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The development of effective heat and power use technology for residential in a PEFC co-generation system

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Abstract

The Japan Gas Association (JGA) has been executing technological programs under the subsidy of the New Energy and Industrial Technology Development Organization (NEDO) to market a polymer electrolyte fuel cell (PEFC) system developed with a view to putting a residential PEFC system into practice. The target will be achieved with all the related technologies designed to maximize output power and heat recovery from fuel cells and a monitoring system for maintenance purposes. This report describes the current state of the technology involved in each of these development targets. © 2002 Published by Elsevier Science B.V.

Keywords: PEFC; Inverter; Hydrogen absorbing alloy; Battery; Self-diagnosis

1. The objective of the development and the items to be developed

1.1. The objective

In order to bring into wide use residential type polymer electrolyte fuel cell (PEFC) co-generation systems in the future, it is aimed to establish the application technologies for the output power and heat recovery in advance of the actual usage (Fig. 1).

1.2. The items to be developed

The Japan Gas Association (JGA) has a plan to market the PEFC co-generation system equipped with a hot water storage tank (equipped with a backup burner) in fiscal 2005. The electrical output will be used with grid-connection, while the thermal output will be used for hot water supply and space heating applications.

The development targets include: the heat recovery system with improved efficiency and temperature output, the hot water stabilization technology for increased user convenience, the inverter with increased efficiency for overall improvement on system efficiency, the battery-aided, high-efficiency operation scheme with optimizing load regulation, the pure hydrogen fuel cell system with capability to absorb load fluctuations, and the self-diagnostic system with capability to indicate the locations of failures or maintenance spots (Fig. 1).

2. The technical development of high efficiency domestic fuel cell peripheral systems

2.1. The development of high efficiency inverters

2.1.1. The outline of the development

The current inverter for 1 kW PEFC has a maximum conversion efficiency of around 86%. For residential PEFC co-generation system, however, an efficiency of better than 90% is necessary for wide use. The challenging point is how to reduce resistance of the switching device. In this development program, a GaN field effect transistor (FET) which can achieve high insulation breakdown voltage due to its large band gap is developed and evaluated under the conditions assuming residential PEFC. After the optimum design of GaN FET, the inverter using the GaN FET is to

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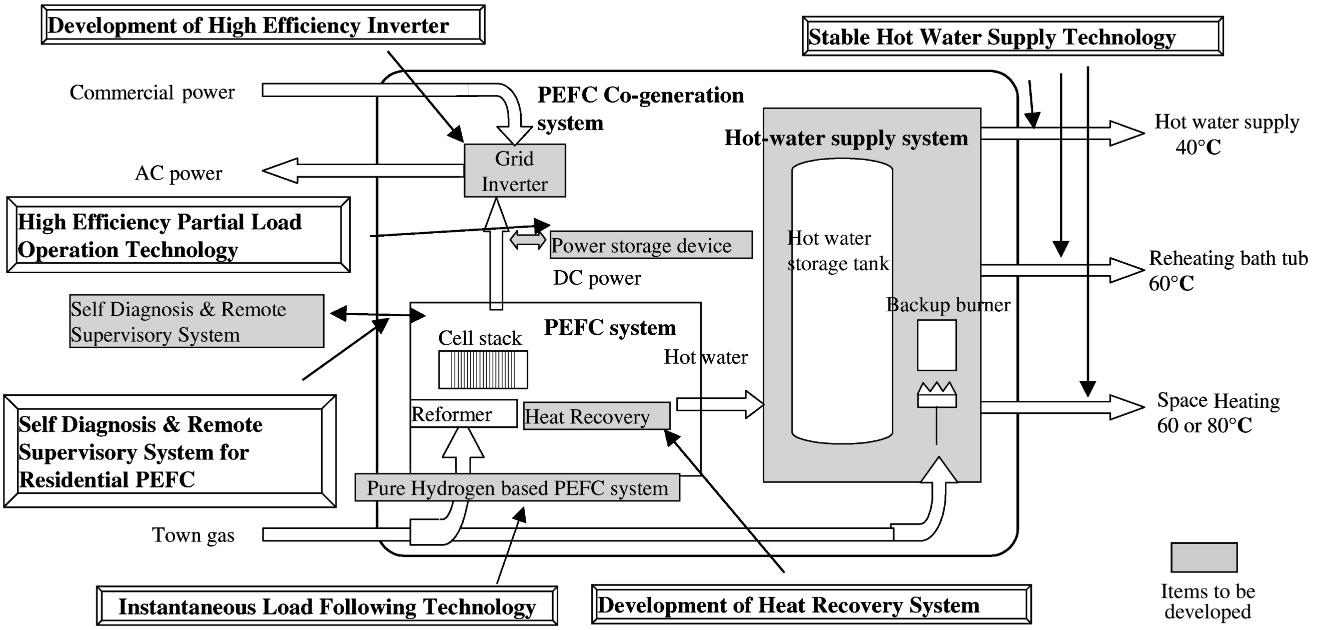


Fig. 1. PEFC co-generation system.

be produced and demonstrated on an actual PEFC co-generation system.

In 2000, the optimum basic FET structure was designed on the basis of the optimized device parameters using a customized GaN crystal determined through device simulation.

2.1.2. The results of the studies in 2000

The studies in 2000 are described in Fig. 2. Parameter analyses were made on the three basic channel structures and 10 GaN crystals having different layer thickness or impurity concentration. Thirteen FET electrode patterns were also designed according to device simulation. Through preliminary experiments, the most favored conditions were found for each fabrication process of GaN FET including electrode formation of source, drain and gate, ion etching, element isolation, etc.

Based on these crystals, electrode patterns and process conditions, trial FETs are fabricated for further testing and evaluation. As a result, 3 Ω of ON resistance and 490 V of withstanding voltage are observed on the most favorable GaN FET element (Fig. 3). Finally, the optimum basic FET structure expected to achieve more than 90% of inverter efficiency at a similar cost as SiC device has been designed.

2.1.3. Future plans

A trial GaN FET for the module will be fabricated after optimizing the device structure based upon the designed basic FET structure. Further, the GaN FET will be packaged into a module form to evaluate its low loss characteristics. The inverter circuit for GaN FET will be also designed for residential PEFC in 2001. Finally, the performance of the inverter using a GaN FET will be demonstrated on a PEFC co-generation system in 2002.

2.2. The development of the heat recovery system

2.2.1. The outline of the development

Higher the heat recovery temperature, better it is for the application and for the possibility of making the storage tank smaller. In this development program, a new heat recovery

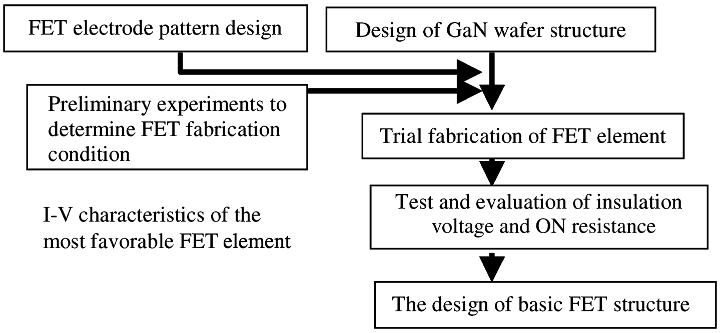


Fig. 2. Design of basic FET structure.

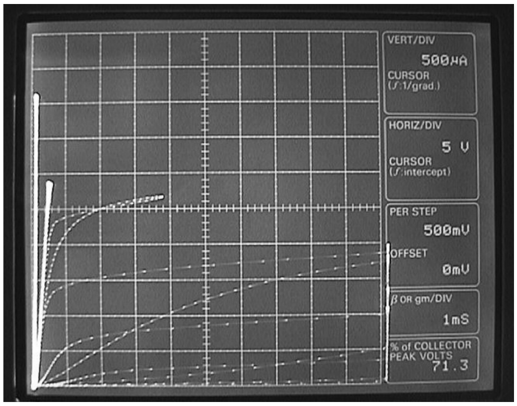


Fig. 3. *I–V* characteristics of the most favorable FET element.

system is to be developed, which allows supplying a sufficient amount of hot water at high temperature even when the waste heat from the reformer is reduced due to the improvement in its thermal efficiency. An auto-circulating system at hot water storage tank is also studied to reduce auxiliary power loss by eliminating circulation pump.

In 2000, prototype units of heat recovery systems for water-cooled and latent heat-cooled cell stacks were built and evaluated. The system for water-cooled cell stacks is designed on auto-circulation. An automated apparatus was designed and prepared to evaluate the efficiency of the heat recovery system.

2.2.2. *The results of the studies in 2000*

For the heat recovery system for a water-cooled type PEFC, heat exchangers to recover waste heat are located at the bottom of the circulation (Fig. 4a). Because the water in the line circulates without external power due to the difference in the specific gravity between circulation line and storage tank, circulation pump can be eliminated. The circulation rate is regulated by a flow control valve to keep the outlet temperature. Temperature-layered storage was achieved by auto-circulation, but due to the pressure drop of the circulation line, the circulation rate decreased with increasing hot water storage.

For the system for a latent heat-cooled type PEFC, the prototype heat exchangers that recover heat from the exhaust from the reformer burner and the cell cathode were designed and tested on the automated apparatus for the evaluation of the heat recovery system (Fig. 4b). To improve heat radiation loss, pressure drop and heat transfer efficiency, low pressure drop and integrated heat exchangers were developed and demonstrated on a PEFC co-generation system (Fig. 5). Hot water (60 °C) was recovered from latent heat-cooled PEFC system (stack operation temperature was 63 °C) at a heat recovery efficiency of 27.9% when the net ac power generation efficiency was 27.6% (LHV).

2.2.3. *Further plans*

Heat recovery performance will be further examined using the PEFC co-generation system produced in 2000.

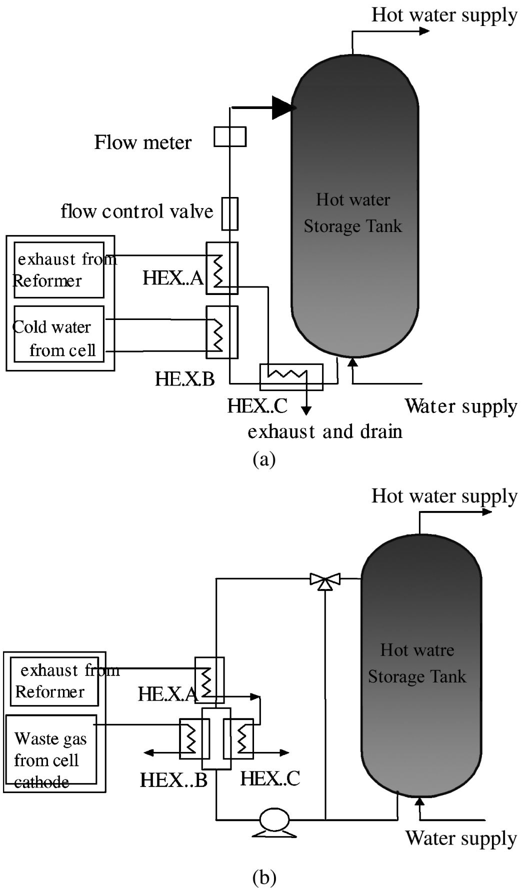


Fig. 4. (a) Heat recovery system for water-cooled cell stacks (auto-circulation system); (b) heat recovery system for latent heat-cooled cell stacks.

In 2001, an improved heat recovery system will be demonstrated on new PEFC co-generation systems for the latent heat-cooled type as well as for the water-cooled type. Furthermore, a heat recovery system that enables us to supply heat for floor heating will be also designed and evaluated using a combined heat exchanger through upgrading the temperature of the recovered hot water.

Finally, the optimized heat recovery system, including for floor heating, will be designed for each type of PEFC, and

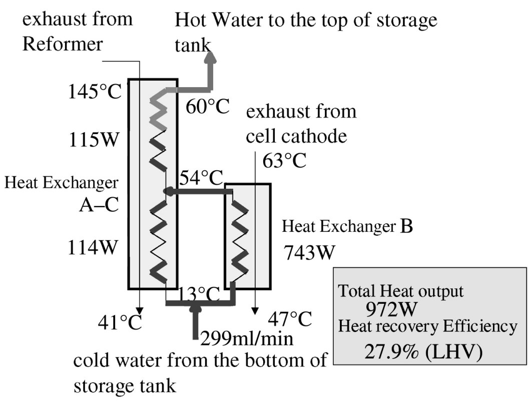


Fig. 5. A result of heat recovery on PEFC co-generation system.

demonstrated on an actual PEFC co-generation system in 2002.

3. The development of energy demand compatible technology

3.1. The development of stabilizing technology for hot water supply

3.1.1. The outline of the development

Residential hot water demands include utility hot water, space heating and bath. Applying the PEFC co-generation system to these applications requires the backup facilities optimized for individual applications and the hot water supply system with control capability. In 2000, two types of hot water supply systems were designed and built based on the PEFC system specifications and specified operating conditions. Co-generation systems were then built with the PEFC system combined with several types of hot water supply systems, and their feasibility was assessed in simulated operating conditions.

3.1.2. The results of the studies in 2000

3.1.2.1. Hot water supply system. It was made possible to test the two systems in the hot water supply system. One was for a single burner type (no burner for bathtubs) and the other was for a dual burner type (a separate burner for bathtubs).

While heating by stored heat (reheating bathtubs), the system was built to reheat bathtubs directly through heat exchangers. In order to study the most effective way of returning the cooled water to the thermally-layered storage tank, the returning point of the cooled water was arranged to switch from one to the other. Fig. 6 shows the system flow chart and Fig. 7 shows the package of the hot water supply system.

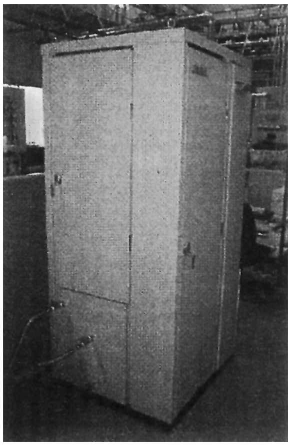


Fig. 7. Package of hot-water supply system.

3.1.2.2. Hot water supply system for heating. A hot water supply system for heating which covers hot water supply, heating and bathtub reheating was designed to perform the two temperature ranges to cope with the normal air-conditioning application (high temperature heating at about 80 °C) and the floor heating application (around 60 °C). Fig. 7 shows the trial unit of the hot water supply system.

The unit was linked up with a PEFC system for testing. Fig. 8 shows one of the test results. It was confirmed that even after the hot water in the storage tank was used up, hot water supply continued by the help of the back-up burner.

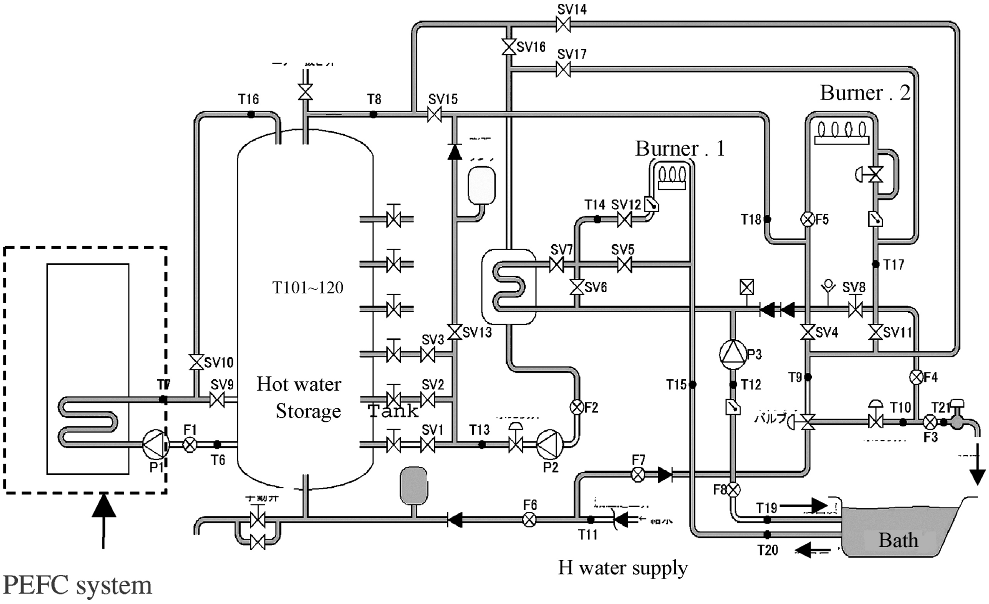


Fig. 6. Hot water supply system flow chart.

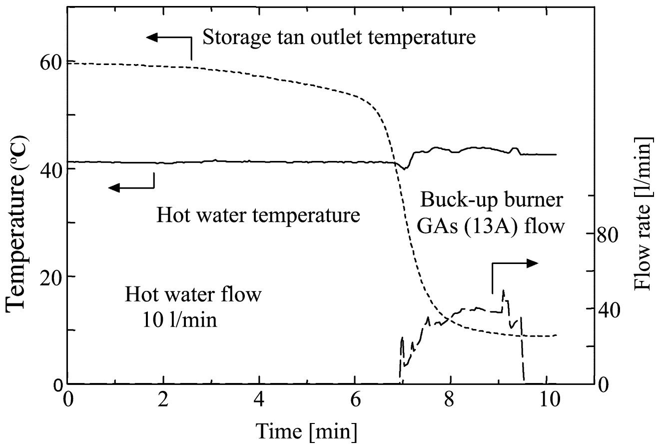


Fig. 8. Testing of hot water supply system for heating use.

3.1.3. Further plans

Further, detailed checks and tests will be conducted on both of the hot water supply systems. Based on the outcome of the study, we will improve the system control and construction.

3.2. The development of technology for instantaneous load following

3.2.1. The outline of the development

In order to fit the electrical output of a PEFC co-generation system to the fluctuating residential power consumption, we are developing a pure hydrogen based PEFC system that takes advantage of the fine load following characteristics of the PEFC fueled by pure hydrogen.

In 2000, the pure hydrogen based PEFC system fueled by pure hydrogen taken from utility natural gas was studied. Also the system's major components, including the pure hydrogen production and storage subsystems and pure hydrogen fueled PEFC, was built to assess their characteristics. Combining all of the major components, the pure hydrogen based PEFC system was build and its' load were following characteristics was tested.

3.2.2. The results of the studies in 2000

The major components as shown in Table 1 were manufactured and tested to verify the performance. A continuous operation and stable production of hydrogen were confirmed on the pure hydrogen production subsystem (Fig. 9a). The hydrogen storage subsystem (Fig. 9b) was confirmed as per the specifications on the storage capacity and the discharge capacity of the two vessels under the given design pressure and temperature conditions (Fig. 10). Also, the two vessels were confirmed through their continuous operation that they were automatically switched from storage to discharge alternately.

Table 1
Subsystem specification

Subsystem construction	Specification
Pure hydrogen production	Production capacity 0.3 Nm^3/h
Pure hydrogen storage	Storage capacity: 6.5 Nm × 2 units (tank switching: once per day, 10 kWh dc per day)
Pure hydrogen fueled PEFC	ac output 1 kW


(a) (b)

Fig. 9. (a) Pure hydrogen production subsystem (left); (b) pure hydrogen storage subsystem (right).

After these verification tests, the three major components were integrated to a single system for a continuous operation to conduct verification testing of the load following characteristics.

3.2.3. Further plans

Further detailed checks and tests will be conducted. Based on the outcome of them, we will improve the system construction and control.

4. The development of a partially loaded high efficiency operation system

4.1. The outline of the subject

The typical residential power demand shows peaks in the morning and evening time bands, and dips in the daytime and midnight time bands. In system grid-connection with no reverse power flow, the PEFC system output must be controlled to follow load variations, which often poses a problem in maintaining high efficiency at the rated output power.

The project aims at the development of the PEFC with high load factor, by combining the 1 kW class residential PEFC co-generation system with a power storage device. In order to secure high output efficiency, the PEFC is constantly operated at a high output power, with load variations absorbed with the power storage device.

In fiscal 2001, some typical residential power demand profiles were surveyed to determine the capacity required for the power storage device and its charging/discharging

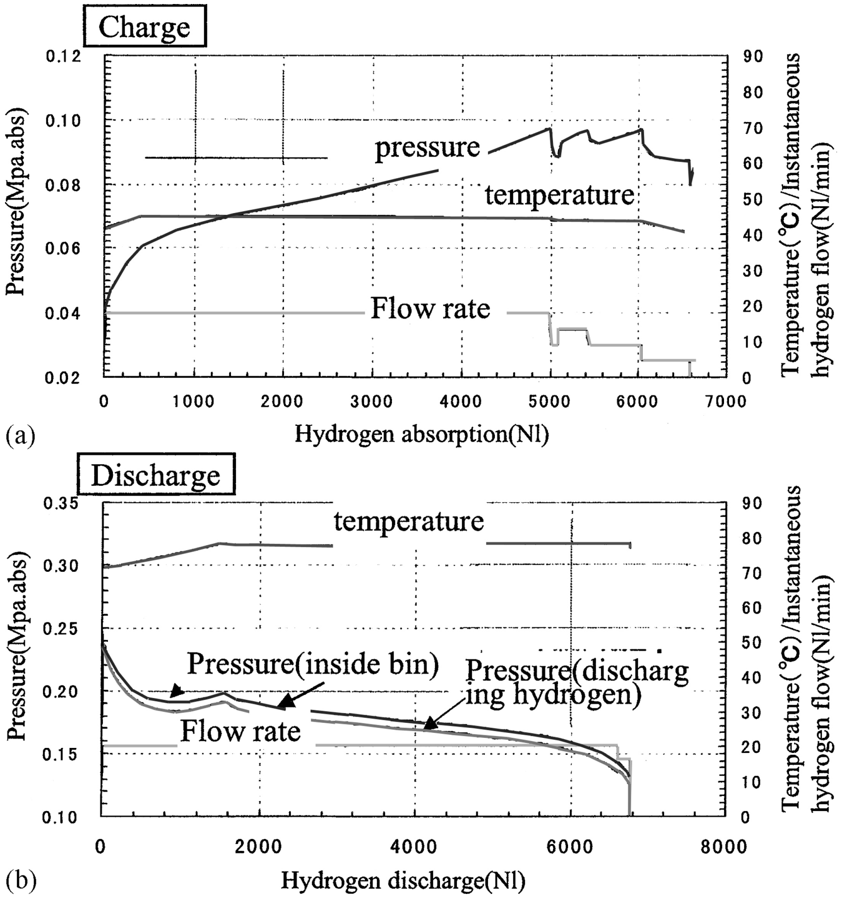


Fig. 10. (a) Hydrogen storage vessel performance; (b) hydrogen storage system performance.

characteristics. The load regulation device to be attached to the power conversion block (DC/DC converter and DC/AC inverter) of the fuel cell was also studied through simulation. A feasibility study system combining the PEFC co-generation system with the load regulation and power storage facilities was built for feasibility assessment.

4.2. The results of the studies in 2000

4.2.1. The system that can cope with power load changes

Power measuring devices were installed at three houses to collect information about the power demand variation patterns (in the winter). At the same time, references were checked. Based on the result (Fig. 11a) of the studies, simulation work was carried out to define the specifications covering the necessary capacity of the power storing device and the charge/discharge characteristics of the cell. The specifications for the function that can cope with the power load variation and that is attached to the power conversion part (a combination of a DC/DC converter and a DC/AC inverter) of the PEFC were also decided.

4.2.2. System integration test

The fact-proving unit that puts together the PEFC co-generation system Fig. 11b, the function that can cope with the power load variation and the power-storing device were test manufactured. The operational test is currently under way.

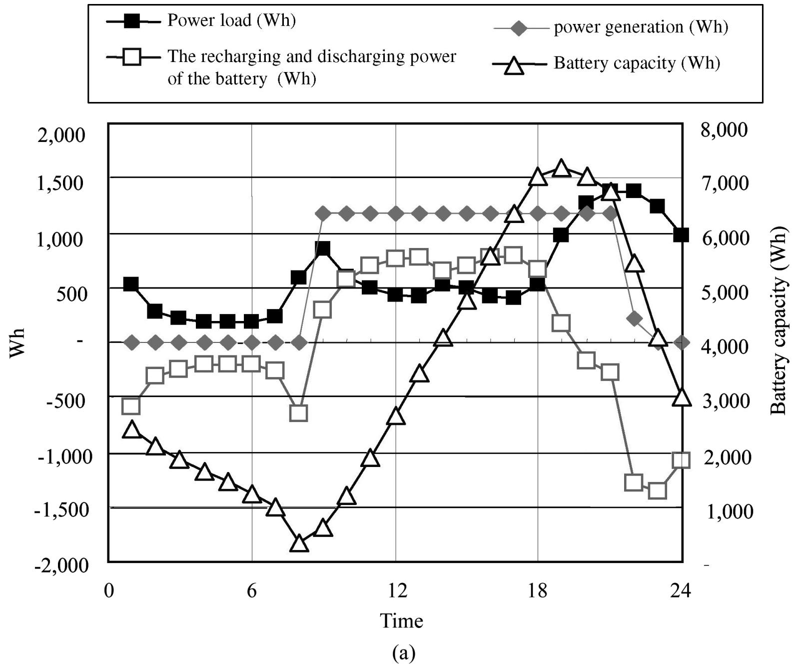
4.3. Further plans

The home survey on the power load variation patterns will continue to the next fiscal year and simulated load devices will be manufactured to simulate the general patterns of power load variation at a ordinary home. Then the study on the optimum cell capacity and the way of controlling the PEFC output will be made to obtain the most appropriate and highly efficient system design.

5. The development of a fuel cell self-diagnosis and remote monitoring system for general household applications

5.1. The outline of the development

For the residential PEFC co-generation system to penetrate widely, the system itself must be equipped with the system monitoring capability that enables the user to check for system conditions at a glance. This requirement will be addressed by the self-diagnostic subsystem that, at



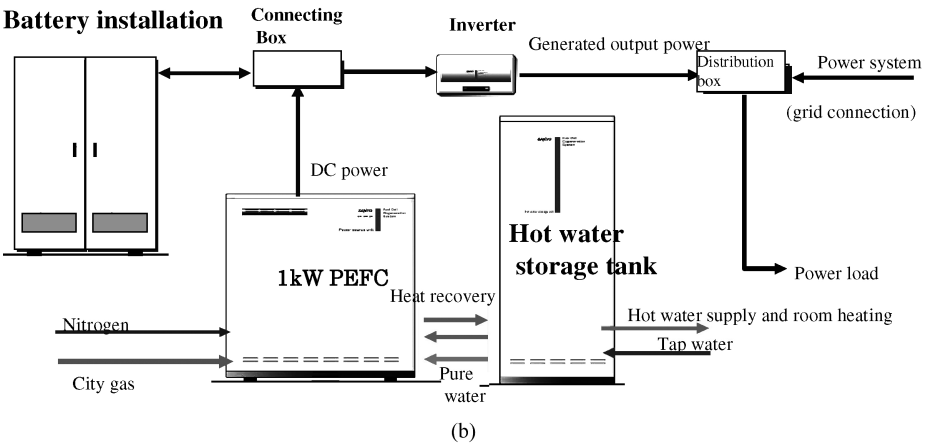


Fig. 11. (a) Characteristics of residential electric load, (b) PEFC battery system.

the same time, is expected to reduce maintenance cost considerably.

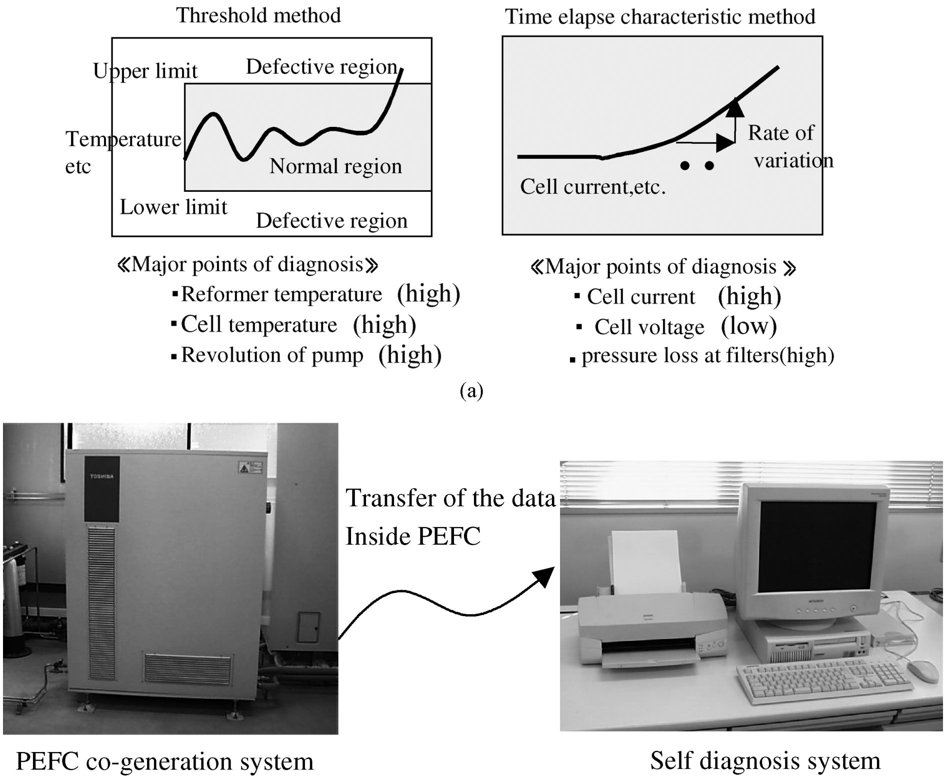
In fiscal 2000, such systems have developed as the system status display facility and the self-diagnostic subsystem with the capability to display the cause of trouble along with user actions required in the event of system failure or maintenance. The PEFC co-generation system with sensors attached to its fuel processing system, power conditioner, cell stack, heat recovery and heat utilization systems have been also built and tested in conjunction with the self-diagnostic subsystem.

5.2. The results of the studies in 2000

A self-diagnostic function was developed based on the two ideas of "threshold" and "time elapse characteristics" methods. The threshold method sets upper and lower limits. If data exceed the boundary of the two limits, the system is judged as defective. With the time elapse characteristics method, data are constantly monitored as a function of time.

If any abrupt changes are observed on the data, then the system is diagnosed as defective (Fig. 12a). A trend graph pattern or a tabular form chart is provided for an easy recognition of the status.

In the trend graph screen, pressure and temperature can be set on the vertical axis, while time can be set on the horizontal axis. An operational test was conducted on the self-diagnostic system being combined with the PEFC co-generation system of which measuring items were selected for the self-diagnosis (Fig. 12b). Through the test, data were gathered for making optimum design works on the conditions of self-diagnosis when the system was in normal operation or in trouble (defect or when a maintenance work was needed).



(a)

(b)

Fig. 12. (a) Two methods of self-diagnosis; (b) PEFC self-diagnosis system.

5.3. *Further plans*

Based on the self-diagnosis system that was manufactured in fiscal year 2000, we wish to manufacture systems and study the self-diagnosis specifications that will be required for each of the following three cases.

1. Self-diagnosis by the main frame PEFC co-generation system ... For general users.
2. Self-diagnosis at a central monitoring location ... For maintenance engineers.
3. Self-diagnosis on each equipment (when it is defective) ... For maintenance workers.

6. Overall plans

We are assuming a PEFC for domestic applications to be fitted with hot water storage tanks and back-up burner functions. We have started development works for the system in fiscal 2000 with the view of utilizing electricity and thermal output as well as the possible maintenance works after the system is introduced to the market.

In fiscal 2001, we will test, improve and complete the systems, which were manufactured in fiscal 2000. After completing the development program, we plan to conduct field testing at actual household users by combining the peripheral technologies with PEFC hardware, development of which is in progress at various equipment manufacturers, thereby the introduction to the market will be realized in the shortest possible period.

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