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Research Article

Development of An Electric Power Generator Using Hydrogen

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Abstract:
Hydrogen is the best form of energy for achieving carbon neutrality, it is also known as the ultimate energy in the new century. H_2 internal combustion engines have significant advantages of zero-carbon, high efficiency, and high reliability, making them one of the uppermost directions for hydrogen energy applications. In the research, we try to develop a hydrogen (H_2) electric power generator and an on-site H_2 generation system based on chemical reaction. In the experiment, firstly, a H_2-based electric generator and H_2 on-site generation system were established. Secondly the performance of the above H_2-based electric power generation system was tested. Finally, since extra heat was generated during the process of on-site hydrogen generation, then heat generated during H_2 on-site generation was recovered through cooling water for reuse. It was found that the maximum output of the generator was 470W under the condition of H_2 generation flow rate of 25L/min and the thermal efficiency was 10.46%. Besides, it was confirmed that at the cooling section, within 10 minutes, the temperature change was up to 8 °C for the cooling water of 10L under the condition of hydrogen generation rate of 30L/min and the heat recovery efficiency was up to 50%.

Keywords: *Hydrogen on-site generation, Electric power generator, Engine performance, Chemical reaction*

1. Introduction

Modern human activities, through the emission of greenhouse gases (mainly carbon dioxide), have led to the gradual aggravation of the global warming climate issue. Based on specific data, the global surface temperature from years 2011 to 2020 was 1.1℃ higher than that from 1850 to 1900. Nowadays, due to the current dependence of humans on fossil fuels, the emission of greenhouse gases is still increasing, and the problem of global warming remains very serious [1].

One of the representative technologies for reducing carbon dioxide emissions involves using H_2 as fuel [2]. H_2 is an efficient and clean form of energy. The combustion of hydrogen does not emit greenhouse gases or particulate materials (PM), which can improve the problem of emission pollution. And hydrogen can be obtained from renewable energy sources (e.g., solar), which is beneficial for the sustainable development of energy. [3]. H_2 is the lightest gas on earth, and as it mostly exists in the form of compounds, it can be produced through various processes. The current mainstream hydrogen production method uses CH_4 as the raw material and steam reforming for production [4]. Another more environmentally friendly method is electrolysis, which involves water electrolysis and does not emit CO_2 during the manufacturing process [5]. However, both methods require large equipment and involve high manufacturing costs. Using hydrogen as an alternative fuel also faces many challenges, such as low volumetric energy density, challenges in storage and transportation, high costs, etc... Hydrogen can be produced from various materials, with the most common methods being reforming and electrolysis.

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Among these, we focused on hydrogen generation technology that utilizes the hydrolysis of substances. The use of sodium borohydride ($NaBH_4$) to generate H_2 is a promising solution to address the forementioned issues. $NaBH_4$ is a stable white solid crystal at room temperature and pressure, and its manufacturing process is simple, involving only a reaction with water. This simplicity helps simplify the implementation of equipment and greatly reduces the cost of hydrogen production equipment. Refer to the example of using $NaBH_4$ to produce hydrogen for power generation. The results show that in a large-capacity reactor with a volume of 18 L, the H_2 generation rate can be as high as 164 L/min, and the corresponding power generation capacity reaches 5.25 kW [6]. In our previous research, an H_2 generation system was established using an aqueous solution of $NaBH_4$ ($NaBH_4$aq) and $C_6H_8O_7$ ($C_6H_8O_7$aq), measuring a flow rate of approximately 30 L/min. And the generator GV16-i was improved to use hydrogen for power generation. In the high-load operation experiment of the generator, a comparative experiment was conducted on two types of air intake systems: throttle valve and surge tank. The results showed that using the surge tank can achieve higher output power because surge tank possibly played a role in supplying enough air for hydrogen combustion inside the engine [7]. Afterwards, an operational experiment was conducted on the on-site hydrogen power generation system, which consisted of the forementioned hydrogen generation device and modified hydrogen generator. The engine could be started, but the load power generation failed [8].

In order to fulfil power generation by employing hydrogen generated on-site based on chemical reaction using $NaBH_4$, firstly, a new power generator and a newly designed surge tank were introduced. Secondly, a series of experiments including fluid simulation for the air intake system for the new engine, comparative experiments on investigating the optimal hydrogen pressure and flow rate condition for new engine startup, electric power generation experiment using hydrogen generated on-site and heat recovery experiments, were conducted this year.

2. Hydrogen generation system

2.1 Principle of hydrogen generation

Sodium borohydride, as a hydrogen production source, is an inorganic compound that can be used as a reducing agent for organic compounds such as aldehydes and ketones. The structure and specifications of sodium borohydride are shown in Figure 1 and Table 1. Sodium borohydride is a white powdery substance with high hygroscopicity, capable of absorbing moisture from the air and gradually decomposing. If stored in a sealed container, it can be stored stably for a long time. In addition, sodium borohydride generates hydrogen through hydrolysis. The reaction equation is as shown in Equation 1.

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

Table 1: Specifications of reactants.

Chemical formula	$NaBH_4$	$C_6H_8O_7$
Shape	White solid crystal	White solid crystal
Molecular weight	37.83	192.12
Density (g/cm^3)	1.074	1.665
Melting point (deg.)	400	153
Boiling point (deg.)	500	175
Solubility (g)	55/ H_2O 100 (25 deg.)	73/ H_2O 100 (20 deg.)

The reaction is exothermic, and sodium metaborate ($NaBO_2$) is the by-product. The hydrolysis of sodium borohydride does not require a catalyst, but it will react more drastically to generate hydrogen gas under acidic conditions. Therefore, citric acid ($C_6H_8O_7$) is used as an acidic condition [9]. The reaction equation is shown in Equation 2.

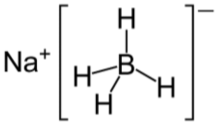


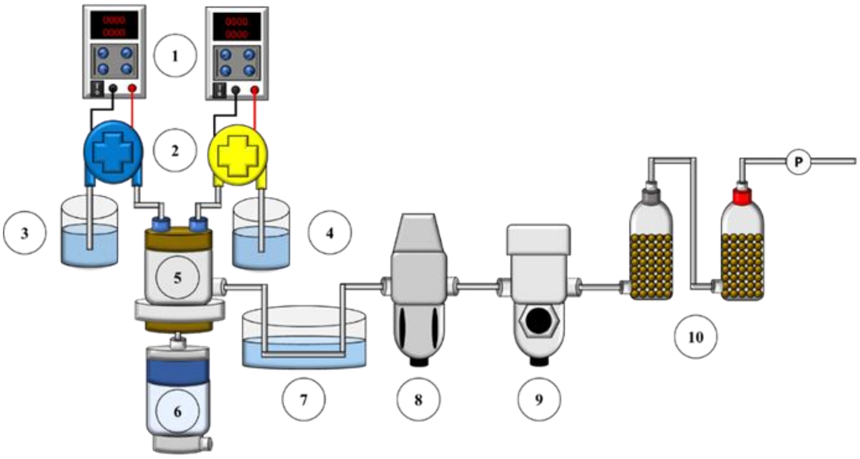
Fig. 1. The structure of sodium borohydride.

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

Due to the high content of water vapor in the hydrogen produced by this reaction at high temperatures, it is necessary to lower the temperature and remove water vapor before introducing the generated hydrogen into the engine. However, the reaction heat generated from the above reaction can be recovered, which is to be described in section 5.

2.2 Experimental system

The experimental setup for the hydrogen generation system is shown in Figure 2. The actual appearance of the experimental setup is shown in Figure 3. Experimental system mainly consists three major parts: the electric part (①~②), the hydrogen generation part (③~⑥), and the moisture removal part (⑦~⑩).



① Power supply unit ② Pump ③ $C_6H_8O_7$aq ④ $NaBH_4$aq ⑤ Reactor ⑥ Waste tank ⑦ Cooling water
⑧ Mist separator ⑨ Water separator ⑩ Desiccant

Fig. 2. H_2 generation system.

2 pumps were driven by 2 separate DC power supply and were used to convey the solutions of sodium borohydride and citric acid to the reactor, respectively. The hydrogen generation reactor is a device used for mixing aqueous solution of sodium borohydride and citric acid. The internal structure of the hydrogen generation reactor is shown in Figure 4. The hydrogen generation reactor is a cylindrical reactor, which is divided into a reaction chamber and a storage chamber. The aqueous solution flowing into the reaction chamber starts the chemical reaction through the reaction tube. The hydrogen produced by the reaction is discharged from the outlet through the partition valve, while the by-product aqueous solution moves to the by-product storage container.

In previous preliminary studies, the optimal reaction conditions were a $NaBH_4$aq of 33.3 wt.% and a $C_6H_8O_7$aq of 27.0 wt.%. Through calculations and experiments, the flow rate of hydrogen generation can be precisely controlled to any value between 10L/min and 30L/min by adjusting the voltages of the electric motors in the electric section.

Assuming a molecular weight of 37.83 for $NaBH_4$ and under normal conditions (0°C, 101325 Pa, 22.4 L), the quantity of aqueous solution needed to produce H_2 (25°C, 101325 Pa, 10 L) was computed. 4 moles of H_2 are produced from 1 mole of $NaBH_4$, and the quantity of $NaBH_4$ can be determined by Equation 3.

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

From the results of Equation 3, the quantity of $NaBH_4$aq with a concentration of 33.3 wt.% is determined by Equation 4.

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

The input ratio is 5:6, so the quantity of $C_6H_8O_7$ can be determined by Equation 5.

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

From the results of Equation 5, the quantity of $C_6H_8O_7$aq with a concentration of 27.0 wt.% is determined by Equation 6.

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

The flow rate of each supplied aqueous solution is closely related to the pump voltage, as shown in Table 2 [10].

Table 2: Relationship between flow rate of each supplied aqueous solution with pump voltage.

aqueous solution	$C_6H_8O_7$	$NaBH_4$
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

Fig. 3. Actual appearance of the H_2 generation system.

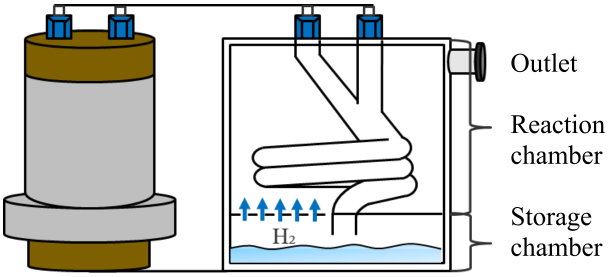


Fig. 4. Internal structure of the reactor.

3. Hydrogen Engine Power Generation Experimental System

3.1 Combustion characteristics of hydrogen

Table 3 shows differences of the characteristics of CH_4, gasoline, and hydrogen fuel [12]. The density of hydrogen is also very low compared to other fuels, at 0.084 kg/m^3. Therefore, the highest heat generated per weight during fuel combustion is 142MJ/kg for hydrogen, and the lowest heat generated per volume is 12.8MJ/m^3. This is one of the main reasons for the decrease in output of hydrogen compared to liquid fuels such as gasoline and natural gas [13].

Table 3: Fuel properties of CH_4, gasoline and H_2.

	CH_4	**Gasoline**	**H_2**
Molecular weight (g/mol)	16	70~90	2
Density (kg/m^3)	0.651	740	0.084
Diffusion coefficient (m^2/s)	2.1×10^{-5}	0.5×10-5	6.7×10^{-5}
Thermal conductivity (W/m·K)	0.03	-	0.17
Minimum ignition energy (mJ)	0.28	0.25	0.02
Flammable range (Vol.%)	5~15	2~10	4~75
Flame propagation speed (m/s)	0.4	0.4~0.5	2.7
Higher heating value (MJ/kg)	55.4	49.0	142.4

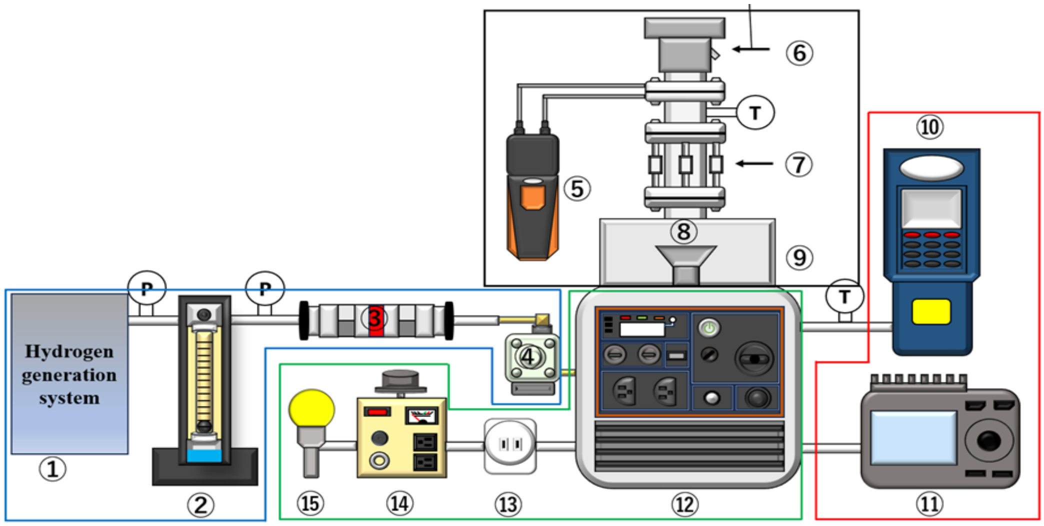
The thermal conductivity of hydrogen is 0.17 W/m·K, which is comparable to that of gasoline and approximately six times higher than that of methane, a similar gaseous fuel. A higher thermal conductivity means that hydrogen can easily absorb heat, which is related to its flammability.

The minimum ignition energy for hydrogen is 0.02 mJ, approximately 1/10 of that for methane and gasoline. Consequently, it can be ignited with a small spark, thereby enhancing combustion performance, much like its thermal conductivity does.

One of the characteristic combustion characteristics of hydrogen is lean combustion. The flammable range is 4~75Vol.%, which is also very wide compared to other fuels. Since lean combustion can reduce fuel consumption, it can be expected to improve thermal efficiency while suppressing the formation of nitrogen oxides (NOx) as harmful substances. In the lean combustion zone, the proportion of fuel gas in the mixture of oxygen and fuel gas decreases, resulting in a reduction of the thermal energy of the mixture. This lowers the combustion temperature, subsequently leading to a decrease in NOx emission concentration and exhaust temperature. Based on the above characteristics of hydrogen combustion and the current technologies of internal combustion engines, generators that use hydrogen as fuel and emit no carbon have promising research prospects.

3.2 H_2 electric generator system

Figure 5 shows the experimental setup of the hydrogen engine generator. The experimental setup mainly consists of a hydrogen supply section (①~⑤), an air intake section (⑥~⑨), a measurement section (⑩~⑫), and a power generation section (⑬~⑮).



①H_2 generation system ② H_2 flowmeter ③ Backfire prevention valve ④ Butterly valve ⑤ pressure difference measuring device ⑥ Air filter ⑦ Air flowmeter ⑧ Intake manifold ⑨ Surge tank ⑩ exhaust gas measuring device ⑪ Data loader ⑫engine generator ⑬power meter ⑭transformer ⑮light bulb load

Fig. 5. H_2 electric generator system.

For H_2 generation system, on-site H_2 generation system described in Section 2 is employed. The specifications of the newly introduced engine are presented in Table 4 and the specifications of the air intake section including intake manifold and surge tank are presented in Table 5. New intake manifolds and surge tanks were designed and manufactured and subsequently assessed for their performance based on the flow simulation described in Section 3.3.

Table 4: Specifications of the new engine generator.

Displacement (cc)	60
Engine speed (rpm)	4800
Ignition method	CDI
Output (kW)	0.9
Voltage (V)	100
Frequency (Hz)	50/60

Table 5: specifications of the intake manifold and surge tank.

 Intake manifold	Inner diameter (mm) Outer diameter (mm) Length (mm)	23 25 60
 Surge tank	Width (mm) Length (mm) Hight (mm) Volume (mm)	183 183 80 2320

3.3 Simulation of flow velocity for air intake system

In H_2 ICEs, the amount of air volume flowing through the intake pipe is a very important factor. This is because hydrogen has a broad flammable range increasing the amount of air results in the emission of fewer harmful substances. It is generally known that as the flow velocity increases, so does the flow rate. In previous experiments, it was concluded that using a surge tank could provide better air consumption at high power than using a throttle valve, and that the larger the size of the surge tank, the higher the suction efficiency. In this research, in order to investigate the flow velocity inside the surge tank, a flow simulation based on Solidwork Flow Simulation was conducted for the new intake system, the simulation conditions are indicated in Table 6. The capacity of the new surge tank is set to be 2320 cc. From Table 6, it is known that a pressure difference between the inlet and outlet of the surge tank is 40 kPa, which is obtained from a pressure measurement conducted before. The working fluid is air, which is drawn through the surge tank and into the intake manifold. Main dimensions of the new surge tank are shown in Figure 6. Figure 7 shows the representative simulation result obtained, describing the image of the air flowing from the surge tank to the inner engine.

Table 6: Conditions of simulation.

Analysis type	Internal flow
Flow type	Laminar and Turbulent Flow
Working fluid	Air
Inlet pressure (Pa)	101325
Outlet pressure (Pa)	61325
Temperature (K)	293.2

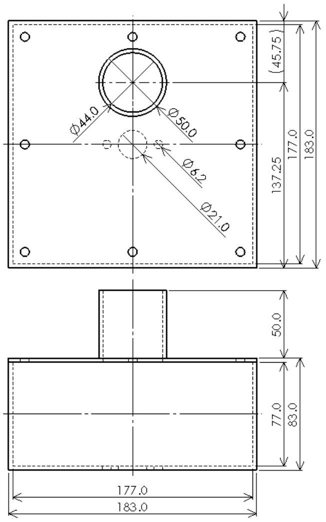


Fig. 6. Surge tank size drawing.

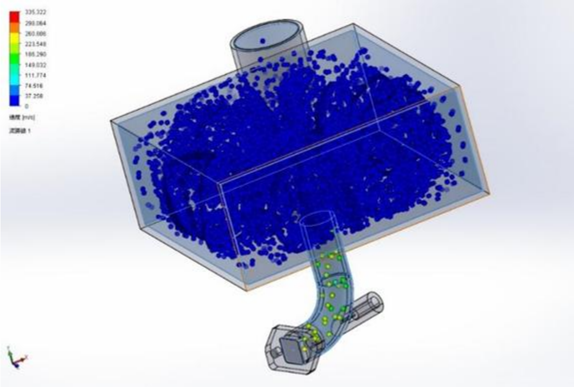


Fig. 7. Simulation fluid trajectory of the air intake system.

4. Power generation experiment using on-site hydrogen generation

4.1 Hydrogen supply conditions and engine startup experiment

Before conducting a power generation experiment using hydrogen generated on-site, it is crucial to conduct an experiment on investigating engine's starting conditions. Due to the introduction of a new engine and air intake system, an engine startup experiment was conducted to find the optimal starting flow rate and pressure condition. Owing to the need for precise control of pressure and flow, this experiment utilizes a hydrogen cylinder for hydrogen supply, with which the flow and pressure of the hydrogen gas can be precisely controlled through a pressure regulating device and a flowmeter. During this experiment, pressure condition was set to 0.01-0.02 MPa and 0.02-0.03 MPa while hydrogen flow rate was set to 10 L/min, 20 L/min and 30 L/min. Under each set of pressure and hydrogen flow rate condition, engine starting operation was tested. Based on the previous experimental result, it was confirmed that under flow conditions below 10 L/min, the engine could not be started successfully, hence in this experiment, minimum hydrogen flow rate was selected as 10 L/min.

4.2 Power generation experiment using hydrogen generated on-site

Hydrogen power generation system using hydrogen generated on-site is shown in Figure 8-1, and the appearance of the experimental apparatus is shown in Figure 8-2.

After identifying the optimal engine start-up conditions, the power generation experiment using hydrogen generated on-site was conducted. The starting hydrogen flow condition was set to 10 L/min and hydrogen flow rate was increased by 1 L/min until 30 L/min. Under each hydrogen flow rate condition, the maximum electric load was tested and recorded while thermal efficiency of the engine was calculated.

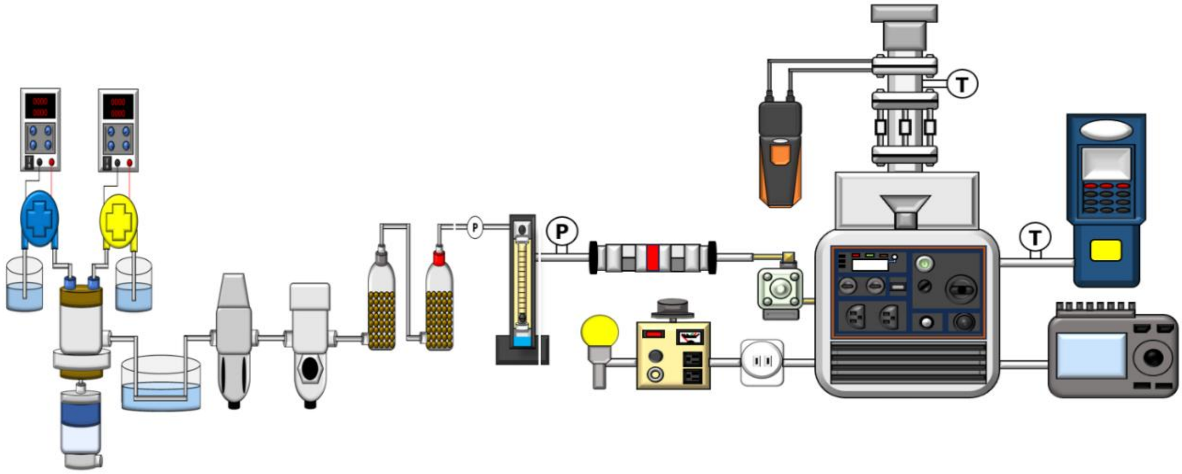


Fig. 8-1. Electric generator and hydrogen generation system.

Fig. 8-2. Appearance of the entire experimental system.

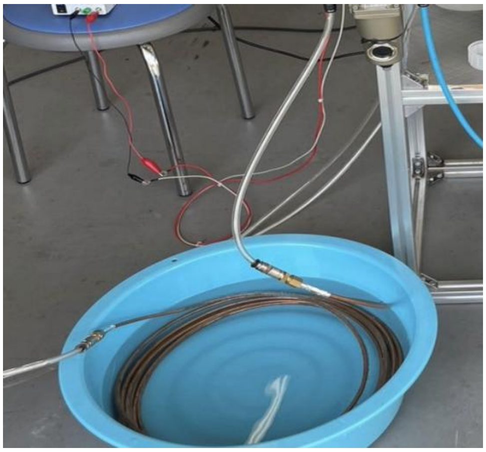


Fig. 9. Appearance of the cooling section**.**

5. Heat recovery experiment in the cooling section

Since on-site hydrogen generation system releases a significant amount of heat during the process of producing hydrogen, from the point view of efficiently utilizing thermal energy, an extra heat recovery experimental apparatus, i.e., a cooling system for generated hydrogen with higher temperature (Figure 9) was established. This cooing system consists of a 6m-long copper tube and a container in which 10 L water at room temperature was prepared. The copper tube was rolled and immersed inside the cooling water. During experiment, the temperature of the cooling water was measured by a thermometer after 10min's on-site hydrogen generation for different hydrogen flow rate starting from 10 L/min and the hydrogen flow rate was increased by 2 L/min until 30 L/min.

6. Experimental results and discussion

6.1 Results of engine starting conditions and backfire experiment

Hydrogen supply conditions including pressure and flow rate and engine startup experimental results are shown in Table 7. It is confirmed that in case of 0.01-0.02 MPa condition, new engine can be successfully started for three flow rates. However, for 0.02-0.03 MPa, when flow rate was 11 L/min or 12 L/min, backfire occurred and the new engine could not be started while in case of 10 L/min, though backfire was confirmed but engine could be started. Besides, since all the backfire phenomena were confirmed inside the surge tank, it can be inferred that when the hydrogen supply pressure is too higher, i.e., more than 0.02 MPa in this this study, some hydrogen would flow into the surge tank and cause the problems of abnormal air-fuel ratio in the combustion chamber and backfire. As a result, it is recommended that the suitable hydrogen pressure range of the hydrogen generation system is between 0.015-0.02 MPa and the minimum hydrogen flow rate 10 L/min for engine start-up.

Table 7: Hydrogen Supply Conditions and Engine Startup Experiment.

	0.01-0.02 MPa	**0.02-0.03 MPa**
10 L/min	The engine starts normally	Backfire occurred but engine could be started
11 L/min	The engine starts normally	Backfire occurred and engine could not be started
12 L/min	The engine starts normally	Backfire occurred and engine could not be started

6.2 Results of flow velocity simulation

Figure 10 illustrates the relation between the velocity of the air flowing into the surge tank with the simulation iteration number for the new intake system. Simulation was finished after 50th iteration and the average velocity was around 240 m/s. Since the average air velocity of the previous engine in the preliminary study ranged from 230 m/s to 270 m/s [14], it can be said that the new intake system suggested in this paper is possible to supply enough air and meet the requirements for hydrogen combustion.

6.3 Results of combined experiment of electric generator and hydrogen generation system

Figure 11 shows the relationship between hydrogen flow rate and generator power output in the hydrogen generation system. When the flow rate is between 10L/min and 13L/min, the generator is in an idle state due to insufficient output power. Normal power generation can be realized at flow rates above 14L/min and with the higher hydrogen flow rate, the output became larger. Currently, 470W power generation can be successfully obtained at a flow rate of 25L/min. Thermal efficiency was derived using Equation 7 and the thermal efficiency is 10.46% at the power of 470W. However, at flow rates above 25L/min, due to the inherent combustion condition limitations of the modified engine, it is unable to further increase power. In the future experiments, in order to enhance power output and thermal efficiency, a new engine with higher output capacity will be introduced and experiment on measuring air-fuel ratio will be conducted by improving the structure of the intake system.

$$\eta = \frac{3600W}{BH} \times 100 \tag{7}$$

W: Output power (W), B: Fuel consumption (kg/h), H: Lower heating value (kJ/kg)

6.4 Results of heat recovery experiment in the cooling section

Figure 13 shows the relationship between hydrogen generation rate and heat recovery from the cooling section. Heat recovery efficiency was derived using equation 8.

$$\eta = \frac{cm\,\Delta T}{BH} \times 100 \tag{8}$$

c: Specific heat capacity of water [J/(kg·K)], m:The mass of water (kg) ΔT: The increased temperature of water (℃) B: $NaBH_4$ consumption (mol/min), H: Theoretical heat release of $NaBH_4$ (kJ/mol).

From the experimental results, it is known that at the maximum flow rate of 30 L/min in the hydrogen generation system, 10 L water can be heated by 8 ℃ within 10 minutes, and the current heat recovery efficiency is around 40%-50% without taking consideration of surface heat loss through pipelines, and convection loss from the top surface of the water container and so on. As for accurate estimation of the surface heat loss through pipelines, and convection loss from the top surface of the water container, some extra datum such as pipeline surface temperature, surface temperature of water container, surface water temperature and hydrogen temperature are needed to be measured. The above-mentioned measurement is scheduled to be conducted in the future.

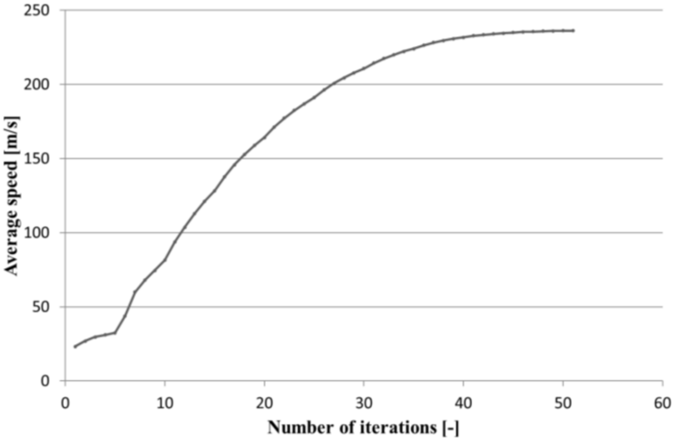


Fig. 10. Flow velocity simulation for the intake system.

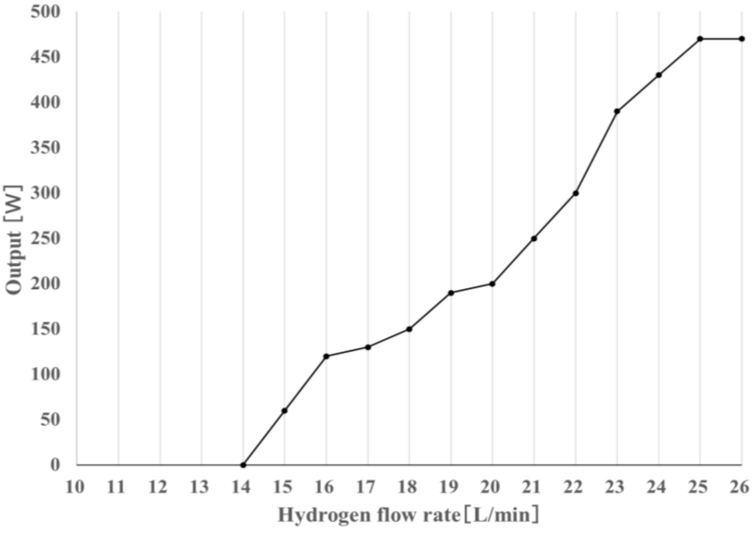


Fig. 11. The relationship between hydrogen flow and the output of generator.

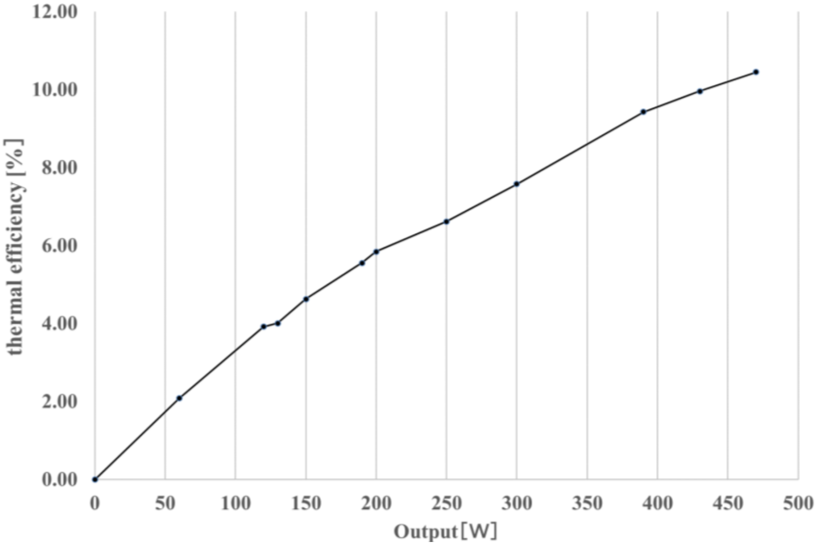


Fig. 12. Thermal efficiency.

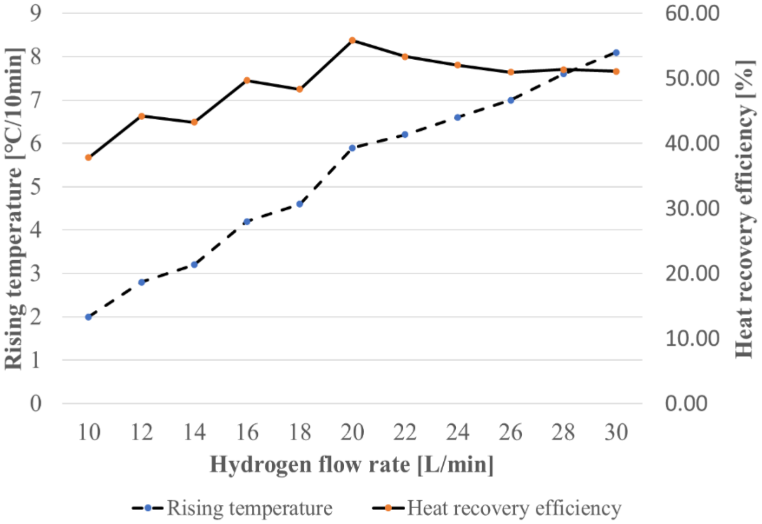


Fig. 13. The relationship between hydrogen generation rate and heat recovery.

7. Conclusion

In this research, a new H_2 electric power generator was developed and an on-site H_2 generation system was established. Power generation experiment and heat recovery experiment aiming at recovering reacting heat during on-site hydrogen generation were carried out. As a result, some conclusions were obtained as follows:

(1) The starting flow rate of the generator is 10 L/min, and the optimal pressure is below 0.02 MPa.
(2) Based on the simulation results, the intake system's air flow velocity is around 240 m/s and can provide sufficient air for the engine's combustion.
(3) Power generation experiment by using hydrogen generated on-site was successfully conducted. Currently the maximum output was 470 W under the condition of generating hydrogen at a rate of 25 L/min and the thermal efficiency was 10.46%.
(4) The cooling section can heat 10 L of room temperature water by 8 °C within 10 minutes at a maximum hydrogen generation rate of 30 L/min and heat recovery efficiency was up to 50%.

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