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FUJI FUEL CELLS TECHNIQUE

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I. INTRODUCTION

Fuel cells may be defined as electrochemical cells that continuously convert the chemical energy of a fuel and oxidant to electrical energy. Therefore, it would be more accurate to call it as a so-called power plant given a birth as a result of integration of chemical, electrical and mechanical engineering rather than to be imagined from a "cell" such as a dry cell, lead storage battery, etc.

One hundred or more years have passed since the principle of this fuel cell was discovered, however, it is only ten and several years ago that it started attracting interests as a new direct power generating system having high energy conversion efficiency. Among various types of fuel cells developed to date, the H_2-O_2 (or air) cell operating at 300°C or lower as well as the low temperature type hydrazine-air cell has put its step towards practical use and their special application fields are spreading more and more. It may be still in remembrance of people that the H_2-O_2 fuel cell has proved its excellent reliability by going on board into the Apollo vehicle as the power supply unit of it.

On the other hand, triggered by such high level techniques for special purposes, development of the fuel cells oriented towards the use of private enterprises has been continued also.

In recent years, with a rise of severe energy problem, large interests and expectation have been put on the fuel cells, particularly on the hydrogen-oxygen (air) cell from the point of view of highly efficient use of the fossil fuel and moreover from the aspect of effective use of hydrogen for preventing public nuisance, namely, as a clean energy in future.

Focusing especially on such features of the fuel cells, we have also studied them for these ten and several years. On the field of the low temperature type hydrogen-oxygen fuel cells in 1970, we developed a 1 kW cell stack[1] having the volume efficiency of 50 W/l and succeedingly, a 10 kW power plant in 1972. At present, efforts are made in order to widen

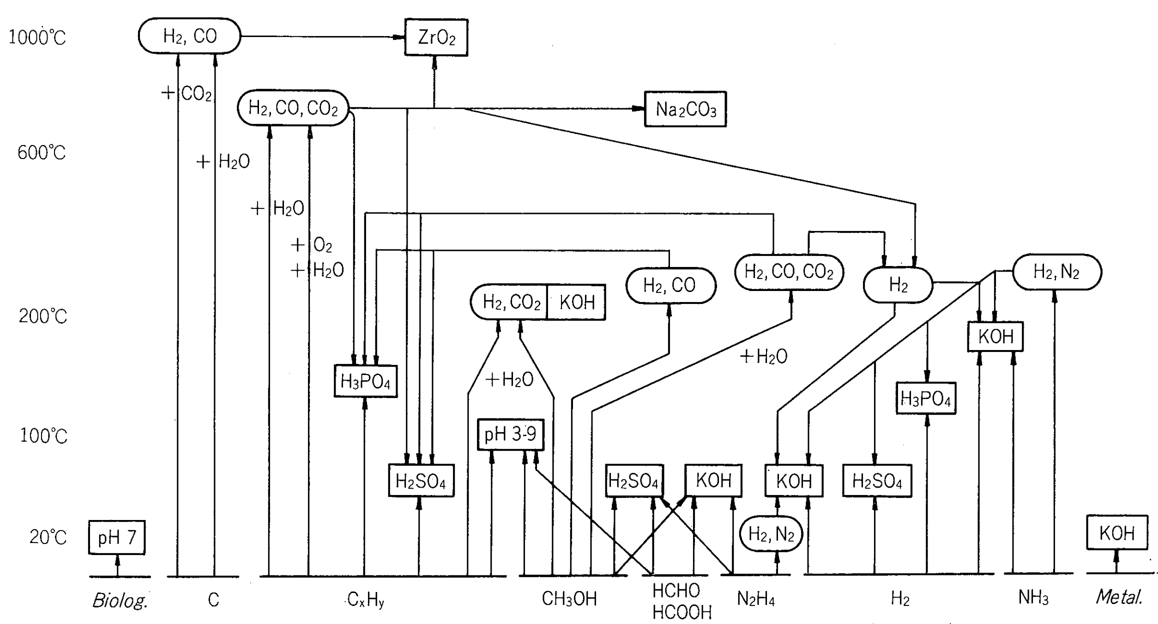

Fig. 1 Types of fuel cells classified by temperature and fuel as well as electrolyte (including various types of converters and purifiers).

* Note : G. Sandstede : "Form Electrocatalysis to Fuel Cells" XXI (1972), Battelle Seatle Research Center.

the fuel cell techniques as much as possible. This paper reports principle, structure and features of the fuel cell and the outline of the latest 10 kW power plant developed this time is also included.

II. PRINCIPLE AND STRUCTURE OF FUEL CELL

The fuel cell could be classified as shown in *Fig. 1*, according to the fuel used, types of electrolyte and operating temperature. The high temperature type solid electrolyte cell and molten carbonate electrolyte cell which have been considered just suitable for high capacity power generation seem to have been put aside from the way to the practical use because of difficulty on the high temperature techniques. As shown in *Fig. 1*, most of cell mechanisms are based on the hydrogen-oxygen cell, following description will therefore be extended in this direction.

1. Principle

Usually, the combustion reaction of hydrogen is expressed by the following reaction equation.

$$H_2 + \frac{1}{2}O_2 \rightarrow H_2O + \Delta H \qquad \text{..............(1)}$$

Where, ΔH: Variations of heat content, (The value of ΔH (generated heat) is 68 kcal/mol when the product water is in the liquid phase.)

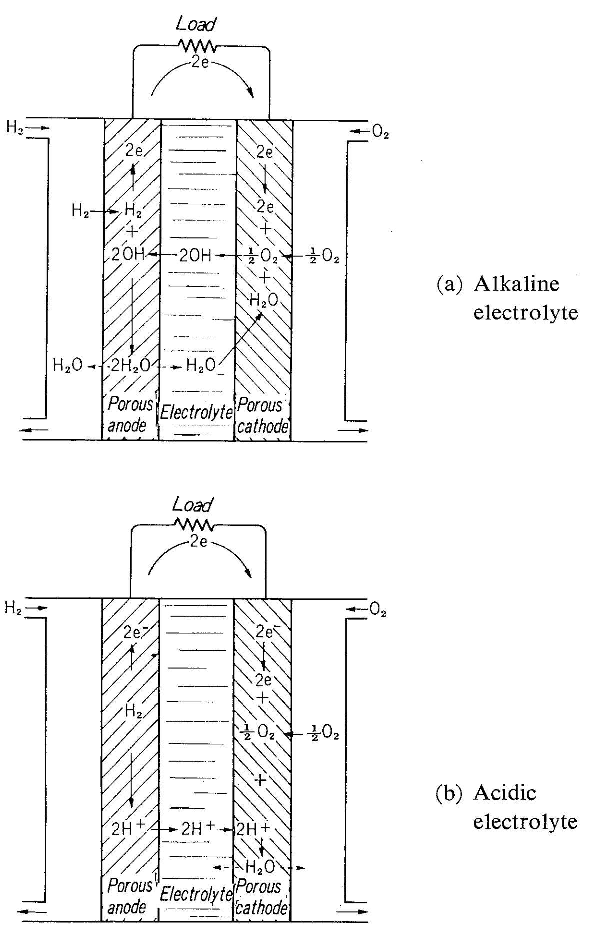

Fig. 2 Basic Configuration of H_2–O_2 Fuel Cell

In case of the fuel cell, such anode reaction and cathode reaction are separately carried out at the anode (hydrogen electrode) and the cathode (oxygen electrode), respectively, as shown in *Fig. 2* and the transfer of electron between these electrodes can be utilized as the electrical power generated. In other words, the hydrogen-oxygen fuel cell employs reverse process of the electrolysis of water. In order to make effective this reaction, porous gas diffusion electrodes and a stable electrolyte having high electric conductivity are generally used.

An electromotive force E is given by the following equations.

$$E = -\Delta G/2F \qquad \text{..............(2)}$$

$$\Delta G = \Delta H - T \cdot \Delta S \qquad \text{..............(3)}$$

Where, ΔG: Change of free energy
F: Faraday constant
ΔS: Change of entropy
T: Absolute temperature

The theoretical value of E is about 1.23 V at 25°C, however, in usual cases it actually becomes 1.1 V or so due to the subreaction, etc. In addition, when the electric current flows the voltage reduces. This is mainly because there are "reaction resistances" such as the activation polarization, concentration polarization and ohmic polarization. Therefore, further investigations have to be made for raising the operating temperature, use of active catalyst, structure of electrodes and cell and operation conditions with a view to making this resistance as small as possible.

2. Cell Structure

1) Porous gas diffusion electrode

The characteristic of this electrode is the basic factors for determining the cell performance. In general, a porous thin plate can be made by sintering carbon powder and metallic powder such as nickel by means of the plastic bonding together with the addition of a catalyst. The electrolyte comes to contact with the gas resulting in reaction at the catalyst surface. Therefore, some contrivances are made for making smaller the pore size on the electrode layer in the solution side than that of the gas side or for reinforcing the hydrophobic characteristic of the layer near to the gas side in order to maintain stable reaction zone. A thin electrode is desirable since a thick one may cause some influences on diffusion of reactants and products. At the same time, however, the mechanical strength has also to be fully satisfied. As mentioned above, possible efforts are made from both points of view of the catalyst and the electrode structure in order to improve the electrode characteristics. In case a cell is used for a long period of time with a high current density, it seems advantage to use a "metal electrode" made of the metal powder as the plaque.

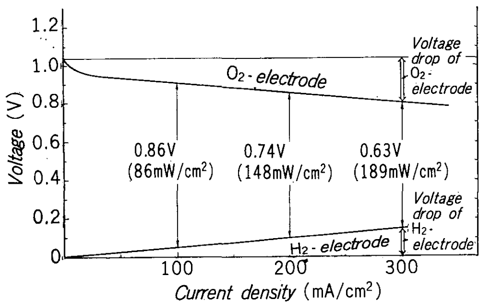

Fig. 3 Performance of single cell

2) Cell stack

Shown in *Fig. 3* is the voltage-current relation of a Fuji's single cell of the H_2–O_2 fuel cell consisting of a pair of electrodes as illustrated in *Fig. 2*. The cell is actually used on the voltage of from 0.7 V to 0.9 V. Therefore, single cells are connected in series electrically for obtaining operating voltage. Since the current is determined by the area of the electrode, the area of a pair of electrodes has to be adjusted or they must be connected in parallel electrically as required for obtaining necessary current values. The cell stack is configurated as explained above, however, it is also essential to supply constantly the reaction gas to each single cell or the electrolyte in case of the electrolyte circulation type method. Since these are usually supplied in parallel to each cell for giving uniform operating conditions, the current (so called leak current) flows from the high voltage side of the single cell to the low voltage side through the electrolyte manifold of the cell stack. This not only results the output loss but also gives some influences on the life of electrodes. Therefore, the electric resistance on the path of the electrolyte must be set higher than the limit values. Simultaneously, however, necessary consideration must be paid for preventing excessive increase of the head loss in the electrolyte path(2).

3) Supply and circulation system

For the effective operation of the cell stack, the operating conditions such as pressure of reactant gas and concentration of electrolyte must be kept stable and moreover supply of reactant gas and removal of reaction products and heat must also be carried out smoothly. For this reason, a fuel cell as the power plant can be said for the first time to be configurated after including additionally the gas and electrolyte supply aud circulation system and control and protection system. Since the power obtained is the DC power, it is usually converted into the AC power by using an inverter.

In *Fig. 4*, the cell stack structure including the fuel system is outlined. For removal of water which is one of the reaction products, utilized is the phenomenon of vaporization of water into the gas ambient from the electrolyte. The water vaporized through the porous electrodes or similar porous film is cooled by water or air, separated from the gas phase and removed as a liquid in the gas line. In the case of H_2-air fuel system, the water vaporized into the air ambient is scattered directly to the outside. The heat generated is removed as the latent

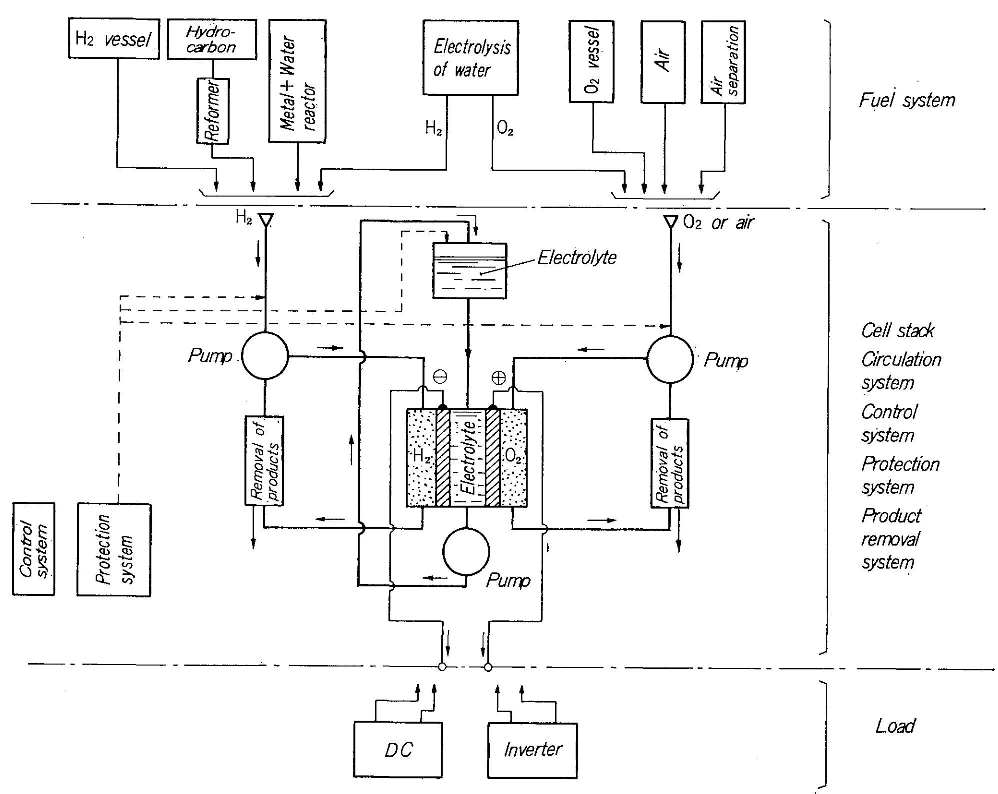

Fig. 4 Schematic of fuel cell system

heat and otherwise, it is removed by cooling the electrolyte in certain cases. Speaking more specificly, several methods are taken according to the purpose and application of fuel cell. In *Fig. 4*, the circulation method is shown for three systems of the reactant gas and the electrolyte. However, no circulations are performed in many cases in the oxygen, especially in the air ambient. Additionally, such electrolytes as immersed into the matrix or using ion exchange resin are also available.

III. FEATURES OF FUEL CELL

1. Efficiency

The energy conversion process and heat efficiency of the existing major power generating systems are shown in *Table 1*. In the heat (thermal) power generating systems, energy of the fuel used is subject to such energy conversion processes as heat→mechanical→electrical energy and the thermal efficiency is restricted by the Carnot cycle. However in case of the fuel cell, it is given by $\Delta G/\Delta H$ as is obvious from the equations (2) and (3). Particularly in case of the H_2–O_2 fuel cell, the theoretical value of 83% can be obtained at 25°C. As mentioned above, it is one of the characteristics of the fuel cell of this type that it has probability for being capable of obtaining high efficiency from its operating principle. Practically, the rated voltage of the cell stack is almost determined under the thermal efficiency of about 60% because of the loss due to the polarization resistance. The efficiency for maximum available electrical energy ($=-\Delta G$: 1.23 V at 25°C) of the cell is termed as the free energy efficiency for identification with the thermal efficiency.

2. Energy Density

Different from the dry cell and lead battery with the reactants in the cell, which specify their discharging capacity according to the amount of the reactants, the fuel cell is capable of discharging continuously so long as the electrodes are active since the reactants are supplied. In addition, the discharging capacity is determined by the external storing volume of the gas. In case of hydrogen, the quantity of electricity per weight of fuel is the largest. Resultingly, it is possible for the H_2 fuel cell to provide the largest energy density. *Fig. 5* shows the relation between the energy density and the weight of various fuel cells. The reason why the H_2–O_2 fuel cell have been selected in the U.S.A. as the power supply for the space vehicle also lies in this relation.

Table 1 Efficiencies and energy conversion process in power generation system

Power generating system	Conversion process	Thermal efficiency (%)
Fuel cell	Chemical to electric energy	30～70
Steam power generation	Thermal to mechanical to electric energy	34～42
Diesel power generation	Thermal to mecanical to electric energy	25～35
Thermal electron converter	Thermal to electric energy	8～15
Thermoelectric converter	Thermal to electric energy	6～10
Solar cell	Light to electric energy	5～15
MHD power generation	Thermal to electric energy	(Note) 50 (assumption)

Note: Combined with the steam power generation system.

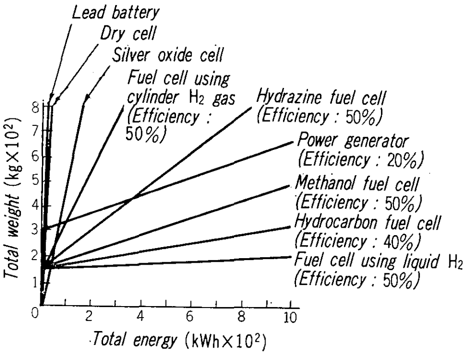

Fig. 5 Weights of 1 kW power sources

3. Reaction Product

The reaction product of the H_2 fuel cell is water. This fact gives qualification to be called a clean energy to the hydrogen (H_2).

IV. PRESENT STATUS OF DEVELOPMENT

Present status of research and development of fuel cells are reported at the Symposium of the Institute of Electric Engineers of Japan(3) held in the last spring or in the other papers. Described hereunder are trends of the research and development studied at present in various Labs.

1. H_2-O_2 Fuel Cell

The types of the H_2–O_2 fuel cells which have already been developed or under development up to now can be tabulated as shown in *Table 2* in a broad sense. The pure H_2–O_2 cell can be limited in its application field only to the special field from the reason that the air is not used. The typical cell of this type is the power supply (operating temperature of 250°C) for the Apollo vehicle of the United Aircraft Corp. Pratt & Whitney Div. On the basis of this technique, a low temperature type 20 kW cell(4) has been developed in 1972 for the use of DSSV (Deep Submergence Search Vehicle) and moreover a 5 kW class cell is also under the development for the use of the Space Shuttle. In these cells, the noble metal catalysts of the platinum group are used as the electrode catalyst. As a result of the life test, the operating life of 6,000 hours or more

Table 2 **Types of H_2-O_2 fuel cells**

Fuel	Oxidizing agent	Electrolyte (Note)	Operating temperature	Catalyst	Major technical problems
Pure hydrogen	Oxygen	Potassium hydroxide	200~250°C	Lithium doped nickel oxide	High temperature, High operating pressure
	Air		Ambient temperature~100°C	Noble metal of platinum group, Non-noble metal	Prevention of carbonization of electrolyte
Impure hydrogen		Phosphoric acid, Sulfuric acid	Ambient temperature~150°C	Mainly, noble metal of platinum group	Corrosion of metals

Note: The ion exchange film is sometimes used as the electrolyte in some pure H_2-O_2 fuel cells.

is assured with the current density of about 80 mA/cm².

On the other hand, research for use of Raney-alloy in place of the noble metal calalysts is also continued traditionally in European countries. Although the Raney-nickel is the highly active catalyst for hydrogen electrode, it is troublesome from the point of view of its handling because it tends to be oxidized. However, as a result of improvement in its stability, the fuel cell manufactured by Siemens wherein the Raney-nickel of 0.2 g/cm² is used for the hydrogen electrode and the Raney-silver of 0.1g/cm², for the oxygen electrode ensures the operating life of 1,400 days (at 25 W) or 5,000 hours (at 100 W).

In addition, a 2 kW cell[5] which uses the Raney-nickel of 0.15 g/cm² for the hydrogen electrode and the silver of 0.05 g/cm² for the oxygen electrode can provide the output voltage of 0.85 V per single cell with the current density of 104 mA/cm² at the operating temperature of 75°C under the configuration of weight; 53 kg, volume; 77ℓ and the average power consumption of auxiliary equipment; 75 W.

As for the cell in general use, the air is used as the oxidizing agent. In case the alkaline electrolyte is used however, the operating life of cells is shortened since the alkaline electrolyte is deteriorated by the carbon dioxide gas. Thereby, studies are continued also for a method to remove electrochemically the dissolved carbon dioxide from the liquid. However, when the impure hydrogen including carbon dioxide is used as the fuel and the air, as the oxidizing agent, it is advantageous to utilize an acid electrolyte which never absorbs any carbon dioxide. In this case, corrosive nature of the electrolyte gives a rise of problem on the corrosion resistance of materials including electrodes. The fuel cell of this type is now under develoment based on the TARGFT program.

The TARGET program[6] has been launched by the Team to Advance Research for Gas Energy Transformation Inc. organized in 1967 with total of 27 gas companies in the U.S.A., aiming at the development of an H_2-Air cell (using a phosphoric acid electrolyte) for the use in a complex residential area through natural gas reformation. Actual research and development works are trusted to the afore-mentioned Pratt & Whitney Div. At present, the cell stated above has completed the field test and reportedly, it enters the 3rd-phase of the production program. Gas companies in Japan have also taken part in this field test.

On the basis of the similar development concept, a cell of 20 MW or so is now under development. In European countries on the other hand, the studies on the cell using the sulfuric and as an electrolyte are continued steadily. Of these cells, the one using the tungsten carbide for the hydrogen electrode has been put into the operating life test of 30,000 hours[7] although its electrode area is comparatively narrow.

2. Hydrazine-Air Cell

In the liquid fuel cells, it is much easier to store and transport the fuel than in the gas fuel cell. Development is continued for this type of cell for application into some particular fields because it is easy to obtain high power density although the hydrazine is very expensive. In Japan[3], the cell of this type is under the trial use as the power supply for unmanned light house or unattendant TV relay station and furthermore efforts are made for the purpose of widening application fields including portable cells.

We also have designed experimentally the model shown in *Fig. 6* as the compact stationary power

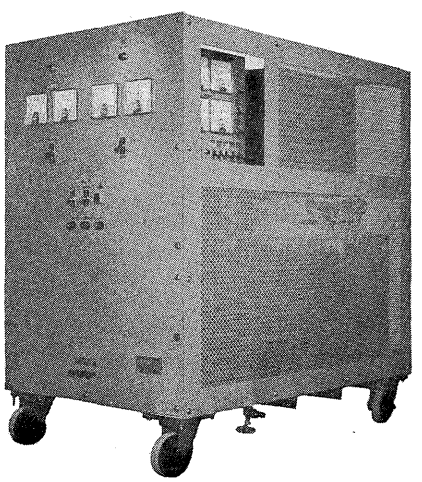

Fig. 6 72 W N_2H_4-Air Fuel cell power source

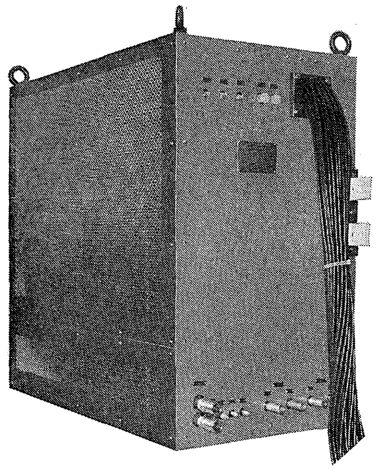

Fig. 7 Outerview of 10 kW H_2–O_2 fuel cell system

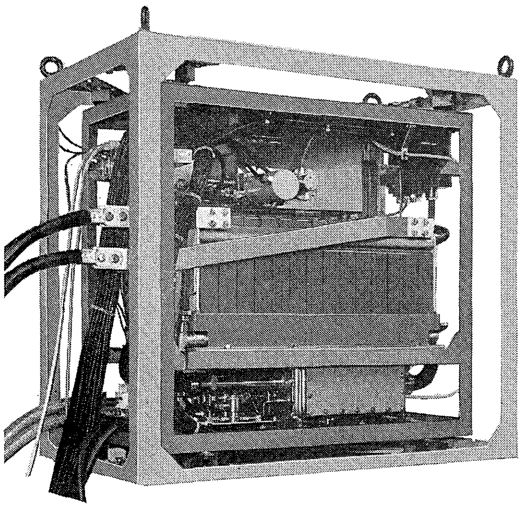

Fig. 8 Internal view of 10 kW H_2–O_2 fuel cell system

source and obtained experiences and precise data concerning fuel efficiency and by-products as a result of long term test.

V. FUJI'S 10 kW H_2-O_2 FUEL CELL

This fuel cell is a power source as s complete unit including circulation system developed by Fuji Electric Co., Ltd. aiming at high performance and high reliability. Its rated current is 900A and voltage is 11.5 V. Basically, this unit is provided with the supply and circulation system as shown in *Fig. 4* around the cell stack. Its outerview and internal view are respectively shown in *Fig. 7* and *Fig. 8*.

1. Structure

1) Electrodes

In this fuel cell, original highly active metal electrodes are used. This electrode is a porous gas diffusion electrode employing the metal which has been subject to the necessary stabilizing treatment on the basis of highly active Raney-alloy as the catalyst. Because of the use of metal electrodes, the electric resistance is very low and the voltage drop within the electrodes is also extremely low even at the time of full-load. This is the significant feature of the cell of this type.

Moreover, special care is paid for providing sufficient mechanical strength required by the cell structure and resistance for electrolyte leakage and gas babbling during operation, and at the same time to form electrode as thinner as possible. Its thickness is about 0.6 mm.

As shown in *Fig. 3*, the excellent I-V characteristic is also obtained, namely it proved as a result of the life test that it is capable of discharging in the order of several thousands hours even with the high current density over 100 mA/cm².

For the cell of 10 kW capacity, the electrode of 1,000 cm² class is used. In the course of this process, the manufacturing method in maintaining uniform characteristic for each part of the electrode without degrading excellent discharging characteristic is established. By making full use of advantages of self-production system, we have sufficiently carried out quality control of electrodes from purification of catalyst to the cell construction.

2) Cell stack

The cell stack consists of 14 single cells which are electrically connected in series. A single cell consists of 10 pairs electrodes which are electrically connected in parallel. The gas and the electrolyte are distributed in parallel. As the electrolyte, the 30% KOH is used and the operating temperature is 65°C. The temperature characteristics of a single cell with the rated current of 900A is shown in *Fig. 9* and it withstands the over load of 5/3 times. In addition, this single cell never caused any abnormal phenomenon even under the long time operation with 1,200A at the electrolyte temperature of 70°C.

3) Gas/electrolyte supply and circulation system

The supply and circulation system can serve for maintaining automatically the operating conditions of the cell to the optimum condition. Moreover the system to be configurated has to satisfy all the

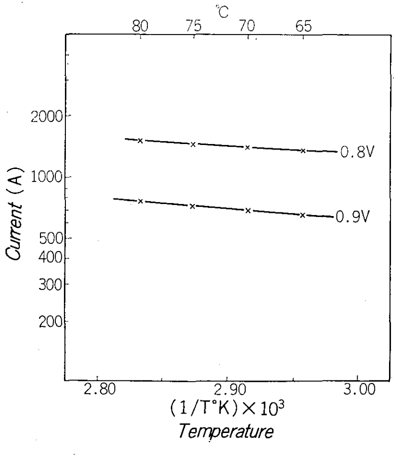

Fig. 9 Effects of electrolyte temperatures on performance

requirements as the power unit. From this point of view, major component parts are all newly developed only for the latest 10kW power generating system. Following factors can be listed as the requirements of the supply and circulation system.

(1) Fixed gas pressure within the cell
(2) Perfect removal and exhaustion of the product water
(3) Maintaining the cell temperature to the optimum condition
(4) Fixed quantity and concentration of the electrolyte
(5) Having the automatic operation and automatic protection functions
(6) Less power consumption, small size and lower weight

The supply and circulation system manufactured this time completely satisfies these requirements and further considerations are taken into account as follows.

For the purpose of keeping the pressures of the hydrogen and oxygen within the cell constant, a pressure control mechanism having a diaphragm of large diameter is provided.

In addition, the sensitivity of the diaphragm is made high and the feedback system is optimized in order to ensure the minimum transient pressure changes. Thereby, the response characteristic of pressure control is successfully raised.

For removing the product water, employed here is a method in which it is vaporized into the gas by means of the circulation of gas in the cell. For the purpose of circulating the gas, a compact and high performance ejector utilizing pressure of the gas supplied is introduced instead of such a device as requiring an auxiliary power like a fan. Sufficient amount of gas circulation is also obtained by designing the ejector efficiently and by minimizing the flow resistance in the gas circulation system. Moreover, in removing the condensation of water vapor in the gas ambient, a compact water cooled fin type device having low flow resistance is employed. Thus, the ability in removal of product water which completely covers the actual product water or more is assured. The concentraiion is controlled by returning a part of the condensated water vapor into the electrolyte.

The cell temperature is kept constant through the temperature control of the electrolyte. For this purpose, a unique temperature control valve which does not require any power at all has been developed and the flow of cooling water is controlled in proportion to the electrolyte temperature. Thus, a high precision control within ±1°C has been obtained.

Besides, the major component parts mentioned above, the temperature, pressure and level sensors, pump, heater, tank and solenoid valve are almost newly developed for the exclusive use. Moreover, these are organically coupled into a unit with a view to attaining compact and light weight, reduction in pipings and improving reliability.

A control panel is additionally provided on the basis of separate installation in order to give variety of functions to the power generating system such as sequential starting, automatic operation, automatic warning and emergency stop. Therefore, the operation is much simplified resulting in as much improvement of safety. The outerview of this control panel is shown in *Fig. 10*.

2. Performance

The electrical characteristic of the 10kW H_2–O_2 fuel cell is shown in *Fig. 11* and the output power of 10.6kW can be obtained with the current of 900A and the voltage of 11.8V. In this case, the power of auxiliary equipment including the control panel is 270W and the cell stack shows the volume efficiency of 60W/*l* or higher. The thermal efficiency is 58% and the free energy efficiency is 66.8%. It is all automatically controlled to maintain concentration of the electrolyte by removing the product water and to keep constant the electrolyte temperature. In other words, satisfactory results have been obtained for entire part of the system.

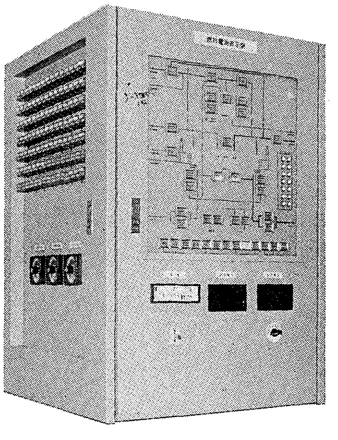

Fig. 10 Outerview of control panel

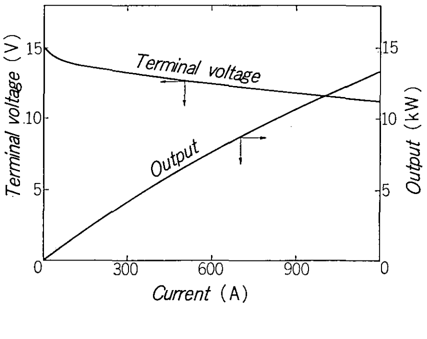

Fig. 11 Performance of 10 kW H_2–O_2 fuel cell

VI. SUMMARY

In this paper, principle, structure and features of the fuel cell, and trend on the way to the practical use have been outlined together with the introduction of Fuji Electric's fuel cell techniques.

The Fuji's 10 kW H_2–O_2 fuel cell has been given a birth through organic combination of the results of research and study for cells for over 10 years and the integrated system techniques in the field of heavy electrical industries. We feel it is our responsibility to further widen and deepen our cell techniques through additional improvements in various points, and to pay our every effort to find out further application fields of fuel cells in the practical use for the time to come.

Finally, we wish to express our acknowledgement to whom it may concern for their heartful encouragement and useful suggestions and we dare say we hope further encouragement.

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