An Experimental Study on Industrial Boiler Burners Applied Low NO_x Combustion Technologies

Changyeop Lee, Sewon Kim, and Minjun Kwon

***Abstract*—Based on flue gas inner recirculation technology, a low NO_x gas burner was developed and tested in a real scale industrial boiler. Some parts of combustion gases were recirculated in the combustion chamber and mixed with combustion air in the burner by its structural characteristics. And a noble low NO_x combustion technology, based on partial oxidation combustion concept in a fuel rich combustion zone, was successfully applied in liquid burner. The burner was designed such that a portion of fuel is heated and pre-vaporized in the furnace then injected into a fuel rich combustion zone so that a partial oxidation reaction occurs. The effects of equivalence ratio, thermal load, and fuel distribution ratio on the emissions of NO_x and CO were experimentally investigated. This newly developed combustion technologies showed very low NO_x emission level, about 12 ppm when light oil was used as a fuel and about 18ppm when LNG was used as a fuel.**

***Index Terms*—Burner, low NO_x, liquid fuel, gas fuel, fuel induced recirculation, partial oxidation.**

I. Introduction

In combustion processes, various kinds of hydrocarbon liquid fuels such as light oil and heavy oil are used. Regarding liquid fuel combustion, due to increasing concerns over environmental pollutants such as carbon monoxide, unburned hydrocarbon and nitrogen oxides, development of low pollutant emission methods has become an imminent issue for practical application to numerous combustion devices. Nitrogen oxides (NO_x) are known to be the most hazardous pollutants which are recognized as acid rain precursors that impose a significant threat to the environment. Therefore, their control is a major issue.

In most conventional liquid fuel burners, thermal NO_x is reduced by decreasing a peak flame temperature using steam injection method or air/fuel staged combustion. However, the formation of fuel NO_x in flame due to the nitrogen components in fuel is significant, and controlling fuel NO_x is very difficult. Further, in conventional multi-staged burners, it is very difficult to divide the reaction region into fuel rich region and fuel lean region completely, making it difficult to prevent the formation of thermal NO_x and fuel NO_x. Therefore, the alternative combustion technologies with new concept of NO_x reduction are needed to reduce NO_x remarkably, and multi-staged burner adapting partial oxidation technique of liquid fuel can be one of the methods to solve these problems.

Multi-staged combustion was demonstrated as a practical NO_x reduction method in the late 1970s [1]. In the 1981, Takagi and Okamoto explained the effect of swirl intensity and air ratio on thermal NO_x [2]. Additional studies have been done to evaluate the effects of air/fuel staged combustion technology on suppression of NO_x for various combustion cases [3], [4]. And a great deal of efforts has been exercised to examine it by changing its aerodynamic characteristics, swirl number or flow velocity [5].

Flue gas recirculation (FGR) is a well-known technology to reduce NO_x in combustion facilities [6]. It shows significant effect on NO_x reduction, however it has a problem of high installation expense. Nowadays, flue gas inner recirculation which is a method to recirculate the flue gas inside of combustion chamber using burner has been developed in various ways [7].

Partial oxidation reaction methods have been extensively applied for thermal cracking of liquid fuels in oil refinery industry. It is well known that the main factors that affect the partial oxidization reaction are reaction temperature and oxidant/fuel ratio. In the 2001, Ranzi *et al*. arranged the procedures in detail kinetic modeling of gasification, pyrolysis, partial oxidation and combustion of hydrocarbon mixture [8]. After two years, researches on cool flame partial oxidation and its role in combustion had been reviewed by Naidja *et al*. [9].

In this study, two low NO_x burners using gas fuel and oil fuel were tested respectively. The aim of the present work is to show the design concept of ultra low NO_x burner using noble techniques for optimal NO_x reduction

II. Experimental Setup

A. Burners

A real scale gas burner of 15MW thermal capacity was developed and tested in water tube boiler. In the burner, several low NO_x combustion technologies were applied such as axial staged combustion, air/fuel staged combustion and partial premixing air and fuel. The most important method applied to the burner was flue gas inner recirculation technique. Flue gases in the combustion chamber were recirculated automatically to an air supply line of the burner by aerodynamic burner structure. Then the flame temperature became lower so that thermal NO_x can be reduced. The schematic diagram of the gas burner is shown in Fig. 1.

And a low NO_x fuel oil burner of 500kW thermal capacity was designed so that both fuel and air are staged

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independently with secondary fuel injection causing partial oxidation reaction. The primary fuel is sprayed at the center through multi-hole nozzle, and the staged air is supplied to swirled primary air around the center nozzle and non-swirled secondary air is supplied at the annulus which is situated outside the primary airport. The primary air, around 60% ~ 80% of total air, is supplied through swirler, while the secondary air, 20% ~ 40% of total air, is injected in axial direction without swirling. Additional secondary fuel, which is about 20% ~ 30% of total fuel, is preheated in fuel line installed inside the burner quarl and injected at several circumferential spud nozzles. In this experiment, 6 spud nozzles were used. The schematic diagram of the burner tested in this study is shown in Fig. 2.

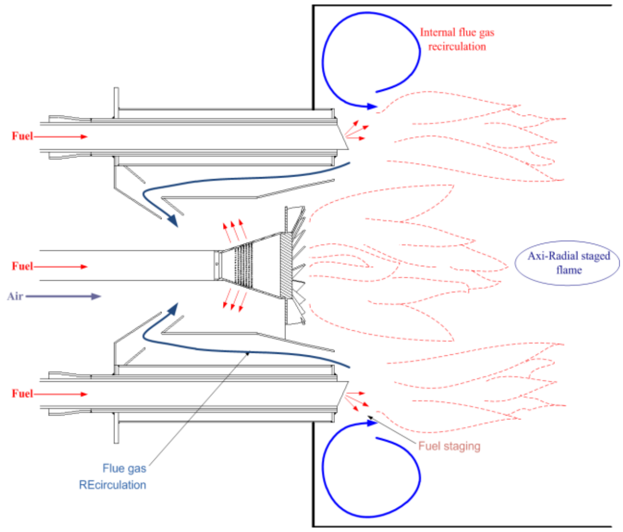

Fig. 1. Schematic diagram of low NO_x gas fuel burner.

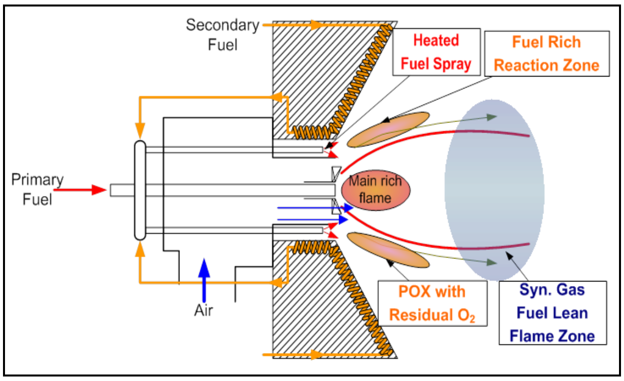

Fig. 2. Schematic diagram of low NO_x liquid fuel burner.

B. Boiler and Furnace

An industrial water tube bolier producing steam 20ton/hr was used in the gas burner demonstration. The volumetric heat release of the combustion chamber inside the boiler is about 2,100 kW/m^3. 4 thermocouples were installed on the upside of the combustion chamber so that radial temperatures were measured in detail at each axial point. A observation window was installed at the back of the combustion chamber.

And a horizontal cylindrical type furnace was used for liquid burner experiment. The volumetric heat release rate of this combustion chamber is 1,000 kW/m^3. On the sidewall of the furnace, temperature measuring probes were installed axially to measure the temperature profile of the flame. The water jacket was installed outside the furnace to control the furnace wall temperature, and a window was installed to observe the flame. The pictures of experimental boiler and furnace are shown in Fig. 3 and Fig. 4, respectively.

C. Gas Analyzer

The exhaust gases were measured using electro-chemical type gas analyzer with heated sampling probe and water trap, and the concentrations of CO, CO_2, NO, NO_2 and O_2 were recorded throughout the experiments.

Fig. 3. Experimental setup for gas burner demonstration.

Fig. 4. Experimental setup for liquid burner performance test

III. Result and Discussion

A. Gas Fuel Burner

For this study, natural gas was used. It was a final demonstration test of prototype burner, so it is focused on low NO_x characteristic by flue gas inner recirculation (FIR).

Fig. 5 shows the temperature distribution when FIR was not applied in the burner, however Fig. 6 showed the temperature distribution when FIR was applied. Except the FIR structure, other conditions were same. As shown in figures, whole temperature distribution in combustion chamber when the FIR was applied to the burner was lower than another case which FIR was not applied to the burner. And especially, peak temperature was lower about 100 degree. It is importation phenomena in gas fuel burner. When the gas fuel is used for combustion, thermal NO_x mechanism become major NO_x

formation process. As thermal NO_x increases rapidly over 1200°C, to lower the peak temperature of flame can be a major cause reducing NO_x.

Fig. 7 shows a NO_x level in flue gas. NO_x level is very low in overall thermal load region. NO_x reduction rate was about 40% compare with non-FIR condtion.

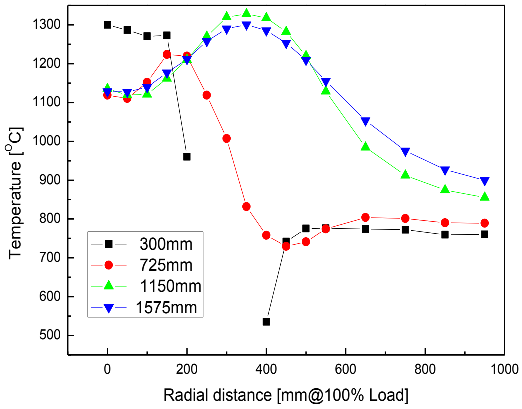

Fig. 5. Temperature distribution in combustion chamber (non-FIR).

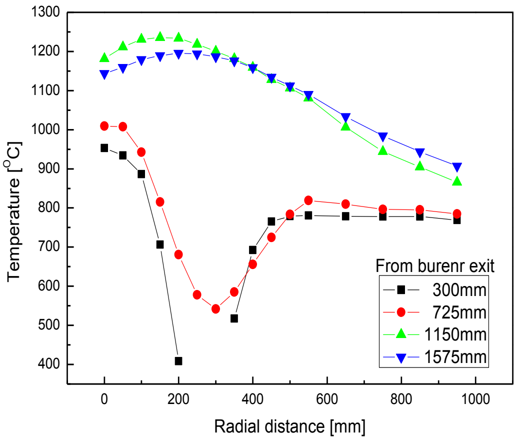

Fig. 6. Temperature distribution in combustion chamber (FIR).

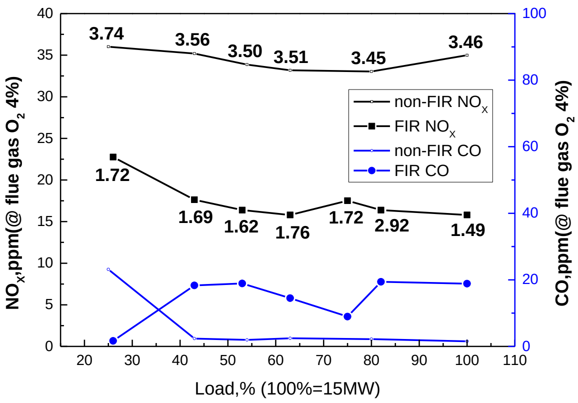

Fig. 7. NO_x and CO level in various thermal heat load.

B. Liquid Fuel Burner

For this study, diesel oil with 0.02 wt % nitrogen was used. Experiments were carried out for wide ranges of air/fuel ratios at various heat input conditions.

The primary fuel and air are operated at fuel rich condition in the primary reaction zone to lower fuel NO_x formation and also to promote the NO_x reduction reaction, while the secondary swirled air is supplied at fuel lean condition. The secondary fuel is preheated through fuel line installed inside the quarl. The injected preheated fuel is instantaneously vaporized in the combustion chamber, and then it reacts with the remaining oxygen in the combustion gas, causing partial oxidation reaction in extremely fuel rich condition.

Fig. 8 shows the reaction pathways of hydrocarbon fuels. As shown in the figure, hydrogen cyanide (HCN) is converted to nitrogen through several reduction reaction sequences in fuel rich condition. On the other hand, HCN is easily converted to NO through other oxidation reaction pathways in fuel lean zone with O, OH radicals present in the reaction regime. That's why fuel rich condition should be kept in the primary zone and partial oxidation reaction zone to accomplish low NO_x combustion, as shown in Fig. 9.

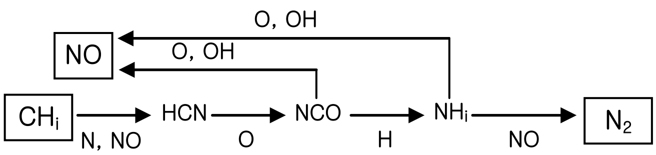

Fig. 8. Reaction pathways of hydrocarbon fuel.

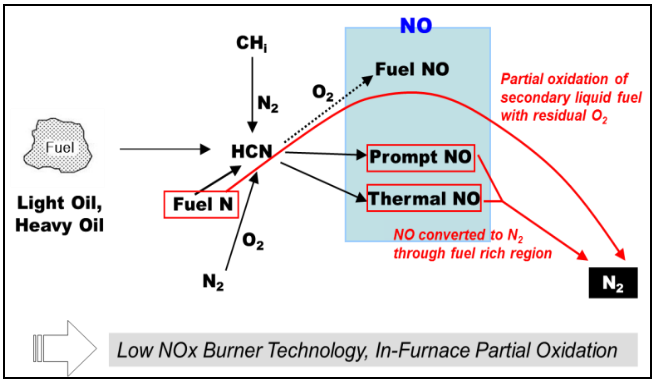

Fig. 9. Formation and reduction of NO.

The formation of fuel NO_x attributable to the oxidation of nitrogen components can also be suppressed by partial oxidation as shown in equation (1). Nitrogen element in liquid fuel is converted to nitrogen gas molecule through gasification reaction in reduction condition. Thus nitrogen compounds become more stable and large amount of fuel NO_x formation is restrained.

$$C_xH_yN_z + O_2 \rightarrow CO + H_2 + N_2 \qquad (1)$$

At downstream of flame, the fuel lean flame zone is established to complete the combustion.

The detailed flame temperature profiles and pollutant emission characteristics were measured at various burner operating conditions. That is, the effects of equivalence ratio, thermal load, injection distance, and fuel distribution ratio of burner are experimentally investigated. As both the fuel and air are staged, especially fuel oil is individually sprayed by main and spud nozzles, the distinct staged flame structure is observed when an appropriate injection pressure, in which a main fuel rich flame and secondary fuel rich flame is established in near burner outlet, then fuel lean flame zone is formed in downstream of main reaction zone.

Fig. 10 shows the effect of fuel distribution ratio on NO_x emission level. Fuel distribution ratio, QR is defined as the percentage of fuel injected to the secondary fuel nozzle over total amount of fuel. As shown in the graph, NO_x levels decrease as the fuel distribution ration increases, but NO_x remains constant as fuel distribution ratio increase over 30%. It is believed that the partial oxidation reaction at the secondary injection nozzle saturates at 30% and excess fuels reacts with secondary air in oxidation condition.

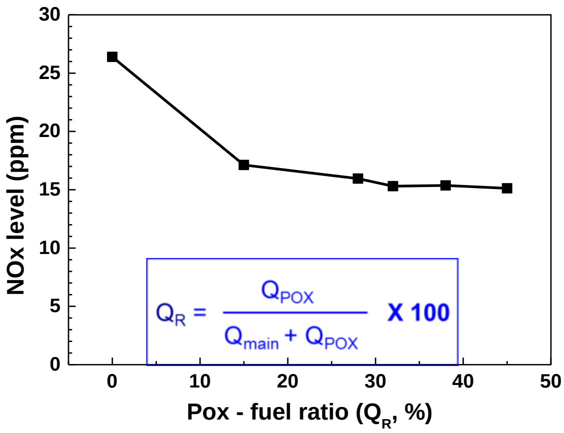

Fig. 10. NO_x level on QR (Equivalence ratio: 0.82).

Fig. 11 shows the flame temperature profiles in the furnace. As shown in the data, the peak temperature region was situated around center of the flame, which is around 1200°C. And the flame temperature was relatively low in the entire region of the flame. That means thermal NO_x formation was fully suppressed in this combustion condition.

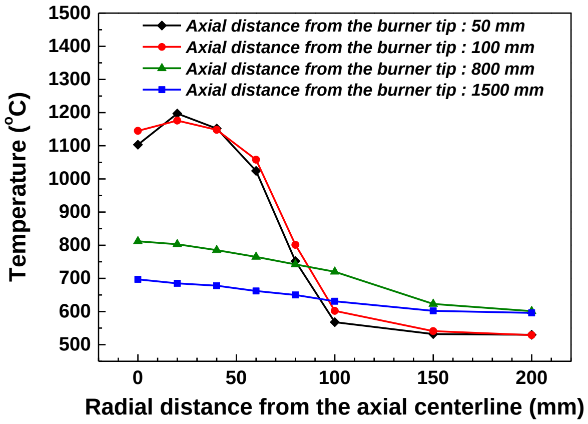

Fig. 11. Temperature distribution along the radial direction.

Fig. 12 shows the effect of equivalence ratio and thermal heat input on NO_x emission level. As shown in graph, this new type of burner has two major advantages in NO_x reduction over other conventional burners. Firstly, as the fuel rich and lean zones were obviously separated, the thermal hot spots were almost diminished so that the formation of thermal NO_x was restrained. Secondly, vaporization of secondary fuel droplets by heat transfer from primary reaction zone and partial oxidation with residual O_2 around the main flame, resulted in formation of extremely rich reaction zone of secondary fuel, thus NO_x reduction and prevention of the formation of fuel NO_x condition were provided. Consequently, in this experiment, the NO_x concentration showed minimum of 12 ppmv at full load, as shown in Fig. 12.

Fig. 13 shows the effect of equivalence ratio and thermal heat input on CO emission level. It shows the different characteristics as thermal input changes. When thermal input was low (350,000 kcal/hr), CO emission characteristic was contrary to other cases, that is, CO concentration increased with the increase of air/fuel ratio. It was believed that at low thermal input conditions, fuel and air mixing behavior was relatively low, so that a partial incomplete combustion phenomenon was occurred. However, in all experimental conditions, CO levels were lower than 50 ppmv which was still quite low compared to conventional liquid burners.

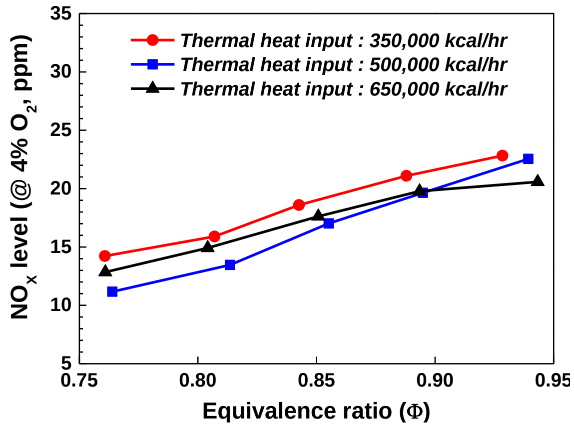

Fig. 12. NO_x emission characteristics.

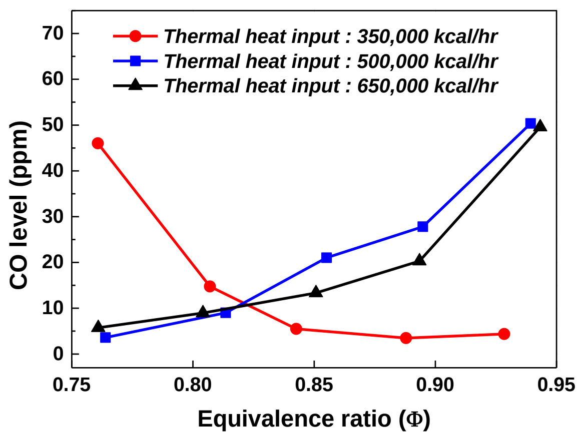

Fig. 13. CO emission characteristics.

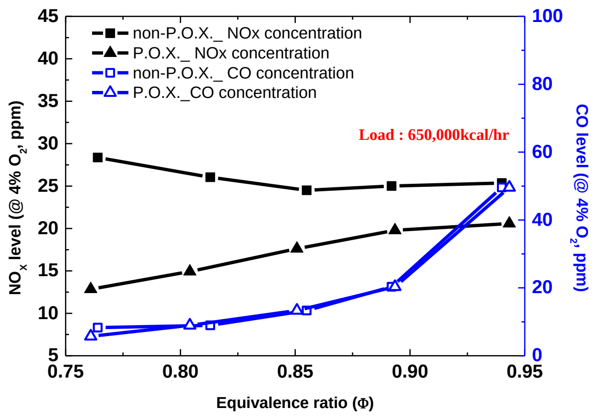

Fig. 14. Comparison of non-P.O.X. and P.O.X. condition.

Fig. 14 shows the comparison of NO_x & CO concentration in non-partial oxidation (non-P.O.X.) condition and NO_x & CO concentration in partial oxidation (P.O.X.) condition. The experiments were performed such that all the fuels were injected to the main center nozzle in the non-partial oxidation reaction condition. As shown in the graph, the maximum concentration of NO_x was about 28 ppmv in the non-P.O.X. condition, which was much higher than 12 ppmv in P.O.X. condition. As equivalence ratio was increased the NO_x concentration was decreased, but in the P.O.X condition, the NO_x concentration was increased as equivalence ratio was increased. Thus, the effect of partial oxidation reaction was clearly shown that it was more effective in the low equivalence ratio condition.

IV. Conclusion

In this paper, detailed experimental studies are performed to examine the performance of burners, prototype low NO_x gas fuel burner with FIR technique and newly designed low NO_x oil burner with partial oxidation reaction technique. The major findings are as follows.

A. Due to the obviously separated fuel rich and lean reaction zone and flue gas inner recirculation, ultra low NO_x emission of gas fuel burner is achieved, the NO_x concentrations are below 16~23ppmv at various thermal heat input conditions without FGR or any other after combustion treatment.

B. In line preheating the liquid fuel within the oil burner quarl is very effective method that achieves the preheating temperature around 400~500K. Then partial oxidation reaction is conveniently induced. In addition, the fuel rich condition for partial oxidation reaction is formed in recirculation zone using the oxygen in combustion gas without the external supply of air for this reaction. In all experimental conditions, CO level is kept below 50 ppmv. The new types of gas burner and liquid burner show very good performance on pollutant formation and reduction. In future studies, more detailed chemical and fluid mechanical research is needed. In addition, other fuels, such as LPG, synthetic gas, heavy oil and bio oil, will be tested as a fuel for this noble low NO_x burners.

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