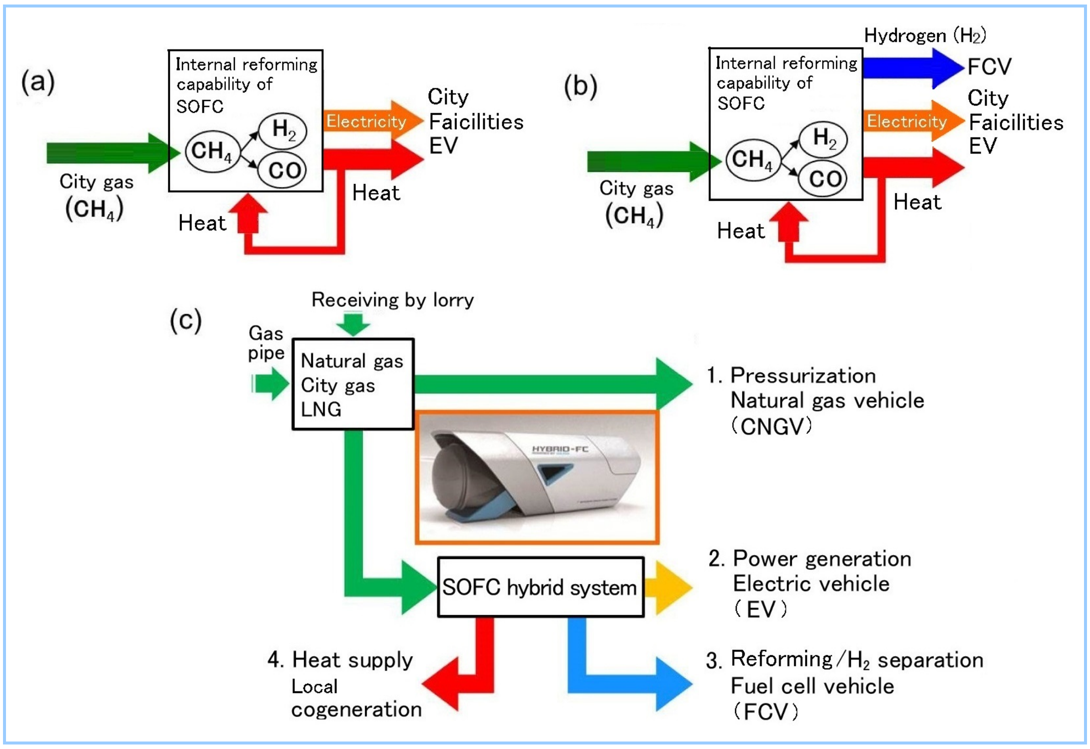

Figure 9　Image of Quatrogen
(a) Supply of electricity and heat by conventional SOFC
(b) Hydrogen production by internal reforming
(c) Application to a hydrogen station.

4.2　Local production of energy for local consumption (use of renewable energy)

It is expected that digestive gas generated at sewage treatment plants in urban areas can be used for the generation of electricity. Furthermore, methane generally constitutes about 60% of digestive gas. Accordingly, it is also considered that the use of the CO_2 separation technique enables high-efficiency digestive gas power generation using high-purity methane as fuel. The application of the aforementioned Quatrogen enables the production of "hydrogen produced in urban areas" derived from digestive gas, and therefore, the "local production of energy for local consumption in urban areas" can be expected (**Figure 10**).

With the creation of these added values through the hybrid system, we would like to accelerate the introduction of SOFC into the market.

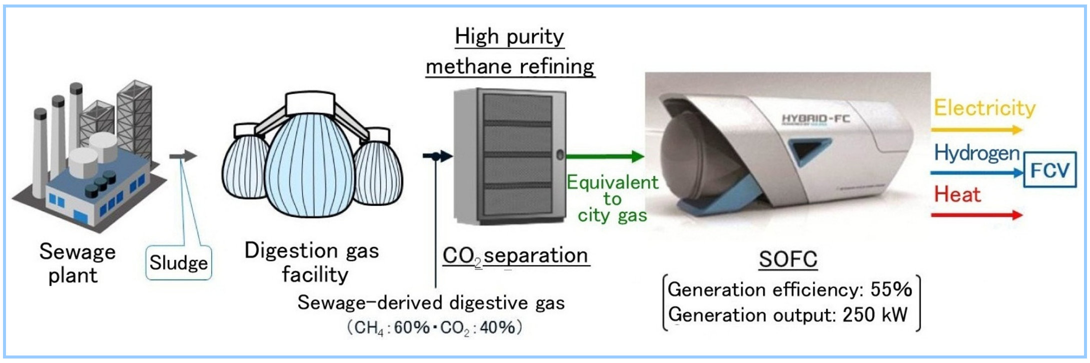

Figure 10　Image of digestive gas power generation

5. Conclusion

The Strategic Road Map for Hydrogen and Fuel Cells of the Ministry of Economy, Trade and Industry was developed in June 2014. In the roadmap, the introduction of stationary fuel cells for commercial and industrial use on the market in fiscal 2017 was also explicitly stated. MHPS would like to steadily establish the SOFC-MGT hybrid system and expedite its commercial application, thus greatly contributing to the development of "a safe and sustainable energy/environmental society."