Development of a Compact Reformer for Fuel Cells

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1. Introduction

The main role of the fuel processor in a fuel cell power plant is to ensure a stable supply of hydrogen to the fuel cell. Hydrogen is produced in a steam reforming reaction in which hydrocarbons in raw gas react with steam at high temperatures in the presence of a catalyst.

Figure 1 shows a configuration of a fuel processor using town gas as raw gas. The fuel processor consists of a desulfurizer which removes the sulfur content in town gas, a reformer which performs a steam reforming reaction, a CO shift converter which reduces the quantity of carbon monoxide in reformed gas, and a heat exchanger which maintains appropriate reaction temperatures in individual reactors.

2. Development Goals of Fuel Processors

At present, cost reduction is the most important challenge to the introduction of on-site fuel cell plants into the market. In this regard, simplification and size reduction are required of fuel processors on the whole.

As a first step in coping with this situation, Fuji Electric has developed a new-model reformer (first-step reformer) with a built-in heat exchanger, which had previously been installed outside the reformer, and in combination has also developed a new model desulfurizer/shift converter consisting of a desulfurizer, a CO shift converter and a heat exchanger. Figure 2 shows this system flow. As a second step, Fuji Electric is developing a compact reformer (second-step reformer) aimed at reducing the size of reformers with a built-in heat exchanger.

3. Development of Reformers

3.1 Basic structure of a reformer

Since the start of the development of on-site reformers, Fuji Electric has been adopting a simple configuration using a single burner and a single reaction tube. Table 1 shows basic specifications of a 100kW reformer. The external view and schematic diagram of the first-step reformer are shown in Fig. 3 and Fig. 4, respectively.

(1) Burner

A down-firing multi-cylinder burner is installed at the top center of the reformer. For fuel, the burner uses town gas at startup, and low-calorie anode exhaust gas.

![Fig.2 Process flow diagram of a fuel processor](image)

![Fig.1 Configuration of a fuel processor](image)

Table 1 Basic specifications of a 100kW reformer

<table>
<thead>
<tr>
<th>Item</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Raw gas</td>
<td>Town gas (LPG)</td>
</tr>
<tr>
<td>Process</td>
<td>Steam reforming</td>
</tr>
<tr>
<td>Quantity of generated hydrogen</td>
<td>100 m³/h (normal)</td>
</tr>
<tr>
<td>Reaction temperature</td>
<td>700°C</td>
</tr>
<tr>
<td>Reaction pressure</td>
<td>Normal atmospheric pressure</td>
</tr>
<tr>
<td>Steam/carbon ratio</td>
<td>3.0</td>
</tr>
</tbody>
</table>
exhaust gas from a fuel cell during normal operation to generate the required quantity of heat for reforming. The calorific value of town gas per unit volume is ten times larger than that of anode exhaust gas, and hence an important development goal is to ensure steady burning of both gases with one burner. For this purpose, swirling blade angles were optimized to adjust the mixing speed of anode exhaust gas and combustion air. In addition, the burner was designed to be recessed inside the reformer to reduce the height of the reformer.

(2) Reforming tube

The heat generated by the burner is transferred from the reforming tube wall to the catalyst bed by radiation and convection. The reforming tube that is filled with catalyst is constructed as a duplex cylinder. Town gas, or raw gas, is mixed with steam and then fed into the reformer at approximately 200°C. The mixture flows from the top to the bottom of the catalyst bed, in the course of which it is heated and converted to reformed gas with hydrogen as the main ingredient. The mixture is heated to approximately 700°C at the bottom outlet of the catalyst bed.

(3) Built-in heat exchanger

In conventional reformers, raw gas must be preheated up to 500°C in the front stage of the reformer and reformed gas must be cooled in the front stage of the CO shift converter, requiring an outside heat exchanger. In the newly developed reformer, since the heat exchange zone for raw gas, reformed gas and exhaust gas is designed to be inside the reformer, the temperature difference between inlet and outlet gases was remarkably reduced, eliminating the need for an outside heat exchanger. Figure 5 shows a combined desulfurizer/CO shift converter that has been developed in conjunction with the reformer. The integration of a desulfurizer and a CO shift converter reduced the number of components such as pipes. The change of the construction of the desulfurizer and CO shift converter from a cylindrical type to a cubic type allowed an effective use of floor space when they were mounted in a fuel processor.

3.2 Basic design

In designing a reformer, it is necessary to understand the reforming reaction in the catalyst bed and the quantity of heat transfer from the burner to the catalyst bed. However, it is difficult to measure the quantity of heat transfer by instrumentation because the surface temperature of the catalyst bed reaches extremely high temperatures up to 900°C. Therefore, a simulation of the basic construction design was
performed based on basic experimental data and theoretical equations. Then, a prototype reformer was manufactured to verify its performance in a unit test and to confirm the validity of the simulation by comparing measured values with calculated values in the simulation. The quantity of steam reforming reaction in individual parts of the catalyst bed is calculated in the following way.

<Steam reforming reaction>

\[ \text{CH}_4 + \text{H}_2\text{O} \rightarrow \text{CO} + 3\text{H}_2 \] (first-order reaction) \hspace{1cm} (1)

\[ \text{CO} + \text{H}_2 \rightarrow \text{CO}_2 + \text{H}_2 \] (second-order reaction) \hspace{1cm} (2)

\[ K_1 = \frac{\text{P}_\text{CO} \cdot \text{P}_\text{H}_2}{\text{P}_\text{CH}_4 \cdot \text{P}_\text{H}_2\text{O}}, \quad K_2 = \frac{\text{P}_\text{CO}_2 \cdot \text{P}_\text{H}_2}{\text{P}_\text{CO} \cdot \text{P}_\text{H}_2\text{O}} \]

where, \( K_1, K_2 \) : chemical equilibrium constants (temperature parameter functions)

\( P_{\text{CH}_4}, P_{\text{H}_2\text{O}}, P_{\text{H}_2}, P_{\text{CO}_2}, P_{\text{CO}} \) : partial pressure of each element

In the first order reaction, the quantity of individual elements generated is obtained based on the theoretical rate calculated from the equation (1) and the reaction rate, or performance characteristics of the reforming catalyst. In the second order reaction, the theoretical rate is applied. Temperatures in individual parts of the catalyst bed are calculated based on the total quantity of heat transfer from the reforming tube and the heat of reaction produced in steam reforming.

Figure 6 shows an example of a reformer simulation. The horizontal axis represents the distance from the inlet in the catalyst bed. The upper graph shows the change in reformed gas temperature from the inlet to the outlet of the catalyst bed. The lower graph shows that the methane gas (CH\(_4\)) content in the reformed gas changes from approximately 90% at the inlet to less than 2% at the outlet, with the progress of the reforming reaction as the temperature rises.

### 3.3 Temperature profile of a reforming tube

In a duplex-cylinder type reformer as described above, it is important to make circumferential temperatures uniform to prevent the catalyst from decomposing into powder and the container from deforming, and to improve durability of the reformer. In the newly developed reformer, circumferential exhaust gas flow was added to the previous axial exhaust gas flow to ensure a uniform gas distribution and to reduce variation in circumferential temperature distribution.

Figure 7 shows temperature distribution of the first-step reformer. There is little difference in temperatures at both the inlet and outlet of the catalyst bed.

![Figure 7: Temperature distribution of the first-step reformer](image)

### Table 2 Comparison of reformers

<table>
<thead>
<tr>
<th>Item</th>
<th>First-step reformer</th>
<th>Second-step reformer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Installation area</td>
<td>100%</td>
<td>58%</td>
</tr>
<tr>
<td>Mass</td>
<td>100%</td>
<td>65%</td>
</tr>
<tr>
<td>Volume</td>
<td>100%</td>
<td>58%</td>
</tr>
<tr>
<td>Quantity of catalyst</td>
<td>100%</td>
<td>59%</td>
</tr>
</tbody>
</table>

![Figure 8: Comparison of external dimensions](image)
3.4 Operational results

The No. 1 unit first-step reformer was mounted on the No. 1 unit first-commercial-type fuel processor for performance evaluation in the factory and underwent an operation of approximately 10,000 hours, showing satisfactory records without degradation in performance. Thus far, three units of the first-commercial-type fuel processors mounted with first-step reformers have been delivered, and they are performing continuous and trouble-free operation.

3.5 Development of the second-step reformer

In order to reduce the size of a reformer with a built-in heat exchanger, it is necessary to increase heat flux towards the catalyst bed. For this purpose, in the second-step reformer, temperature distribution in the reforming tube was optimized, and the flow rate of reformed gas and exhaust gas was increased to remarkably increase heat flux. Table 2 shows a comparison of the first- and second-step reformers, and Fig. 8 a comparison of external dimensions. Both volume and mass were reduced by approximately 40%. Testing of the prototype reformer showed satisfactory results.

Figure 9 shows the test results of the second-step reformer. The conversion ratio was as projected over the whole range of temperatures.

The second-step reformer is mounted on the fuel processor for in-house evaluation and is being operated to perform a life cycle test.

4. Conclusion

This paper has introduced the present development status of compact reformers. Fuji Electric is determined to develop lower-cost reformers and to establish a technology necessary for reforming various raw gases in order to expand the market for fuel cells.

Finally, many thanks must go to the parties concerned for their cooperation and guidance in developing the reformer.
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