Development of Electric Power Generator by Using Hydrogen †

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Abstract: In this research, we developed a hydrogen (H2) electric generator in an H2 generation system based on chemical reactions. In the experiment, we tested the performance of the H2 electric generator and measured the amount of H2 generated. The maximum output was 700 W and the thermal efficiency was 18.2%. The theoretical value and measured value were almost the same, and the maximum error was 4%.

Keywords: hydrogen; electric power generator; intake manifold; on-site hydrogen generation

1. Introduction

Recently, the impact of global warming has become serious due to an increase in greenhouse gases emitted from industrial activities [1]. The decarbonization of mobility and power generation systems is considered as a countermeasure. One of the representative technologies is the use of internal combustion engines (ICEs) using H2 as fuel [2]. H2 is attracting much attention as an alternative fuel for automobiles. However, there are few practical examples of electric generators that use H2 as fuel. The purpose of this research was to develop a small H2 electric generator that operates stably with a maximum output of 1 kW by improving the fuel supply part of the conventional gasoline electric generator, and establishing an H2 generation system using chemical reactions. In the previous research [3], a surge tank was introduced to homogenize the mixture of H2 and air. As a result of measuring the maximum output of the electric generator, power was supplied stably at 800 W. In this research, the effect of the shape of the intake manifold on electric generator performance was confirmed. In addition, the H2 generation system using a chemical reaction between an aqueous solution of sodium borohydride (NaBH4aq) and aqueous solution of citric acid (C6H8O7aq) was adopted as an on-site H2 generation method, and theoretical and actual values were compared.

2. Hydrogen Engine Generator Performance Test

2.1. Combustion Characteristics of Hydrogen

The combustion reaction of H2 is shown in Equation (1). H2 combines with oxygen (O2) at a high temperature to produce water and thermal energy. H2 is environmentally friendly because it does not emit carbon dioxide (CO2). However, it also has the disadvantage of producing harmful nitrogen oxides (NOx) at high temperatures.

\[
2H_2 + O_2 = 2H_2O + 248 \text{ kJ/mol}
\] (1)

The main combustion characteristics of H2 are early ignition and lean burn. Table 1 shows a comparison of the fuel properties of methane (CH4) and H2 [4]. The minimum ignition energy of H2 is about 1/10 that of CH4, indicating that even a small spark burns it. In addition, the flammability range of H2 is 4 to 75, which indicates lean burn. In terms of
flame propagation, H\textsubscript{2} has a six times faster speed than CH\textsubscript{4}. H\textsubscript{2} is a material with excellent ignition and combustion properties. It is also susceptible to abnormal combustion such as backfire requiring a preventative measure. The basic experimental conditions are listed in Table 1.

Table 1. Fuel properties of CH\textsubscript{4} and H\textsubscript{2} [4].

<table>
<thead>
<tr>
<th></th>
<th>CH\textsubscript{4}</th>
<th>H\textsubscript{2}</th>
</tr>
</thead>
<tbody>
<tr>
<td>Molecular weight (g/mol)</td>
<td>16</td>
<td>2</td>
</tr>
<tr>
<td>Density (kg/m\textsuperscript{3})</td>
<td>0.651</td>
<td>0.084</td>
</tr>
<tr>
<td>Diffusion coefficient (m\textsuperscript{2}/s)</td>
<td>2.1 × 10\textsuperscript{-5}</td>
<td>6.7 × 10\textsuperscript{-5}</td>
</tr>
<tr>
<td>Thermal conductivity (W/m·K)</td>
<td>0.03</td>
<td>0.17</td>
</tr>
<tr>
<td>Minimum ignition energy (ml)</td>
<td>0.28</td>
<td>0.02</td>
</tr>
<tr>
<td>Flammable range (Vol.%)</td>
<td>5~15</td>
<td>4~75</td>
</tr>
<tr>
<td>Flame propagation speed (m/s)</td>
<td>0.4</td>
<td>2.7</td>
</tr>
</tbody>
</table>

2.2. Experimental Method and Conditions

Figure 1 shows the H\textsubscript{2} electric generator test equipment. The electric generator in the experiment adopted a forced air-cooled 4-cycle gasoline overhead valve inverter with a total displacement of 79 cm\textsuperscript{3}, a rated output of 1.9 kW, and a compression ratio of 9.4. In the fuel supply system, a supply port injection was used. The H\textsubscript{2} supply port was attached to the bottom of the intake so that it could be mixed with the inflowing air. The surge tank was a box-type one with a capacity of 1670 cm\textsuperscript{3} to temporarily store air and make the flow rate uniform.

![Figure 1. H\textsubscript{2} electric generator test equipment.](image)

Figure 1. H\textsubscript{2} electric generator test equipment. ① H\textsubscript{2} cylinder; ② H\textsubscript{2} flowmeter; ③ backfire prevention valve; ④ regulator; ⑤ air flowmeter; ⑥ surge tank; ⑦ electric generator; ⑧ intake manifold; ⑨ converter; ⑩ light bulb.

Table 2 shows the experimental conditions. We designed and manufactured three types of intake manifolds to confirm the effect of intake air volume and air–fuel ratio (AFR). Figure 2 shows its appearance. In the experiment, the output was changed from 100 W to 1 kW using a converter. The engine speed was constant at each output, and partial load operation was performed. Then, we measured the intake air volume of H\textsubscript{2} at each output to evaluate the performance.
Table 2. Dimensions of intake manifolds.

<table>
<thead>
<tr>
<th>Dimension</th>
<th>Type1</th>
<th>Type2</th>
<th>Type3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inner diameter (mm)</td>
<td>21</td>
<td>23</td>
<td>23</td>
</tr>
<tr>
<td>Outer diameter (mm)</td>
<td>23</td>
<td>25</td>
<td>25</td>
</tr>
<tr>
<td>Length (upper part) (mm)</td>
<td>33</td>
<td>66</td>
<td>82</td>
</tr>
<tr>
<td>Length (lower part) (mm)</td>
<td>95</td>
<td>95</td>
<td>95</td>
</tr>
</tbody>
</table>

![Type1](image1), ![Type2](image2), ![Type3](image3)

Figure 2. Appearance of intake manifolds.

3. Hydrogen Generation

3.1. Principle of Hydrogen Generation

H₂ can be produced from various resources, such as the reforming method, which extracts H₂ from generated gas by burning fossil fuels, and the electrolysis method, which extracts H₂ from water with electricity. H₂ is classified into three types, gray H₂, green H₂, and blue H₂, depending on the manufacturing method [5]. Gray and blue H₂ are produced using fossil fuels, and green H₂ is produced using renewable energy. Considering the global environment, the latter method is considered ideal. H₂ is known to be a clean energy that does not emit CO₂. However, there are issues with using it as fuel. One of the typical physical properties of hydrogen is its low density per volume. A common solution to these issues is pressurized gas and liquefied storage. These methods are not widely used due to high handling risks and costs.

We proposed an H₂ onsite generation system using sodium borohydride (NaBH₄) to solve the above problems. Table 3 shows the specifications of the samples and their appearances. NaBH₄ is a powdery white solid crystal and is stable at normal temperature and pressure. The mass density of H₂ is 10.6 wt.%, which is higher than high-pressure gas and liquefied H₂. NaBH₄ reacts with water to generate H₂ which is accelerated under certain temperature or acidic conditions. In this research, as shown in Figure 3, we used this property and adopted a production method by a chemical reaction with NaBH₄ using a C₆H₄O₇ [6]. The chemical reaction formula is shown in Equation (2).

\[
3\text{NaBH}_4 + 2\text{H}_2\text{O} + \text{C}_6\text{H}_8\text{O}_7 + 9\text{H}_2\text{O} \rightarrow 12\text{H}_2 + \text{Na}_3\text{C}_6\text{H}_5\text{O}_7 + 3\text{B(OH)}_3
\]

(2)

Table 3. Specifications of samples.

<table>
<thead>
<tr>
<th>Chemical Formula</th>
<th>NaBH₄</th>
<th>C₆H₄O₇</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shape</td>
<td>White solid crystal</td>
<td>White solid crystal</td>
</tr>
<tr>
<td>Molecular weight</td>
<td>37.83</td>
<td>192.12</td>
</tr>
<tr>
<td>Density (g/cm³)</td>
<td>1.074</td>
<td>1.665</td>
</tr>
<tr>
<td>Melting point (deg.)</td>
<td>400</td>
<td>153</td>
</tr>
<tr>
<td>Boiling point (deg.)</td>
<td>500</td>
<td>175</td>
</tr>
<tr>
<td>Solubility (g)</td>
<td>55/H₂O 100 (25 °C)</td>
<td>73/H₂O 100 (20 °C)</td>
</tr>
</tbody>
</table>
3.2. Experimental Method and Conditions

Figure 4 shows the H₂ generation system. In this system, NaBH₄ and C₆H₈O₇ were pumped up and reacted in a reactor to generate H₂. This reaction produces boric acid and sodium citrate in addition to H₂. These by-products were diverted in the flow path and sent to the waste tank. The H₂ generated is at a high temperature due to the exothermic reaction and contains water vapor that must be removed. The H₂ flow quantity was measured using a flow meter. Therefore, the temperature of H₂ was lowered by cooling water and measured after being passed through a desiccant.

![Figure 4. H₂ generation system.](image)

Figure 3. Appearance of samples.

The concentration of the two aqueous solutions used in the experiment was an important factor, and precipitation and sticking occurred if the concentration was not appropriate. The results of previous research [7] indicated that the NaBH₄aq was 33.3 wt.% and the C₆H₈O₇aq was 27.0 wt.% also. The input ratio of the aqueous solution was 5:6, and the amount was derived from the following formula. Assuming a molecular weight of 37.83 for NaBH₄ and standard conditions (0 °C, 1 atm, and 22.4 L), we calculated the amount of aqueous solution required to generate H₂ (25 °C, 1 atm, and 10 L). Equation (2) shows that 4 mol of H₂ is generated from 1 mol of NaBH₄, and the amount of NaBH₄ can be obtained from Equation (3).

\[
NaBH₄ = 37.83 \times \frac{1}{4} \times \frac{1}{22.4} \times \frac{273}{298} = 3.87 \text{ g}
\]  \hspace{1cm} (3)

From the results of Equation (3), the amount of NaBH₄aq with a concentration of 33.3 wt.% is given by Equation (4).

\[
NaBH₄aq = 3.87 \times \frac{100.0}{33.3} = 11.6 \text{ g}
\]  \hspace{1cm} (4)
Since the input ratio of NaBH₄ and C₆H₈O₇ is 5:6, the amount of C₆H₈O₇ is given by Equation (5).

\[
C₆H₈O₇ = 3.87 \times \frac{6}{5} = 4.64 \text{ g}
\]  

(5)

From the results of Equation (5), the amount of C₆H₈O₇aq with a concentration of 27.0 wt.% is given by Equation (6).

\[
C₆H₈O₇aq = 4.64 \times \frac{100.0}{27.0} = 17.2 \text{ g}
\]  

(6)

4. Results and Discussion

4.1. Influence of Intake Manifold Shape on Intake Air Volume

Figure 5 shows a comparison of intake air volume. It increased for all types to produce 600 W. When the output reached 700 W, the intake air volume decreased, and the operation became unstable. ICE used in the experiment was naturally aspirated and the air could not be adjusted. Therefore, the intake air volume was obtained during high output operation. The condition with the highest value was Type1, and the intake air volume increased by about 15% compared to Type2. As a result, the straight and short intake pipe was more susceptible to the pulsation effect. Therefore, the intake air volume increased.

![Figure 5. Comparison of intake air volume.](image)

4.2. Influence of Intake Manifold Shape on AFR

Figure 6 shows a comparison of the AFR that is derived from the H₂ flow rate and intake air volume and is expressed in Equation (7).

\[
\lambda = \frac{\rho_{\text{Air}} \times Q_{\text{Air}}}{\rho_{\text{H₂}} \times Q_{\text{H₂}}}
\]  

(7)

(λ: AFR; ρ_{\text{Air}}: air density (kg/m³); ρ_{\text{H₂}}: H₂ density (kg/m³); Q_{\text{Air}}: intake air volume (L/min); Q_{\text{H₂}}: H₂ flow rate (L/min)).

![Figure 6. Comparison of AFR.](image)
The theoretical AFR of the H\textsubscript{2} ICE was 34:1, so it tended to lean burn overall. As the power increased, the AFR gradually decreased, reaching approximately 70 at 700 W for Type1. The output did not increase as the intake air volume was greatly reduced in the high-output range. Therefore, the actual AFR fell below the theoretical AFR, and the operation became unstable.

4.3. Influence of Intake Manifold Shape on Thermal Efficiency

Figure 7 shows a comparison of thermal efficiency. It is derived from output and H\textsubscript{2} consumption and is shown in Equation (8).

$$\eta = \frac{3600W}{BH} \times 100$$  \hspace{1cm} (8)

($\eta$: thermal efficiency (%); W: output (kW); B: H\textsubscript{2} consumption (kg/h); H: low heating value (kg/kJ)).

The maximum thermal efficiency was 18.2% under Type3. Comparing the maximum thermal efficiency of each type, the difference was about 2%. Therefore, there was no significant correlation between the shape of the intake manifold and the thermal efficiency.

4.4. Measurement of Hydrogen Generation

The amount of aqueous solution required to generate 10 L/min of H\textsubscript{2} was determined as 11.6 g (NaBH\textsubscript{4}aq) and 17.2 g (C\textsubscript{6}H\textsubscript{8}O\textsubscript{7}aq) (Equations (5) and (6)). Also, it must be mixed in a 5:6 ratio. The amount of aqueous solution varied with the voltage of the pump and had to be adjusted to achieve a 5:6 ratio. We explored the relationship between voltage and input amount prior to the performance of the pump. Table 4 shows the relationship between the aqueous solution and the pump voltage required to generate 10 to 20 L/min of H\textsubscript{2}.

Figure 8 shows a comparison of theoretical and measured values of H\textsubscript{2}. The theoretical value and measured value were almost the same, and the maximum error was about 4%. This result indicated that on-site power generation by combining an H\textsubscript{2} generator and an H\textsubscript{2} engine was possible. In the future, we will experiment with the two devices.
Table 4. Relationship of aqueous solution and pump voltage.

<table>
<thead>
<tr>
<th>H₂ Flow (L/min)</th>
<th>Voltage (NaBH₄)</th>
<th>NaBH₄ Voltage (C₆H₈O₇)</th>
<th>C₆H₈O₇ Voltage (L/min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>8.05</td>
<td>0.0116</td>
<td>8.95</td>
</tr>
<tr>
<td>11</td>
<td>8.65</td>
<td>0.0128</td>
<td>9.68</td>
</tr>
<tr>
<td>12</td>
<td>9.25</td>
<td>0.0139</td>
<td>10.42</td>
</tr>
<tr>
<td>13</td>
<td>9.90</td>
<td>0.0151</td>
<td>11.15</td>
</tr>
<tr>
<td>14</td>
<td>10.50</td>
<td>0.0162</td>
<td>11.90</td>
</tr>
<tr>
<td>15</td>
<td>11.10</td>
<td>0.0174</td>
<td>12.55</td>
</tr>
<tr>
<td>16</td>
<td>11.70</td>
<td>0.0186</td>
<td>13.25</td>
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<tr>
<td>17</td>
<td>12.30</td>
<td>0.0197</td>
<td>14.02</td>
</tr>
<tr>
<td>18</td>
<td>12.85</td>
<td>0.0209</td>
<td>14.75</td>
</tr>
<tr>
<td>19</td>
<td>13.60</td>
<td>0.0220</td>
<td>15.50</td>
</tr>
<tr>
<td>20</td>
<td>13.99</td>
<td>0.0232</td>
<td>16.20</td>
</tr>
</tbody>
</table>

Figure 8. Comparison of theoretical and actual value.

5. Conclusions

In this research, the influence of the shape of the intake manifold on performance and the amount of H₂ generated were researched. As a result, the following conclusions were obtained. The maximum output of the H₂ electric generator was 700 W, which was less than half of the rating. It was found that the intake shape showed little effect on the thermal efficiency, and the maximum value was 18.2% for Type3. Type1 showed the highest intake air volume, improving by 15% compared to Type3. The amount of H₂ generated was almost the same as the theoretical value, and the maximum error was 4%.

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References

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