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Development of High Efficiency Fuel Cell Power Plant Combined with Gas Turbine

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ABSTRACT

A high temperature fuel cell power plant combined with gas turbines is a new power generation style that can provide extremely high efficiency and low pollutant. A number of cycle simulations about the efficiency of the molten carbonate fuel cell (MCFC) or the solid oxide fuel cell (SOFC) combined with gas turbines have been carried out as high temperature fuel cell power plants. Several basic technology establishments on the fuel cells themselves and the developments of the balance of plant machineries lead to recent demonstrations of small capacity power generation units. Performance and cost that can meet the market requirements should be attained as the most important items throughout the demonstrations prospecting the deployment to the larger capacity power plants.

INTRODUCTION

Fuel cells attract attention from all over the world as the efficient and environmental friendly power generation technology. The developments expecting the various applications especially in the fields of automotive or residential use has been actively executed under the deregulation trends. On the other hand, the gas turbine technology occupies the primary position for the high efficiency power generation systems according to the combined cycle developments. If these 21st century's main technologies can be put together, the newly power plants with much higher efficiency and much stronger environmental maintainability can be established. This paper clarifies the position of each fuel cell, describes the features of high temperature fuel cells, and overviews the developmental status of fuel cell power plant combined with gas turbines, the progress on fuel cell technology and the demonstration program of small capacity power plants. Also, deployments for larger power plants are also looked over.

FEATURES OF FUEL CELLS

Fuel cells are electrochemical power generation devices and have many features such as high efficiency, low pollution, flexible output capacity, and flexible site selection, which can't be provided by conventional power plants. Based on these features, fuel cells are supposed to be used for wide range application from residential generators to large power plants. Four types of fuel cell are now mainly under development. Table 1 summarizes the features of each fuel cell and its application fields expected. Plant efficiency with capacity is shown in Figure 1.

Polymer electrolyte fuel cells (PEFCs), which operate at low temperature (about 350K), are expected to attain 60 to 70 % of overall efficiency, if they can utilize the hot water obtained at the same time, in spite of rather lower electric power generation efficiency of 30 to 35%. They are supposed to be applied for small capacity power generation, because of their easy handling and higher efficiency comparing to gas engine unit. However, the PEFC contains Pt catalyst in its electrode for accelerating reaction and it can easily poisoned by CO. Therefore, the CO concentration in fuel must be lower than 10 ppm and the fuel processing system of the PEFC system has the big limitation.

Phosphoric acid fuel cells (PAFCs) also contain Pt catalyst, however, they can utilize the fuel up to about 1% CO concentration because they operate around 480K. PAFCs can provide not only hot water but also steam. Therefore, they can offer wide selections of heat utilization. Various configurations of heat utilization systems have been applied by using 200kW units. Since the power

Table 1 Types of fuel cells under development

	PEFC	PAFC	MCFC	SOFC
Op. Temp.	350 K	480 K	850-950 K	950-1150K
Electrolyte	Polymer Membrane	Phosphoric Acid	Molten Carbonate	Solid Oxide
Fuel	H_2 NG MeOH	NG MeOH	NG Coal residuals	NG Coal residuals
Application	DG automobile mobile	DG	DG, Centralized PP	DG, Centralized PP
Note	Pt poisoned by CO	Pt poisoned by CO		

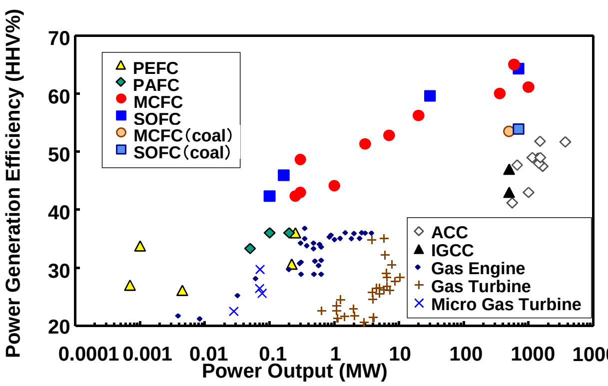

Figure 1 Power generation efficiency with output capacity in various systems

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generation efficiency is limited around 40%, it is supposed to be difficult that PAFC power plant is applied as a substitute of conventional thermal power plant as well as PEFC.

In contrast, there are high temperature fuel cells (HTFCs) such as molten carbonate fuel cells (MCFCs) and solid oxide fuel cells (SOFCs). Since MCFCs operate around 850 to 950 K and SOFC around 950 to 1150 K, high temperature exhaust gases are available similar to the operation temperature level. It approves the combination with gas turbines (GTs) and it can accomplish extremely high power generation efficiency. Furthermore, HTFCs don't need Pt catalyst for reaction acceleration and can utilize high CO content fuel. Therefore, it can configure the power plant, which can utilize not only natural gas but also gasified coal or waste gas.

FUEL CELL POWER PLANT CONFIGURATION

Basic configuration of a fuel cell power generation system

There are several basic requirements to configure power generation systems using fuel cells. First, reactants such as fuel gas and oxidant gas (usually air) supplying systems are needed. Second, the temperature of such supplied reactants should be matched to the level of the operation temperature of fuel cells. Third, adequate cooling system is required to keep a fuel cell stack at a constant temperature.

To configure the MCFC or SOFC power generation system satisfying above requirements, a natural gas reformer or a coal gasifier is expected as a fuel supplier, and a compressor or a blower is expected as an oxidant supplier. However, special considerations should be paid for supplying temperature and stack cooling because of high temperature operation. In the case of low temperature fuel cells, water can be used as the coolant and the generated heat at the stack can be usually recovered as steam by using the latent heat at evaporation. However, HTFCs cannot use water. The generated heat at the stack is usually removed by heat exchange process with reactants. HTFCs actively promote this heat exchange and oxidant gas is generally used as the main coolant because of its larger gas flow rate. Cooling by fuel gas is unreal because it causes fluctuation of fuel utilization followed by lowering the efficiency.

The fuel gas supplying temperature to the stack is usually controlled by fuel processor operation, and the oxidant gas supplying temperature is adjusted by heat exchange between inlet and outlet oxidant or by gas mixing of fresh air and recycling gas as a part of cathode exhaust. These processes are called a heat exchange method and a cathode gas recycling method, respectively. The cathode gas recycling can circulate large amount of oxidant gas through cathode channels and keep the stack temperature at an appropriate level under the wide range of operation conditions. Inlet and outlet temperature at the cathode side are determined by heat exchange temperature and by supplied air flow rate in case of heat exchange method. Recycling gas amount and supplied airflow rate from compressor conversely determine the inlet and outlet temperature of the cathode in case of a cathode gas recycling method.

A schematic system diagram is outlined in Figure 2 corresponding to the basic requirements of system configuration.

Configuration of HTFC/GT combined power generation systems

The plant, in which a HTFC only generates power, can use high temperature exhaust as heat only, therefore the power generation efficiency would be limited even if the fuel cell generates power at the maximum point with the highest fuel utilization condition. Combination with GTs can afford additional power generation by the effective heat utilization, and provide higher efficiency. An air compressor is connected to the GT and the compressed air obtained the heat expands in the turbine and makes additional power. In this case a combustor is replaced with HTFC and the GT operates as an expander.

A high-temperature and high-pressure fluid supplied into the turbine can be the exhaust directly from a HTFC itself or high-pressure fluid obtained heat by a heat exchange process with HTFC exhaust. In the former case, the HTFC should be operated at the pressure corresponding to the turbine inlet pressure. And the GT is placed directly downstream of the HTFC in this case. In the latter case, pressurized FC operation is not necessary. The compressed air obtained heat by a heat exchange is supplied to the turbine in this case. After generating power at the turbine, the air is supplied to the HTFC cathode as the oxidant. Each configuration is shown in Figure 3. The HTFC is a toping cycle in the FC's pressurized operation case as shown in (a), and the HTFC is a bottoming cycle in the case of the FC's atmospheric operation as shown in (b). Furthermore, Figure 3 (a) corresponds to the regenerative Breton cycle from the point of view of the GT cycle.

The pressurized operation of HTFCs has the advantages and disadvantages as shown in Table 2.

The advantages and disadvantages correspond to the

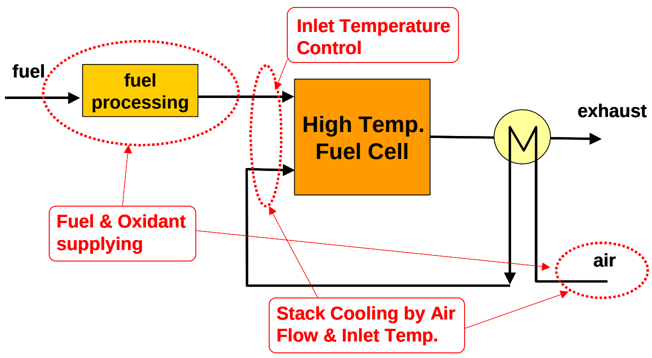
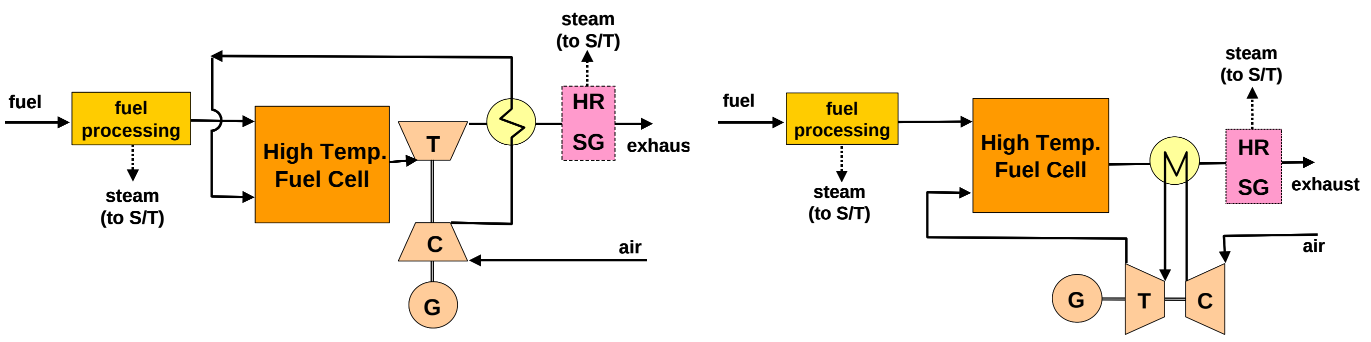


Figure 2 Basic configuration of HTFC system



(a) HTFC pressurized operation

(b) HTFC atmospheric operation

Figure 3 HTFC combined system configuration disadvantages and advantages of the HTFCs operated at ambient pressure, respectively. Adding to these advantages and disadvantages, we have to consider about the carbon deposition phenomena that can occur in high temperature and high-pressure operation condition from the carbon content within fuel.

In case of a combination with the steam turbine, the steam is generated in the coal gasifier and/or the heat recovery steam generator, which is installed just in front of the plant exhaust at an ambient pressure.

DEVELOPMENT OF HTFC POWER PLANTS

Progresses on system performance evaluation technologies

A number of cycle simulations, have been carried out on the HTFC combined cycle. Most of the basic configurations were examined in the context of the DOE program before the 1980s. However, at that time, the simulation results were based on a mere assumption of the stack performance, which is the most important factor for the simulations. Central Research Institute of Electric Power Industry (CRIEPI) has developed the "performance estimation equations"[1] for estimating the MCFC performance under various operating conditions up to a pressure of 5.0 MPa, and therefore making full use of the stack's inner condition simulation and the plant design.

The system configuration and the optimal operating conditions are selected in consideration of the aspects mentioned above. Based on the plant simulation, an efficiency of about 60 to 65 % (HHV net, same as below except special note) is obtained in the natural gas fueled hundreds MW class system[2][3]. For the coal fueled power plant, the efficiency is calculated at about 50 to 55% with steam turbine addition[4][5]. In this system, gasified coal gas mainly containing CO is supplied directly to the MCFC or SOFC via a coal gasifier and a gas clean-up unit. For the small capacity applications, such as several hundred to several thousand kW range, the power generation efficiency are calculated in 45 to 55% adopting either external or internal natural gas reforming methods[6]-[9]. This capacity range has a big possibility as the initial introductive market considering distributed power generation application.

The simulation results of such typical power generation systems are exemplified in Figure 4[2]-[9]. Both coal-fueled systems in the figure adopt steam turbines, oxygen-blown gasifiers and wet gas clean up systems. The major power generation apparatus is HTFC in both MCFC and SOFC system. However, the power output from gas turbines or steam turbines are slightly larger in SOFC system than in MCFC system.

Improvements of stack and main machinery performance

The development of hardware technology for the HTFC itself and the BOP machinery has made a significant progress recently. The improvements of the MCFC performance are especially remarkable. CRIEPI has proposed a modification of the electrolyte and verified performance improvements. A stable operation over 10,000 hours has been attained using a 10 kW class stack with Li/Na electrolyte and a press typed separator configuration as shown in Figure 5[10]. In terms of SOFC, a seal less module configuration with tubular cell bundles[11] developed by Siemens Westinghouse Power Co. (SWPC) has shown a great technological progress as it contributes to the realization of SOFC power generation systems. CRIEPI has also developed basic technologies of a ceramic interconnect to enhance the SOFC's inherent features of high temperature operation[12]. Catalytic combustion technologies have been improved with regard to fuel processor and the direct combustion of high steam content fuel becomes possible. It means that the system configuration eliminating water recovery from the anode exhaust would be possible. These main machinery performance improvements boost up the realization of the plants. Also, in the MCFC, the Ni shortening phenomenon due to the formation of an internal short circuit in the matrix, which is a life limiting issue especially under high-pressure operation and caused

Table 2 Advantages and disadvantages of pressurized HTFC operation in hybrid systems

Advantages:
- Efficiency increases with pressure.
- Volume of piping and recycling blower can be reduced.
- The GT can generate power while HTFC's maintenance.
- The plant is also able to run at peak load.

Disadvantages:
- The plant must keep the pressure fluctuation within an acceptable range in case of emergency.
- Cost of pressure vessel containing the HTFC will increase.
- Pressurized operation of the HTFC is impossible while GT's maintenance.

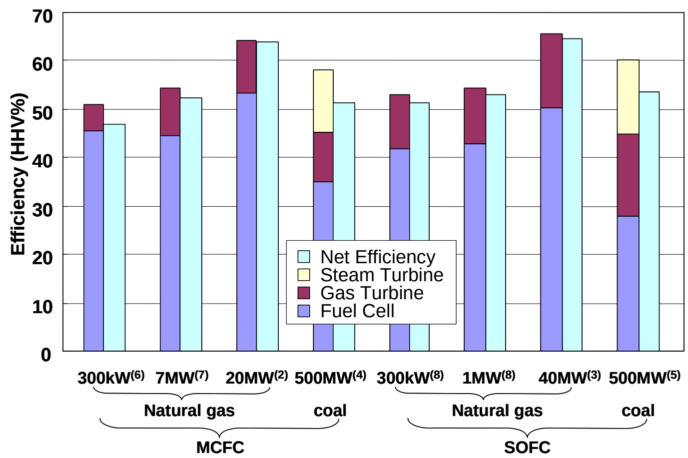


Figure 4 Typical system efficiency of various HTFC combined systems[2]-[9]

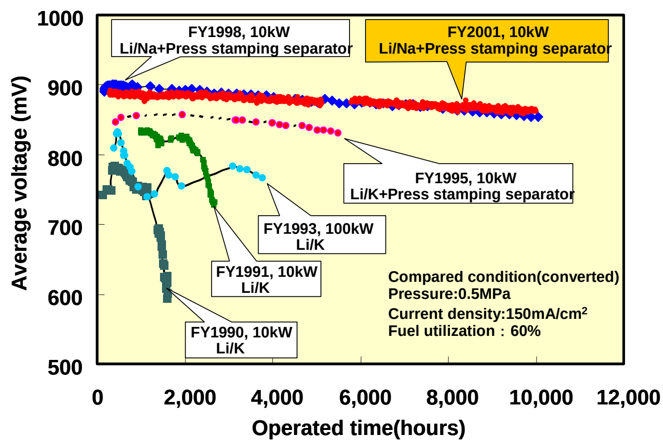


Figure 5 Average cell voltage history of the short stack comparing former tested stacks

by NiO cathode dissolution and deposition, has been clarified for high-pressure operation mode[13]. The information necessary for an adequate pressure selection has been established[14]. These improvements and performance clarifications have contributed greatly towards making the system design more realistic.

Developments and demonstrations of small power generation systems

The recent technology progress of micro GTs is remarkable. Based on the technology improvements of the HTFC itself, the development of the fuel cell combined system has reached the stage of setting up several demonstration plants combined with GTs. This is greatly indebted to the progress of the micro GT technology. The general capacity of the micro GT is around several 10kW, therefore, the total capacity of the HTFC/MGT hybrid system is around several 100 kW.

MCFCs have been developed in the context of a governmental program in Japan[15][16]. So far the program has been oriented towards large-size, efficient power plants for electric utilities. However, the emphasis is now on small-distributed generators for early market penetration from the point of view of a rapid response to the global greenhouse issue. A small generation system with a capacity of 300kW developed by Ishikawajima-Harima Heavy Industries Co.,Ltd. (IHI) started its power generation test in early 2003 as shown in Figure 6. This system has adopted a plate-fin type external reformer, and the MCFC, which are contained in the cylindrical pressure vessel in a horizontal layout. It is combined with a GT developed by IHI. The system is operated at 0.4 MPa and the efficiency is expected to be about 47% (LHV net). IHI has also delivered the 300kW MCFC unit to Chubu Electric Power Co.Inc. and Toyota Motor Co.. Chubu Electric is developing the power plant fueled by gasified waste gas[17]. Toyota is developing a self-directed distributed co-generation plant[18]. They are aiming to exhibit the system at the international exhibition, which will be held in middle Japan area in 2005. In contrast, FuelCell Energy (FCE) Co. [19] in the U.S. has developed 250 kW internal reforming unit with MTU[20] in Germany and delivered about ten units in the U.S., Germany and Japan. This system doesn't have a combined configuration, however, FCE is now testing the combination of MCFC and micro GT in its factory aiming to develop the combined system with MCFC's atmospheric operation.

For the SOFC field, SWPC finished 220kW hybrid system demonstration using micro GT after a 100kW demonstration that only contains an ambient type SOFC generator. The stack in the hybrid system operates under 0.3MPa pressure and improved 300kW hybrid system is under development[11].

As mentioned above, the possibility of such small capacity hybrid systems is gradually being verified technically.

Perspectives of larger power plants

Applications of the HTFC to large power plants can enhance the plant efficiency to the maximum level and it is an excellent utilization method from which the electric power company can bask in its favor. It is reported that the total efficiency of the high performance heat pump system operated by the electricity supplied by centralized combined power plant using present electric network is higher than that of the co-generation system with distributed generator[21].

Developments of large-scale power plants have been conducted especially for the MCFC assuming the application of natural gas fuel in the context of the ongoing Japanese governmental program[15][16]. A "High-performance module" is being developed with the aim of introducing larger, more efficient power plants in the future. It is designed for 1.2MPa operation using horizontal cylindrical pressure vessel that contains two stacks and a compact plate-fin type external reformer. This high-performance module will be the basic element in larger plants. The module offers flexibility regarding the capacity, simply by adjusting the number of modules. It will also contribute to cost reduction and reliability

Figure 6 Installation of pressurized compact system at Kawagoe site

improvement by standardization and mass production. The module will be operated in FY2005, and it could be a big step for the future development of large power plants.

Investigations are also being conducted for coal gasification combined cycles. Gasified coal or waste gas contains various impurities such as sulfur compounds, halogen compounds, nitrogen compounds, dust, and heavy metals. The effect of such impurities on cell performance would be the most important issues to be solved to develop the coal fueled HTFC combined power generation system. Impurity effects are now under examination systematically, and the gas clean-up technology is progressing to reduce the impurities below the acceptable level. The system configuration is being reviewed in consideration of the shift reaction change, which is affected by impurities[22]. The discussion of future larger plants is steadily becoming more and more realistic in regard of all these aspects.

In the development of MCFC in the U.S., FCE is developing 1MW and 2MW internal reforming atmospheric operation power generation systems. There is a plan to connect it to the Integrated Gasification Combined Cycle (IGCC) [20].

For the SOFC, SWPC lines up the several MW class power generation systems with each specification, and a couple of field test plans are announced including several hundred kW system demonstrations[11]. DOE also put the efforts to analyze SOFC plant configurations aiming significant efficiency improvements in the Vision 21 program.

These activities indicate the steady progress of large HTFC power plant developments.

CONCLUSIONS

The HTFC combined systems with GTs become more realistic by the initiation of small capacity demonstration systems. Various applications of such systems are expected and the possibility of the systems will be examined from various angles. The verification of these small systems and following cost reduction are the most important key for the realization of HTFC combined system, and its accomplishment is looked forward to. Based on the success of the small systems, future large plant introductions accompanying huge amount of CO2 reduction can be anticipated.

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