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Research Report

MCFC/MGT Hybrid Generation System

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MCFC/MGTハイブリッド発電システム

畦上修

Abstract

A hybrid power system consisting of a pressurized molten carbonate fuel cell (MCFC) and a micro gas turbine (MGT) has been developed to demonstrate the system's high power generation efficiency (target of 55 %), very low NOx emissions, and the ability to use high-temperature gasification gas (biogas) as its fuel.

The MCFC generator is pressurized, and is powered by reformed fuel and process air supplied by the compressor of the MGT. The MGT is a single-shaft gas turbine that powers a high-speed direct-drive alternator. The MGT generator offers increased power output and thermal efficiency thanks to its utilization of thermal energy from the pressurized MCFC exhaust gas. The heat exhausted from the MGT is recovered by a heat recovery steam generator (HRSG) and the low-temperature heat exchanger of a hot water driven absorption refrigeration machine.

The MGT combustor plays an important role during system start-up. The system is able to operate, however, without any combustor firing within a load range of 75 % to 100 %. Therefore the NOx emissions are almost zero.

This system was demonstrated at the Aichi World Exposition held in 2005, Japan. The MCFC/MGT hybrid system can use both high-temperature gasification gas (biogas) as well as town gas as its fuel. A maximum efficiency of 52 % at 300 kW was obtained, and the total on-site operating time reached about 5,200 hours with no failures.

Keywords MCFC, MGT, Hybrid system, Co-generation system

要　旨

溶融炭酸塩形燃料電池 (MCFC) とマイクロガスタービン (MGT) を組み合わせた加圧型ハイブリッドシステムを用いて，大型発電設備に匹敵する高い発電効率とNOx等の排出がない優れた環境調和性を兼ね備えた小型自立分散型コージェネレーションシステムの開発を行っている。このシステムは，MCFCの特徴である高温運転による排熱 (排ガス温度は約650℃) を利用してMGTで発電を行うハイブリッドシステムである。またMCFCの作動圧力を上げる (4気圧程度) ことにより燃料電池の効率を向上させることができる。MGT下流には蒸気ボイラ，温水ボイラを設置し，排熱回収を行っている。さらに，新たなMGT制御方法を開発することで，高負荷発電時にMGT燃焼器を消火させるので，NOxがゼロのクリーンな排気を実現した点もこのシステムの特徴である。愛知万博会場で行った実証試験において，最大負荷303kW，最高効率52 %を達成した。期間中，5,200h以上の運転時間を記録したが，トラブルなく運転を行うことができた。

キーワード　溶融炭酸塩型燃料電池，マイクロガスタービン，ハイブリッドシステム，コージェネレーションシステム

1. Introduction

Since 2001, we have been developing a small-capacity distributed co-generation system with a high power generation efficiency (equal to that of large power plants) and which produces very low levels of NOx emissions, using a pressurized molten carbonate fuel cell (MCFC) and a micro gas turbine (MGT) hybrid system.

High-temperature Fuel cells have the ability to generate power from fossil fuels and renewable fuels more efficiently and benignly than other power generation technologies. Because the MCFC is a so-called "high-temperature fuel cell", which are characteristically more tolerant to carbon compounds, it offers the best promise for utilizing fossil fuels.

Moreover, since the temperature of the MCFC exhaust gas is approximately 940 K, the MCFC generator can be synergistically integrated with a gas turbine engine generator.

A discussion in Appleby and Foulkes[1)] indicates that the integration of fuel cells and gas turbines has been considered in the past. Also, interest in the fuel cell/gas turbine hybrid cycle has increased in recent years. Papers by Liese and Gemmen[2)] and Agnew et al.[3)] provide recent examples of hybrid cycle performance analyses. Also, the combination with biomass gasification is examined.[4)] Several hybrid systems have already been demonstrated.[5-7)]

In some papers, the authors have set out with a main goal of improving system efficiency, but practically, it is probably more important to be able to apply effective control from partial to full load. Only a few articles have taken this approach. We investigated whether it would be possible to control the system characteristics by employing an MGT. This paper describes the MGT that we developed for the hybrid system, the control sequence of the hybrid system, and the results of the demonstrative project presented at the Exposition.

2. System description

2. 1 System construction

A simplified schematic diagram of the pressurized MCFC/MGT hybrid system is shown in **Fig. 1**. The MCFC generator is pressurized, and operates on reformed fuel and process air supplied by the compressor of the MGT. The efficiency is enhanced by the fact that the MCFC generator operates at high pressure. Also, the hybrid system achieves higher efficiencies and increased power output through the use of the gas turbine generator that utilizes thermal energy from the pressurized MCFC exhaust stream. The efficiency improves by about 4 points as a result of the pressure and by about 6 points through the use of the MGT.

The target that we set for the system performance was an output power of 350 kW and an efficiency of 55 %, as shown in **Fig. 2**. We also aimed for a heat recovery efficiency of about 15 %. The target of total energy efficiency was thus approaching 70 %. In Fig. 2, the system performances other than MCFC/SOFC (Solid Oxide Fuel Cell) are the values for an actual product or were obtained experimentally. The estimated performances of MCFC/SOFC have a deflection of about 10 points depending on the assumed conditions. An estimate

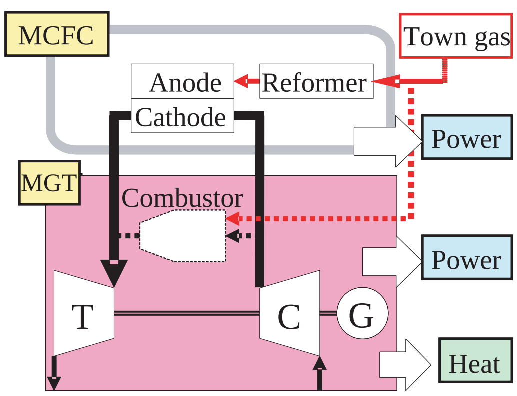

Fig. 1 MCFC/MGT hybrid system cycle.

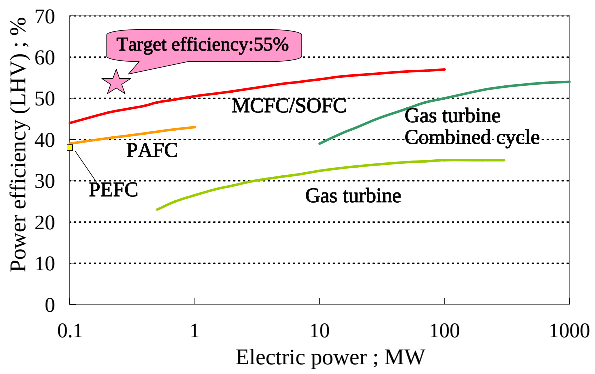

Fig. 2 Power efficiency of various power generating facilities.

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of the MCFC/MGT power system performance is shown in **Table 1**.

The flow of the MCFC/MGT hybrid system is shown in **Fig. 3**. The MCFC generator consists of two cell stacks housed in a horizontal cylindrical pressure vessel. The reformer and catalyst combustor were also installed in the vessel. The heat exhausted from the MGT is recovered by the heat recovery steam generator (HRSG) for producing steam and the low-temperature heat exchanger of a hot water driven absorption refrigeration machine. Moreover, there are some ancillaries such as a cathode blower and gas compressor that are used to pressurize the town gas. The cathode blower recycles the carbon dioxide needed by the cathode of the MCFC to form carbonate ions as its electron carrier across the electrolyte.

Table 1 MCFC/MGT hybrid system performance estimates.

MCFC stack	2 stack
Operating pressure (MPaG)	0.335
Cell voltage (V)	0.726
Current density (mA/cm^2)	158
Stack temperature (^{o}C)	580/670
MCFC AC Power (kW)	310
MGT AC Power (kW)	48
System AC Power (kW)	358
Efficiency (%:Gross AC/LHV)	55

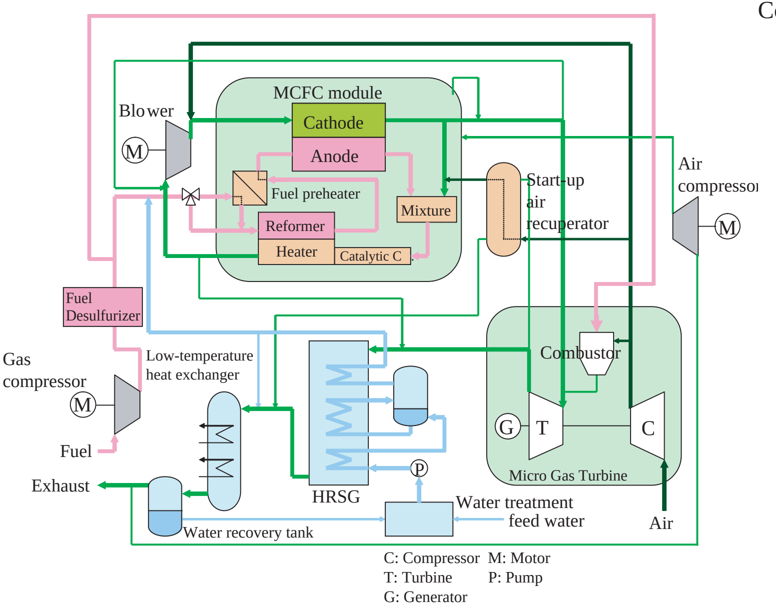

Fig. 3 Schematic flow of the MCFC/MGT hybrid system.

2. 2 MGT modification for the hybrid system

The MGT used in the hybrid system is shown in **Fig. 4**. This is an all-in-one package that incorporates the engine, inverter, control unit and fuel controller. The engine shown in **Fig. 5** is a modified version of the 50-kW recuperated gas turbine that TOYOTA Turbine and Systems is commercializing for use in cogeneration systems. The MCFC generator is sized to match the turbine of the MGT. The compressor of the MGT supplies process air to the MCFC generator, and hot MCFC exhaust gas is received at the gas turbine combustor outlet. The MGT is a single-shaft gas turbine that powers a high-speed, direct-drive alternator, which rotates at a maximum of 80,000 rpm. The compressor was modified so that the air flow rateis about 30 % lower than the original air flow rate. The radial compressor was newly designed with a revised inlet tip diameter and outlet blade height.

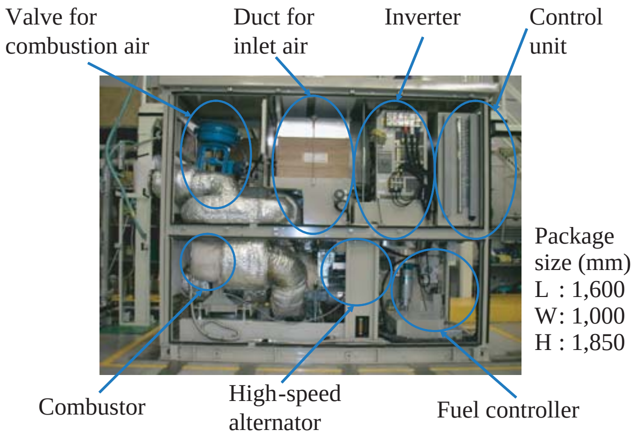

Fig. 4 MGT for hybrid system.

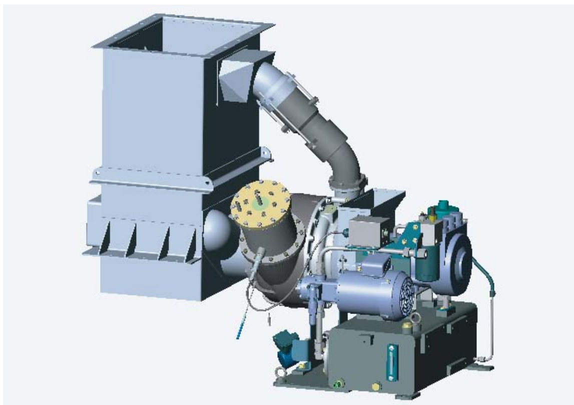

Fig. 5 Schematic of 50 kW recuperated gas turbine engine.

All of the gas turbine inlet air is used for the process air of the MCFC generator. As indicated in **Fig. 6**, a valve was installed at the outlet of the compressor to control the air flow rate for the combustor of the MGT and the operating pressure of MCFC generator. Figure 6 shows four MGT operating patterns.

(Fig. 6 (A)) The system starts, connection to the grid is made at 62,500 rpm, and the MGT generates about 20 kWe at 70,000 rpm.

(Fig. 6 (B)) The compressor outlet air is divided into process air for the MCFC generator and combustion air for the combustor of the MGT. The MCFC generator is gradually pressurized so that it can be connected to the MCFC generator and the MGT. During the pressurizing process, the difference in the pressure between the MCFC stack and the vessel is controlled within a range of 20 kPa. During this process, the MGT introduces process air to the MCFC generator, but it does not receive the MCFC exhaust gas at the gas turbine combustor outlet.

(Fig. 6 (C)) While the MCFC generator and the MGT are connected, the MCFC exhaust gas combines with the exhaust gas at the combustor outlet of the MGT. The combustor demands a high fuel flow rate at the early start-up stages because the MCFC exhaust gas temperature is very low. But, it is necessary to stabilize the combustion, even when the MCFC exhaust gas temperature is high, at around 900 K, and the fuel flow rate is a little. The structure of the bluff body and pilot nozzle are modified, relative to the original combustor design, to suit the wide operating conditions.

(Fig. 6 (D)) The system was operated with no combustor firing within a load range of 75 % to 100 %, with all of the gas turbine inlet air being used for process air of the MCFC generator. As indicated in Fig. 6, a valve was installed at the outlet of the compressor to control the flow rate of the air to the combustor of the MGT and the operating pressure of the MCFC generator. Of course, re-ignition is possible, if necessary. A new sequence for controlling the MGT is described in a later chapter.

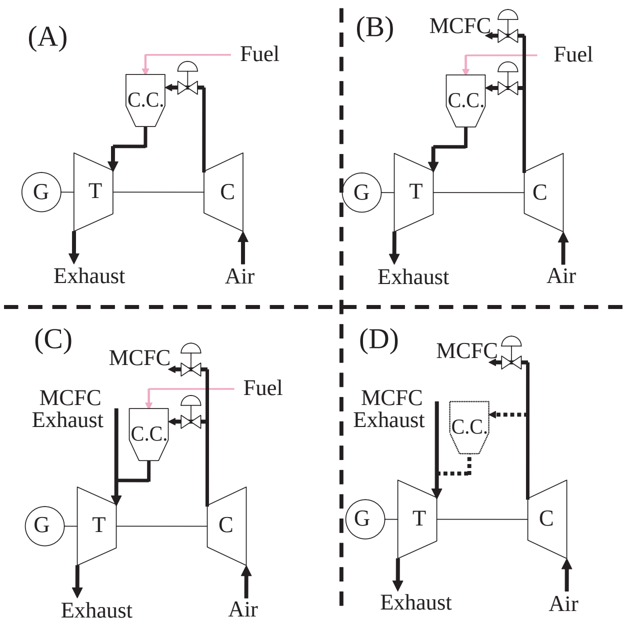

Fig. 6 MGT operation mode.

2. 3 Molten carbonate fuel cell (MCFC)

The MCFC uses a mixture of lithium carbonate and sodium carbonate as its electrolyte. The MCFC operates at about 900 K, a temperature at which these carbonates remain in the molten state. The MCFC stack is shown in **Fig. 7** and the stack specifications are listed in **Table 2**. The MCFC stacks are manufactured by Ishikawajima-Harima Heavy Industries.

Fig. 7 MCFC stack.

Table 2 Stack specifications.

Stack structure :	Intermediate gas holder type
Manifold type :	Internally manifolded type
Gas supply method :	Co-flow
Composition :	Li/Na
Number of cells :	140 cells
Electrode area :	1.015 m^2

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3. Control method for the hybrid system

3. 1 Control sequence for the hybrid system at start-up

The MCFC of this system generates power at a cathode inlet temperature of 850 K. **Figure 8** shows a transition of the cathode inlet temperature up to 850 K. It is divided into that stage in which pressurizing and heating are performed, and that in which power is generated by the MCFC. The process of pressurizing and heating is itself divided into three parts (Fig. 8 (A)-(C)).

It takes about 60 hours until the process (Fig. 8 (A)) of pressurizing and heating is completed. The compressor inlet air temperature (**Fig. 9**③), the air flow rate for the MCFC generator (Fig. 9⑤) and the MCFC exhaust gas temperature (Fig. 9②) change gradually during the progress.

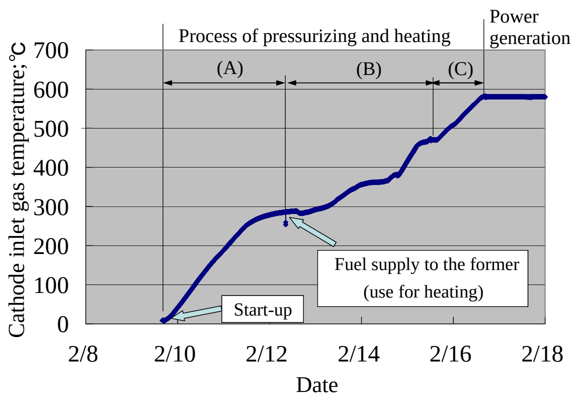

Fig. 8 History of the cathode inlet gas temperature.

The MGT operating conditions are influenced by changes in these conditions. Therefore, any change in the MGT operating conditions will result in one or more of the following problems.

(1) The heating rate of the MCFC stack falls.
(2) The flow rate exceeds the range that the control valves can handle.
(3) The upper limit on the combustor outlet temperature is exceeded.

A new control sequence for the hybrid system was added to maintain a uniform pressure (Fig. 9④), temperature (Fig. 9①) and air mass flow rate in the MGT.

3. 2 Operating without firing by the MGT combustor

To achieve higher power generation efficiency, very low NOx emissions and an increase in the amount of MCFC process air, high-load operation is performed without combustor firing. Operation without combustor firing means that no fuel is supplied to the MGT. Therefore, it is impossible to control the rotational speed of the MGT by using the feedback control for the fuel flow rate. Moreover, if the fuel flow rate reaches the lower limit, the MGT rotational speed increases as the power demand falls.

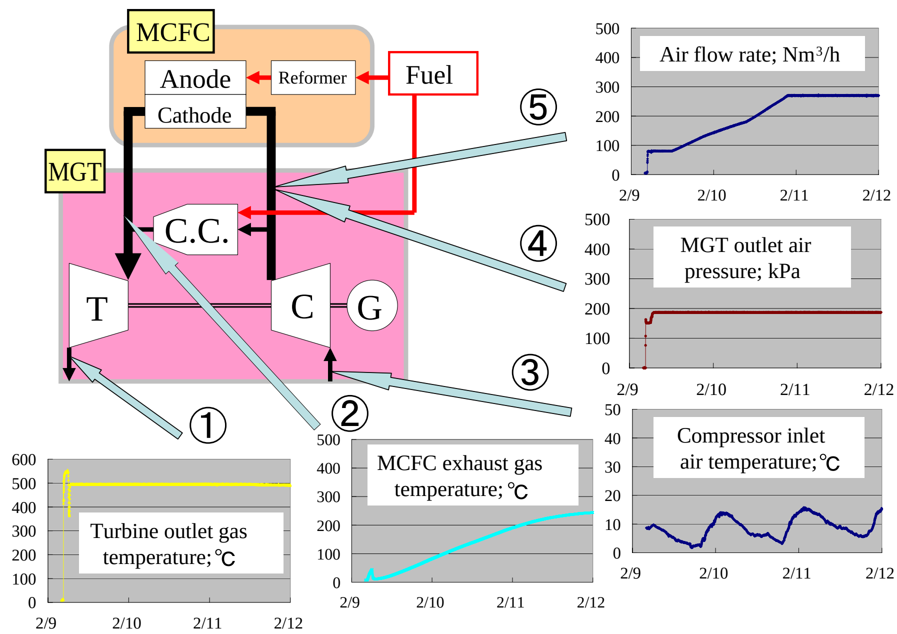

Fig. 9 Control sequence at start-up.

Also, in this case, it is impossible to control the MGT rotational speed.

A new control sequence was developed, employing feedback control for both the fuel flow rate and the power. The new control method was applied to all the operating ranges, without using the former method at all, because it could be applied even to the parts shown in **Fig. 10** (A). The result of operation with the new control sequence is shown in Fig. 10. The MGT speed demand and actual MGT speed agree with each other because the MGT is driven according to received instructions.

(Fig. 10 (A)) Fuel flow rate control functions mainly for MGT speed feedback control.

(Fig. 10 (B)) When the demand for power falls, the fuel flow rate decreases gradually. But once the valve reaches its preset smallest opening, the fuel flow rate becomes constant. Only electric power control has an effect on the MGT speed control.

(Fig. 10 (C)) The fuel valve is shut completely, such that the fuel flow rate is zero. Blow-off and re-ignition is judged based on the combustion outlet temperature.

This system supports operation with no firing combustor within a load range of 75 % to 100 %. There was no harmful influence on the MCFC generator upon re-ignition.

4. Demonstration project at the 2005 World Exposition

4. 1 Regional power supply plant using new energy sources

In a demonstration project, we evaluated the performance of this hybrid system and its durability. A summary of this project is presented here.

The "New Energy Plant" was constructed at the EXPO 2005 site to perform a demonstration study addressing the global issue of reducing CO_2 emissions while pursuing a highly efficient regional recycling-based system.

The new energy system consists of three types of fuel cell (PAFC, SOFC, MCFC), photovoltaic power (PV-1, PV-2, PV-3), and batteries for energy storage (NaS). The whole system is controlled and operated by the Distributed Power Supply Management System, an optimal control system for multiple new energy systems capable of responding to changing demand, as shown in **Fig. 11**.

This project was carried out by a consortium of

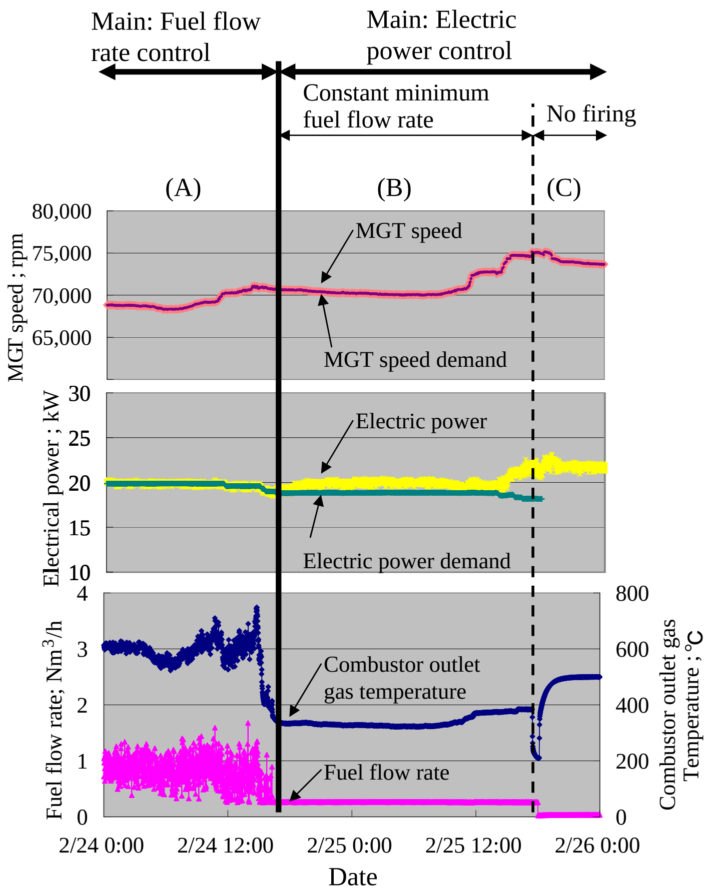

Fig. 10 Operating without any MGT combustor firing.

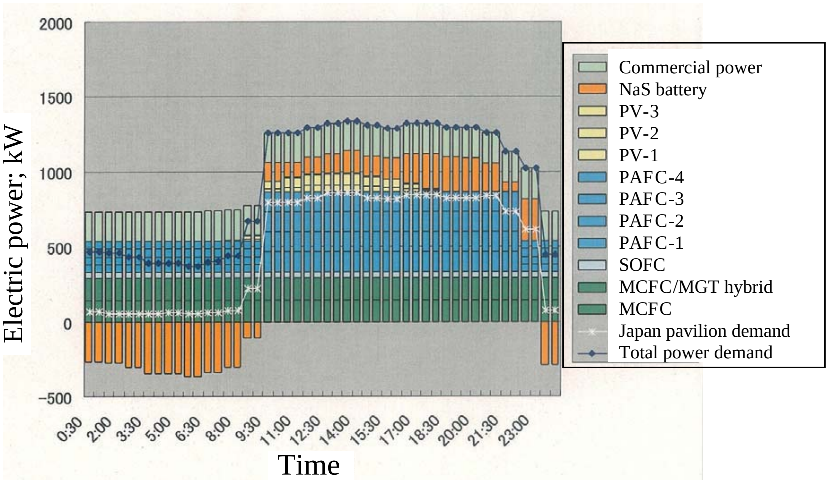

Fig. 11 Optimization of operating schedule.

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nine organizations under the leadership of NEDO (New Energy and Industrial Technology Development Organization). TOYOTA was in charge of the development of the MCFC/MGT hybrid system (**Fig. 12**) and high-temperature gasification system. The MCFC/MGT hybrid system was operated using the fuel produced by the high-temperature gasification system, in addition to town gas.

4. 2 High-temperature gasification system

Figure 13 shows the principle of the gasification system. Wood waste that was generated during the construction of the EXPO 2005 site, as well as waste plastic from the site, are used as fuel for the high-temperature gasification system. The gasifier is a drop-tube furnace. Organic material such as wood waste and waste plastic is fed through the burner at the top of the furnace. It is supplied together with pure oxygen at a ratio much lower than the theoretical requirement for complete combustion. The reactor section of the gasifier is maintained at a high temperature of about 1,500 K. Gaseous fuel including hydrogen and carbon monoxide is obtained by the pyrolysis of the organic material and its reaction with oxygen (partial oxidation). The quantitative feeding of ground organic material as fuel enables the stabilization of the reaction within the furnace.

Before the gas is supplied to the MCFC, the sulfur oxides and chlorine compounds must be removed, as both are poisonous to the MCFC. Once these poisoning compounds have been removed, the gas is homogenized, stabilized in the buffer tank, and then pressurized to about 0.7 MPa by a compressor.

4. 3 Results obtained at the exposition site

In the first instance, the operation of two stacks was almost achieved. In the second stack, unfortunately, the performance of one cell was different from the others. The cell voltage was much lower than that of the other cells even when the fuel consumption was high. Therefore, control of the exposition plant was based on a fuel utilization rate of 75 % while the target had been 80 %.

As shown in **Fig. 14**, a maximum power output of 303 kW and an efficiency (LHV) of 52 % were

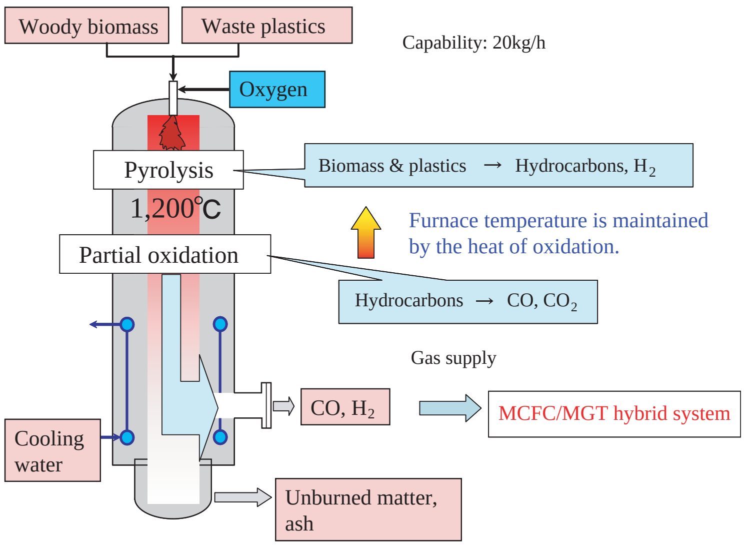

Fig. 13 MCFC/MGT hybrid system.

Fig. 12 MCFC/MGT hybrid system.

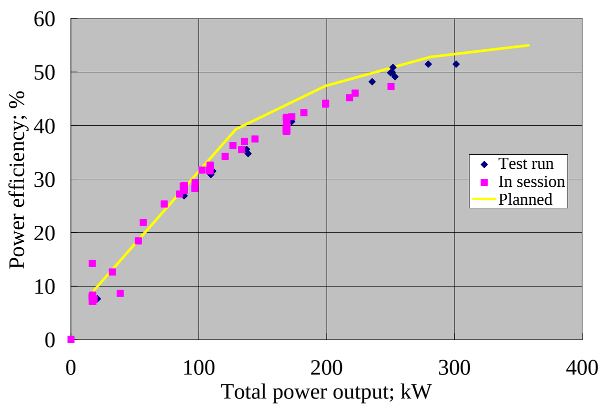

Fig. 14 Plant performance.

achieved. The total power generation time was 5,200 hours with no failures, as shown in **Fig. 15**. The hybrid system stopped for only two hours as a result of an earth fault problem in the power grid. Hot start was done immediately after the restoration. During the Exposition, the hybrid system was controlled by the Distributed Power Supply Management System. The average output power was about 170 kW.

There were no problems when the gasifier fuel flow rate was more than 60 % of the gasifier fuel, plus the town gas flow rate. When gas from the gasifier was introduced, the flow of the town gas was automatically adjusted. But it became impossible to supply gas any longer because of the drop in the MCFC exhaust gas temperature.

5. Summary

An MGT and control system have been designed, and the system optimized to enable practical use of an MCFC/MGT hybrid system. This system was demonstrated at the Aichi World Exposition held in 2005, where it was combined with a high-temperature gasification system.

(1) An MGT control method was developed for the hybrid system.

(2) The system has been operated without MGT combustor firing within a load range of 75 % to 100 % by using the developed control sequence. Therefore, the NOx emissions are almost zero.

(3) A maximum power output of 303 kW and an efficiency (LHV) of 52 % were achieved.

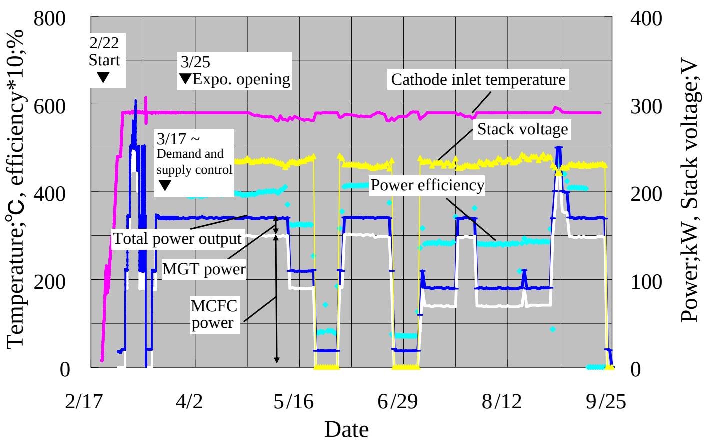

Fig. 15 Operating record at the Exposition site.

(4) The MCFC/MGT hybrid system was operated using the fuel produced in the high-temperature gasification system. There were no problems when the gasifier fuel flow rate was more than 60 % of the gasifier fuel plus the town gas mix flow rate.

(5) In total, the system ran at the Exposition for 5,200 hours without any failures.

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