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Effect of Fuel Lean Reburning Process on NOx Reduction and CO Emission

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Abstract**—**Reburning is a useful technology in reducing nitric oxide through injection of a secondary hydrocarbon fuel. In this paper, an experimental study has been conducted to evaluate the effect of fuel lean reburning on NOx/CO reduction in LNG flame. Experiments were performed in flames stabilized by a co-flow swirl burner, which was mounted at the bottom of the furnace. Tests were conducted using LNG gas as the reburn fuel as well as the main fuel. The effects of reburn fuel fraction and injection manner of the reburn fuel were studied when the fuel lean reburning system was applied. The paper reports data on flue gas emissions and temperature distribution in the furnace for a wide range of experimental conditions. At steady state, temperature distribution and emission formation in the furnace have been measured and compared. This paper makes clear that in order to decrease both NOx and CO concentrations in the exhaust when the pulsated fuel lean reburning system was adapted, it is important that the control of some factors such as frequency and duty ratio. Also it shows the fuel lean reburning is also effective method to reduce NOx as much as reburning.

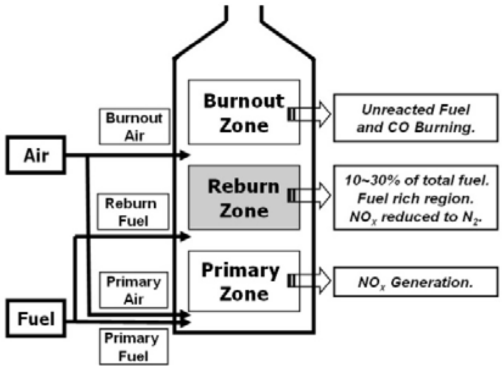
Keywords**—**Fuel lean reburn, NOx, CO, LNG flame.

I. Introduction

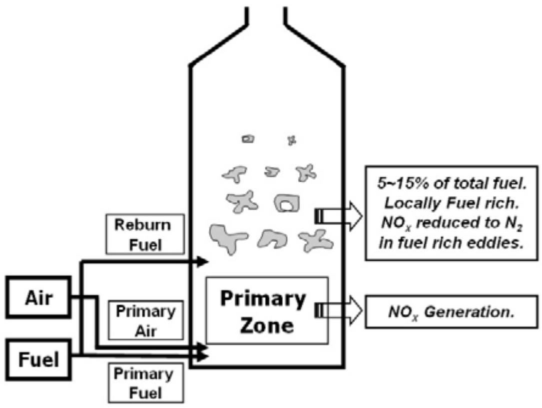
TOXIC gases, which are produced in a fossil fuel boiler and furnace, have been mainly responsible for the air pollution. Due to increasing concerns over environmental pollutants such as soot particulates, carbon monoxide, unburned hydrocarbon, nitrogen oxides and sulfur dioxide, a development of emission reduction methods has now become an imminent issue for practical application to numerous combustion devices. Especially, NOx (nitrogen oxides) among the gases is severely harmful to human health and is regarded as the cause of acid rain and photochemical smog.

Several technologies have been developed to reduce NOx emissions such as selective catalytic reduction (SCR), selective non-catalytic reduction (SNCR), steam injection, air/fuel staged combustion and reburning technology. Reburning is one of the most useful and economical technologies to reduce nitric oxide in combustion system. The reburning process was demonstrated as an effective NOx reduction method through injection of a secondary hydrocarbon fuel. The reburning process was demonstrated as an effective NOx reduction method which could achieve more than 50% reduction of NO. The overall reburning process occurs within three zones [1]. Among them, the primary zone is the main combustion zone in which most of the fuel is burned under normal fuel-lean conditions so that less NOx is generated with excess air. The reburn zone is the secondary reaction zone in which the reburn fuel (10~30% of the total fuel) is supplied to establish local fuel-rich conditions so that hydrocarbon radicals (CHi) are generated. These hydrocarbon radicals react with NOx in the reburn zone to form HCN and then N2. Afterwards, additional air is added to the burnout zone where the unreacted fuel is completely burned.

Nowadays, advanced reburning technologies such as hybrid reburning with SNCR or air staging and biomass reburning have been developed to adopt various commercial combustion systems [2-5]. Fuel lean reburning is one of the most effective methods to reduce NOx economically without using burnout air [6], however it is not easy to get high NOx reduction efficiency. Fig. 1 shows the difference between reburning and fuel lean reburning.



(a) Reburning system



(b) Fuel lean reburning system

Fig. 1 Schematics of reburning and fuel lean reburning systems

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In this paper, an advanced fuel lean reburning method which supplies reburn fuel with oscillatory motion is introduced to increase NOx reduction rate effectively. The forced oscillating injection of reburn fuel is realized by electronic solenoid valve, so that fuel rich region and fuel lean region is established alternately. In the fuel rich region, NOx is converted to N2 by reburning reaction, however unburned hydrocarbon and CO is oxidized in the fuel lean zone and the mixing zone at downstream where slightly fuel lean region is formed by mixing of two regions. The aim of the present work is to confirm the effect of oscillating reburn fuel injection on NOx reduction in reburning process.

II. Experimental Setup

A. Experimental Apparatus

A laboratory size experimental furnace with a burner was designed and fabricated. The furnace was vertically oriented, while the burner was installed at the bottom of furnace so that the flame was established in an upward direction. Experimental gases such as LNG and air were controlled and provided through separate mass flow controllers. The overall experimental setup shows in Fig. 2.

Furnace

A cylindrical type of furnace had been used for experiment. Its inner diameter is 0.45m and height is 1.35m. On the sidewall of the furnace, nine ports were made to measure gas temperature inside the furnace. Reburn fuel is designed to be injected from the nozzles installed at 5 locations along the axial direction. The refractory materials were used for insulation inside furnace.

Burner

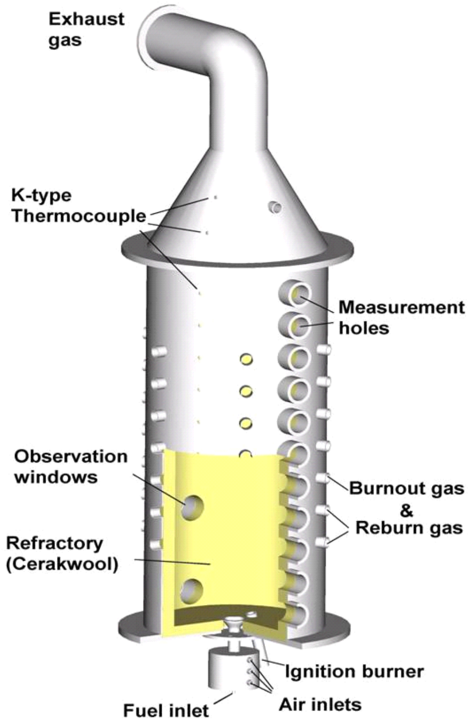
A coaxial type burner was used to make an LNG diffusion flame. The thermal capacity of burner is 40kW. The burner is connected to a chamber for the oxidizer to be supplied homogeneously into the furnace. An igniter is located beside the burner, which makes it possible to light a flame without opening and closing the lower portion of the furnace. At the tip of the burner, there is a swirler to generate a stable flame. It is radial flow guide vane type swirler with vane angle of 45 degrees. Following (1) has been used to compute the swirl number [7]:

$$S = \frac{2}{3}\left[\frac{1-(d_h/d)^3}{1-(d_h/d)^2}\right]\tan\theta \qquad (1)$$

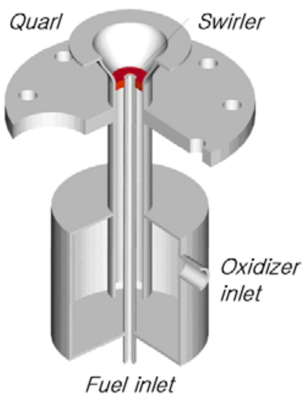
where d is inner diameter of the swirler, d_h is hub diameter of the swirler and is vane angle of the swirler.

Nozzle

Commercial nozzles were used to supply reburning fuel, burnout air and ammonia. Those are flat type injection nozzle with injecting angle of 95 degrees.

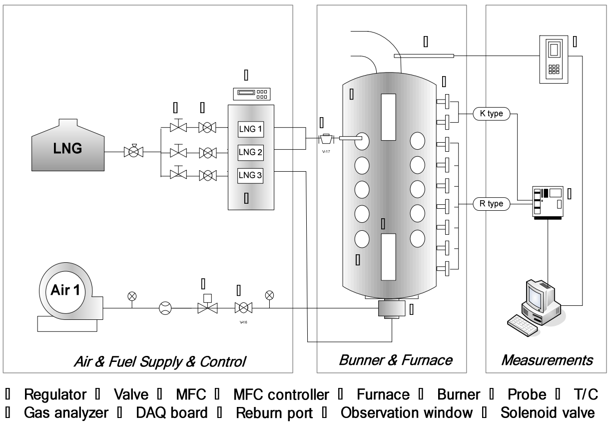


(a) Furnace



(b) Burner

(c) Nozzle



(d) System schematics

Fig. 2 Experimental setup

B. Measurement Equipment

Temperature Sensor

To measure the temperature, two types of thermocouple were used. K-type thermocouple was used to measure the surface temperature and low gas temperature in the furnace. Exposed R-type thermocouple was used to measure high gas temperature distribution in the furnace and they were electrically coated for protecting them from oxidation in the flame zone.

Gas Analyzer

Environmental pollution gases, NO, NO_2 and CO, and O_2 were measured by electro chemical type gas analyzing system. Sample gases were analyzed after removal of H_2O.

III. Result and Discussion

A. Experimental Conditions

LNG was used by main fuel as well as reburn fuel. The property of LNG which is used in this experiment is shown in Table I. All experimental data were collected after the thermal condition inside furnace reached its steady state. K-type thermocouples were used to measure the temperature at furnace wall, until it did not change any more.

In this study, three test conditions were considered. Throughout the experiments, the equivalence ratio in each zone was kept constant.

Case 1 was an experiment to show the effect of fuel lean reburning on NOx reduction in various reburn fuel fraction. It was a fundamental experiment prior to major tests. The reburn fuel fraction (RFF) is defined as the thermal input ratio of reburn fuel to the total fuel, and it was varied from 0.05 to 0.15 in Case 1. Case 2 was tested for evaluating the effects of frequency on NOx or CO in constant reburn fuel fraction and duty ratio. Case 3 was tested when the duty ratio was varied. The duty ratio is the ratio of fuel injection time to a cycle time. The overall experimental conditions are listed in Table II.

TABLE I
Properties of LNG

Component (mol %)	CH_4	90.16
	C_2H_6	6.16
	C_3H_8	2.41
	i-C_4H_{10}	0.53
	n-C_4H_{10}	0.56
	i-C_5H_{10}	0.03
	n-C_5H_{12}	0.01
WI		13,300
Specific gravity		0.62
Heating value (kcal/Nm^3)		10,500

TABLE II
Experimental Conditions

Case		1	2	3
Thermal input (kw)	Primary fuel	40	40	40
	Reburn fuel	2~7.5	4	4
Frequency (Hz)		-	0.25~5	1
Duty ratio		-	0.5	0.2~0.8
Equivalence ratio (Ω) of exhaust gas		0.95	0.95	0.95
Reburn fuel fraction		0.05~0.15	0.09	0.09

B. Effects of Reburn Fuel Fraction

Fig. 3 shows the temperature distribution along the centerline when the reburn fuel fraction 0.1. It shows a typical temperature distribution of diffusion flame. The maximum temperature is about 1380^{o}C and the overall temperature distribution is high enough to induce the reburning reaction. There is no temperature disturbance because the fuel lean reburning system without overfire was adopted throughout the experiments.

Fig. 4 shows the effect of reburn fuel fraction on NOx reduction in the fuel lean reburning system. Likewise other reburning system, the NO reduction reactions occur under partial fuel rich condition as following mechanisms (2)~(6):

$$C, CH, CH_2 + NO \rightarrow HCN + \ldots \quad (2)$$
$$HCN + O \rightarrow NCO + H \quad (3)$$
$$NCO + H \rightarrow NH + CO \quad (4)$$
$$NH + H \rightarrow N + H_2 \quad (5)$$
$$N + NO \rightarrow N_2 + O \quad (6)$$

As shown in (2), the partial oxidation and pyrolysis of the hydrocarbon reburn fuel results in the formation of CHi radicals that react with NO, generating HCN. This HCN is converted to N_2 through the reaction sequence of (3)~(6). Since the formation of HCN relies strongly on the concentration of hydrocarbon species, more injection of LNG as reburn fuel would reduce NOx formation. However, due to its reaction constraint limited by mixing, the effects of reburning on NOx reach a limitation. Another reason is that hydrocarbon radicals react with oxygen. This reaction and (3) competitively consume CHi.

However its NOx reduction rate isn't so high in Fig. 4, because it is hard to establish complete fuel rich region unlike other reburning systems.

The CO emission was checked in this test. When the reburn fuel fraction was under 0.1, the CO emission was almost zero. However, the CO emission increased up to 20ppm when the reburn fuel fraction was 0.15. Although it wasn't a serious level, lower reburn fuel fraction value was selected in major tests because it has a possibility to affect NOx level.

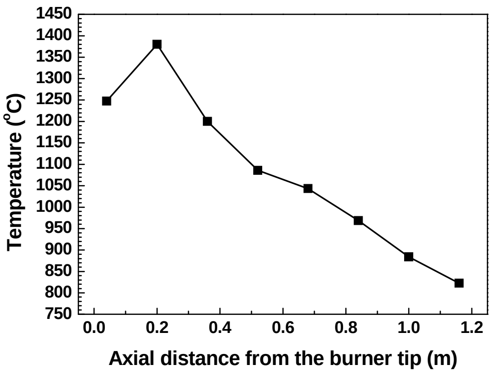


Fig. 3 Temperature distribution along the centerline

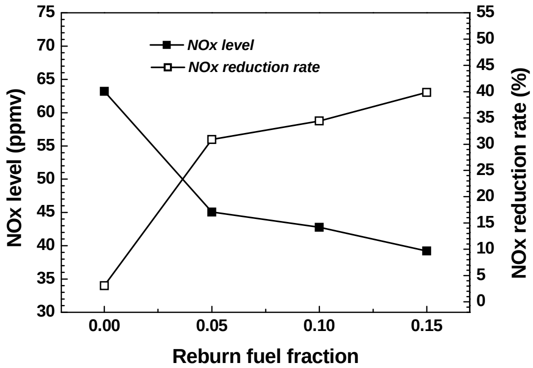


Fig. 4 Effect of RFF on NOx (Case 1)

C. Effects of Reburn Fuel Injection Frequency

In case 2, oscillating injection of reburn fuel is tested. The frequency is varied from 0.25Hz to 5Hz.

Fig. 5 shows the ideal cycles of oscillating reburn fuel injection. However, there are uncertainties in the real cycles such as time delay of valve opening and closing. Then the straight line in graph might be distorted and changed to the curve line. As shown in Fig. 5, the amplitude, amount of reburn fuel in here, is kept constant to keep the reburn fuel fraction. The valve open and closed times are same in this experiment, because duty ratio is kept 0.5.

Fig. 6 shows the effect of reburn fuel injection frequency on NOx reduction. When the frequency is 4Hz, the NOx reduction rate becomes maximized. It shows 41% NOx reduction while the NOx reduction rate of fuel lean reburning (FLR) method is 34%. When the frequency becomes higher, it becomes similar condition with fuel lean reburning. On the other hand, when the frequency becomes lower, the NOx reduction rate is stagnated because it takes effect to flame region and mixing state in reburn fuel with NOx. Although there are many additional experiments are needed to clear the reason and optimal condition in other combustion conditions, this result has a meaning to improve the NOx reduction efficiency in very simple way. The effect of oscillating reburning on NOx reduction is demonstrated in this test; however, the optimal frequency value should be changed according to geometry of furnace, inner gas flow and residence time in other systems. To find the relations between the optimal frequency and mentioned conditions, additional tests should be performed.

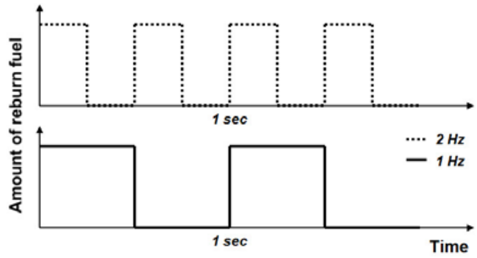


Fig. 5 Comparison of ideal reburn fuel supplying cycle according to frequency

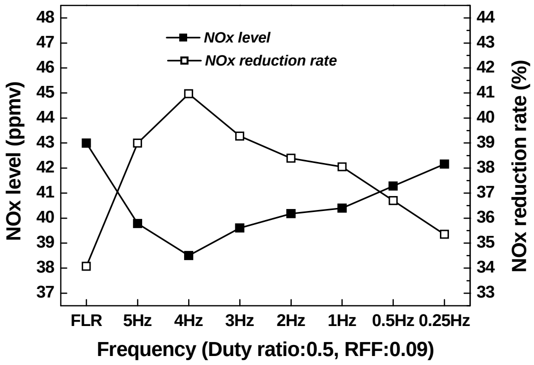


Fig. 6 Effect of frequency on NOx (Case 2)

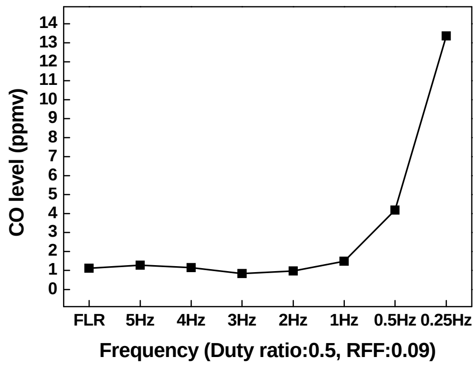


Fig. 7 Effect of frequency on CO (Case 2)

Fig. 7 shows the CO emission level of oscillating reburning system. The CO emission is very low when the frequency is 1Hz or more, while it becomes higher in small frequency such as 0.5Hz and 0.25Hz. This phenomenon might result from an imperfect mixing of two regions, fuel lean region and fuel rich region. When the frequency becomes smaller, the one cycle time becomes longer, and it means that the cycle repeat number becomes too small to mixing completely at downstream.

D.Effects of Duty Ratio

Fig. 8 shows the cycles in two duty ratio. The change of duty ratio condition is affect to the amplitude. When the duty ratio become smaller, the amplitude become bigger, because same amount of fuel should be supplied in a shorter valve open time.

Fig. 9 is a result of case 3 experiment. It shows the effect of duty ratio on NOx reduction in a constant frequency condition. When the duty ratio is 1, it is the fuel lean reburning system without oscillating. The NOx reduction rate is about 38% when the duty ratio was 0.5 or 0.33, and promoted 4% of NOx reduction efficiency. However it tends to show similar trend with non-oscillating system when the duty ratio becomes higher.

Fig. 10 shows the effect of duty ratio on CO emission. On the whole duty ratio, the CO emissions aren't high. However, the smaller duty ratio induces the higher CO emission. It means that the supplying of large amount of reburn fuel in a short time is unfavorable to the CO emission in an oscillating reburing.

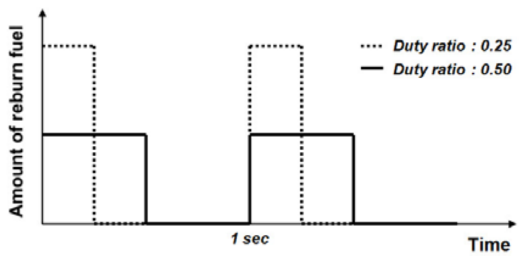


Fig. 8 Comparison of ideal reburn fuel supplying cycle according to duty ratio

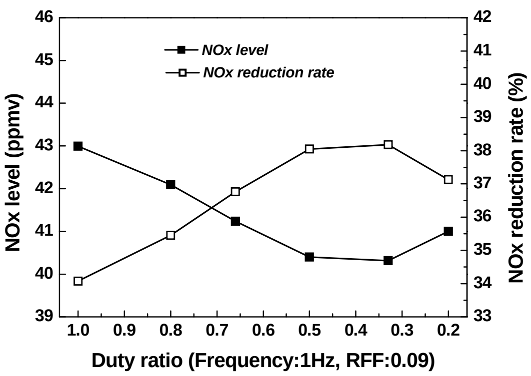


Fig. 9 Effect of duty ratio on NOx (Case 3)

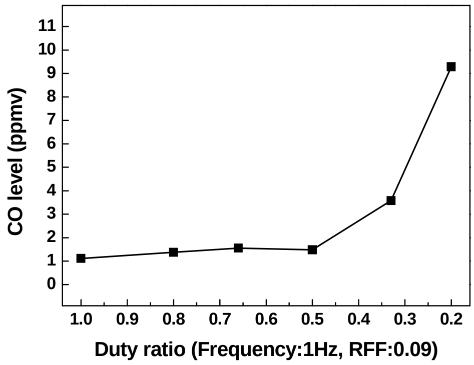


Fig. 10 Effect of duty ratio on CO (Case 3)

IV. CONCLUSION

In this paper, an experimental study is performed to examine the effect of oscillating reburn fuel injection on NOx reduction and CO emission. The major findings are as follows.

A. The oscillating injection of reburn fuel can be more effective methods in the fuel lean reburning system. In this experimental system, the maximum NOx reduction rate in oscillating injection is 41% compared to 34% in non-oscillating method.

B. The optimal frequency value in the oscillating reburning needs to be further investigated. The optimum frequency in this experiment was 4Hz.

C. To maximize NOx reduction rate in an oscillating reburning system, optimal duty ratio needs to be found. The NOx reduction rate becomes lower in high duty ratio, and the CO emission increases in low duty ratio.

ACKNOWLEDGMENT

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