Influence of Secondary Fuel Injection on Fuel-rich Diffusion Combustion

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Abstract: The Chemical Gas Turbine (ChGT) system has two combustors which produce high temperature gas required to drive two gas turbines. The thermal efficiency of ChGT system was expected to be about 2.5% higher than that of the conventional gas turbine/steam turbine (GT/ST) combined cycle system by performance analysis. In the ChGT system, the first combustor is operated under a fuel-rich condition. However, fuel-rich combustion has some problems such as flame instability and soot production.

In order to solve these problems, a new technique has been proposed: Secondary fuel is injected into the combustion chamber with stable main flame formed by a main burner under a fuel-lean condition. The effects of secondary fuel injection on the exhaust gas composition and profiles of chemical species have been investigated experimentally. Also, the structure of the non-flame flow in a combustor was visualized by particle image velocimetry (PIV). The results of PIV indicated that the mixing of fuel was effectively enhanced since the vortexes were formed by secondary fuel injection. The concentration of combustible gas species increased with an increase in equivalence ratio and in injection angle and a decrease in injection position. The greatest generation of combustible gas species was obtained at 70mm in injection position, 60 deg. in injection angle and 3.1 in equivalence ratio.

Keywords: Gas turbine, Diffusion combustion, Dimethyl ether(DME), Performance analysis, PIV

1. INTRODUCTION

In many countries, thermal power generation depends largely on fossil fuels. To raise the thermal efficiency on thermal power generation plants is almost equal to developing a new energy resource. The gas turbine technology as one of the power generation methods has been steadily advancing, causing a rapidly growing demand for energy crisis in these days.

The thermal efficiency of gas turbine for the power generation is improved about 2% with a rise of every 100 deg. C at turbine inlet temperature (TIT). A conventional gas turbine/steam turbine (GT/ST) combined cycle power generation system is the favored method for the increase of thermal efficiency. The efficiency is easily achieved 50% when TIT is 1500 deg. C. The temperature of gas turbine combustor is over 1500 deg. C, but TIT is limited to 1500 deg. C due to resistance to heat of the gas turbine blades. Therefore fuel-lean combustion (equivalence ratio, φ<1.0) temperature is cooled by using the cooling air. The steam after having driven steam turbine goes along the condenser and changes it into water. Heat loss at the condenser is large, therefore it is preferable that the proportion of power generation of the gas turbine to the entire GT/ST system is increased. To raise the thermal efficiency further, we should develop heat-resistant materials for turbine blades and a new gas turbine system as a breakthrough in existing gas turbine technology.

Our former research group, Kobayashi et al. [1, 2] and Yamamoto et al. [3, 4], have proposed an innovative gas turbine/steam turbine combined cycle system called Chemical Gas turbine/steam Turbine combined cycle system (ChGT/ST) in Fig. 1. The proposed system consists of two stage gas turbines and steam turbine. This system has two combustors which produce high temperature required to drive two gas turbines. The first combustor is operated under a fuel-rich condition (equivalence ratio, φ>1.0) for control of combustion temperature before gas turbine inlet. The exhaust gas coming out from the first gas turbine driven contains hydrogen and carbon monoxide, which have chemical energies. The exhaust gas is led into the second combustor, and is completely combusted under a fuel-lean condition (Equivalence ratio, φ<1.0), followed by driving the second gas turbine. Heat waste of exhaust gas from the second turbine is used for steam generation, and the generated steam is used to drive the steam turbine.

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As we have described before, in the ChGT/ST, fuel-rich combustion is used. It is well known, however, the fuel-rich combustion fueled by methane has negative impacts [2-4]. Combustion in high equivalence ratio is unstable because stability of flame depends on flammability limit (0.5 < $\bar{\phi}_{CH_4} < 1.7$). Also the soot is easily produced in fuel-rich conditions. Therefore, we newly proposed fuel injection using DME as fuel instead of methane in order to overcome these negative impacts.

DME is considered a very interesting, multi-purpose clean energy carrier in the next future. Many properties of DME are very similar to those of propane, butane and their commercial mixture liquefied petroleum gases (LPG). In particular, the DME boiling point and vapor pressure are very close to those of LPG so that it can be easily liquefied under pressure as well as stored, handled and transported by means of the LPG devices. It is well known that DME combustion reduces generation of soot compared with methane combustion because its molecule (CH$_3$-O-CH$_3$) does not have C-C bond. And the fuel has wider flammability limit (0.5 < $\bar{\phi}_{DME}$ < 5.8) compared with methane.

A new technique using fuel injection in a fuel-rich condition has been proposed: Secondary fuel is injected into the combustion chamber with stable main flame formed by a main burner under a fuel-lean condition (closed to stoichiometric equivalence ratio). It seems that the followings are merits of this combustion method: (1) effective reforming reaction of the fuel, (2) a decrease of soot generation because of decreasing of locally high equivalence ratio area and (3) stable combustion because of stable flame formed at the main burner.

The objective of this study is to analyze the performance characteristics of ChGT/ST and to investigate the influence of the secondary fuel injection on fuel-rich combustion. First, the performance characteristics of ChGT/ST system were analyzed and this thermal efficiency was compared with the thermal efficiency of conventional GT/ST system. In the fuel-rich condition, to investigate the effects of secondary fuel injection on flow structure, flow structure was visualized by using the particle image velocimetry (PIV). And, the effects of injection point of secondary fuel from the top of the main burner nozzle, injection angle and equivalence ratio on the flammability characteristics for flame stabilization, were investigated experimentally.

### 2. PERFORMANCE ANALYSIS OF ChGT/ST SYSTEM

The performance analysis of ChGT/ST system was made by use of the process simulator “HYSYS” [5]. The temperature, pressure and gas concentration in each component were calculated taking into account the compositions and properties of the gases. The thermal efficiency of ChGT/ST was estimated based on them. The conditions of the system analysis are shown in Table 1. In this calculation, the steady-state operation was investigated. The pressure drops and heat losses in each component were neglected.

Figure 2 shows temperature and composition of the DME-air combustion exhaust gas at 20 in pressure ratio for each equivalence ratio. The maximum temperature was about 2300 deg. C at 1.0 in equivalence ratio. As the equivalence ratio was high, the combustion temperature was decreased. When the equivalence ratio was 2.5, combustion temperature was just 1500 deg. C. Therefore, in the range of 1.5 to 3.1 in the equivalence ratios, since first gas turbine TIT temperature was 1500 deg. C, the cooling agent was injected into the first combustor to turn

### Table 1 Calculation conditions for ChGT/ST system

<table>
<thead>
<tr>
<th></th>
<th>ChGT/ST</th>
<th>DME</th>
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</thead>
<tbody>
<tr>
<td>Fuel</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Higher heating value (HHV) [MJ/mol]</td>
<td>1451 MJ/mol</td>
<td></td>
</tr>
<tr>
<td>Inlet temperature of fuel and air [deg. C]</td>
<td>25 deg. C</td>
<td></td>
</tr>
<tr>
<td>Inlet pressure of fuel and air [atm]</td>
<td>1 atm</td>
<td></td>
</tr>
<tr>
<td>Adiabatic efficiency of compressor [%]</td>
<td>84 %</td>
<td></td>
</tr>
<tr>
<td>Adiabatic efficiency of gas and steam turbine [%]</td>
<td>90 %</td>
<td></td>
</tr>
<tr>
<td>Pressure ratio of gas turbine [-]</td>
<td>20</td>
<td></td>
</tr>
<tr>
<td>First turbine's inlet-temperature (TIT) [deg. C]</td>
<td>1500 deg. C</td>
<td></td>
</tr>
<tr>
<td>Second TIT [deg. C]</td>
<td>1500 deg. C</td>
<td></td>
</tr>
<tr>
<td>Adiabatic efficiency of pump [%]</td>
<td>90 %</td>
<td></td>
</tr>
<tr>
<td>Pressure ratio of steam turbine [-]</td>
<td>250</td>
<td></td>
</tr>
<tr>
<td>Steam turbine's inlet-temperature (TIT) [deg. C]</td>
<td>610 deg. C</td>
<td></td>
</tr>
<tr>
<td>Final exhaust gas temperature [deg. C]</td>
<td>200 deg. C</td>
<td></td>
</tr>
<tr>
<td>Pressure loss and heat losses in each component [%]</td>
<td>0 %</td>
<td></td>
</tr>
</tbody>
</table>
down combustion temperature. In contrast, in the range of 2.5 to 5.8 in the equivalence ratios, the used fuel and air were preheated by the heat waste of the exhaust gas from the first gas turbine to turn up combustion temperature.

DME-air combustion is anticipated to proceed, based on the following reaction formulae:

\[
\begin{align*}
\text{CH}_3\text{OCH}_3 + 3\text{O}_2 & \rightarrow 2\text{CO}_2 + 3\text{H}_2\text{O} \\
\text{CH}_3\text{OCH}_3 + \text{CO}_2 & \rightarrow 3\text{CO} + 3\text{H}_2 \\
\text{CH}_3\text{OCH}_3 + \text{H}_2\text{O} & \rightarrow 2\text{CO} + 4\text{H}_2
\end{align*}
\]

When the equivalence ratio was higher than 1.0, the concentrations of hydrogen and carbon monoxide were more increased as shown in Fig. 2. At equivalence ratio, \(\phi = 1.2\), the presence of DME was not confirmed.

Figure 3 shows the thermal efficiency of ChGT/ST system compared with conventional GT/ST combined cycle system fueled by DME. The broken line shows the maximum thermal efficiency of conventional GT/ST combined cycle system in Fig. 3. It was highest at 0.5 in equivalence ratio, and was 53.6% (in HHV-based). The thermal efficiency of ChGT/ST system was higher than conventional system when the equivalence ratio was higher than 2.1. The thermal efficiency at 3.1 in equivalence ratio was highest, and was 56.2%. The increase rate of thermal efficiency was about 2.5% at 3.1 in equivalence ratio. However the efficiency was decreased at higher value than 3.1 in equivalence ratio because combustion temperature could not be achieved 1500 deg. C for ITT of first gas turbine.

It would appear that the thermal efficiency of ChGT/ST system was improved by the following things: (1) cascade use of chemical potential, (2) the increase of the percentage of the gas turbine in the power generation compared with that of steam turbine and (3) the reduce of compressed-air power required to cool the exhaust gas from the first combustor.

The experiments were performed between 1.5 and 3.1 in the equivalence ratio from the current result.

3. EXPERIMENTAL
3.1. Combustor and burner

Figure 4 shows the schematic drawing of experimental combustor and burner. The combustor is 700 mm in the height and 95 mm in internal diameter. The tube is made of quartz to observe the flame structure from outside. The combustor consists of main burner, burner tile to stabilize the flame and two secondary fuel injection ports.

The diffusion burner is used as a main burner. The main burner has double-injector nozzle. Inner flow is the primary fuel, and outer flow is the air. The air injector is designed to provide swirl with 45 deg. In the main burner, the internal diameter of the primary fuel flow is 7 mm, while the outer diameter is 20 mm. The height of the burner tile is 45 mm.

The secondary fuel is injected from two injectors symmetrically equipped with the combustor. The diameter of secondary injectors is 4mm. The injection positions are 70 and 120 mm from the top of main burner nozzle, and the angles are 30, 45 and 60 deg.

The total fuel equivalence ratios are 1.5, 1.9, 2.3, 2.7 and 3.1, however the primary fuel equivalence ratio at the main burner is fixed at 0.8. The air flow rate is fixed at 30 L/min, and the secondary fuel flow is changed to adjust the total equivalent ratio. Table 2 summarizes the experi-
3.2. PIV analysis for flow structure

The flow pattern in the non-flame model combustor was examined. Therefore, we made a non-flame model of the combustor of acrylics cylinder and visualized the flow structure by using PIV. The experiments were performed at 70 mm in secondary fuel injection position from the top of main burner nozzle and 60 deg. in injection angle.

The principle of PIV is to determine the particle velocity by obtaining two sheets of the particle image illuminated by a pair of laser pulses with a very small interval of time. Figure 5 shows the conceptual drawing of the non-flame model experimental setup and the measured area in PIV. The experimental setup consists of a particle feeder, a main burner, an acrylic cylinder (internal diameter 95 mm and length 1000 mm) with two secondary injectors, a Nd-YAG double-pulse laser (TSI Incorporated), a synchronizer (TSI Model 610034) and a high-speed CCD camera (TSI Model 630046).

The particle feeder is an ultrasonic feeder, and silica particles (average particle diameter: 50 μm) are fed into the acrylic cylinder with only the outer flow carrier in Fig. 5. The total flow rates are the same as those shown in Table 2. The outer flow and secondary flow are the air flow, instead of the primary and secondary fuel.

The CCD camera has a resolution of 1024 pixels horizontally and 1024 pixels vertically. The maximum beam power of the Nd-YAG double-pulse laser is about 200 mJ. Its pulse separation is 0.05 pulse per second.

The Nd-YAG double-pulse laser is irradiated to the cylindrical lens to make laser sheet from the laser beam. The synchronizer makes the pulse interval of time ($Δt_{axial} = t_1 - t_0$) of the double pulse is about 200 μs ($Δt_{axial}$) for the axial velocity measurement. A pair of illuminated particle images for the same single particle is taken by a high-speed CCD camera synchronized with the pulse. The $t_0$ is initial time and $t_1$ is the second pulse interval of time. The continual 30 pair-shots (60 images) of particle images are collected, and we analyze the date of the moving distance and direction at each pulse interval of time.

The configuration of the measured areas for axial velocity in the experimental setup is shown in Fig. 5. The image size of the axial direction is ±45 mm × 115 mm from the top of burner tile. Each vector and velocity magnitude is calculated by using the analyzing software (Tecplot) from the 30 pair-shots of particle image picture. The vector means the direction that the particles move. Vector length represented the velocity magnitude. The velocity magnitude is obtained by the following relations:

$$|V'_{axial}| = \frac{X(x, y)}{Δt_{axial}} = \sqrt{V_x^2 + V_y^2} \quad (4)$$

where $|V'_{axial}|$ is the x-y section velocity magnitude, $X$ is the moving distance, and $Δt_{axial}$ is the pulse interval of time for the axial measurement. And $V_x$ and $V_y$ are the velocity vector of the x-axis and y-axis, respectively.

The vorticity was studied for understanding mixing primary fuel, secondary fuel and air flow. The vorticity means the strength of the turbulence flow, and its value could be calculated by differentiation of the velocity vector of x- and y-axes. The vorticity ($ω_{axial}$) is defined as follows:

$$ω_{axial} = \left(\frac{∂V_y}{∂x} - \frac{∂V_x}{∂y}\right)/2 \quad (5)$$

3.3. Combustion experimental

Figure 6 shows a schematic drawing of experimental apparatus. Table 2 summarizes the experimental conditions.

The combustion gas species such as hydrogen, carbon monoxide and methane are sampled by probe which was inserted from top of the combustor. It has internal diameter of 1 mm, and is cooled by water. The combustion gases are analyzed by using a gas chromatograph with thermal conductivity detector (TCD).

To observe the soot generation directly, soot species were observed by using a CCD camera (SBIG, ST-6) with interference filter (central wavelength = 490nm, half-band width = 10) because of soot luminescence intensity at 490 nm. The observed size is 105 mm × 95 mm.
4. RESULTS AND DISCUSSION

4.1. Effect of secondary injection on the mixing of fuel

Figure 7 shows the axial vector and axial velocity magnitude obtained by the PIV measurement (a) at 0.8 in equivalence ratio (primary flow only), (b) at 3.1 in equivalence ratio with secondary flow from 70 mm in injection point and 60 deg. in injection angle, and (c) at 3.1 in equivalence ratio with primary flow only. In the vicinity of a burner tile, the strong flow rate was visualized in all the conditions of (a), (b) and (c), because the outer flow was swirling at 45 deg. In the range of 85 and 110 mm, the strong flow was visualized in Fig. 7 (b), due to secondary flow injection.

Figure 8 shows the axial distribution of vorticity for each condition of (a), (b) and (c). The positive vorticity is clockwise rotation and the negative one is counterclockwise. From the results of Fig. 8 (b), it was found that there were strong vorticities compared with those in Figs. 8 (a) and (c), especially in the height range of 85 and 110 mm.

When secondary flow was not injected into the combustor, the vector, velocity magnitude and vorticity are almost the same, independent of the value in the equivalence ratio (Figs. 7, 8 (a), (c)). Meanwhile, when the equivalence ratio was 3.1 (Figs. 7, 8 (b), (c)), there were sharp contrasts between (b) and (c). Since the swirling flow of 45 deg. from main burner dashed over the counterflowing flow of 60 deg. produced by the secondary flow, effective mixing between main burner flow and secondary fuel flow occurs. The effective mixing may promote the favorable reforming reactions, corresponding to reaction formulae (2) and (3), for the production of the exhaust gas having a concentration of combustible gas species such as hydrogen and carbon monoxide.

4.2 Effects of secondary fuel injection point and injection angle

Figure 9 shows the results of the concentration of combustible gas species in exhaust gas at 70 or 120 mm in injection position, 3.1 in equivalence ratio and 45 deg. in injection angle. The current results demonstrated that, as the injection point got close to the burner, the concentration of combustible gas became high.

Figure 10 shows the luminescence intensity of soot species at 70 or 120 mm in injection position, 1.9 in equivalence ratio and 45 deg. in injection angle. It was found that the luminescence intensity of soot species at 70 mm in injection position was higher than that at 120 mm, as in the case of concentration of combustible gas.

Figure 11 shows the results of concentration of combustion gas species in exhaust gas at 30, 45 or 60 deg. in injection angle, 3.1 in equivalence ratio and 70 mm in injection position. The concentration of combustion gas species was highest at 60 deg. in injection angle.

Figure 12 shows the luminescence intensity of soot species at 30, 45 or 60 deg. in injection angle, 1.9 in equivalence ratio and 120 mm in injection position. The results indicated that the luminescence intensity distribution hardly varied with the injection angle.
When secondary fuel injection position was lower and the angle was smaller, carbon dioxide and water which were generated at a main burner according to the reaction of formula (1) were effectively mixed with secondary fuel in the lower position of combustor near the top of a main burner. These results suggest that the effective mixing in the lower position of a combustor may be responsible for the effective reforming of carbon dioxide and water to carbon monoxide and hydrogen, respectively.

4.3 Effect of total equivalence ratio on flammability characteristics

So far, it was found that the optimum condition under which a largest amount of combustible gas were generated, were 70 mm in secondary injection point and 60 deg. in injection angle. Therefore, the effect of total equivalence ratio on concentration of combustible gas species was investigated at 70 mm in injection point and 60 deg. in injection angle.

Figure 13 shows the results of concentration of combustible gas species in exhaust gas for each total equivalence ratio in the range of 1.5 to 3.1. The results obtained by thermodynamic calculation are also shown in Fig. 13. It was found that the higher total equivalence ratio resulted in the higher concentration of combustible gas species in exhaust gas. This is due to the increase of the amount of fuel injected into a combustor with the total equivalence ratio.

As shown in Fig. 13, the production of methane at experimental data was detected. This is considered due to the following pyrolysis reaction formulae, beside reaction formulae (1), (2) and (3) in Chapter 2:

\[
\ce{CH_3OCH_3 \rightarrow CH_4 + H_2 + CO} \quad (6)
\]

\[
\ce{CH_3OCH_3 \rightarrow 3/2CH_4 + 1/2CO_2} \quad (7)
\]

Figure 14 shows the luminescence intensity of soot species for 1.5, 1.9 or 2.3 in total equivalence ratio at the injection point of 70 mm and angle of 45 deg. The results unfortunately demonstrated that the higher the total
equivalence ratio was, the higher the luminescence intensity of soot species also was.

Figure 15 shows the specific heating value of measured combustible gas for each equivalence ratio. The specific heating value estimated by the results of thermodynamic calculation in Fig. 13 is also shown in Fig. 15. The specific heating value was almost the same as that of calculation, indicating that the measured exhaust gas in respect of the specific heating value is acceptable as a fuel on driving the second gas turbine in ChGT system.

5. CONCLUSION

In this research, the performance characteristics of ChGT/ST system were analyzed and compared with those of GT/ST combined cycle system. The effects of secondary fuel injection on the flow pattern of mixing of fuel were visualized by PIV. And the effects of injection point, injection angle and equivalence ratio of secondary fuel in the fuel-rich condition on the combustible gas concentration in exhaust gas and soot production, were investigated experimentally. The main results were summarized as following:

1. The thermal efficiency of the ChGT/ST system was improved about 2.5 % compared with conventional GT/ST combined cycle system fueled by DME.
2. The mixing of fuel was enhanced by addition of secondary fuel flow.
3. The concentration of combustible gas species was highest at 70 mm in injection point, 60 deg. in injection angle and 3.1 in equivalence ratio.
4. Soot species concentration also was higher at lower injection point and higher equivalence ratio.

REFERENCES