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FUZZY CONTROL OF HYDROGEN GENERATION BY THE REACTION OF ACTIVATED ALUMINUM PARTICLES AND WATER

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ABSTRACT

The purpose of this paper is to design a fuzzy control system for generating hydrogen at a desired level by a reaction between water and activated aluminum particles. The activated aluminum particles are produced shredded aluminum sawdust. It is difficult to characterize the reaction quantitatively because the characteristics of hydrogen generating reaction vary as depending on the samples, the environment of the reaction and so on. The experimental system consists of a fuel cell (FC) of 100[W], a water tank, a reaction vessel, pressure sensors, a water pump, a radiator and a one-chip microcomputer. The fuzzy control system is designed to determine the quantum of water which is supplied to the activated aluminum particles. The error forms a desired value of the pressure of the reaction vessel and the change of the error are chosen as the labels of the fuzzy membership functions. The proposed fuzzy control system is applied to maintain the pressure of the reaction vessel of the developed hydrogen generation system at a certain level. The developed hydrogen generation system is confirmed to provide hydrogen to the FC by experiments under various conditions.

Keywords: Fuel cell, Hydrogen generation, Activated aluminum particles, Fuzzy control.

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1. INTRODUCTION

Recently, global warming increases the frequency of natural disasters such as torrential rains, landslides and floods. The inhabitants of the isolated area by such disasters are forced to live inconveniently, in the emergency situation that the lifeline such as electricity, gas, and water is affected. Because the inhabitants might be confronted by a life-threatening situation by not gathering information it is necessary to secure a power supply for information terminal devices such as mobile phones. In abysmal weather, photovoltaic generation and the wind-generation cannot be used. The use of general diesel engine generates make vibration and noise. Furthermore, toxic materials in the exhaust gas cause the deterioration of living environments. Therefore, it is required the development of a clean portable power supply which is easily operated.

A fuel cell (FC) system has a high energy density and good environmental performance. However, there are many problems which are not only the generation of hydrogen but also the storage and transportation method. Under the societal background, many studies to produce hydrogen online have been conducted. For example, a portable hydrogen generator using the reaction of caustic soda solution and aluminum was proposed by Stannard [1]. Mohring [2] and Murooka [3] constructed each different system for supplying hydrogen generated by $NaBH_4$ which is soluble in water to a FC vehicle. Any high pressure facilities are not needed for those systems, but there is a risk that strong alkaline solution produced causes an accident. The authors developed a hydrogen

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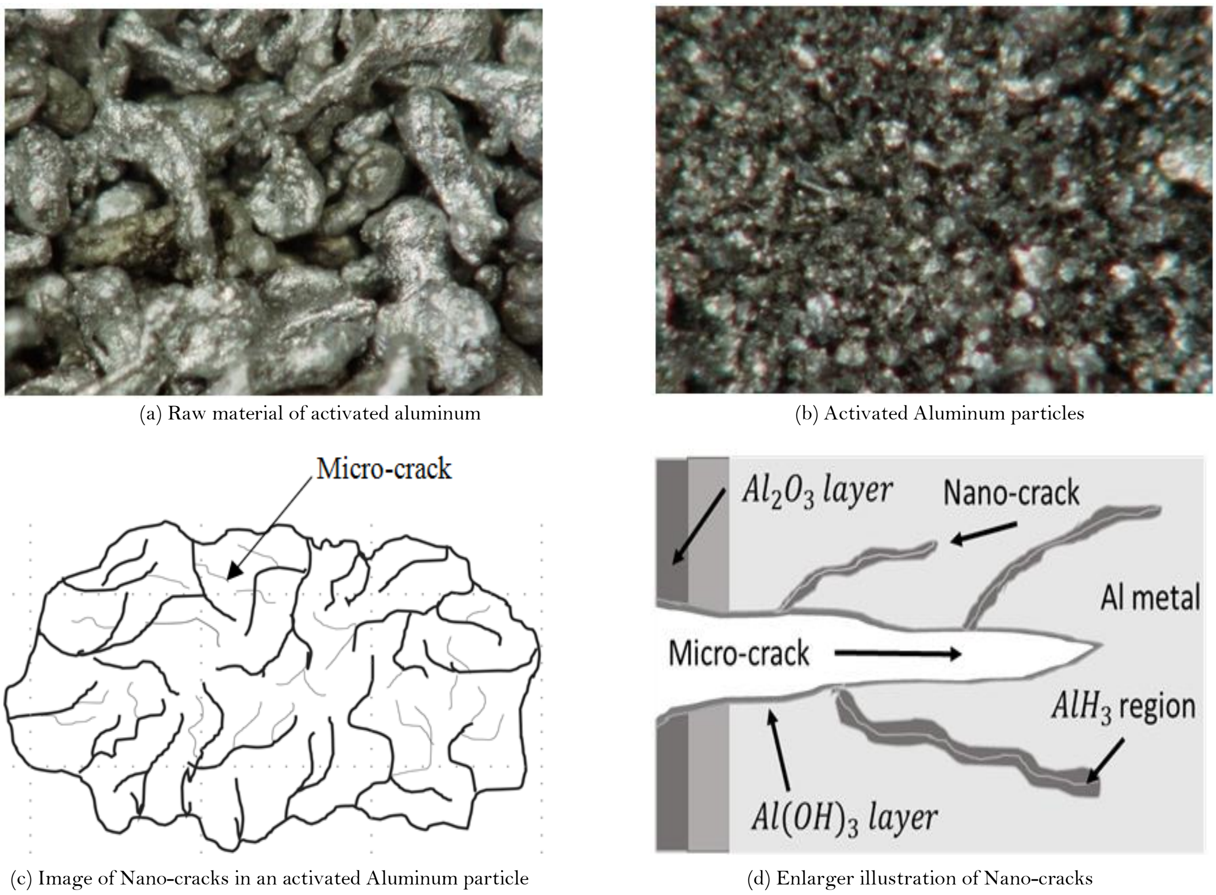
generation system using activated aluminum particles [4]; [5]. The activated aluminum particles produce pure hydrogen by reacting with pure water.

Here, a control system for generating hydrogen at a desired level by a reaction between water and activated aluminum particles is proposed. The activated aluminum and the portable FC system with the developed hydrogen generator is described, firstly. Secondly, the fuzzy controller is designed to maintain pressure of the reaction vessel of the developed hydrogen generation system at a certain level based on the characteristics of the hydrogen generation.

2. MATERIALS AND METHODS

2.1. Activated Aluminum Particles

Activated aluminum particles are made from shredded aluminum sawdust or atomized aluminum. Firstly, shredded aluminum sawdust or atomized aluminum are milled by a special stone mill in cold water. After milling they are activated. The size of an activated particle equal to or less than 20[μm]. The above processes make many nano-cracks inside the activated aluminum particle. Fig 1 shows the pattern diagram of an activated aluminum particle. AlH_3 is assumed to exist around the tip of nano-crack and expanded along each crack by corrosion reaction [6]; [7].



(a) Raw material of activated aluminum (b) Activated Aluminum particles

(c) Image of Nano-cracks in an activated Aluminum particle (d) Enlarger illustration of Nano-cracks

Fig-1. Activated aluminum particles

The surface reaction of aluminum with water is generally expressed by formula below (1).

$$Al + 3H_2O \rightarrow Al(OH)_3 + \frac{3}{2} H_2 \quad (1)$$

Because the solubility to water of aluminum hydroxide is low, reaction stops at the surface of aluminum. Therefore, unreacted aluminum is left in the inside of the particle.

On the other hand, there are many cracks in the inside of the activated aluminum particle. The interfacial reaction which occurs along the cracks in the activated aluminum particles is described as chemical formula follows.

$$3Al + 3H_2O \rightarrow Al_2O_3 + AlH_3 + \frac{3}{2} H_2 \quad (2)$$

Hydrogen is generated as follows by $Al(OH)_3$ and AlH_3 which are produced by (1) and (2), respectively.

$$Al(OH)_3 + AlH_3 \rightarrow Al_2O_3 + 3H_2 \quad (3)$$

The formula (2) and (3) are the reactions in the inside of the crack of the activated aluminum.

These reactions are summarized as follow chemical formula (4).

$$2Al + H_2O \rightarrow Al_2O_3 + 3H_2 \quad (4)$$

Because the crack is grown by the internal stress by the reaction, the reaction of hydrogen generation is spread in the whole of the activated aluminum particle.

In theory, 1.35[*l*] of pure hydrogen is generated from 1[g] of the activated aluminum particles and 1[m*l*] of water under the condition of 1atm and 25°C. It is confirmed that an average of 1.1[*l*] of hydrogen is generated by 1[g] of the activated aluminum in experiments.

It is considered that the surface of the activated aluminum particles is coated with hydroxide film, which indicates low probability of dust explosion. Therefore, it is conceivable to be useful as hydrogen source of a FCV because it is transferred and stored safely.

The reaction of hydrogen generation of the activated aluminum exhibits the following characteristics.

(i) It is exothermic reaction.
(ii) It has temperature dependence.
(iii) It is a kind of mechanochemical reaction promoted by mechanical energy from the outside.
(iv) It becomes active gradually and converges in association with decreasing reactant.
(v) When hydrogen is generated briskly, it is difficult to stop the reaction.

The reaction rate differs according to the sample of activated aluminum.

2.2. Portable FC System with the Developed Hydrogen Generator

Fig 2 shows the outline of the portable FC system with the developed hydrogen generator. It consists of a FC (Chemix 100[W]), a water tank, an electrical pump (FEM1.09 KPSM-2, KNF Co. Ltd.), a reaction vessel, a buffer tank, a radiator, and a one-chip microcomputer (Arduino Uno). The pressure of the reaction vessel is measured in the buffer tank. The generated hydrogen is humid and is separated in the radiator. The separated water is recovered from the radiator to the water tank.

Hydrogen generation rate is changed according to the water flow. When water is supplied to the reaction vessel at 25[m*l*/min] and 35[m*l*/min], hydrogen is generated at about 3.0[*l*/min] and 4.5[*l*/min], respectively.

The amount of hydrogen consumed in an FC depends on the connected load. The required hydrogen changes due to the value of the load. Therefore, it is necessary to generate the quantity of hydrogen consumed in the FC to supply electricity due to the change of the load. When hydrogen is consumed in the FC, the pressure in the buffer tank connected to the FC decreases. Hence, a control system to maintain the pressure in the buffer tank at a certain level is designed in order to generate hydrogen consumed with a FC.

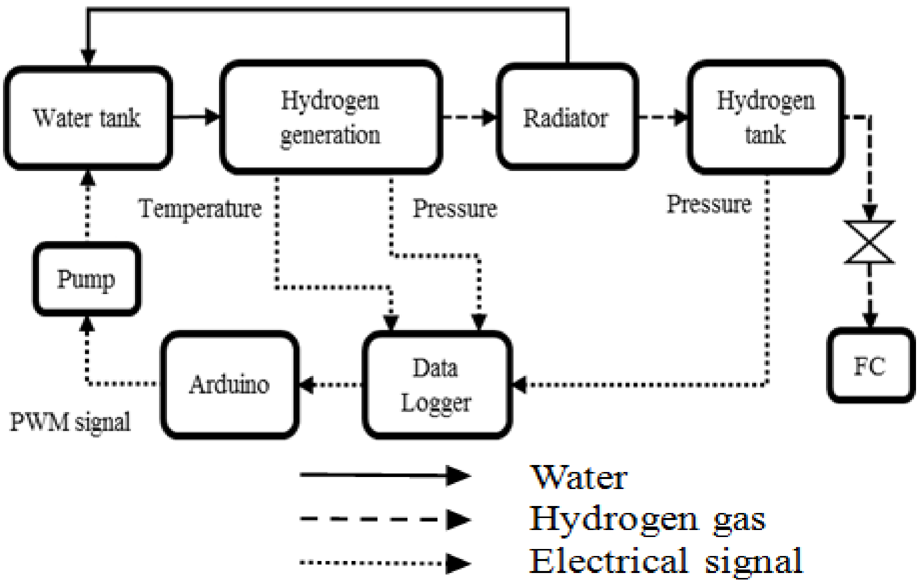


Fig-2. Hydrogen generation system

3. FUZZY CONTROLLER AND EXPERIMENTS

It is difficult to characterize the quantitative reaction of hydro generation as above mentioned. Therefore, the qualitative characteristics of the reaction can be grasped. Therefore, the controller is designed based on a fuzzy theory.

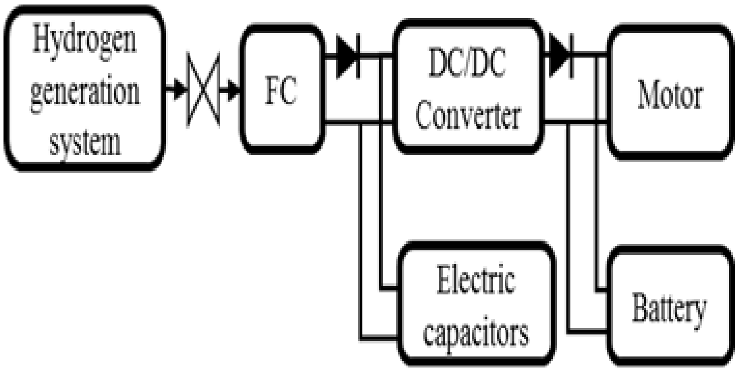
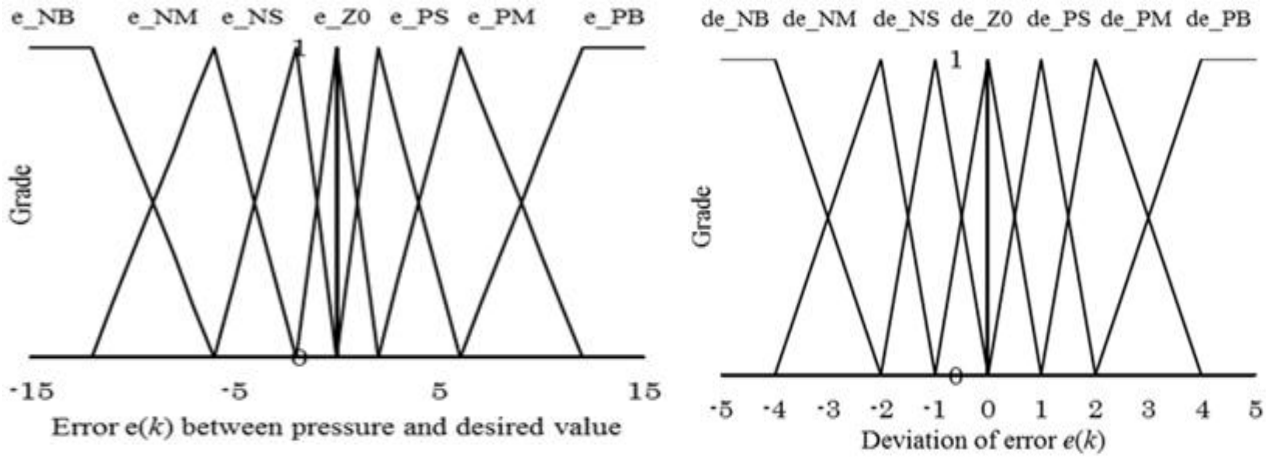


Fig-3. Driving system



(a) Membership function of error (b) Membership function of deviation of error e(k)

Fig-4. Membership functions

Table-1. Fuzzy control rule

	de NB	de NM	de NS	de Z0	de PS	de PM	de PB
e NB	PB	PB	PM	PM	PM	PM	PS
e NM	PM	PM	PM	PM	PM	PS	Z0
e NS	PM	PM	PS	PS	PS	Z0	NS
e Z0	PM	PM	PS	Z0	Z0	Z0	NM
e PS	PM	PS	PS	Z0	NS	NS	NM
e PM	PS	PS	Z0	NS	NM	NM	NB
e PB	PS	Z0	Z0	NS	NM	NB	NB

The output $y(k)$ is chosen as the pressure of the reaction vessel which is measured in the buffer tank. The input $u(k)$ is chosen as the water supply. The fuzzy rule for a fuzzy PI control to determine the water supply is determined as follows.

If $e(k)$ is AA and $\Delta e(k)$ is BB then $\Delta u(k)$ is CC (5)

Here, $y(k)$ and y_d are the pressure of the reaction vessel and its desired value, respectively. $e(k)$ is the error form a desired value of the pressure of the reaction vessel y_d. $\Delta e(k)$ is the change of the error e(k). $\Delta u(k)$ is the deviation of the u(k).

That is,

$$e(k) = y(k) - y_d \qquad (6)$$

$$\Delta e(k) = e(k) - e(k-1) \qquad (7)$$

The water supply is determined as

$$u(k) = u(k-1) + \Delta u(k) \qquad (8)$$

The designed fuzzy membership functions are shown as Fig 4. And the fuzzy control rule is determine illustrated in Table 1.

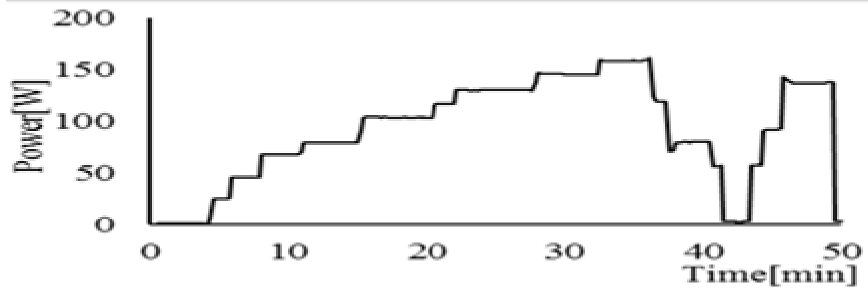
When $e(k)$ is positive, because the value the hydrogen generation rate exceeds the desired value y_d, it is necessary to wait until the reaction settles down. When $\Delta e(k)$ is positive, the reaction gradually become more active.

For example, when $e(k)$ is NS (negative small) and $\Delta e(k)$ is PB (positive big), the pressure of the reaction vessel is a little smaller than the desired value, and the reaction become much active. In such a case, the increase of the water supply may make the reaction violent progression. Because the temperature in the reaction vessel falls when water supply is too much, the reaction may become inactive. Therefore, in this case, the water supply is reduced.

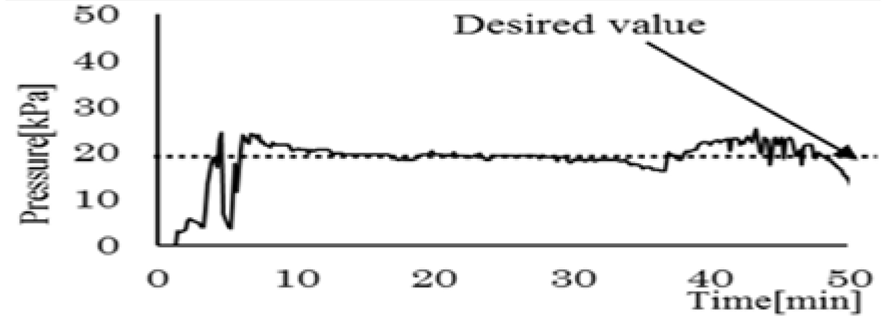
The variable resistor is connected to the developed portable FC system. In order to confirm the control performance to the change of the load, the value of the resistor is changed stepwise. Fig 5 shows one of the experimental results. In the figure, (a), (b), (c) and (d) is power of FC, pressure of the reaction vessel, water supply and temperature in the reaction vessel, respectively. In the figure, it is confirmed that the water supply increases due to the increase of the load. About 40 [min] after the start of the experiment, when the load is set small the pressure becomes high temporarily. After that, the water supply decreases and the pressure converges at 20[kPa]. Therefore, the developed portable FC system can be automatically regulated due to the change of the resistor.

Next, the FC system is applied to the trial small FC vehicle which is a delta trike based on a trishaw [8]. An in-wheel motor (M0124D-V, 24V, 100W, MITSUBA) was attached as a front wheel.

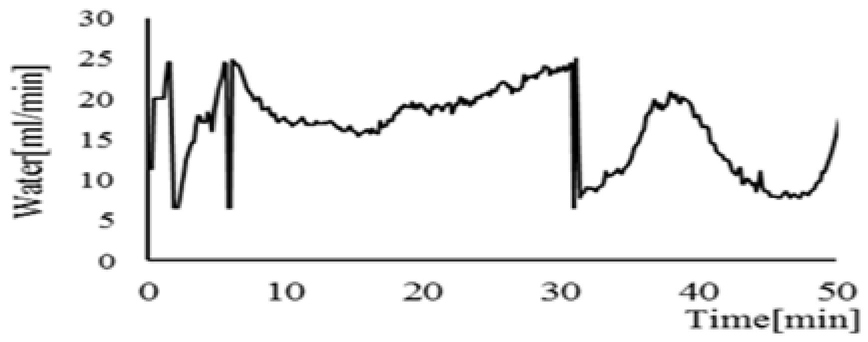
The portable FC system is put on the rear carrier. A DC-DC converter, a lead battery, and electric double layer capacitors of 2 [F] are connected to the output of the FC in parallel with the controller of the motor.



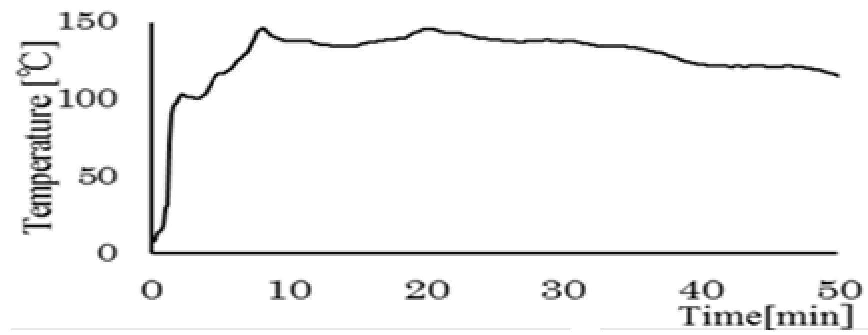
(a) Power of FC



(b) Pressure in reactor vessel

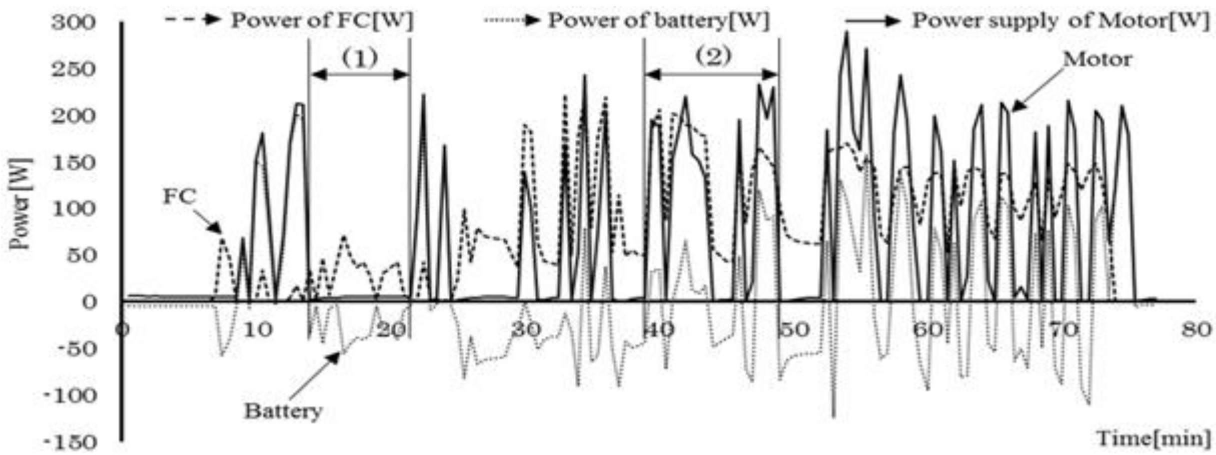


(c) Water supply

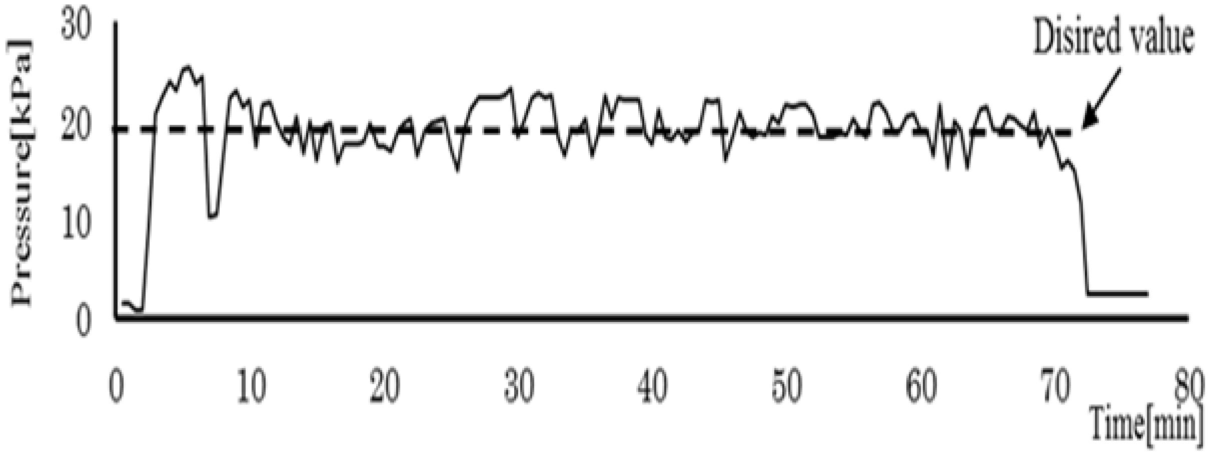


(d) Temperature in reactor vessel

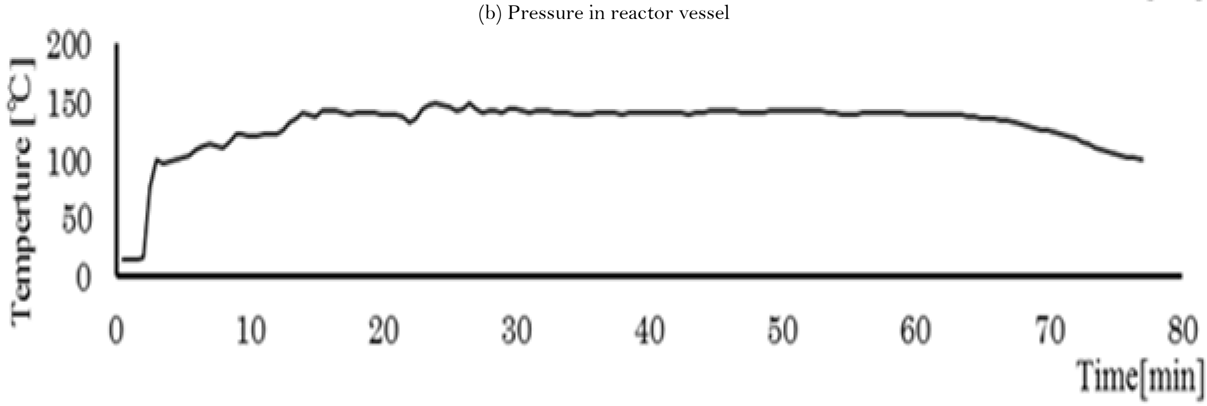
Fig-5. Experimental result to the change of the connected load



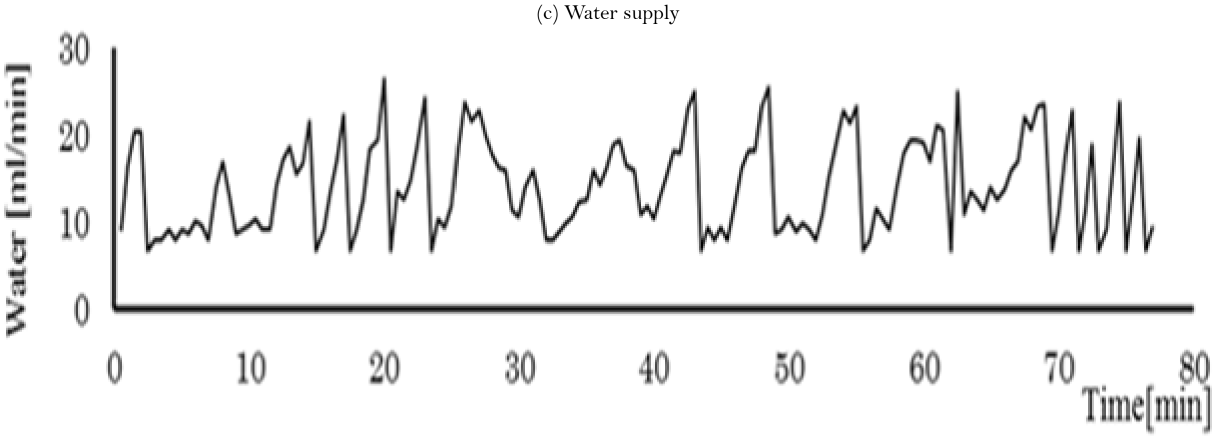
(a) Total electric power



(b) Pressure in reactor vessel



(c) Water supply



(d) Temperature in reactor vessel
Fig-6. Results to driving experiment

Fig 6 shows the outline of the FCV system. The lead battery and the capacitors are used to compensate for electrical power at the time of starting or at the time of driving up a slope. Driving experiments are conducted in the parking of Fukuoka Institute of Technology. One lap of the driving course is about 105[m]. In the driving course, there is an easy slope of 30[m] with an angle less than 1[degree]. One liter of water was poured into the water tank.

The electric power generated from FC is supplied to both the motor controller and the lead battery when the FCV stops or runs at low load. On the other hand, the power from the lead battery is supplied to the motor controller in starting or climbing.

Fig 6 shows one of the result of driving experiments. The power of the FC, the lead battery and total electric power to be supplied to the motor controller are shown in Fig 6 (a). And Fig 6 (b), (c), and (d) is pressure of the reaction vessel, water supply and temperature in the reaction vessel, respectively. In the Fig 6 (a), the charging power is shown as negative value, and discharging power is shown as positive value. For example, the electric power from the FC is supplied to the lead battery during the stop of the FCV show as range (1) in Fig 6. When the electricity consumption of the motor increases the electricity is supplied to the motor from both the FC and the battery show as range (2) in Fig 6. In the case of the driving experiments, it is confirmed that the portable FC system supplies electricity power to the motor controller and the battery by regulating the water supply according to the change of the driving state.

4. CONCLUSIONS

This study design the fuzzy control system of hydrogen generation by the reaction between water and activated aluminum particles. The fuzzy controller is implemented on the developed portable FC system with the hydrogen generator. The portable FC system can automatically regulate the water supply to the activated aluminum in the reaction vessel due to the change of the resistor by the experiments. Furthermore, the portable FC system is applied to the trial small FCV. By the driving experiments, the portable FC system appropriately generates electricity power to the motor controller according to the driving state of the FCV. It is confirmed that the developed fuzzy controller is useful for generating hydrogen by the reaction between the activated aluminum and water under various conditions.

The potential for hydrogen generation of the activated aluminum particles change during the reaction. Thus, the fuzzy membership functions of the controller should be changed according to the generating state of the hydrogen. It is a future issue to design an adaptive fuzzy controller with variable fuzzy membership functions.

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Competing Interests: The authors declare that they have no competing interests.

Contributors/Acknowledgement: All authors contributed equally to the conception and design of the study.

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