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Design of a Fuzzy Control System to Efficiently Generate Hydrogen using Activated Aluminum Particles and Water

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Abstract— The purpose of this study is to develop a portable fuel cell (FC) system with a hydrogen generation system using a reaction between water and activated aluminum particles. Numerous nano-cracks form on the surface of the activated aluminum particles through a production process. It is thought that water enters the cracks of the activated aluminum particles and reacts with AlH3 around the crack tips to generate H2 and Al2O3. The cracks created by the reaction create new reactive surfaces, so that the reaction precedes through all of the activated aluminum particles. It is difficult to grasp the characteristics of the reaction quantitatively because the hydrogen generating reaction varies depending on the samples, the environment of the reaction, and so on. A portable FC system consists of a fuel cell of 100[W], a water tank, a reaction vessel, pressure sensors, a water pump, a radiator, a one-chip microcomputer, and so on. A PI fuzzy control system is synthesized to determine the quantity of water supplied to the activated aluminum particles. A small FCV was manufactured experimentally using a delta trike and it was driven by a 100 [W] brushless motor as a front wheel. The developed portable FC system was equipped on the FCV. It was confirmed that the FCV runs for more than 120 [min] using generated hydrogen at about an average 20 [km/h] speed.

Index Terms— **Fuel Cell, Hydrogen Generation, Activated Aluminum Particles, Fuzzy Control.**

I. INTRODUCTION

In Japan, supplies of fuel such as gasoline and light oil have been greatly disrupted because supplying sites were seriously affected by the Tohoku earthquake [1]. Furthermore, the demand for fuel increased due to disaster victims living in their cars to avoid the danger of house collapse, as in the case of the Kumamoto Earthquake [2]. On the other hand, because the diffusion of fuel cell vehicles and hydrogen stations are promoted by the Council for Regulatory Reform in Japan [3], fuel cell mounted equipment is predicted to become widespread. In such a situation, fuel supply systems might be disrupted even more significantly during disasters. Therefore, it is necessary to develop methods of acquiring hydrogen on demand without depending upon hydrogen supply systems during disasters. For example, Stannard *et al*. proposed a portable hydrogen generator using the reaction of a caustic soda solution and aluminum [4]. Systems to supply hydrogen produced by $NaBH_4$, which is soluble in water, for a fuel cell vehicle were proposed [5],[6]. Those methods generate hydrogen easily without high pressure facilities, but there are some risks of accidents due to the use of a strong alkaline solution.

The authors developed a hydrogen generation system [7] utilizing activated aluminum particles [8]. Activated aluminum particles are produced by putting shredded aluminum sawdust through a special manufacturing process. They are stored for long periods and generate pure hydrogen through reactions with water. The authors have already proposed a fuzzy control system of hydrogen generation using the reaction activated aluminum and water [9]. Although the proposed fuzzy system controlled hydrogen generation adequately, the controller sometimes determined large amounts of water to supply. That reduced the total amount of hydrogen generation because of a sudden drop in the temperature of the reaction vessel. Here, the fuzzy control rule will be redesigned to efficiently generate hydrogen using activated aluminum particles and water. The modified fuzzy control system will be applied to a portable FC system, and the usefulness of the proposed system will be confirmed by experiments.

II. MATERIALS AND METHODS

A. Activated Aluminum Particles and Hydrogen Generation

Activated aluminum particles are produced by compressing and destroying shredded aluminum sawdust in a millstone with cold water. A great number of nano-cracks are distributed on the entire surface of the activated aluminum particles. It is thought that AlH3 is produced on the tips of the cracks by the activating process. On the other hand, the surfaces of activated aluminum particles are covered with hydroxide alumina. Therefore, the risk of an activated aluminum particle dust explosion is much smaller than with pure aluminum particles. That is, activated aluminum particles are considered to be convenient for storage and safe transport. Because hydrogen can be obtained just by adding water to the activated aluminum particles at ordinary temperatures and pressures, it is possible to construct a hydrogen generation system simply without utilization of a high-pressure tank of hydrogen.

Although hydrogen generation is a reaction of water decomposition, it is not simple surface oxidation of aluminum. Water intruding into the cracks are accelerating decomposed around the tips of the cracks by a mechanochemical reaction and aluminum hydride AlH_3 is produced at the tips of cracks. Then, the cracks expand along the aluminum hydride with the reaction and water decomposition is accelerated even further. Therefore, all of activated aluminum particles react with water because the reaction proceeds into the particles three-dimensionally. An average hydrogen of 1.1 [*l*] is

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generated by 1 [g] of activated aluminum particles. The reaction is an exothermal reaction and is accelerated with rises in temperature. Moreover, when hydrogen is generated actively, it is difficult to stop the reaction. Therefore, it is difficult to describe the reaction quantitatively because the characteristics of the hydrogen generating reaction vary depending on the environment of the reaction and other such variables. Here, the controller is designed based on a fuzzy theory.

B. Portable FC system with Hydrogen Generator

Figure 1 shows the outline of a portable FC system with a hydrogen generator. Its primary components consist 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). A package of activated aluminum particles is set in the reactor vessel (the hydrogen generator). The package is made of a laminated sheet and a nonwoven fabric having an excellent air permeability. Water is supplied to the reactor vessel from the water tank through the pump driven by external signals. The external driving signals are sent by the one-chip microcomputer. When water is supplied to the package of activated aluminum, hydrogen is generated. Then, because temperature and humidity inside the vessel increase, generated hydrogen gas is at a high temperature and high humidity. The hydrogen gas goes to the radiator, the water recycling tank, and the buffer tank before being supplied to the FC. The water content in the hydrogen gas is removed and recycled through those instruments. The pressure of the generated hydrogen is measured in the buffer tank. The one-chip microcomputer determines the input of water based on the measured pressure data and drives the pump. The generated hydrogen is utilized as an energy source of a fuel cell (FC), here.

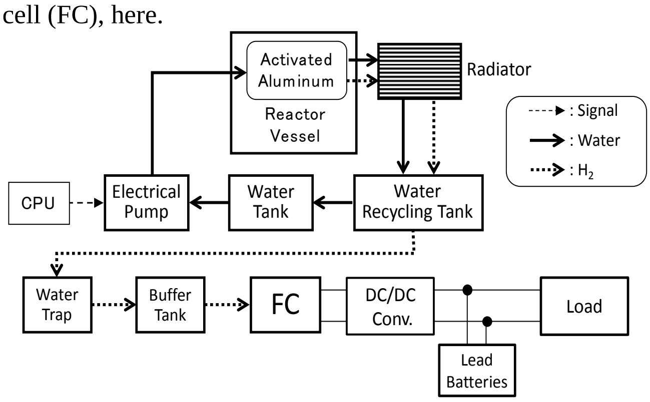

Fig. 1: Outline of a portable FC system with a hydrogen generation system

C. Modified Fuzzy Controller

It is difficult to describe the characteristics of the hydrogen generating reaction quantitatively because its characteristics depend on the environment of the reaction and other variables, as previously mentioned. Therefore, the controller is designed based on a fuzzy theory here.

The amount of hydrogen gas consumption in an FC changes due to changes in the connected load. When the FC is connected to a constant load, the amount of hydrogen gas consumption in the FC per unit time does not change. When the connected load becomes larger, hydrogen gas consumption increases. On the other hand, when the connected load becomes smaller, hydrogen gas consumption decreases. Therefore, it is necessary that the control system replenishes the hydrogen consumed in an FC. That is, the control system is designed to maintain the pressure of the buffer tank, which is connected to the FC, by generating hydrogen appropriately.

The pressure in the buffer tank and the added quantity of water are chosen as the output and the input of the control system, respectively. Here, $e(k)$ is the error of the measured value from a desired value of the pressure of the buffer tank and $\Delta e(k)$ is the change of the error $e(k)$. $\Delta u(k)$ is the deviation of water supply $u(k)$. In order to adjust the water supply precisely, the widths of the membership functions of the error are designed narrowly, around zero. The fuzzy membership function is designed as shown in Fig. 2.

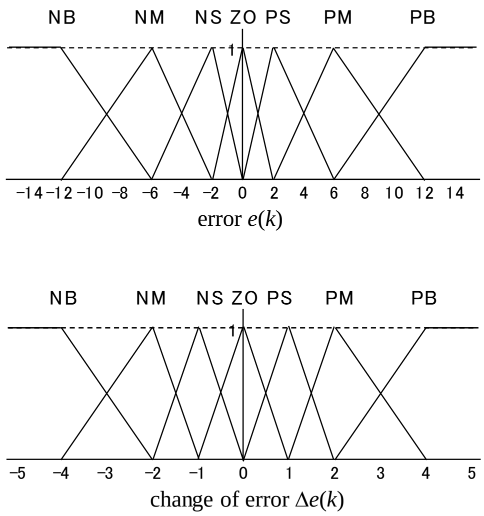

Fig. 2: Fuzzy membership functions

When e(k) is positive, it is necessary to wait until the reaction settles down as previously mentioned. When Δe(k) is positive, the reaction gradually becomes more active. For example, when e(k) is PS (positive small) and Δe(k) is PB (positive big), the pressure of the reaction vessel is a little larger than the desired value, and the reaction becomes too active. In such a case, the water supply should be decreased to inhibit the reaction.

The water supply is determined as follows.

If $e(k)$ is *AAA* and $\Delta e(k)$ is *BBB* then $\Delta u(k)$ is *CCC*

The fuzzy rule to determine $\Delta u(k)$ is modified as shown in Table 1.

Table 1: Fuzzy rule

		$\Delta e(k)$						
		NB	NM	NS	ZO	PS	PM	PB
$e(k)$	NB	1	0.8					0.5
	NM	0.8				0.5		0.2
	NS	0.8	0.5		0.2			-1

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<table>
<tr><td rowspan="4"></td><td>ZO</td><td rowspan="3">0.5</td><td colspan="2"></td><td colspan="2">-1</td><td rowspan="2">-2</td></tr>
<tr><td>PS</td><td>0.5</td><td>0.2</td><td>-1</td><td rowspan="2">-2</td></tr>
<tr><td>PM</td><td>0.2</td><td>-1</td><td>-2</td><td>-3</td></tr>
<tr><td>PB</td><td>0.2</td><td>-1</td><td>-2</td><td colspan="3">-3</td></tr>
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The above rule is determined by repetition of trial and error. The hydrogen generation reaction does not stop until the activated aluminum particles which touch the water react completely. Therefore, when water is supplied to the reactor vessel soaking the activated aluminum particles, the generation of hydrogen proceeds even if the water supply is stopped. Because the generated hydrogen is never absorbed into the activated aluminum particles, only the consumption of hydrogen gas in the FC can decrease the pressure of the tank. Therefore, the control system must be designed to not generate a large quantity of hydrogen through the supply of excess water. The parameters of the proposed fuzzy controller in Table 1 are chosen to gradually increase the water supply when hydrogen is required, and to substantially decrease it when hydrogen is no longer required. For example, when the measured pressure value is slightly smaller than the desired value and is increasing suddenly, the hydrogen generation becomes active. If the water supply is increased greatly, the temperature in the reaction vessel falls and the reaction may become inactive. Therefore, the water supply is reduced as "If $e(k)$ is NS and $\Delta e(k)$ is PB then $\Delta u(k)$ is NS (-1)". On the other hand, when the measured pressure value is larger than the desired value and is increasing, the hydrogen generation becomes very actively. In such a case, the water supply is reduced greatly. $\Delta u(k)$ is determined by fuzzy reasoning using the product-sum-gravity method [10]. The input value $u(k)$ is calculated by the following equations. Here, y_d is the desired value of the pressure in the tank.

$$e(k) = y(k) - y_d$$
$$\Delta e(k) = e(k) - e(k-1)$$
$$u(k) = u(k-1) + \Delta u(k)$$

In the next Section, the usefulness of the proposed portable FC system is confirmed by experiments.

III. EXPERIMENTS AND RESULTS

Figure 3 illustrates the trial FCV which is manufactured experimentally using a delta trike. An in-wheel motor (M0124D-V, 24V, 100W, MITSUBA) is used for the front wheel. The portable FC system is put on the rear carrier rack. Electric double layer capacitors of 2[F] are connected in parallel between the FC and the DC-DC converter. The capacitors are compensators for electrical power at such times as starting the vehicle or driving up a slope, etc. In the experiments, a mixture of 200 [g] of activated aluminum particles and 200 [g] of atomized aluminum are set in the reaction vessel. The oxygen required to generate electricity is provided from the air by a fan on the FC. A purge gas valve is opened once every two minutes to drain water from the FC.

Driving experiments were conducted in the parking lot of the 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].

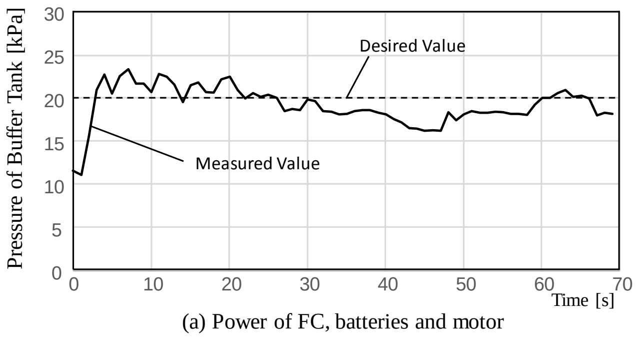
Figure 4 shows an example of the driving experiment results. The electric power of the FC and the input/output power of the batteries and the motor are illustrated as a solid line, an alternately long and short dashed line, and a dotted line in Fig. 4 (a), respectively. Furthermore, the discharging power of the batteries is shown as a negative value, and its charging power is shown as a positive value. The pressure of the buffer tank is shown in Fig. 4 (b). The solid line and the dotted line are the measured pressure value of the buffer tank and the desired value, respectively. The desired value is set at 20 [kPa].

Section I in Fig. 4 (a) shows the result at the time the FCV was stopped. Here, the power of the motor is zero and the power of the FC almost coincides with the input/output power of the batteries. That is, the FC charges the batteries when the FCV is stopped. In section II of Fig. 4 (a), the power of motor is approximately equal to the sum of the power of the FC and the power of the batteries. When the power of the FC is insufficient for the power requested by a load, the batteries compensate for the lack of electricity. The pressure of the buffer tank is controlled at around the desired value in Fig. 4 (b). We consider that the fluctuations in the measured value is influenced by temperature variation in the reactor vessel. Furthermore, it was confirmed through long-term driving experiments that the portable FC system can provide hydrogen and electricity to the small FCV, which runs at an average speed of about 20 [km/h], and for more than 120 [min].

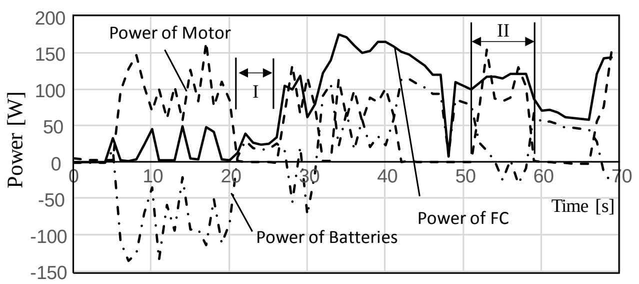
Fig. 3: Trial small FCV

Therefore, we consider that the proposed portable FC system generates the amount of hydrogen necessary for the FC, according to fluctuations in power consumption, and utilizes the activated aluminum particles efficiently.

Because activated aluminum particles, which are capable of reacting with water, decrease if hydrogen generation continues, the characteristics of hydrogen generation vary. Furthermore, the hydrogen generation reaction varies due to reaction temperature, as mentioned above. Therefore, we are investigating the design of a fuzzy control system with adaptive membership functions to cope with changes in various situations.



(a) Power of FC, batteries and motor



(b) Pressure of buffer tank

Fig.4: Driving experimental results

IV. CONCLUSION

This study produced a fuzzy control system for hydrogen generation using the reaction of water and activated aluminum particles. The portable FC system equipped with the hydrogen generation system was applied to an experimental three-wheeled vehicle. The control rule is determined by trial and error. It was confirmed that our proposed portable FC system generates the amount of hydrogen necessary for the FC, according to fluctuations in power consumption by the experiments.

In this system, the total quantity of generated hydrogen is decided by the quantity of the activated aluminum in the generator. Therefore, it is necessary to replace a new activated aluminum package in the hydrogen generator in order to acquire electric power for a long duration. In such a case, because there is a possibility that the new activated aluminum may react with residual water in the vessel, a power storage system and/or a hydrogen storage system will be required when not controlling hydrogen generation. Furthermore, it is a future issue to design a fuzzy controller with variable controller parameters according to the temperature of the vessel, because the hydrogen generation reaction is temperature dependent.

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REFERENCES

[1] Agency for Natural Resources and Energy, Ministry of Economy, Trade and Industry (2011). About fuel supply in the Great East Japan Earthquake, Retrieved from http://www.meti.go.jp/committee/kenkyukai/energy/sekiyu_gas_antei_wg/001_s01_00.pdf

[2] Agency for Natural Resources and Energy, Ministry of Economy, Trade and Industry (2016). On Emergency Petroleum Supply in the Kumamoto Earthquake. Retrieved from http://www.meti.go.jp/committee/sougouenergy/shigen_nenryo/pdf/017_05_00.pdf

[3] Ministry of the Environment, Government of Japan (2017). Promotional programs of hydrogen energy based society using renewable energy. Retrieved from http://www.env.go.jp/air/car/ lev/h28/h28gaiyo.pdf

[4] Stannard J. H., Fitzpatrick N. P., Rao B. M. L. & Anderson W. M. (1990). A Portable Hydrogen Generator for Vehicles. Hydrogen Energy Progress, 8(2), 935-944.

[5] Mohring, R. & Luzader, R. (2001). A Sodium Borohydride On-board Hydrogen Generator for Powering Fuel Cell and Internal Combustion Engine Vehicles. SAE Technical Paper. 2001-01-2529, https://doi.org/10.4271/2001-01-2529.

[6] Murooka S., Tomoda K., Hoshi N., Haruna J., Cao M., Yoshizaki A. & Hirata K. (2012). Consideration on Fundamental Characteristic of Hydrogen Generator System Fueled by NaBH4 for Fuel Cell Hybrid Electric Vehicle. Proceedings of the 2012 IEEE International Electric Vehicle Conference. 1-6.

[7] Maekawa K. Takahara K. & Kajiwara T. (2012). A Portable Fuel Cell System Using Activated Aluminum, IEEJ Transactions on Industry Applications, 132 (10), 997-1002.

[8] Watanabe M., Kawaguchi H. & Takahara K. (2005). Hydrogen Generation from Water Molecules with Using Activated Aluminum Particles for Operating Mobile/Micro Fuel Cells. The Journal of the Japan Society of Applied Electromagnetics and Mechanics. 13 (3), 230-234.

[9] Giap B. T., Takahara K., Kajiwara T., & Maekawa K. (2017). Fuzzy Control of Hydrogen Generation by the Reaction of Activated Aluminum Particles and Water, International Journal of Natural Sciences Research, 5 (1), 1-7, DOI: 10.18488/journal.63/2017.5.1 /63.1.1.7

[10] Ohki M., Hayashi S. & Ohkita M. (2000). A Fast Computational Algorithm of a Fuzzy Reasoning Using the Product-Sum-Gravity Method. Systems and Computers in Japan,31(3),40-48,DOI:10.1002/(SICI)1520-684X(200003)31:3<40::AID-SCJ5>3.0.CO; 2-Y.

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