# Development of 200kW Class SOFC Combined Cycle System and Future View

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*The SOFC (Solid Oxide Fuel Cell) is a fuel cell designed to work at high temperatures of 900 to 1000°C. A huge variety of fuels can be used for the SOFC, including coal. Regardless of the scale, the SOFC achieves a high power generation efficiency even with a single unit, in comparison with a conventional thermal engine. Because the SOFC works at a high temperature, a combined cycle with gas turbines can be adopted. The tubular-type SOFC developed by Mitsubishi Heavy Industries, Ltd. (MHI) is robustly structured and suitable for systems with dynamic fluctuations, such as combined cycle systems with gas turbines. It can generate power with an efficiency of 70% or higher with natural gas fuel, and 60% or higher with coal fuel. With features such as these working in its favor, this SOFC may become a trump card for $CO_2$ reduction.*

## 1. Approach of MHI

MHI has been developing cell materials, cell structures, manufacturing technologies, and cell modules since in 1984. As a first step towards a combined cycle with SOFC and gas turbines designed to take maximum advantage of the features of the SOFC from MHI, the New Energy and Industrial Technology Development Organization (NEDO) commissioned MHI to develop a "High-Efficiency Combined Cycle System with a Tubular Type SOFC" in FY 2004. MHI worked on the project, developing and demonstrating a cell technology and control technology by the end of FY 2005. MHI then began manufacturing a 200kW-Class Combined Cycle System (**Fig. 1**) by combining the tubular type SOFC and a micro gas turbine (MGT), from FY 2006.

## 2. Features of combined cycle system

In the SOFC-MGT combined cycle system, the SOFC is installed upstream of the combustor of the gas turbine. First, the fuel is fed into the SOFC and the chemical energy is directly converted into electric power. Next, all of the remaining fuel is fed to the gas turbine and used for power generation. Air, meanwhile, is pumped up to a high pressure by the gas turbine, supplied to the SOFC for use as an oxidizing agent, and sent to the gas turbine with high-temperature exhaust heat. Even the sensible heat and pressure of the hot pressurized air are used as part of the heat source in the gas turbine, and both are converted into electric power. A high power-generation efficiency in the whole system is thus realized.

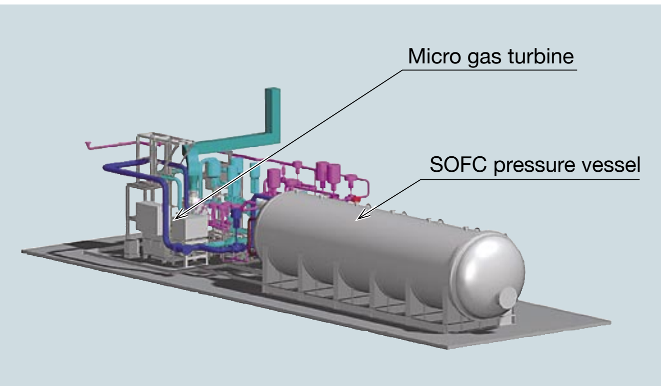


**Fig. 1 200kW-class SOFC-MGT combined cycle system**
The world's largest-class pressurized combined cycle system combined with a micro gas turbine.

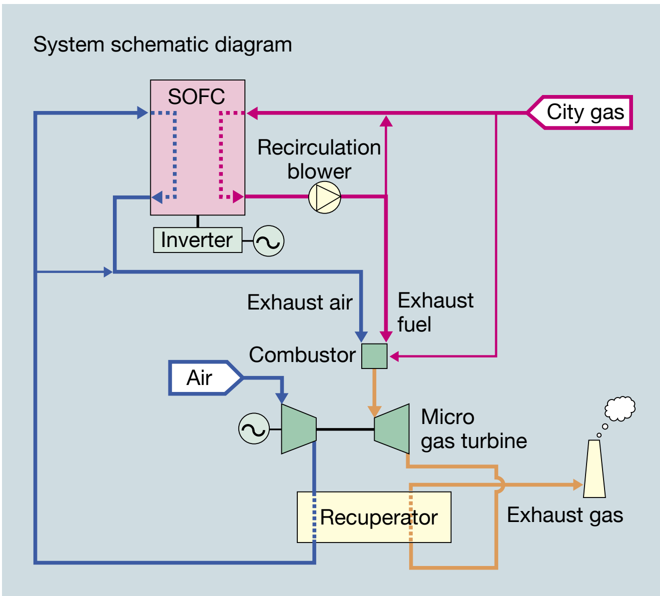


**Fig. 2 Main systematic diagram of the 200kW-class SOFC-MGT combined cycle system**
Configuration in MHI's tubular-type SOFC system.

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In the tubular type SOFC from MHI, the exhaust fuel isn't combusted in the SOFC module. Instead, the system is configured to enable the separate removal of the exhaust fuel and exhaust air (**Fig. 2**). In comparison with the system in which the exhaust fuel is combusted in the module, the temperature of the exhaust fuel and that of the exhaust air are low at the SOFC module outlet, raising the temperature of the gas turbine inlet derived from the combustion in the gas turbine combustor, and the gas turbine can be operated under conditions of high efficiency and high power. The separate removal of the exhaust fuel and exhaust air is more beneficial, as high-temperature pipes impose major restrictions in the design of large-capacity combined cycle systems.

## 3. Development of the high-efficiency tubular-type SOFC combined cycle system

### 3.1 Technology to realize the high-power cell tube

A high-power cell tube (**Fig. 3**) with improved cell tube performance was developed for application to the 200kW-class SOFC-MGT combined cycle system. A power output of 143 W was confirmed at the planned operation voltage (0.65 V/cell), and the maximum rated power was 151 W. The performance did not deteriorate before or after the heat cycle test (**Fig. 4**).

**Fig. 3 Appearance of the tubular type cell tube**
Cell tube of 1500 mm length and 28 mm diameter.

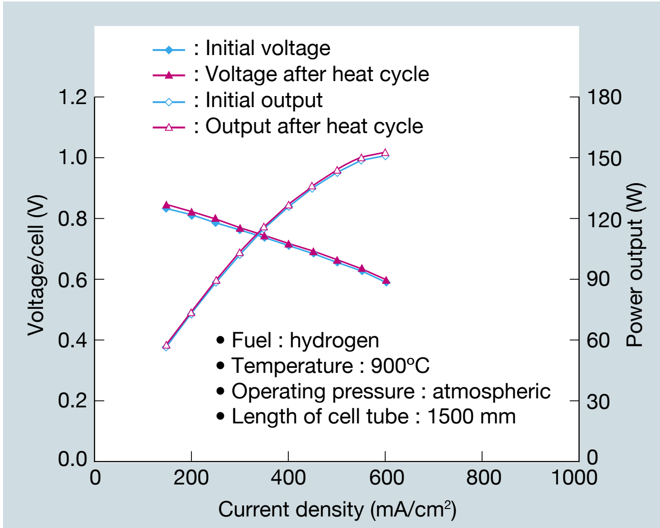


**Fig. 4 Current/voltage characteristics of high-power cell tube**
Verification of maximum rated output of 151 W using a high-power cell tube.

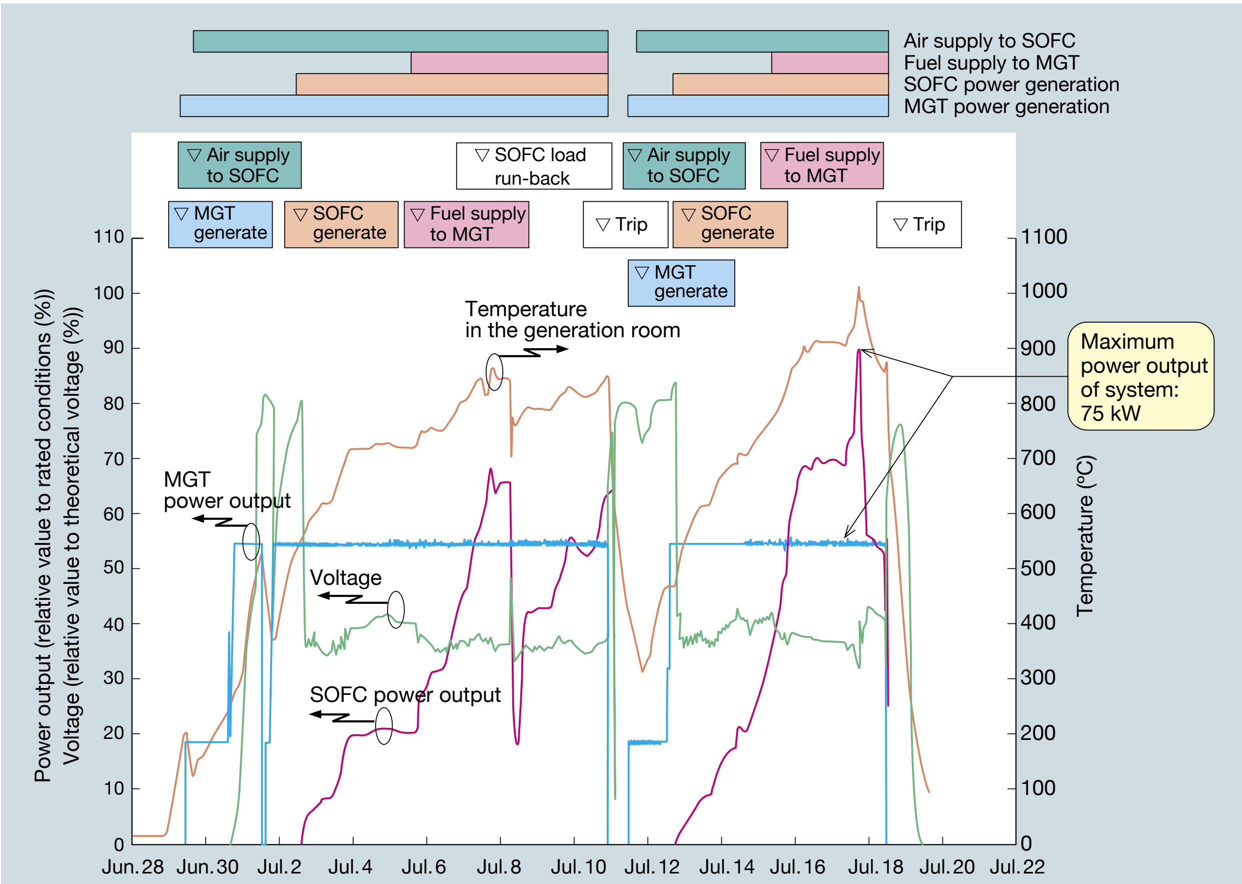


**Fig. 5 Verification test for the SOFC-MGT combined operation**
Stable power generation operation can be achieved in a state of combined cycle operation. A maximum combined cycle power output of 75 kW has been verified.

### 3.2 Low calorie fuel burning MGT

The gas turbine for the SOFC combined cycle requires a technology to stably combust low-calorie fuel (any fuel with a heating value of one-tenth of city gas, or less) after consuming a major part of the chemical energy in the SOFC. MHI designed and manufactured a low-calorie combustor for the SOFC combined cycle by applying a technology for combusting low-calorie gasses such as blast furnace gas, a technology cultivated for MHI's industrial gas turbines, to the combustor for the MGT. Operation tests with this combustor installed on the MGT confirmed that stable operation can be achieved even with a low-calorie gas simulating the SOFC exhaust fuel.

### 3.3 Operation test for the SOFC-MGT combined cycle system

An operation test on the 40kW-class module was carried out with SOFC single body. Afterwards, the SOFC 40kW-class module that had been used for the operation test was connected to the MGT on which the low-calorie gas combustor was installed, to perform a verification test on combined operation. Thus, we succeeded in the SOFC-gas turbine combined cycle for the first time ever in Japan. The verification operation confirmed that power could be stably generated during combined cycle operation, with maximum combined generated power of 75 kW (**Fig. 5**).

### 3.4 Development of the modified sub-module

The cartridge is the minimum unit used to supply the fuel and air, and to collect the electric power. Each cartridge is made up of an assembly of 104 cell tubes, and four cartridges make up one sub-module. The sub-modules are installed in the pressure vessel, for the pressurized operation, making up one module. The modules are configured to easily enable increases in the unit capacity by allocating the sub-modules in the longitudinal direction of the pressure vessel (**Fig. 6**).

We performed the modification design to homogenize the temperature in the module generation room. The configuration adopted enables the fuel to flow downwards inside the cell tube, and the air to flow upwards outside the cell tube. Heat is exchanged between the hot exhaust air and cold fuel in the upper part of the cell tube, and between the cold air and hot exhaust fuel in the lower part of the cell tube. Thus, the power-generation part can be maintained at a high temperature. In the modified module, the thermal insulation of the upper part has been enhanced, and the amount of heat dissipated from the generation room to the outside has been suppressed. In parallel, the heat transfer surface of the upper part of the cell tube has been increased, and the temperature of the upper part of the cell tube has been raised. In the lower part of the cell tube, the air temperature has been raised by increasing the amount of heat exchanged from the hot exhaust air outside the generation room. The temperature in the lower part of the cell tube has been raised. In this way, the temperature of the upper part and the lower part in the generation room have all been raised as well, and we sought to homogenize the temperature distribution in the generation room.

We manufactured the modified sub-modules for application to the 200kW-class SOFC-MGT combined cycle system, and carried out a single unit performance test (**Fig. 7**). The sub-modules are confirmed the effect of the homogenized temperature distribution in the generation room. They performed adequately.

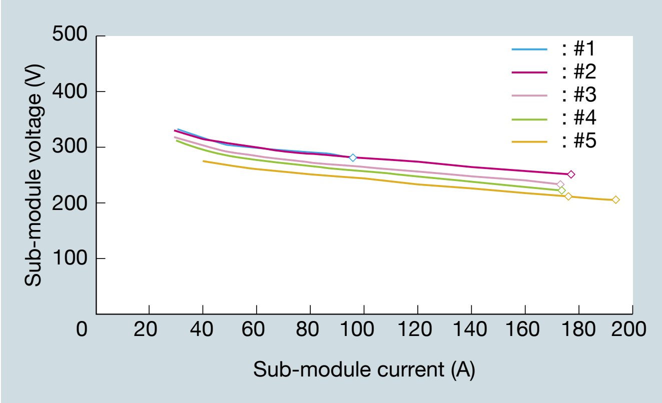


**Fig. 7 Single sub-module performance of the modified module**
Adequate performance of each sub-module has been confirmed.

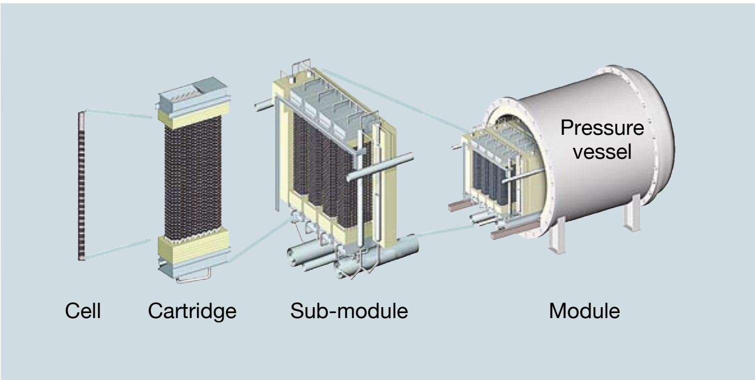


**Fig. 6 Structure of module**
The cartridge configuration adopted for the module has excellent reliability and expandability.

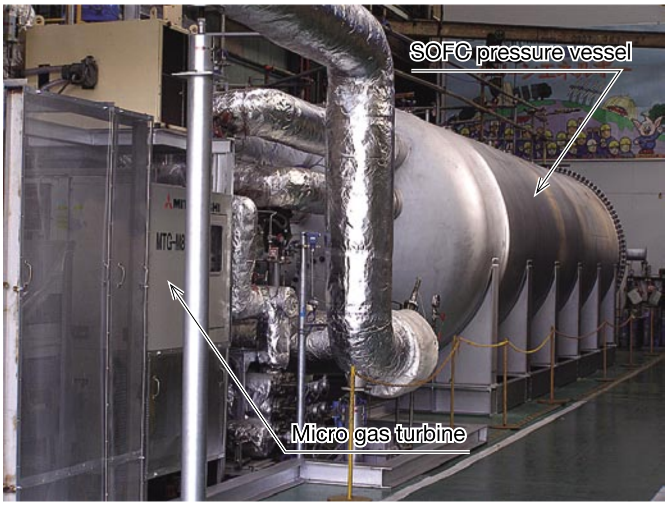


**Fig. 8 Appearance of the 200kW-class SOFC-MGT combined cycle system**
The 200kW-class SOFC-MGT combined cycle system was manufactured

### 3.5 200kW-class SOFC-MGT combined cycle system

Based on the cell development, control technology development, and performance plan until now, we designed and manufactured the main body of the 200kW-class SOFC-MGT combined cycle system (cell tubes, cartridges and modules) and peripheral components, and confirmed performance by a trial run (**Fig. 8**).

The net power generation efficiency of the total system was 50% (LHV) at the planned operation point of the 200kW-class SOFC-MGT combined cycle system.

## 4. Approach for practical application

In planning out its product concept for the ultimate SOFC, MHI seeks to develop an SOFC-gas turbine-steam turbine combined cycle system consisting of an SOFC and gas turbine-steam turbine combined cycle system in a large-scale commercial thermal power generation plant. This system, as MHI envisions it, will be fully capable of extracting the high-efficiency power generation provided by the SOFC, and adoptable as an alternative to a large-scale thermal plant, in the future. A net power generation efficiency as high as 70% (LHV) or more can be achieved with a natural gas fired several-hundred-MW-class SOFC + gas turbine + steam turbine combined cycle system (see the figure at the beginning of this report). It will even be possible to achieve a net power generation efficiency as high as 60% (LHV) or more with a several-hundred-MW-class coal gasifier (IGCC) + SOFC + gas turbine + steam turbine combined cycle system. Thus, power producers may be able to play this new SOFC as a trump card for $CO_2$ reduction.

As a market for the first practical application, MHI has been considering a middle-capacity SOFC-MGT combined cycle system (several hundred kW thru several MW) for application to the natural gas and partial topping system in which a relatively small-capacity SOFC is installed upstream, with countermeasures for efficiency improvement of the existing gas turbine combined cycle system. We will continue to develop cell technologies in pursuit of improved reliability and low cost, together with a technology to realize the system, with an unflagging commitment to realize commercial products in the future.

This technology has been established under commissioned research and joint research work. We would like to express our thanks to the commissioning organization and joint research parties.




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