Abstract

Recently, the interests for energy depletion and rapid climate change have emerged around the world. To address the problems, the research about clean coal technology has been conducted actively. The business, which gasification accounting for a large proportion of the technology, has been performed in USA, China, Korea, etc. Gasification technology can generate synthetic gas which is spotlighted as a next generation of fuel from solid coal through carbon capture and storage technique (CCS). However, the study is still not enough to investigate the combustion characteristics. For this reason, there are many researchers studying about fuel flexibilities and combustion characteristics of the synthesis gas. In this study, combustion experiment was performed to investigate the combustion characteristics for H2/CH4 SNG gas in the partially premixed model gas turbine combustor equipped 1/3 scaled down GE 7EA nozzle. Chemiluminescence measurements were performed to study the flame structure and characteristics of syngas combustion over various equivalence ratio. Abel inversion method was applied to obtain 2-D chemiluminescence flame images from 3-D accumulated chemiluminescence image.

NOx emission characteristics is similar at the same heat load because of the same Wobbe index based on higher heating values of the fuel compositions. Moreover, NOx increases with increasing equivalence ratio and heat load. This characteristics investigate that major NOx mechanism is thermal NOx. CO emission rapidly peaks near stoichiometric condition and it is affected OH radical in chemical reaction. Carbon dioxide is more effective to NOx reduction than nitrogen diluent because of its high diluent heat capacity. Combustion instability should avoid in order to prevent the combustor liner thermal and fatigue damage.

Nomenclature

SNG synthetic natural gas
WI Wobbe index
NOx nitrogen oxide
HHV higher heating value
LHV lower heating value
Eq equivalence ratio
ref reference fuel composition(CH4)
DR dilution ratio
TC thermo-couple
DP dynamic pressure sensor
OH* OH radical

Introduction

Power generation with gasification has been changed from using a fossil fuel combustion in order to meet the regulation of limited emission and improve the efficiency of the system. Gasification has advantage that reduce emission such as nitrogen oxide, sulfur oxide and carbon dioxide in exhaust gas. In addition, low-quality fossil fuel is changed into high value gaseous fuel and
these fuel increase the efficiency of the power system. The risk of fire, caused by scattered tiny dust when the coal is crushed, transported and storaged, is relatively smaller than gaseous fuel. Furthermore, the structure of conventional boiler furnace is larger than that of gas turbine. However, price is high because of the cost including gasification process and enough study of gas fuel combustion have not been carried out, still.

The first Korea Gwangyang SNG project was launched in 2010 by POSCO in Korea. The goal of this project is to generate SNG production 500,000 ton in year and 92MWe power generation in gas turbine system[1, 2].

In order to meet this trend of using substitute fuel, researches of gas turbine power generation using SNG, biogas, syngas, and other substitute gases have been performed steadily.

S. Dodo et al. investigated that NOx emission is allowed to be less 10 ppm in dry low NOx gas turbine combustor with hydrogen rich syngas fuels[3]. S. Park et al. studied that NOx emission and the combustion efficiencies of three kinds of SNG with different hydrogen content are almost identical at the same load. The flame length decreases by 3.2% and the flame angle based on the dump plane increases by 4.2% with respect to increase hydrogen content to 3% in volumetric ratio. In addition, pattern factor defines ratio of peak temperature and average temperature[4]. S. Goke et al. carried out flame structure characteristics, stability and NOx generation mechanism using reactor network on a rich-quench-lean and premixed combustor with steam dilution. High steam dilution ratio enable to lower risk of flashback for hydrogen-containing fuel. CO emissions are not significantly affected for moderate amount of steam dilution and remain low level[5].

K. Kim et al. studied that V-flame geometry is modified to an M geometry when the flame propagation speed increases in premixed gas turbine combustor. Furthermore natural gas flames with high hydrogen mole fractions can make more stable in terms of combustion dynamics. Flame transfer function (FTF) is defined thermoacoustic network modeling to predict self-induced combustion instability and represented as the normalized ratio of heat release and velocity fluctuations, as shown in equation (1)

$$FTF(f, A) = \frac{Q'(f)/Q}{V'(f)/V}$$

Where, $Q$ is about the heat release rate, $V$ is the mixture velocity in the mixing section, and $f$ is forcing frequency by pulsator such as siren and speaker[6].

Methanation is a chemical process in SNG gasification to make methane from a mixture gas of carbon monoxide and hydrogen or carbon dioxide and hydrogen. CO shift exchange carbon monoxide to carbon dioxide using water or hydrogen. Therefore, gasification process can make various gaseous fuels and use these fuels for different compositions[7].

Dilutions in combustion such as nitrogen, carbon dioxide, and steam are very effective in reducing the flame temperature and thermal NOx emissions[8]. As well as, these diluents are a byproduct from the gasification process, therefore it is easy to use in SNG power plant.

In this study, NOx and CO emission characteristics, and combustion instability are investigated for SNG compositions in increasing hydrogen ratio on gas turbine combustor using Abel-inversed OH
chemiluminescence images[9]. Nitrogen and carbon dioxide dilution experiments are conducted with increasing from 0% to 200% with respect to the amount of fuel in partially premixed gas turbine combustor.

**Experimental Apparatus and Method**

**A. Model gas turbine combustor**

For the purpose of this study, a model gas turbine combustor is designed, which consists of a swirl injector, an air heater, an optically accessible quartz section, an exhaust duct, and a variable-length plug nozzle, as shown in Fig. 1.

![Figure 1 Schematic of model gas turbine combustor and location of sensors](image)

An air heater can heat air up to about 500K and provide a combustor with the heated air through the injector. Fuel and air mixture is supplied through 14 annularly arranged swirl vane of which the angle is 45 degree, and the fuel injected in the swirl vane at about 3 mm upstream of the dump plane. The very short mixing length forms a partially premixed flame, however, strong swirl number enable the fuel-air mixing well. To take flame image and pass a laser beam, a 200mm quartz section is equipped in front of the combustor dump plane and prevent damage from flame concentration by cooling air. Several thermocouples and pressure sensors are used to control inlet air temperature, measure flame temperature and comprehend the combustion characteristics. Movable plug nozzle set in the combustor to simulate turbine blade block ratio and cooling water circulates in the plug nozzle to avoid thermal damage, because, the plug nozzle blocks about 90% of flow of the burned gas.

To measure emissions such as NOx, CO, unburned hydro carbon, and O2, the TESTO 350K gas analyzer is equipped at the end of the exhaust duct. NO and CO sensor resolution are 0.1 ppm and 1 ppm, respectively. These resolutions are adequate to analyze the emission characteristics.

**B. Test condition and image acquisition**

<table>
<thead>
<tr>
<th>Table 1 Combustor load test condition</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>unit</strong></td>
</tr>
<tr>
<td>H2 Vol%</td>
</tr>
<tr>
<td>CH4 Vol%</td>
</tr>
<tr>
<td>C3H8 Vol%</td>
</tr>
<tr>
<td>WI MJ/Nm³</td>
</tr>
<tr>
<td>Eq</td>
</tr>
<tr>
<td>Load kW</td>
</tr>
<tr>
<td>DR %</td>
</tr>
</tbody>
</table>

Table 1 is the test condition for this research. C1, C5, C10 and C15 listed in Table 1 have hydrogen fuel composition of 1%, 5%, 10% and 15% based on heating value, respectively. Wobbe index (WI) is the parameter comparing the combustion energy output of different composition fuel gases in an appliances. WI expresses higher heating value over square root specific gravity. Furthermore, propane gas is adjusted to maintain the WI of each test conditions.

Equivalence ratio varies from 0.5 to 1.0 in increments of 0.1 by shifting the air flow rate with a fixed fuel flow rate. The power load are 25.4, 38.1, 50.8 and 63.5kW, which is calculated using the lower heating values of the fuel composition and dilution ratio (DR) represented the ratio of the flow rate of diluent and sum of flow rate of the fuel, as shown in
Nitrogen and carbon dioxide are used as a diluent in this study and supplied into air feed line from 0% to 200%.

\[ DR_{N_2} = \frac{\text{flow rate of } N_2 \text{[slpm]}}{\text{sum of flow rate of fuel [slpm]}} \] (2)

A PI-MAX ICCD camera is used for flame visualization through the quartz section and an OH* band-pass filter is applied on the camera to investigate OH chemiluminescence distribution in the flame zone. Abel deconvolution method is also used to obtain two-dimensional information from line of sight overlapped images.

**Results and Discussion**

**A. Emission (NOx and CO) characteristics of SNG combustion without N2 and CO2 diluents**

NOx emission is increased with the equivalence ratio and heat input as shown in Fig. 2. These NOx emissions are effected flame temperature related in the equivalence ratio and heat load. However, there is no great difference NOx emission compared with the gap of hydrogen content in SNG compositions at the same heat load. This is the effect of the Wobbe index of the above mentioned experimental method. Fig. 3 is the averaged NOx emission each heat load. It shows that large NOx emissions generate on the high heat load condition, therefore diluents such as nitrogen and carbon dioxide need to lower flame temperature.

CO emission is different trend from the NOx emission. Fig. 4 is the CO emission characteristics each heat load with respect to the equivalence ratio. CO emissions maintain under 5 ppm@15%O2 up to stoichiometric condition and then increase at the stoichiometric condition steeply some cases. In methane-air chain reaction, the oxidation of CO is the final chemical reaction of hydrocarbon combustion. The CO–O2 oxidation is very slow by itself, however small quantities of steam or hydrogen can induce fast reaction by generating hydroxyl radical (OH).

\[ \text{CO + OH} \rightarrow \text{CO}_2 + \text{H}_2 \] (3)

The OH radical affects the CO oxidation directly. To investigate a reason of a lot of CO emission in some SNG compositions, maximum OH intensity of the flame images is compared as shown in Fig. 5. Dotted circles indicates the conditions.
where the CO increase steeply.

Figure 4 CO emission characteristics of SNG combustion without N\(_2\) and CO\(_2\) diluents with hydrogen compositions. (a) 25.4kW, (b) 38.1kW, (c) 50.8kW, (d) 63.5kW

CO emission decreases with increasing heat load because CO chemical reaction is occurred well at the high flame temperature and a lot of OH radical accelerate the CO oxidation. Maximum OH intensity decrease in the region where CO emission increase rapidly. The reduction of OH radical induces CO-O\(_2\) reaction suppression, which CO as the incomplete combustion by-product is emitted to the atmosphere as a state not converted to CO\(_2\). These trends are displayed in ref and Cl fuel composition, which hydrogen ratio is relatively small, that is consisted a high percentage methane relatively. Mixing near the injector does not occur efficiently in the high methane ratio in SNG composition for the heavy methane molecular weight relative to the hydrogen fuel. Poor mixing suppresses the uniform flame and OH generation. Thus, CO emission increases in accordance with these effects.

B. NOx reduction characteristics of SNG combustion with N\(_2\) and CO\(_2\) dilution

High flame temperature in combustion zone affects adverse effect on exhaust emissions. Dilution is the method to solve the problem. In this study, nitrogen and carbon dioxide are used to lower flame temperature supplying air line and investigate the combustion characteristics of SNG. NOx reduction is defined the difference between NOx emission without diluent and NOx emission with diluent in ppm 15% O\(_2\) shown by the following equation.

\[
\text{Diluent reduction [ppm 15% O\(_2\)] = (NOx without dilution) - (NOx with dilution)}
\]  

Figure 5 Maximum OH chemiluminescence intensity of SNG flame image without N\(_2\) and CO\(_2\) diluents with hydrogen compositions. (a) 25.4kW, (b) 38.1kW, (c) 50.8kW, (d) 63.5kW

Figure 6 NOx reduction with N\(_2\) and CO\(_2\) diluent

Fig. 6 is the NOx reduction with respect to diluent flow rate of nitrogen (circle) and carbon dioxide (blank) on each heat load. The solid line and dotted line are
the fitting line of NOx reduction each experimental condition.

NOx reduction increases logarithmically as diluent flow rate increase and the trend appears in high heat load definitely. It seems to show carbon dioxide is more effective to reduce NOx emission than nitrogen from Fig. 6. However, the NOx reduction in partially premixed gas turbine combustion is related to the diluent heat capacity rather than the kind of diluent gas. Diluent does not has any influence on the chemical reaction. The heat capacity is calculated on diluent mass flow rate and specific heat of the diluent as shown equation (5).

\[ \text{Dilution heat capacity [J/Ks]} = m_{\text{diluent}} \cdot C_p_{\text{diluent}} \] (5)

<table>
<thead>
<tr>
<th>Table 2 diluent specific heat on 500K</th>
</tr>
</thead>
<tbody>
<tr>
<td>@500K N2 CO2</td>
</tr>
<tr>
<td>Cp [kJ/kg K]</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Cp [kJ/mol K]</td>
</tr>
<tr>
<td></td>
</tr>
</tbody>
</table>

Table 2 is the specific heat of each diluent. High heat capacity of the diluents stores more heat at the same heat load and reduce flame temperature, as a result, NOx emission decrease. Fig. 7 shows the effect of diluent heat capacity and demonstrates that NOx reduction is the function of the diluent heat capacity and heat load. The heat capacity of carbon dioxide diluent is much larger than that of nitrogen at the same mass flow rate, because specific heat of carbon dioxide is large relatively. Therefore, Small amount of carbon dioxide has the similar effect as a large amount of nitrogen diluent.

C. Dump plane temperature and flame structure

Dump plane temperature is measured to investigate the effect on the combustion instability. Combustion instability is defined as higher than 5% fluctuation of static pressure in combustor. In this study, 0.15 psi is selected as the criteria of the combustion instability. Fig. 8 is the dump plane temperature with respect to the root mean square (RMS) amplitude of the pressure on combustion zone in 50.8kW without dilution. Dump temperature is formed below the 500 ºC in stable conditions, however the temperature increases in combustion instability because the flame vibrates back and forth and reach the dump plane.

Figure 7 NOx reduction with respect to the diluent heat capacity of N2 and CO2

Table 3 is Abel-inversed OH chemiluminescence images of 50.8kW without dilution. All of images show outer recirculation zone and the recirculation zone influence on the dump plane temperature as well. Flame length decreases with increasing hydrogen ratio of fuel
composition from ref to C15. In addition, OH intensity on equivalence ratio 1 is lower than equivalence ratio 0.9 as identified above Fig. 5. Although the flame length is shorter, the amount of heat released from the flame is relatively high due to the same heat load[11]. Therefore, OH intensity of high hydrogen content fuel composition is stronger relatively.

Table 3 Abel-inversed OH-chemiluminescence images in 63.5kW heat load without dilution

<table>
<thead>
<tr>
<th>E.q</th>
<th>ref</th>
<th>C1</th>
<th>C5</th>
<th>C10</th>
<th>C15</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.6</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.7</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.8</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.9</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Conclusion

combustion characteristics (NOx, CO and flame structure) is investigated on partially premixed SNG flame adjusting hydrogen ratio to make each fuel composition with same Wobbe index. Nitrogen and carbon dioxide are used as a diluent and supplied into air feed line from 0% to 200% based on amount of fuel mixture. From the results, we obtained the following conclusions.

1) Main NOx generation mechanism is thermal NOx according to the relation with equivalence ratio and heat. CO emission increases sharply at equivalence ratio 1 and OH-radical affects CO-oxidation directly.

2) NOx reduction is the function of the diluent heat capacity and heat load and dilution of carbon dioxide is more effective than nitrogen, because the heat capacity of carbon dioxide diluent is much larger than that of nitrogen at the same mass flow rate.

3) Flame fluctuation influence dump plane temperature in combustion instability. All of combustion compositions occur outer recirculation zone. Combustion instability should be avoid in order to prevent combustor liner damage.

Acknowledgments

This work was supported by National Research Foundation of Korea(NRF) grant funded by Korea government(MSIP) (No. 2015R1A2A2A010043) and the New & Renewable Energy Core Technology Program(201195101001C) of the KETEP grant funded by the MOTIE.

Reference


8. Minchul Lee, Seokbin Seo, Jisu Yoon, Minki Kim, Youngbin Yoon, Experimental Study on The Effect of N2, CO2, and Steam Dilution on The Combustion Performance of H2 and CO Synthetic Gas in an Industrial Gas Turbine, Fuel, 102 (2012), 431-438

