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Improvement of Output Efficiency of a Fuel Cell by Using Oxygen

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Abstract: This study aims to extend the previous research on PV generation systems. The author previously proposed the new PV generation system where surplus electric power is used for electrolysis of water to generate hydrogen, converting into electricity by Fuel Cell (FC) at nighttime or in bad weather. In the current system, oxygen is produced as a by-product of the process. Therefore, this paper investigates the use of this oxygen for power generation, which makes the system more effective than the old system of FC with the air. The latest FC technology, Polymer Electrolyte Fuel Cell (PEMFC), is used to conduct the whole experiment to get the best result. Using air and oxygen shows that when oxygen is used, FC efficiency increases by 12%, and the output power is increased twice as much as air. This research has added into the domain of FC and its usage. Valuable recommendations are given based on the analysis and results.
Keywords: *High efficiency, increasing output, use of oxygen*

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I. INTRODUCTION

As of late, the popularity of FC is growing faster because of its efficiency and non-polluting components. A FC is actually an electrochemical device, which is continuously able to convert the potential energy from the hydrogen fuel with an oxidizing agent like oxygen, through an electrochemical reaction. There is no pollution occurs in this electrochemical reaction. That is why the popularity of this device is increasing as an Eco-Friendly device. Recently FC is being used in different places, for example, electric train, electric tram and other vehicles [1, 2, 3, 4]. Moreover, FC is now using with lots of other components like the hybrid energy storage system, super capacitor, battery, etc. [5, 6].

As per the recent analysis, the research on FC is still not so much. The most recent research on FC are minimum fuel consumption strategy for Proton-Exchange Membrane (PEM) FCs [7], which proposed a system that minimizes the fuel consumtion while supplying required power for the load. Theoretical result on stabilizability of oxygen excess ratio for PEM FC [8], proposed a solution for the oxygen ratio value which can be controlled by using a continuous state feedback. Design and development of FC Oxygen Tree (FCOT) [9], which is research of using a FC to perform a reverse electrolysis by using hydrogen as a fuel for generating electricity and clean water. Integrated motion and powertrain predictive control of intelligent FC/battery hybrid vehicles [10], where an intelligent system was introduced that is able to reduce the fuel consumption for hydrogen and balance the vehicle battery charge and power consumption. Active disturbance rejection control for fuel processing system of FCs [11], Control Lyapunov function based control strategy for air supply system of PEM FCs [12], Model predictive control for oxygen starvation in air supply system of PEM FC [13], Renewable (REW)/FC Hybrid Power System with mitigation of the REW variability by the FC fuel flow control [14], Explicit model predictive control for PEM FC systems [15], Simulation of Oxygen and Water Mass Fraction in the Cathode for the PEM FC [16], Application of microbial FC in wastewater treatment system by using algae as the oxygen supplier in cathodic chamber [17], A theoretical result on stabilizability of oxygen excess ratio for PEM FC [8] all of these research paper are based on

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FC.

The author previously proposed the new Photovoltaic Generator (PV) generation system where surplus electric power is used for electrolysis of water to generate hydrogen, which will use to convert into electricity by FC at night time or in the bad weather. In that system, surplus electric power used for electrolysis of water in an independent photovoltaic power generation system to generate and store the hydrogen. So that it can be used later on. However, in this paper we have carried out a fundamental study on the effect of FC power generation when actively using oxygen in the FC to find out the method for obtaining high output efficiency from the FC system.

All the recent researches on FC has conducted for fuel control system, as mentioned before when introducing the recent paper based on FCs. However, it is yet to conduct the research on the system of increasing the efficiency of the output of a FC, using oxygen. Therefore, our work is to conduct the research to compere both of the output, while using air and oxygen and find out the maximum output efficiency while using oxygen along with hydrogen. To find out the most efficient points, we have used voltage vs current, efficiency vs output power and power vs voltage characteristics and compare with the old system of using air with the new system of using oxygen.

There is an investigation of Influence of oxygen concentration on performance of PEM FC [18]. They have conducted the research based on the characteristics of voltage vs current, showing the concentration of oxygen on the FC performance by using a FC of only one cell. Therefore, they did not conduct any investigation on the output efficiency of a FC. However, our paper focuses on the effect of output efficiency and investigating the result through three different characteristics (voltage vs current, efficiency vs output power and power vs voltage characteristics) by using FC stack.

A. FC/Solar Power Generation Combined System

Fig. 1 shows the concept of FC power. In Fig. 1, surplus power flows from the Maximum Power Point Tracking (MPPT) device. The oxygen is generated during the decomposition of water. In the decomposition equipment, oxygen is generated at the anode side and hydrogen at the cathode side. It is a system of which supplies FC

generated electricity to the load when the battery generates little power at night, cloud or rain situation. In this system, the effect of using raw oxygen will be discussed.

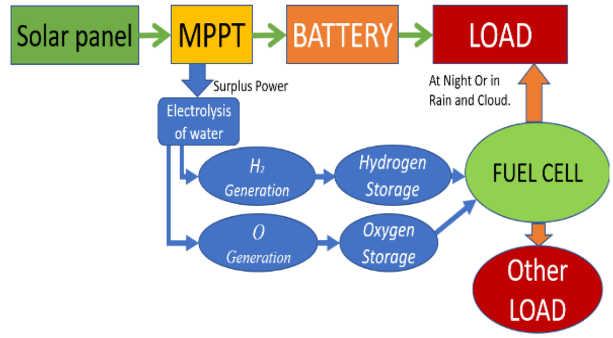

Fig. 1. Conceptual diagram of the proposed system

Maximum Power Point Tracking (MPPT) device is an electronic device, which is used for controlling the charge and extracting the maximum power from the solar panel. This device optimizes the power between the solar panel and the battery to draw the maximum output from the solar panel.

Previously we have done a research on MPPT [19], [20]. In which a new type of MPPT control method was introduced, where the I-V characteristics scanned with detection interval control at a specified interval and the maximum power point is monitored. Fig. 2 depicts the proposed control system. In this MPPT system PV modules are connected in parallel, according to their required power rating. A step-up DC-DC converter is applied to the load to boost the PV output voltage V_{PV}.

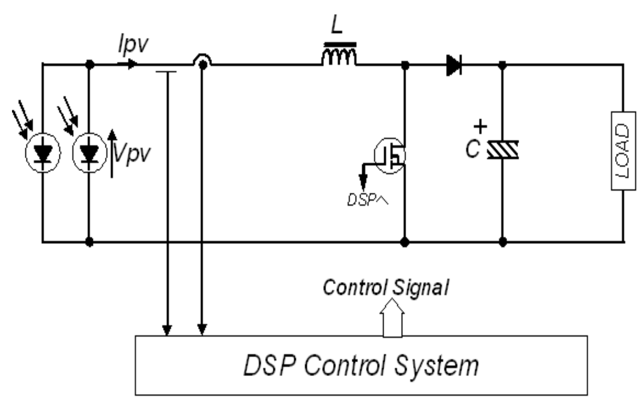

Fig. 2. Circuit configuration

Fig. 3 shows the waveforms generated during the operation. The carrier wave (indented wave) V_C is compared to the reference signal wave Vref using a comparator, which yields the PWM control signal. When the maximum power point, which needs to be determined, switch S to turned off, gradually decreases the PV current I_{PV}. When the V_{PV} reaches the open circuit voltage V_{OC}, the I_{PV} is regarded as zero. After then, switch S is turned on.

I_{PV} rises from zero to short-circuit current I_{SC}. The optimum voltage V_{OP} corresponding to the P_{max} point can be precisely calculated during this detecting interval by monitoring the change in V_{PV}. The time required of this interval is a few hundred μsec [21]. Subsequently, the PI regulator maintains the V_{PV} at the detected V_{OP} using a DC-DC converter with a high switching frequency. This method allows for the realization of a high MPPT efficiency over the tracking interval. The system then alternates between P_{max} point detection and tracking operations at a constant frequency (1/T).

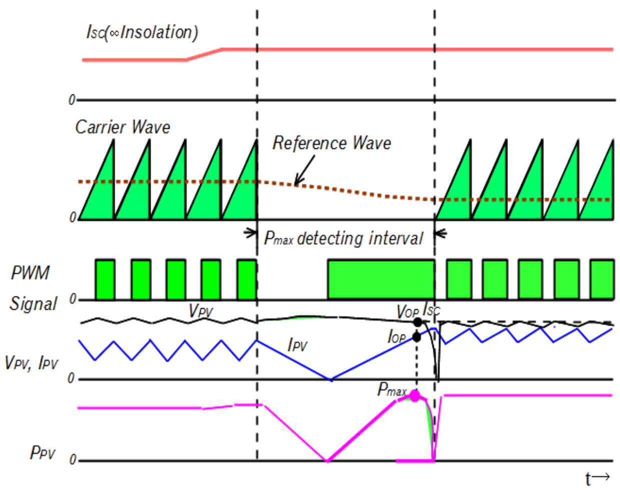

Fig. 3. Operational waveforms

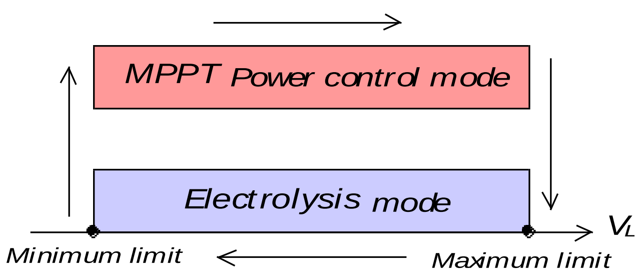

Fig. 4. MPPT control system

Additionally, The Battery is used for the uninterrupted power supply to the external load and when the battery is fully charged, surplus power supply to the battery will be stopped and passed for the use of generating hydrogen and oxygen. All the hydrogen and oxygen gas will be collected to use later on at the time of low power supply to the load. Moreover, for external control, as shown in Fig. 4, if the voltage of the battery V_L (the energy level) reaches the maximum limit, operation stops and electrolysis mode activated for the electrolysis. If the value of V_L reaches the minimum limit, the system immediately begins to operate in the MPPT power control mode.

Electrolysis is a process by which electric current passes through a substance to effect a chemical change. The chemical change is one in which the substance loses or gains an electron (Oxidation or reduction). The process carried out in an electrolytic cell, an apparatus consisting of positive and negative electrodes held apart, dipped into a solution containing positively and negatively charged ions.

In this experiment, we use the water (H_2O) solution, as it is an easy source of hydrogen and breathable oxygen. By electrolysis of water, we can get hydrogen gas and oxygen gas [22].

Cathode (reduction): 2 H_2O (l) + 2e $\rightarrow$ H_20 (g) +2OH$^-$ (aq)

Anode (oxidation): 2 OH$^-$ (aq) $\rightarrow$ 1/2 O_2 (g) + H_2O (l) + 2 e$^-$

Electrolysis of water has done by the surplus energy from the PV panel. In this system, hydrogen has generated to the cathode and oxygen has generated to the anode side as shown in Fig. 5. After that, generated hydrogen and oxygen gas are stored for use later on, in the FC when needed.

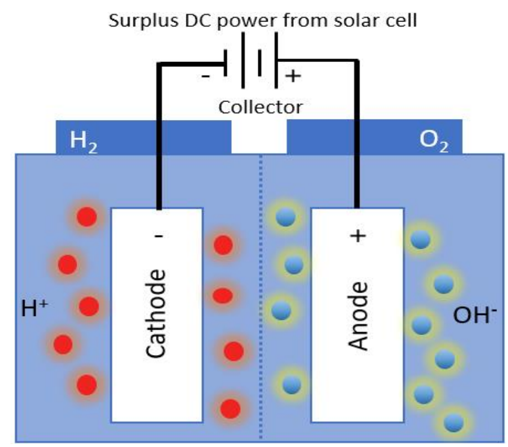

Fig. 5. Electrolysis of water

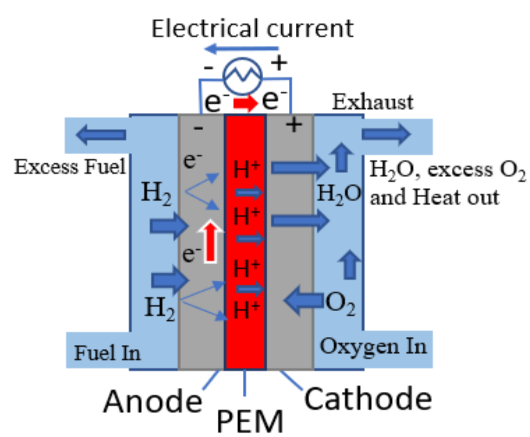

Fig. 6. FC functions

FC function is shown in Fig.6. Here, H_2 gas enters from the anode side, releases the electron, becomes H^+ ion, and enters in the PEM layer. O_2 enters from the cathode side. After that, O_2 is combined with the hydrogen ions that coming through the electrolyte from the anode. Combining with hydrogen it becomes water, which is getting out through the exhaust. Heat is also released in this way.

Therefore, this time our research is on the FC output efficiency to make the output power increase of the FC.

B. FC Test System

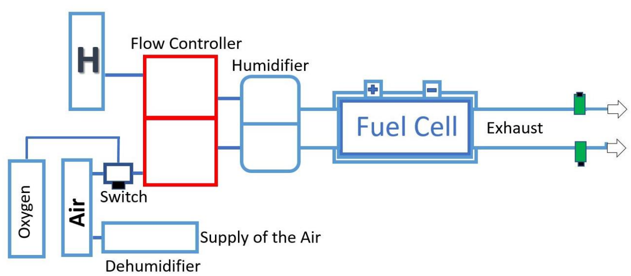

Fig. 7. FC test system

The FC experiment system is shown in Fig. 7. Air passes through the dehumidifier and input gas passes through the humidifier and enters to the FC. A switch changes the flow between oxygen and air. The flow controller controls hydrogen and oxygen flow. After the flow controller, a humidifier which is very important for a FC is connected. Humidifier is needed during the fuel intake process [23]. It provides the necessary humidity and temperature for the peak performance of the FC. Moreover, it will allow getting the humidity and temperature that is needed for a steady FC. Exhaust is used for output of the gases.

Fig. 8 shows the PEMFC, which is used in this experiment. The specifications of the polymer electrolyte FC are as follows: 7 cells in cell size, cell area 50[cm^2] (1 cell), rated output 50[W].

Fig. 8. PEMFC

The conversion efficiency of the FC is related to temperature [24]. Therefore, ambient temperature of the FC, where hydrogen and oxygen are supplied and compared with the case where air is used must be kept on a constant temperature. In this experiment, the temperature is kept at the fixed value of 70[°C]. The constant temperature oven and flow controller are shown in Fig. 9.

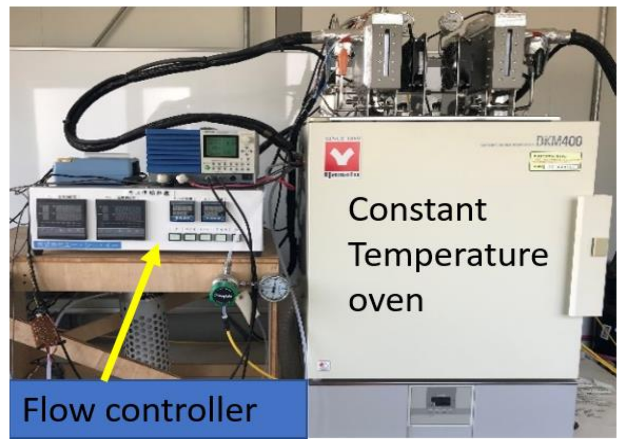

Fig. 9. Temperature oven and flow controller

Experimental conditions are 0.25[MPs] pressure for both fuel side and oxidizer side, 30[°C] temperature on the moisture dew-tipped side, FC ambient temperature 70[°C], hydrogen supply amount is 1[L/min], air supply amount is 2[L/min], oxygen supply amount is 0.6[L/min].

II. EXPERIMENTAL RESULTS

In this experiment, the output power is compared, to find out the maximum efficiency, when normal air and oxygen are used individually. Fig. 10 shows overall output performance comparison when air and oxygen are used in the experiment. The combined overall output performance is based on the output voltage and current of the FC. In the graph, green line shows the output of the oxygen and blue line shows the output of air. From upside it shows the graph of current vs voltage and downside shows the graph of current vs power. With the increase of current, voltage falls down fast for air while it falls very slowly for oxygen. In the current vs voltage graph, comparing the voltage in respect of current Interferential Current (IFC) at 5[A] the output voltage for air is 5.2[V] and the output voltage for oxygen is 5.7[V] which is higher than the output voltage for air. At 10[A] the output voltage for air is 4.9[V] and the output voltage for oxygen is 5.55[V] which is still higher than the output voltage for air.

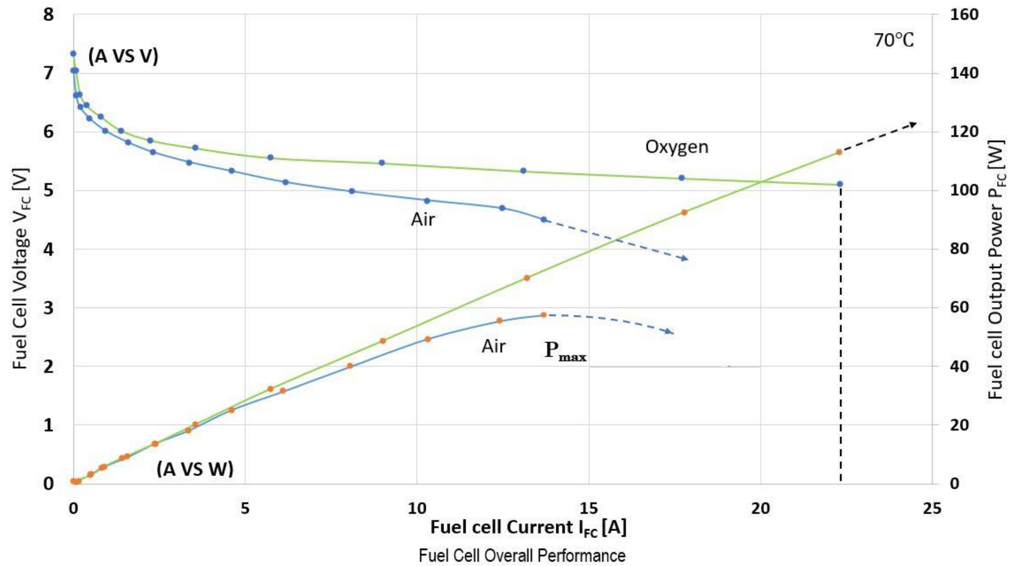

Fig. 10. Combined overall output performance

To ensure the safety of the FC, we could not help but to stop the experiment with the oxygen at 22[A]. If the output current cross 22[A], there is a big possibility that it will damage.

In the current vs power graph although the output power is same at the beginning, the power has raised much for oxygen as the current increased. Comparing the output power at 14[A] it is 58[W] for air and 70[W] for oxygen which is still higher than the output power of air. After reaching the maximum power, P_{max} the output power for air decreases with the increase of current. However, the output power for oxygen can be increase more than 120W but we had to stop the experiment at 22[A] to ensure the safety of the FC. From this figure, it can be confirmed that when oxygen is used, the maximum output is more than twice that of air.

Fig. 11 shows the characteristics of fuel efficiency ζ for FC output power.

$$\text{Where,}\zeta = \frac{\text{FC output power}[W]}{H_2\text{flow rate}[L/min]} \tag{1}$$

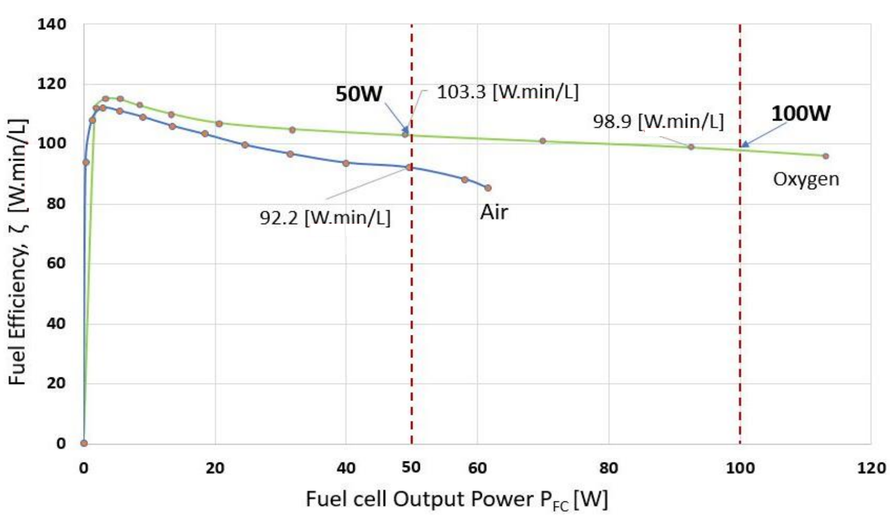

Fig. 11. Fuel efficiency vs output power characteristics

In this figure, green line shows the fuel efficiency vs output power for oxygen and blue line shows the fuel efficiency vs output power for air. For 50[W] power, fuel efficiency of air is only 92.2[W.min/L] while fuel efficiency of oxygen is 103.3[W.min/L], which is higher than the fuel efficiency of air. Moreover, for 100[W] the fuel efficiency of oxygen is 98.9[W.min/L], which is still higher than the fuel efficiency of air at 50[W].

However, for oxygen, the efficiency is quite stable and the efficiency falls very slowly. After that, the efficiency falls down for air. From this figure, it can be clearly seen that ζ is 92.2[W.min/L] for air at the rated output of 50[W], whereas it increases by 12% at 103.3[W.min/L] for oxygen. Furthermore, It is confirmed that the maximum value of 98.7[W.min/L] is maintained even at the maximum output power of 100[W] when oxygen is used and the effectiveness of using oxygen is clarified.

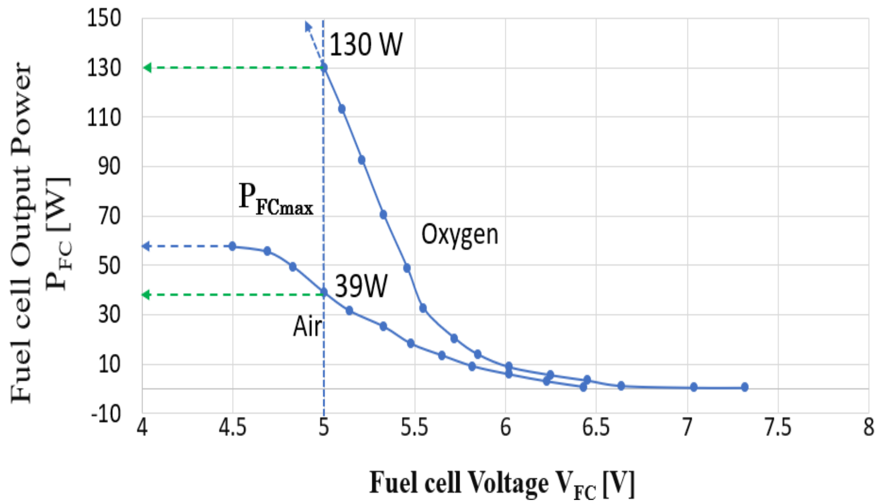

Fig. 12. FC voltage vs FC output power

Fig. 12 shows the FC voltage vs FC output power. The maximum power for oxygen is 130[W] with 5[V] while it is only 39[W] for the air. The output power is two times more than that of the system using air. Moreover, keep decreasing the voltage of FC for the system of oxygen, the FC output power is increasing more than that of the system using air.

III. DISCUSSION

In our research, we have investigated the efficiency for the FC output. Here, air and oxygen is used as a variant fuel and hydrogen as a constant fuel. Although both the variant fuel contains oxygen, however the output increase when using direct oxygen. In addition, from our research result we have find out that the output performance is much higher than that of the system using air. To find out a more accurate result, we have used FC stack with the comparison of voltage vs current, efficiency vs output power and power vs voltage characteristics. However, there is an influence of fuel crossover in the whole experiment. Because of fuel crossover, the durability, performance and efficiency of the FC can be degraded. That is, Equation 1 is represented by Equation 2.

$$Z = \frac{\mathrm{P_{FC}[W]}}{\mathrm{H_{2FC}}\left[\frac{\mathrm{L}}{\mathrm{min}}\right] + H_{2O}\left[\frac{\mathrm{L}}{\mathrm{min}}\right]} \tag{2}$$

Where, H_2FC[L/min] is the hydrogen flow consumed by load of FC, and $H_2O[L/min]$ is the hydrogen flow lost by crossover. From Equation 2, it can be seen that the efficiency ζ decreases for the hydrogen loss H_2O by crossover. When the denominator of Equation 2 is expressed by current, Equation 3 is obtained.

$$\zeta = \frac{V_{\mathrm{FC}}[\mathrm{V}] \cdot \mathrm{I_{FC}[A]}}{\mathrm{K}\left(\mathrm{I_{FC}} + \mathrm{I_{FC0}}\right)\left[\frac{\mathrm{L}}{\mathrm{min}}\right]} \tag{3}$$

Where, K is a proportional constant between hydrogen consumption and current, and is the constant based on the Faraday's law. I_{FC0} is obtained by converting H_2O into current using K. This I_{FC0} has a small value and can be considered as constant. In the region where I_{FC} is small and I_{FC} « I_{FC0}, Equation 3 is approximated by the following Equation 4.

$$\zeta \fallingdotseq \frac{V_{FC} \cdot I_{FC}}{K \cdot I_{FC0}} \tag{4}$$

Therefore, ζ in Fig. 11 approaches 0 when I_{FC} approaches 0. In the region where I_{FC} is large and I_{FC0} can be ignored, Equation 3 is approximated by the following Equation 5.

$$\zeta \fallingdotseq \frac{V_{FC} \cdot I_{FC}}{K \cdot I_{FC}} = \frac{V_{FC}}{K} \tag{5}$$

Therefore, in the region where I_{FC} is large in Fig. 11, the characteristic of ζ is similar to the characteristic of V_{FC}. From the above, the ζ characteristic of the FC has one peak with respect to the change of the FC current.

IV. CONCLUSION AND RECOMMENDATIONS

From this experiment, the increase in the output of the FC and efficiency is quantitatively revealed as the result of fundamental study on the effect of FC power generation using oxygen which is generated by the electrolysis of water in the proposed system (Fig. 1). It is confirmed that when oxygen is used, the output power is more than double that of air. It is also found that efficiency increases by 12%. The reason behind this is the increase in FC voltage due to the use of oxygen. That is, the efficiency characteristic is almost the same as the FC voltage characteristic in a region where the FC current is large. In addition, this efficiency characteristic is affected by the crossover of the FC.

Although the research is about efficiency of the output of a FC, still other area could be utilizable for increasing the overall efficiency of a FC. As we face several problems with the control method while doing experiment in future, we are planning to investigate a new efficient power control method for this system on the premise of using oxygen to increase the efficiency further.

Declaration of Conflicting Interests

No identifiable competing interests are present in this work.

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