Journal of Research and Applications in Mechanical Engineering
ISSN: 2229-2152 (Print); 2697-424x (Online)
(2024) Vol. 12, No. 2, Paper No. JRAME-24-12-027
[DOI: 10.14456/jrame.2024.27]

Research Article

Hydrogen Generation based on Chemical Reaction and its Application

Y. Takeuchi[1]
N. Zhu[1,*]
K. Amano[1]
K. Fukuda[2]
[1] *Shizuoka Institute of Science and Technology, Shizuoka, 437-8555, Japan*
[2] *Daytona Corporation, Shizuoka, 437-0226, Japan*

Received 27 September 2023
Revised 9 February 2024
Accepted 11 February 2024

Abstract:
In recent years, the effects of global warming due to CO_2 emissions have become serious. Since internal combustion engines (ICEs) where gasoline or diesel are used as fuel release huge amount of CO_2, attentions have been paid to the new decarbonization countermeasures of Ices. Among them, H_2 is regarded as a kind of eco-friendly fuel not only for fuel cell but also for Ices. So far, we have modified a gasoline electric power generator for using H_2 as fuel by amounting a surge tank with a special intaking flow system. Though many useful results have been obtained, problems such as H_2 supply method for on-site operation or backfire phenomenon at high load still remain. Therefore, in current paper, in order to deal with the above-mentioned problems. Firstly, H_2 generation method based on chemical reaction for onsite operation is suggested and verified. Secondly, a new intake flow system for stable operation was designed and manufactured based on simulation and engine performance test was experimentally investigated. Finally, engine operation test using H_2 generated by chemical reaction on-site was conducted. As a result, the maximum H_2 generation was 29.3 L/min, and the error from the theoretical value was 2.4 %. In engine performance test for new Intaking flow system, the maxi mum output was 900 W, and the thermal efficiency was 19.0%. In engine operation testing generated H_2 on-site, the engine speed decreased by up to 900 rpm compared to compressed H_2.

Keywords: *Hydrogen generation, Chemical reaction, Sodium borohydride, Citric acid*

1. Introduction

The world's energy consumption is steadily increasing with economic development, and fossil fuels such as oil and coal constitute approximately half of the primary energy sources [1]. As the consumption of fossil fuels rises, the issue of global warming caused by greenhouse gas emissions has become increasingly serious. According to the IPCC Sixth Report, the atmospheric concentration of CO_2 is extremely high at 410 ppm in 2019, suggesting that this is likely due to human factors such as industrial activities [2]. At the current rate of CO_2 emissions, it is anticipated that the average global temperature will rise by at least 1.5 to 2.0 degrees Celsius by the end of the 21st century. Therefore, Japan is actively promoting the adoption of renewable energy and electrification, with a target of reducing greenhouse gas emissions by 46% by 2030 compared to the levels in 2013 [3].

* Corresponding author: N. Zhu
E-mail address: zhu.ning@sist.ac.jp

Japan also have experienced a high frequency of natural disasters, primarily attributed to geographical factors and global warming. Geographically, Japan is situated at the convergence of continental and oceanic plates, leading to frequent earthquakes due to plate distortion. Global warming contributes to this by causing a rise in atmospheric temperature, leading to an increase in seawater temperature and the creation of updrafts. These updrafts form cumulonimbus clouds, evolving into typhoons that result in significant damage. When disaster events occur, a major concern is the interruption of power supply. Although electric power generators are commonly used to provide electricity, their reliance on gasoline as fuel becomes a significant source of CO_2 emissions. Thus, there is a pressing need to develop electric power generators that operate without fossil fuels.

One of the representative technologies for reducing CO_2 emissions involves utilizing H_2 as a fuel [4]. H_2 is the lightest gas on the earth, and since most of it exists in compounds, it can be produced through various processes. The majority of H_2 production methods employ steam reforming, utilizing CH_4 as a raw material [5]. The H_2 extracted through this process is highly concentrated, making it widely utilized in industrial applications. Another environment-friendly method is the electrolysis approach, which involves water electrolysis and emits no CO_2 during the manufacturing process [6]. However, both methods necessitate large-scale equipment and entail high manufacturing costs, which are not suitable for use in electric power generators that usually employed at the shelter when disasters occur.

Utilizing sodium borohydride ($NaBH_4$) for H_2 generation emerges as a promising solution to the above issue. $NaBH_4$, a stable white solid crystal at normal temperature and pressure, offers a straightforward manufacturing process involving a reaction only with water. This simplicity facilitates the streamlining of equipment for its implementation and appeared to be feasible when used at shelter.

As an example of research using $NaBH_4$, Murooka and his colleagues conducted an investigation to determine whether employing $NaBH_4$ as the fuel for a fuel cell electric vehicle, coupled with connecting a H_2 generation system to a fuel cell with a rated output of 100W, would yield the same power generation capacity as using compressed H_2. $NaBO_2$ is produced as a byproduct during the H_2 generation process. Recognizing that an increase in $NaBO_2$ could lead to a decrease in H_2 production, a centrifugal separation mechanism was incorporated into the H_2 generator to prevent the accumulation of $NaBO_2$. The experimental results revealed no significant output drop in the fuel cell utilizing the H_2 generation system, confirming its power generation performance to be equivalent to that of compressed H_2 [7].

Suekawa and his colleagues proposed a H_2 power generation system utilizing $NaBH_4$. They conducted measurements of the H_2 flow rate and power generation amount, varying the volume and structure of the H_2 generation reactor. The results indicated that in a large-capacity reactor with a volume of 18 L, the H_2 generation rate reached 164 L/min, with a corresponding power generation amount of 5.25 kW being confirmed [8].

Until now, research has been conducted on developing H_2 generators using $NaBH_4$ and applying them to fuel cells, yet there have been few published research reports on their application to electric power generators. As for the development of the H_2-based electric power generator, in our previous research, a gasoline-based electric power generator was modified. Measures such as removing the vaporizer and adding the special intake flow path for H_2 to be mixed with air were taken. To obtain the stable output for the modified electric power engine, through trial-and-error research, it was found that mounting a surge tank in which a specially designed intake system was designed and prepared was a best choice. Then through a serial of engine performance test based on compressed H_2 supply, it was confirmed that the electric power generator's output was more stable when utilizing a surge tank, reaching a maximum of 800 W.

In prior research, a compact H_2 generation system utilizing an aqueous solution of $NaBH_4$ and $C_6H_8O_7$ was assembled, and the generated H_2 quantity was quantified. Additionally, a novel intake system was integrated into a compressed H_2-powered generation system, and the output characteristics were compared when employing a surge tank and throttle valve. The experimental outcomes affirmed the achievement of a stable H_2 production rate of up to 20 L/min. It was observed that the electric power generator's output was more stable when utilizing a surge tank, reaching a maximum of 800 W [9].

Hence, in this research, in order to establish an electric power supply system with maximum output of 1 kW for the people in shelter using H_2 generated on-site, firstly a H_2 generation system employing a chemical reaction with $NaBH_4$ and citric acid ($C_6H_8O_7$) as catalysts was suggested and experimentally investigated. Secondly, based on the flow simulation surge tank with two kinds of the intake flow models were manufactured and amounted for engine performance test by using compressed H_2. Finally, engine performance test was carried out by using H_2 generated on-site.

2. Experiment of the Hydrogen Generation

2.1 Principle of the Hydrogen Generation

$NaBH_4$, a H_2 source, is an inorganic compound utilized as a reducing agent for organic compounds such as aldehydes and ketones. The details and specifications of $NaBH_4$ are shown in Fig. 1 and Table 1 [10, 11]. This substance remains stable at normal temperature and pressure, making it easier to handle than compressed or liquefied H_2. Additionally, it exhibits high hygroscopicity, absorbing moisture from the air and gradually decomposing. When stored in a sealed container, it can be stably preserved for an extended period. $NaBH_4$ generates H_2 through hydrolysis [12], and the basic reaction formula for generating H_2 on-site is expressed in equation (1)

$$NaBH_4 + 2H_2O \rightarrow 4H_2 + NaBO_2 \tag{1}$$

Here $NaBO_2$ is the byproduct. Although this reaction does not require a catalyst, it is known that the reaction will proceed actively under acidic conditions [13]. Hence, in this research, besides water, $C_6H_8O_7$, which is less harmful and highly versatile, was used too, and the final reaction formula is expressed in equation (2).

$$3NaBH_4 + 9H_2O + C_6H_8O_7 \rightarrow 12H_2 + Na_3C_6H_5O_7 + 3B(OH)_3 \tag{2}$$

Since H_2 produced by this reaction is at a high temperature and contains a significant amount of water vapor, so special measures must be taken to deal with those problems.

(a) $NaBH_4$ (b) $C_6H_8O_7$

Fig. 1. Details of $NaBH_4$ and $C_6H_8O_7$

Table 1: Specifications of $NaBH_4$ and $C_6H_8O_7$ [10, 11]

Chemical formula	**$NaBH_4$**	**$C_6H_8O_7$**
Shape	White solid crystal	White solid crystal
Molecular weight	37.83	192.13
Density (g/cm^3)	1.074	1.665
Melting point (deg.)	400	153
Boiling point (deg.)	500	175
Solubility (g)	55/ H_2O 100 (25deg.)	59.2/ H_2O 100 (20deg.)

2.2 Experimental Method and Conditions

Fig. 2 shows the schematic of H_2 generation system, while Fig. 3 shows the actual experiment equipment. The system comprises an electrical component, including a power supply unit and a pump, and a H_2 generation component, which consists of two types of aqueous solutions, a reactor, a waste tank, and a dehumidification system. This dehumidification system consists of a coolant container, a water separator, and a desiccant container. Additionally, a flow meter measurement unit is included as part of the system.

In the experiment, aqueous solutions of $NaBH_4$ and $C_6H_8O_7$ are pumped up separately by applying proper voltage to two pumps, then inside the reactor, when two kinds of solutions mix together as they flow in, and the reaction will start. As described before, since the H_2 produced contains a significant amount of steam with higher temperature up to 90 degrees, therefore, the dehumidification system is employed to lower the temperature and remove the extra water vapor from the generated H_2. Subsequently, the amount of generated H_2 is measured by using a flow meter.

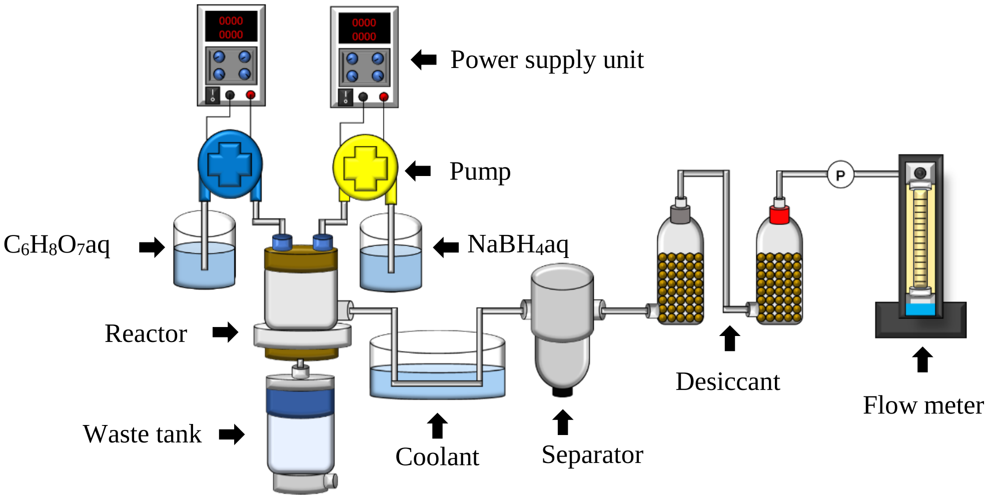


Fig. 2. Schematic of H_2 generation system

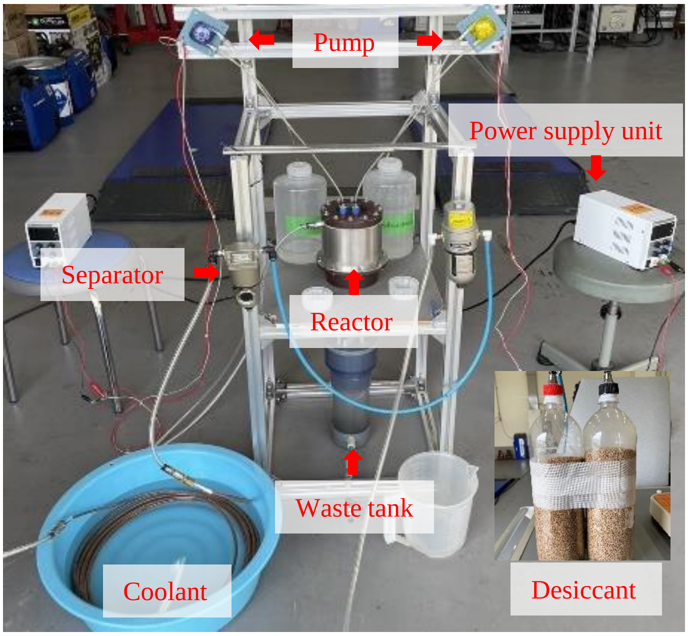


Fig. 3. Actual H_2 generation system

The H_2 generation experimental conditions are shown in Table 2. The measurement range for H_2 generation was set at 10 to 30 L/min. As for the concentrations of NaBH4aq and $C_6H_8O_7$aq, based on the earlier investigation conducted, the optimum concentrations of $NaBH_4$aq and $C_6H_8O_7$aq were determined to be 33.3 wt.% and 27.0 wt.%, respectively. It has been reported that at inappropriate concentrations of the aqueous solution, solidification or precipitation may occur in the storage tank or reactor during low temperatures.

In regard to the necessary quantity of the reactants, they can be calculated based on information such as molecular weight, moles, volume, and temperature. However, since the necessary quantity of the reactants in the form of aqueous solutions volume that is achieved through the adjustment of pump voltage, the relationships between the quantity of the reactant and voltage for $NaBH_4$aq as well as $C_6H_8O_7$aq must be investigated in advance. Thus, in section 2.3, these relations will be clarified.

Table 2: H_2 generation experimental conditions

	$NaBH_4$	**$C_6H_8O_7$**
Concentration (wt.%)	33.3	27.0
Reactant (g)	3.87 ~ 11.61	4.64 ~ 13.92
Aqueous solution (L/min)	0.0116 ~ 0.0348	0.0172 ~ 0.0516
Input ratio (powder)	5	6
Input ratio (aqueous solution)	2	3
Voltage (V)	8.17 ~ 19.16	9.65 ~ 23.63
Measurement range (L/min)	10 ~ 30	

2.3 Derivation of the Aqueous Solution Volume and Pump Voltage

According to Equation (2), 4 moles of H_2 are generated from 1 mole of $NaBH_4$. As a prerequisite, assuming a molecular weight of $NaBH_4$ as 37.83, temperature at 273 K, pressure at 101325 Pa, and volume at 22.4 L, the amount of $NaBH_4$ required to produce 10 L of H_2 (293 K, 101325 Pa) is expressed by Equation (3).

$$NaBH_4 = 37.83\ g \times \frac{1\ mol}{4\ mol} \times \frac{10\ L}{22.4\ L} \times \frac{273\ K}{298\ K} = 3.87\ g \tag{3}$$

If the concentration of $NaBH_4$aq is 33.3 wt.% according to Table 2, the volume of $NaBH_4$aq is expressed by Equation (4).

$$NaBH_4aq = 3.87\ g \times \frac{100.0\ wt.\%}{33.3\ wt.\%} = 11.6\ g = 0.0116\ L \tag{4}$$

If the input ratio of $NaBH_4$ to $C_6H_8O_7$ is 5:6, the volume of $C_6H_8O_7$ is expressed by Equation (5).

$$C_6H_8O_7 = 3.87\ g \times \frac{6}{5} = 4.64\ g \tag{5}$$

If the concentration of $C_6H_8O_7$aq is 27.0 wt.% according to Table 2, the volume of $C_6H_8O_7$aq is expressed by Equation (6).

$$C_6H_8O_7aq = 4.64\ g \times \frac{100.0\ wt.\%}{27.0\ wt.\%} = 17.2\ g = 0.0172\ L \tag{6}$$

Next, a method for determining the pump voltage corresponding to the volume of the aqueous solution will be explained. The specifications of the pump used in the experiment are shown in Table 3 [14]. The pump voltage and the rotation speed of the rotor are interrelated, such that once the rotation speed is known, the flow rate is determined.

Table 3: Specifications of the pump [14]

Colour	Blue ($C_6H_8O_7$)	Yellow ($NaBH_4$)
Tube inner diameter (mm)	2.4	2.4
Voltage (V)	8 ~ 24	8 ~ 24
Rotation speed (rpm)	37.5 ~ 150	37.5 ~ 150
Flow rate per revolution (mL/rpm)	0.35	0.3
Flow rate (L/min)	0.0131 ~ 0.0525	0.0112 ~ 0.0450

The volume of $NaBH_4$aq required for 10 L/min of H_2 is 0.0116 L, as determined by Equation (4). The rotation speed of the rotor at this point is expressed by Equation (7).

$$N_{NaBH_4} = \frac{0.0116\ L \times 1000}{0.3\ mL/rpm} = 38.7\ rpm \tag{7}$$

The relationship between pump voltage and rotation speed can be expressed as a linear function with a slope of 0.14. Assuming the reference values are 8 V and 37.5 rpm, the pump voltage at a rotation speed of 38.7 rpm is expressed by Equation (8).

$$V_{NaBH_4} = 0.14 \times (38.7 - 37.5) rpm + 8\ V = 8.17\ V \tag{8}$$

The quantity of $C_6H_8O_7$aq required for 10 L/min of H_2 is 0.0172 L, as determined by Equation (6). The rotation speed of the rotor at this point is expressed as per Equation (9).

$$N_{\mathrm{C_6H_8O_7}} = \frac{0.0172\ L \times 1000}{0.35\ mL/rpm} = 49.1\ rpm \tag{9}$$

The pump voltage at a rotation speed of 49.1 rpm is expressed by Equation (10).

$$V_{C_6H_8O_7} = 0.14 \times (49.1 - 37.5) rpm + 8\ V = 9.65\ V \tag{10}$$

Table 4: Relationship between aqueous solution and pump voltage

H_2 flow rate L/min	Voltage ($NaBH_4$) V	$NaBH_4$ L/min	Voltage ($C_6H_8O_7$) V	$C_6H_8O_7$ L/min
10	8.13	0.0116	9.83	0.0172
11	8.67	0.0128	10.31	0.0189
12	9.23	0.0139	11.02	0.0206
13	9.78	0.0151	11.72	0.0224
14	10.32	0.0162	12.42	0.0241
15	10.88	0.0174	13.12	0.0258
16	11.44	0.0186	13.82	0.0275
17	11.98	0.0197	14.52	0.0292
18	12.53	0.0209	15.22	0.0310
19	13.09	0.0220	15.93	0.0327
20	13.63	0.0232	16.46	0.0344
21	14.19	0.0244	17.33	0.0361
22	14.75	0.0255	18.02	0.0378
23	15.29	0.0267	18.72	0.0396
24	15.84	0.0278	19.42	0.0413
25	16.40	0.0290	20.12	0.0430
26	16.94	0.0302	20.83	0.0447
27	17.50	0.0313	21.53	0.0464
28	18.05	0.0325	22.23	0.0482
29	18.60	0.0336	22.93	0.0499
30	19.15	0.0348	23.63	0.0516

Based on the preceding calculations, the volume of aqueous solution and pump voltage necessary for H_2 generation at a rate of 10 L/min were determined. The relationship between aqueous solution and pump voltage within the measurement range of up to 30 L/min is shown in Table 4.

3. Performance Test of the Hydrogen Electric Power Generator

3.1 Principle and Structure of Intake System

Usually for a gasoline engine-based electric power generator, air-fuel mixture is supplied a fuel tank and throttle valve. However, when using H_2 as the fuel, it is necessary to remove the fuel tank and throttle valve. So far, in our previous study, a gasoline engine-based electric power generator has been modified to a specification capable of generating power with H_2 by attaching a special intake manifold and a surge tank.

Fig. 4 shows the structure of the special intake system for the H_2 engine-based electric power generator. This system is installed to ensure the stable supply of the mixture supplied to the engine. The incoming air first passes through an air filter where dust and debris are removed. To facilitate a stable supply, the air is temporarily stored in the surge tank. Subsequently, it flows into the intake manifold from the surge tank. As the air passes through the intake manifold with smaller diameter, the flow velocity will increase and lead to the increase in intake air volume. H_2 injection nozzles are installed at the bottom of the intake manifold, from which H_2 flows in and mix with air flowing from the up part of manifold and then supplied to the engine.

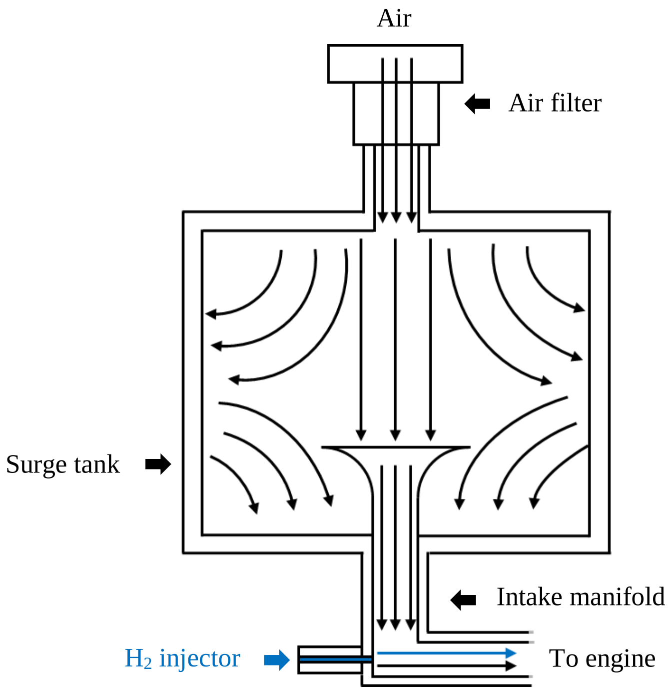


Fig. 4. Structure of the special intake system for the H_2 engine-based electric power generator

According to our previous study, the proper shape and structure of intake manifold and a surge tank are very crucial for stable operation in the high-power range for H_2-based engine, in this study, to obtain stable output of 1kW, based on a pre-analysis through flow velocity simulations, two types of surge tank and intake manifold were newly designed and manufactured as Type A and Type B. Their structures will be described later.

3.2 Experimental Method and Conditions

Fig. 5 shows the schematic of H_2 electric power generator test equipment, while Fig. 6 shows the actual experimental equipment. This equipment comprises a H_2 section (H_2 cylinder, flow meter, dry safety device, and regulator), an air section (air filter, differential pressure gauge, air flow meter, surge tank, and intake manifold), an output adjustment section (electric power generator, output meter, converter, and light bulb), and a measurement section (exhaust gas analyzer and data logger).

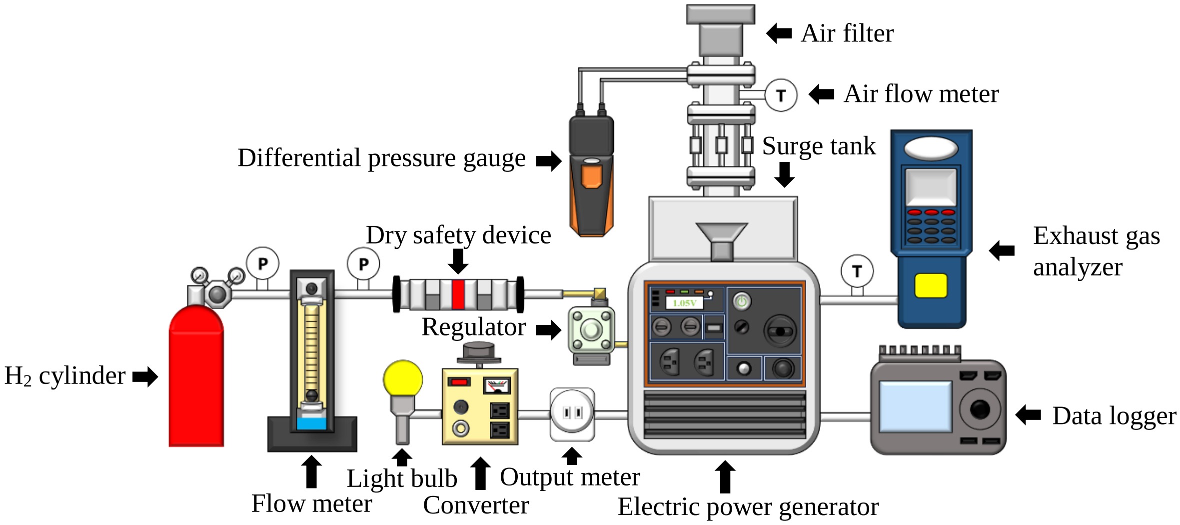


Fig. 5. Schematic of H_2 electric power generator test equipment

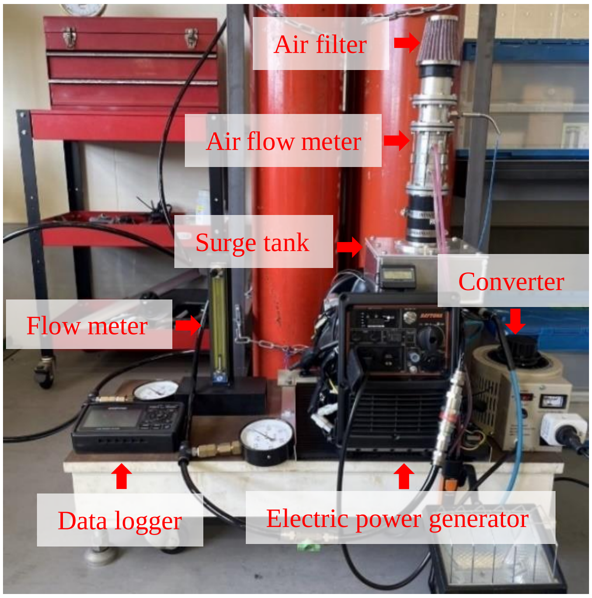


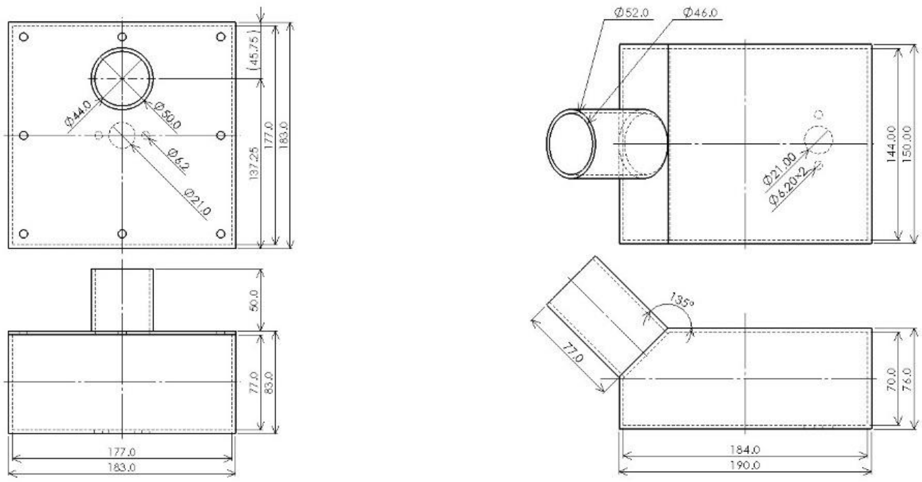
Fig. 6. Actual H_2 electric power generator

The test electric power generator is a forced-air-cooled 4-cycle gasoline overhead valve inverter electric power generator with a total displacement of 79 cm^3, a rated output of 1.9 kW, and a compression ratio of 9.4. The H_2 supplied from the H_2 cylinder is adjusted to a desired flow rate using a flow meter, with the initial flow rate set to 10 L/min during startup. A light bulb serves as the engine load, and its output is regulated by a converter. To measure the amount of intake air, a laminar airflow meter is employed. This measurement is achieved by establishing measurement points at two locations within the cylinder and calculating the intake air volume based on the differential pressure at these points. Temperature data is transmitted to a data logger, while exhaust gas data is measured by an exhaust gas analyser.

The experimental conditions are shown in Table 5. As mentioned above, two new combinations of surge tank and intake manifold for intake system were prepared, and their performances were compared. The details of surge tank are shown in Fig. 7, and the details of intake manifold are shown in Fig. 8. Type A is a combination of a surge tank with a volume of 2320 cc and an intake length of 125 mm, while Type B combines a surge tank with a volume of 1670 cc and an intake length of 186 mm.

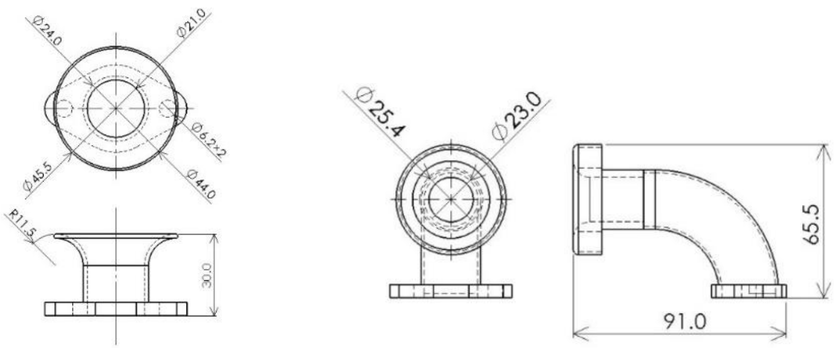
Table 5: Experimental conditions

		Type A	Type B
Intake manifold	Inner diameter (mm)	21	23
	Length (mm)	125	186
Surge tank	Width (mm)	183	150
	Length (mm)	183	190
	Hight (mm)	80	76
	Volume (cm^3)	2320	1670
Pressure (MPa)		0.2	
Output range (W)		0 ~ 1000	
H_2 flow rate range (L/min)		10 ~30	



(a) Type A (b) Type B

Fig. 7. Details of surge tank



(a) Type A (b) Type B

Fig. 8. Details of intake manifold

4. Engine Combustion Experiment using Generated Hydrogen

Fig. 9 shows the schematic of electric power generation system utilizing generated H_2, while Fig. 10 shows the actual experimental equipment. During this experiment. H_2 generated on-site is used for engine performance test. The experimental conditions are shown in Table 6. Throughout the experiment, the fuel flow rate was adjusted from 10 L/min to 16 L/min under a no-load condition, and the engine speed and intake and exhaust temperature was measured at each interval. For comparison, compressed H_2 was also used as fuel.

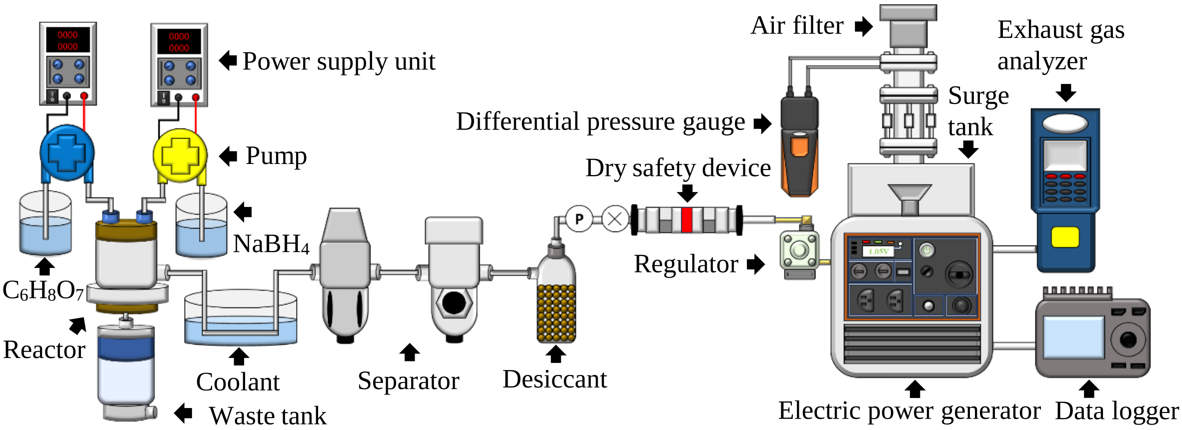


Fig. 9. Schematic of electric Power generation system utilizing generated H_2

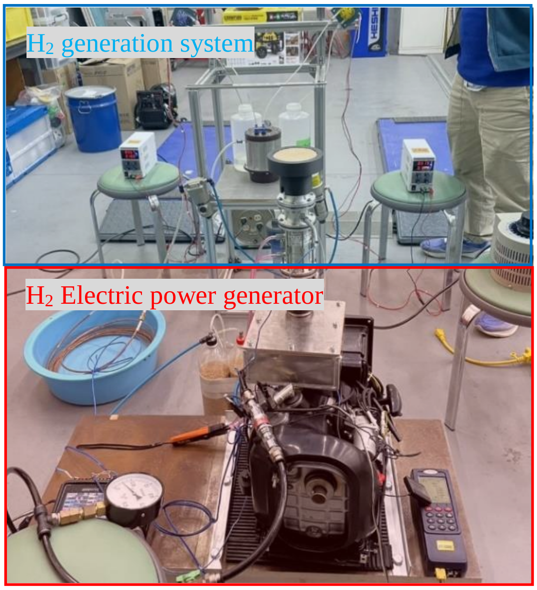


Fig. 10. Actual electric power generation system utilizing generated H_2

Table 6: Experimental conditions

Flow rate range (L/min)	0 ~ 16
Output (W)	0
Atmospheric pressure (hPa)	1007
Pressure (MPa)	0.1
Intake system	Type A

In the experiment, external load ranges from 0 to 1 kW, and measurements were taken from o to 1 kW with 100 W interval. Intake and exhaust temperatures, exhaust gas concentration, and intake air volume, and H_2 flow rate are measured respectively. Finally, the thermal efficiency is calculated.

5. Experimental Results and Discussion

5.1 Experiment of Hydrogen Generation

The relationship between aqueous solution and voltage required for H_2 generation at flow rates of 10 L/min to 30 L/min was determined using equations (8) and (10), as depicted in Fig. 11. The amount of $C_6H_8O_7$aq introduced is slightly higher compared to $NaBH_4$aq. When preparing 2 litters of each aqueous solution, the duration of operation under no-load conditions is approximately 2 hours.

Fig. 12 shows a comparison between theoretical and measured values of H_2 generation. The measured and theoretical values of H_2 generation are in close agreement within the range of 10 to 30 L/min. The maximum H_2 generation was 29.3 L/min, with a 2.4% deviation compared to the theoretical value of 30 L/min. This result clarifies that the calculated solution volume and input ratio are appropriate.

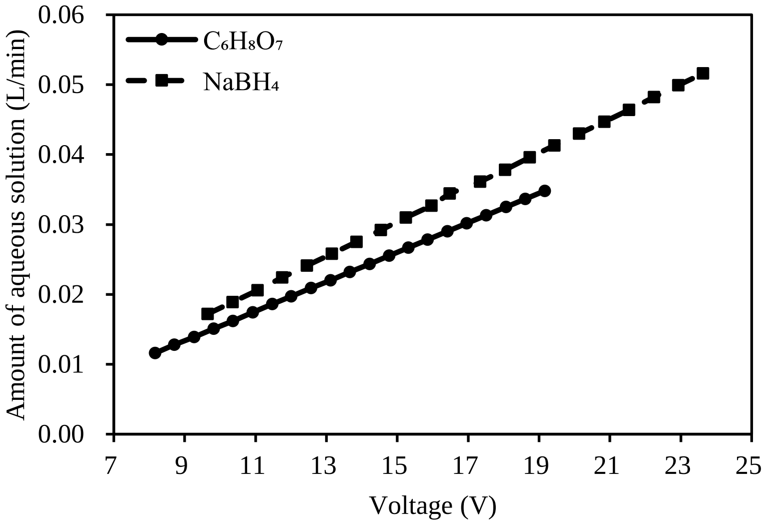


Fig. 11. Relationship between aqueous solution and the voltage

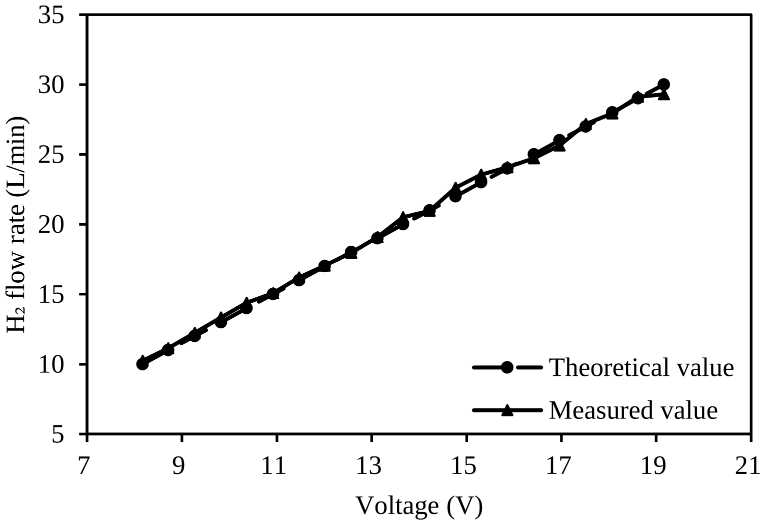


Fig. 12. Comparison between theoretical and measured value of H_2 generation

5.2 Performance Test of the Hydrogen Electric Power Generator

Fig. 13 shows a comparison of intake air volume. The maximum output was 900W for Type A and 800W for Type B. In the low-output range, Type B exhibits a higher intake air volume, while in the high-output range, Type A tends to have a higher intake air volume. The potential factor contributing to this trend is considered to be the length and shape of the intake manifold. Generally, the length of the intake manifold is related to intake efficiency, with longer lengths favouring higher intake efficiency at low outputs and shorter lengths at high outputs. This trend is prominently reflected in the experimental results, and it is considered as one of the factors contributing to the improvement in maximum output.

Fig. 14 shows a comparison of thermal efficiency. Firstly, the derivation formula for thermal efficiency is shown in Equation (11). Type A consistently exhibits higher thermal efficiency, reaching a maximum of 19.0%. Improvement in thermal efficiency is attributed to the fuel consumption, specifically the H_2 flow rate. From 700W onwards, a noticeable increase in the intake air volume for Type A contributes to the difference in thermal efficiency. It is evident that, even within the same output range, Type A achieves a reduction in fuel consumption.

$$\eta_G = \frac{3600 W_G}{BH} \times 100 \tag{11}$$

η_G: Thermal efficiency (%), W_G: Generator output (kW), B: Fuel consumption (kg/h), H: Calorific value (kJ/kg)

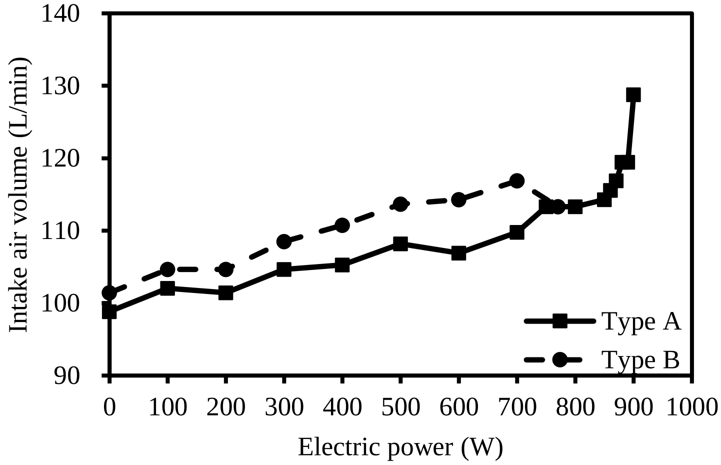


Fig. 13. Comparison of intake air volume

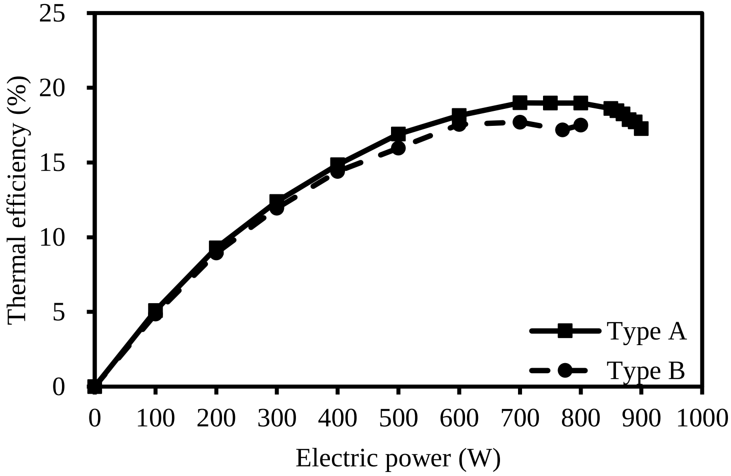


Fig. 14. Comparison of Thermal efficiency

5.3 Engine Combustion Experiment using Generated Hydrogen

Fig. 15 shows a comparison of engine speed concerning H_2 flow rate. With an increase in H_2 flow rate, the engine speed rises. However, when using generated H_2, the engine speed is significantly lower compared to compressed H_2, with a noticeable difference of 900 rpm observed at 16 L/min. One possible factor for this is the decrease in combustion temperature.

Fig. 16 shows a comparison of exhaust temperature concerning H_2 flow rate. The post-combustion exhaust temperature for compressed H_2 and generated H_2 show a difference of 15-40 degree, which widens as the H_2 flow rate increases. The potential cause for this is considered to be the temperature decrease due to the evaporative heat of moisture in the generated H_2. While the moisture content in compressed H_2 is minimal, generated H_2 may contain a higher amount of moisture produced during the reaction. Although the H_2 generation system includes a moisture removal mechanism, as the amount of generated H_2 increases, the significant temperature decrease suggests a potential reduction in removal efficiency.

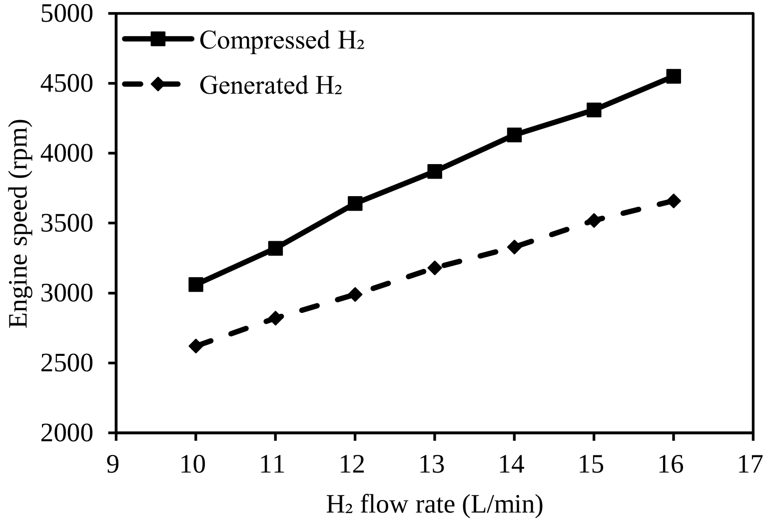


Fig. 15. Comparison of engine speed

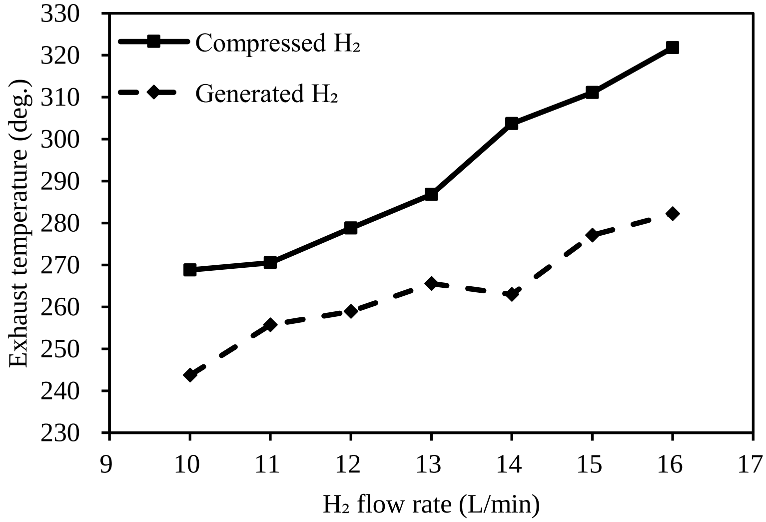


Fig. 16. Comparison of exhaust temperature

6. Conclusion

In this research, a H_2 electric power generator was proposed as a solution to the global warming problem, and its performance was evaluated based on the shape of the intake system. In addition, a H_2 generation system using $NaBH_4$ and $C_6H_8O_7$ as raw materials was proposed, and the generated H_2 was measured. The generated H_2 was introduced into a H_2 electric power generator, and the combustion characteristics of the generated H_2 and compressed H_2 were compared. As a result of the experiment, the following results were obtained.

1) The measured and theoretical values of H_2 generation are in close agreement within the range of 10 to 30 L/min. The maximum H_2 generation was 29.3 L/min, with a 2.4% deviation compared to the theoretical value.
2) The maximum output of the H_2 electric power generator was 900 W when equipped with the Type A intake system, showing a 100 W improvement compared to Type B.
3) The Type A intake system consistently demonstrated high thermal efficiency, reaching a maximum of 19.0%. The improvement in thermal efficiency is attributed to the fuel consumption, particularly the H_2 flow rate, and the increase in intake air volume resulted in a reduction in fuel consumption.
4) In the combustion experiment using generated H_2, the engine speeds decreased by 900 rpm compared to compressed H_2. This reduction is attributed to the influence of the evaporative heat caused by moisture.

It has been observed that the output of a H_2 electric power generator is approximately half that of gasoline. Future experiments will involve the use of an electric power generator with even higher output capacity. If performance levels of 1 kW or higher are confirmed, consideration for commercialization will be given. Additionally, power generation experiments utilizing the generated H_2 will be conducted under partial load conditions to comprehensively assess its output characteristics.

References

[1] BP plc. Statistical review of world energy 2022 [Internet]. London: BP; 2022 [cited 2023 Oct 5]. Available from: https://www.bp.com/content/dam/bp/business-sites/en/global/corporate/pdfs/energy-economics/statistical-review/bp-stats-review-2022-full-report.pdf

[2] IPCC. Sixth assessment report [Internet]. Japan: Ministry of the Environment; 2023 [cited 2023 Oct 5]. Available from: https://www.env.go.jp/earth/ipcc/6th/index.html (In Japanese)

[3] Global Warming Prevention Headquarters. NDC [Internet]. Japan; 2021 [cited 2023 Oct 5]. Available from: https://www.kantei.go.jp/jp/singi/ondanka/kaisai/dai48/pdf/ndc_kouken.pdf (In Japanese)

[4] Yamane K. Recent technology and prospect of reciprocating hydrogen Fuelled engines. Hydrogen Energy System. 2006;31(1):12-19. (In Japanese)

[5] Kensyukan. Hydrogen production technology [Internet]. Japan: Independent Administrative Agency; 2006 [cited 2024 Jan 30]. Available from: https://www.inpit.go.jp/blob/katsuyo/pdf/chart/fippan20.pdf (In Japanese)

[6] Abe I. Hydrogen production by water electrolysis. Hydrogen Energy System. 2008;33(1):19-26. (In Japanese)

[7] Murooka S, Tomoda K, Hoshi N, Cao M, Yoshizaki A, Hirata K. Validity verification of sodium borohydride as fuel for fuel cell electric vehicle. IEEJ Trans Ind Appl. 2012;132(2):299-300. (In Japanese)

[8] Suekawa T, Nitta H, Goto Y, Hoshi N, Fukuda K. Comparison of Volumetric Energy Densities of Hydrogen Reactors for Hydrogen Power Generation Systems Fueled by NaBH4. Journal of the Japan Institute of Power Electronics. 2020;46:124. (In Japanese)

[9] Sian FJ. Development of small hydrogen engine generator [Thesis]. Japan: Shizuoka Institute of Science and Technology; 2021. (In Japanese)

[10] Showa Chemical Co Ltd. Sodium Borohydride [Internet]. Japan: Showa Chemical Co Ltd; 2020 [cited 2023 Oct 5]. Available from: http://www.st.rim.or.jp/~shw/MSDS/19263350.pdf (In Japanese)

[11] Showa Chemical Co Ltd. Citric Acid Anhydride [Internet]. Japan: Showa Chemical Co Ltd; 2023 [cited 2023 Oct 5]. Available from: http://www.st.rim.or.jp/~shw/MSDS/03312250.pdf (In Japanese)

[12] Yoshizaki A. Method and device for producing sodium borohydride [Internet]. Japan: Google; 2015 [cited 2023 Oct 5]. Available from: https://patents.google.com/patent/WO2015190403A1/ja (In Japanese)

[13] Ishizuka K. Research on small reactor for emergency hydrogen generator using sodium borohydride and citric acid [Thesis]. Japan: Tokyo University of Science; 2018. (In Japanese)

[14] WELCO Co Ltd. WPX1 Peristaltic pump [Internet]. Japan: WELCO Co Ltd; 2023 [cited 2023 Oct 5]. Available from: https://www.welco-web.co.jp/product/tubepump/wpx1.html (In Japanese)