LOW NO_x COMBUSTION OF DME BY EXHAUST GAS RECIRCULATION

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ABSTRACT This study focuses on the fundamental characteristics of DME combustion aiming at the development of low-NO_x combustion technology with exhaust gas recirculation (EGR) under high pressure. DME has high potential of applicability of exhaust gas recirculation even at the high mixing ratio because of its high burning velocity and low ignition temperature. Prior to the high pressure combustion test, the combustion test under an atmospheric pressure was conducted with laboratory-scale 11.6kW combustor, where O₂ concentration and temperature at the combustor inlet was systematically regulated, so that the exhaust-gas recirculation at various mixing ratios was simulated. The maximum EGR ratio is 91% at the initial air ratio $\lambda=1.5$ with preheated diluted air at 700K. The NO_x emission reduced to 14ppm, which is about 13% of that at EGR=0%. The stable combustion sustains even at low oxygen concentration by preheating diluted-air. The exhaust gas recirculation is effective means especially for DME in reducing NO_x emission drastically.

Keywords: DME (Dimethyl Ether), EGR (Exhaust Gas Recirculation), Diffusion Combustion, Gas Turbine

1. Introduction

Increasing attention has been focused on new alternative fuel, DME (Dimethyl ether), from the energy security and the environmental aspects for gas turbine fuel for electric power generations. DME is a new synthetic fuel and the most simple ether compound, expressed by the chemical formula CH₃OCH₃. Recently, the direct synthesis process of DME from CO and H₂ are being reformed from the coal gasification [1]. Thus, DME can be produced from any kinds of carbon resources, such as natural gas, coal-bed methane associated in the coal mine.

The physical properties of DME are listed in Table 1 [2]. DME does not contain sulfur component and is quite suitable for diesel engine because of high cetane number and no emission of suspended particle matters. Adiabatic flame temperature is sufficiently high, but DME has rather low ignition temperature with high burning velocity compared with methane. The fact causes a difficulty in the use of use of the lean pre-mixed combustion system for low-NO_x combustion of DME. Thus the burner should be, in principle, diffusion-type. In order to develop combustion technology of DME for gas turbines, it is essential to introduce alternative concept for low NO_x combustion [3].

This study focuses on the fundamental characteristics of DME combustion aiming at development of low-NO_x combustion technology with exhaust gas recirculation, EGR. The concept of the external exhaust gas recirculation is illustrated in Fig.1. The recirculated exhaust gas is introduced into the combustion chamber to control the oxygen concentration and the combustion gas temperature, so that NO_x emission is significantly reduced. The exhaust gas recirculation at high mixing ratio, however, may lead to unstable combustion of conventional fuels, methane. On the other hand, DME has high potential of applicability of EGR even at the high mixing ratio because of its high burning velocity and low ignition temperature.

Table 1 Physical properties of DME

Property	DME	Propane	Methane
Chemical Formula	CH ₃ OCH ₃	C ₃ H ₈	CH ₄
Boiling point, K	248	231	112
Liquid density, g/cm ³	0.67	0.49	N.A.
Gas specific gravity relative to air	1.59	1.52	0.55
Saturated vapor pressure, atm at 298.15K	6.1	9.3	246
Ignition temperature, K	623	743	923
Cetane number	55-60	5	0
Net calorific value, MJ/m ³ _N	59.5	91.3	36
Net calorific value, MJ/kg	28.9	46.5	50.2
Adiabatic flame temperature, K	2227	2250	2236
Burning velocity, cm/s	50	43	37
Stoichiometric ratio, m ³ /m ³	14.3	23.8	9.52

Fig.1 Schematic view of external exhaust gas recirculation

In this study, the NO_x emission characteristic of DME combustion with EGR is investigated under the high pressure. On the first stage of this study, the combustion test under the atmospheric pressure is carried out with laboratory scale of 11.6kW combustor. In this experiment, oxygen concentration and temperature at the combustor inlet was systematically regulated, so that the exhaust gas recirculation at various mixing ratios was simulated. The blow off limits and the exhaust gas concentration were measured, and these results are compared with that of city gas 13A and LPG. Finally, NO_x reduction ratio of laboratory scale combustor and industrial-scale boilers is discussed.

2. Experimental apparatus

Figure 2 shows the experimental setup of 8kW combustor under the high pressure of 0.5MPa. The flow rate of the fuel gas supplied at the room temperature was measured by a volumetric flow meter. The purity of the DME gas is 99.9%. The city gas 13A consists of methane of 88.9%, ethane of 6.8%, propane of 3.1% and butane of 1.2% and its low heating values is 40.4MJ/m³_N. LPG consists of propane and propylene of 80%, butane of 20% and its low heating value is 99MJ/m³_N. To simulate the exhaust gas recirculation, the oxygen concentration and the temperature of combustion air were controlled by diluting with nitrogen gas preheated up with an electrical heater. Air and nitrogen flow rates were regulated by means of a mass flow meter, and were well-mixed in the gas mixer. The oxygen concentration of the combustion air was measured by O₂ meter.

Fig.2 Experimental setup for high pressure combustion test.

The combustor, shown in Fig.3, consists of the multi-port diffusion burner and the combustion chamber. The combustion chamber is a cylindrical chamber of 123mm in inner diameter and 400mm in height. At the bottom of chamber, the diffusion burner is installed. The inner walls of the chamber are covered with fireproof materials. All the metallic parts of the setup consist of SUS304. The pressure of the combustion chamber is controlled by a pressure control valve.

The multi-port diffusion burner was designed by the authors to achieve well-mixed condition of fuel gas, steady and strong re-circulation followed by stable combustion and small but uniformly distributed flames [4]. The fuel gas was issued from the center hole and the combustion air was from small multiple ports placed around the fuel port.

Fig.3 Combustion chamber and multi-port burner for the high pressure combustion test.

Fig.4 shows the combustion chamber for the atmospheric pressure. The combustion chamber has a cross-section of 100mm×90mm and 582mm in height. The combustion gases were sampled at 530mm from the burner exit by using a water-cooled sampling probe, and were analyzed with the gas analyzer (Horiba Corp. PG-235a). The CO, NO_x and O₂ concentrations were measured by infrared absorption, chemiluminescence, and zirconia oxygen sensor, respectively. The gas temperature was measured by R-type thermocouple at the same position as the gas sampling.

Fig.4 Combustion chamber for the atmospheric pressure.

3. Estimation of the EGR simulation model

Exhaust gas recirculation ratio, EGR ratio, is defined as follows;

$$\text{EGR ratio} = \frac{\text{Flow rate of recirculation exhaust gas } V_{EGR}}{\text{Air flow rate } V_{air}} \quad (1)$$

Equation (1) can be expressed as Eq.(2) by using the oxygen concentrations of the exhaust gas and the diluted air.

$$\text{EGR ratio} = \frac{21\% - \text{Diluted air } O_2 \%}{\text{Diluted air } O_2 \% - \text{Exhaust gas } O_2 \%} \quad (2)$$

The exhaust gas recirculation suppresses the NOx emission by increasing the flow rate of the combustion gas to be reduced the flame temperature. The EGR models are shown in Fig.5. The flow rate of the diluted air is sum of the V_{air} and V_{EGR} . On the actual EGR model, the flow rate of the diluted air becomes larger than that of the simulated EGR model at the same EGR ratio, due to the recirculated exhaust gas has several percent of oxygen concentration. Thus, the adiabatic flame temperature on the simulated EGR model has higher than that at the actual EGR model.

Figure 6 shows the adiabatic flame temperature to the EGR ratio at the various recirculation gas-temperature. The initial air ratio is $\lambda=1.5$. Adiabatic flame temperature decreases with increasing EGR ratio, while the adiabatic flame temperature increases by preheating diluted air, which is induced by increasing recirculation exhaust gas temperature. Because of difference of the flow rate of the combustion gas, the adiabatic flame temperature of EGR simulation is higher than that of actual EGR. This indicates that this experiment in this study simulates severe conditions for the NOx emission.

4. Result and discussion of combustion tests

Figure 7 shows the NOx and CO concentrations of the exhaust gas as a function of the air ratio λ without the exhaust gas recirculation. The air ratio λ is defined as the ratio of air volume relative to stoichiometric volume of air, i.e. the inverse of the equivalence ratio. The air ratio is approximately related to the O_2 concentration of the exhaust gas by $\lambda=21/(21-O_2[\%])$. The NOx emission decreases with increasing the air ratio on city gas 13A and DME combustion, while the CO concentration is sufficiently low. The NOx emission is around 100 ppm at the range of 1.2 to 1.6 of the air ratio in DME combustion, which is higher than that of the city gas and propane. The combustion tests with the simulated exhaust gas recirculation were carried out based on the air ratio 1.2 and 1.5.

Figure 8, 9 and 10 show the results of the city gas, DME and propane combustion tests with exhaust gas recirculation. Experiments were carried out by changing the flow rate of nitrogen gas, which corresponds to the exhaust gas recirculation ratio, EGR ratio. In this experiment, the EGR ratio is estimated from the measured O_2 concentrations of the exhaust gas and diluted combustion air, i.e., O_2 concentration of the combustion air.

Figure 8 shows the combustion test of the city gas at the air ratio $\lambda=1.5$. The NO_x concentration decreased successively with increasing the EGR ratio, while the flame blow-off occurred at 18% of EGR ratio when the inlet temperature of the combustion air was at 300K.

By imposing the exhaust gas recirculation, the low oxygen concentration causes the slow heat release in the combustion chamber. The flame temperature shows relatively mild temperature distribution and the local hot spot is avoided from the flame [5]. Thus, the exhaust gas recirculation is an effective method to reduce the NO_x emission. However, combustion with the low-oxygen concentration usually becomes unstable. By preheating the diluted air to 700K, the stable combustion can be achieved and the flame blow-off extended to at 50% of the EGR ratio, as shown in Fig.8. In the actual exhaust gas recirculation, the combustion air is preheated by mixing with the high temperature exhaust gas.

On the DME combustion at the air ratio $\lambda=1.5$, the blow off limitation is extended to higher EGR ratio than that of city gas, as shown in the Fig.9. The blow-off occurred at 47% of EGR ratio for 300K. By preheating the diluted air to 700K, the blow-off observed at 93% of EGR ratio. The NO_x concentration drastically reduced to 14ppm at 0%- O_2 for 90% of EGR ratio with 700K of the preheating diluted air. This indicates that DME has a high possibility of reducing NO_x emission by means of EGR. Such characteristic may be due to the high burning velocity and low auto-ignition temperature.

On the LPG combustion at the air ratio $\lambda=1.5$, the blow-off limitation is contracted to lower EGR ratio than that of DME, as shown in the Fig.10. The blow-off occurred at 33% of EGR ratio for 300K. By preheating the diluted air to 700K, the blow-off observed at 80% of EGR ratio. The NO_x concentration decreased as well as at city gas and DME with increasing the EGR ratio.

The blow-off limits of the flame at combustion rate of 8kW are plotted in the relationship between the O_2 concentration and inlet temperature of the diluted air in Fig.11. The stable combustion is realized in the left-side area of the blow-off limit expressed by solid lines. The blow-off limit is a function of the oxygen concentration of diluted air independent of the air ratio. By preheating the diluted air, the stable combustion range becomes wide. DME has a wider stable combustion range than that of the city gas and LPG. M. Katsuki et al propane blow-off limit expressed by dashed-dotted line [5]. Though it is not possible to compare directly with experimental result of this study by difference of such as burner, it is shown that the stable combustion is possible in extremely low oxygen concentration of 10% by preheating diluted air. The auto-ignition temperature of DME is 623K expressed by horizontal dash line, which is lower than that of methane 923K and propane 743K. Though diluted air is preheated

Fig.8 Effect of EGR on exhaust gas concentration for city gas 13A combustion, $\lambda=1.5$.

Fig.9 Effect of EGR on exhaust gas concentration for DME combustion, $\lambda=1.5$.

Fig.10 Effect of EGR on exhaust gas concentration for LPG combustion, $\lambda=1.5$.

Fig.11 Stable combustion range combustion rate of 8kW.
(Plots shows the blow off limit.)

over the auto-ignition temperature of DME, stable combustion range did not extended greatly.

Figure 12 shows the NO_x reduction ratio relative to the case without EGR. The plotted data includes all result of 11.6kW laboratory-scale combustion tests and industrial-scale boilers of 700 kW-class (1ton/hour steam output) and 7MW-class (10ton/hour steam output). These two boilers have been developed by Hirakawa Guidom Co. Ltd. in the framework of R&D project for DME used by METI [6], [7], [8]. The detailed description is found elsewhere [9]. Fundamental design of these boilers is based on the tube-nested combustion aiming at the effective low-NO_x combustion. The tube-nested combustor [10] consists of the water tube in its furnace to cool the burning flame directly in the field of burning reaction. Agitation of the burning flame with the installed water-tube-nest enhances combustion and brings about a uniform flame temperature distribution leading to further NO_x reduction. Further detailed description on the tube-nested combustor was described in the previous report [7]. In 11.6kW laboratory-scale combustion tests, DME is applicable even up to the high EGR ratio of 90%, and the NO_x emission reduced about 13% of that at 0% of EGR ratio. In addition, all the experimental data falls into a single curve. In industrial-scale boilers, on the other hand, the NO_x reduction ratio shows the similar trend in spite of the difference in the burning capacity. The NO_x emission drastically decreases with EGR ratio until about 50% of EGR, while decreasing moderately over 50% of EGR and the reduction is almost 10 % compared with the case of NO_x emission without EGR.

Above-mentioned results of experiment under the

Fig.12 NO_x reduction ratio on 11.6kW combustion test,
700kW and 7MW-class test boiler.

atmosphere pressure indicate that the exhaust gas recirculation is effective means especially for DME in reducing NO_x emission drastically. For the future, combustion tests under the high pressure will be conducted to investigate the NO_x emission characteristic of DME combustion with exhaust gas recirculation. The results will be presented at ICOPE-09.

5. Conclusions

This study focuses on the fundamental characteristics of DME combustion with exhaust gas recirculation. Combustion tests were conducted with laboratory-scale 11kW combustor under a atmospheric pressure as the preliminary test. The results are summarized as follows:

(1) EGR simulation experiment is carried out under the severe conditions for the NO_x emission than the actual EGR.

(2) The NO_x emission is lowered to 14ppm at high EGR ratio of 90%. Such a high EGR ratio corresponds to decreasing the O₂ concentration. This is mainly because of the high burning velocity and low ignition temperature of DME together with the enthalpy recirculation from the exhaust gas.

(3) In term of NO_x reduction ratio and EGR ratio, there exists a similarity law effective in the larger scale low NO_x combustor.

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