EFFECTS OF HYBRID REBURNING SYSTEM WITH SNCR AND AIR STAGING ON NOX REDUCTION AND THERMAL CHARACTERISTICS IN OXYGEN-ENHANCED COMBUSTION

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The reburning process has been demonstrated to be a very effective and simple technique for reducing NOx emission and has been successfully applied to many industrial fields. Likewise, the air staging process is one of the most effective techniques for control of NOx emission. Nowadays, selective non-catalytic reduction (SNCR) method has been suggested as the advanced process for NOx reduction. The main goal of this study is to examine the effects of hybrid reburning system with SNCR and air staging on NOx reduction. Experimental study has been done to examine the formation characteristics of NOx in a lab scale combustor (15 kW) with various oxygen-enhanced combustion conditions. This study reports four experimental cases. Experimental case 1 was performed regarding the reburning process. Reburn fuel fraction in the reburning zone and the amount of additional air in the burnout zone have been studied for NOx reduction. Air staging and hybrid reburning with air staging effects were considered in experimental case 2. The effects of air staging on the gas temperature distribution and heat flux rate were studied. For case 3, SNCR process was considered. The effects of various NH3 fraction values and the amount of main air on NOx reduction and CO emission were considered when oxygen enhanced combustion was used. Finally, hybrid reburning system with SNCR and air staging were studied for case 4. Based on the effectiveness of each De-NOx process, the advantage of hybrid reburning system with SNCR and air staging was found and discussed.

Keywords: Air staging; LPG; Oxygen enhanced combustion; Reburning; SNCR

INTRODUCTION

In recent years, concern regarding environmental pollution has continuously grown. In particular, the most serious problem is atmosphere pollution due to a remarkable growth in industry. Combustion process adopted in plants or various facilities usually produce several hazardous air pollutants (e.g., CO, SOx, and NOx).
Acid rain precursors leading to a significant threat to the environment are caused by unwanted products attributed to a pollutant chemical reaction. Therefore, in order to strictly regulate the air pollutants, NOx emission limits have especially approached single digit (ppm) values by volume in the developed countries. Over the last decade, diverse methods for restricting air pollutants have been proposed using many experiments or numerical techniques. Through unceasing efforts by many researchers (e.g., Smoot et al., 2004), several technologies have been developed and applied to the many industrial circumstances. Among other technologies for NOx reduction, the reburning, air/fuel staged combustion, and SNCR were found to be effective for NOx reduction. Usually, NOx was generated in three ways in the combustion process. Thermal NOx, as represented by Zeldovich (1946), is produced when nitrogen and oxygen in the combustion air supply combine at high flame temperature. Prompt NOx, as noted by Fenimore (1971), is formed at the hot spot region on the flame surface due to the combination of hydrocarbon atom and atmospheric nitrogen. Finally, the conversion of chemically bound nitrogen in the fuel leads to Fuel NOx. However, in this study, only the thermal and prompt NOx formations are considered, because experiments have been conducted using liquefied petroleum gas (LPG) as the reburn as well as main fuel, which does not contain any nitrogen molecules. LPG consists of 95% propane and 5% other mixtures, such as butane or methane.

Reburning was first proposed by Wendt et al. (1974), who noticed that some injection of CH4 just downstream of the primary flame zone could reduce NO emission by up to 50%. Since then, its reburning efficiency was improved, and this technique was applied to practical industry. In the early 1980s, Mitsubishi (Takahashi et al., 1983) first applied this reburning technology in full scale in Japan. In the 1990s, Folsom et al. (1991) reported that NOx and SOx emission was reduced by up to 60% and 20%, respectively. Even a 55–60% NOx reduction was demonstrated in coal-fired power plant. However, reburning reaction kinetics and heat transfer characteristics have not been sufficiently investigated so far.

The reburning process can be usually divided into three parts. In the primary combustion zone, main combustion takes place with a slightly excessive air condition so that most of pollutant species are emitted here. At the downstream zone, a small quantity of fuel (called reburning fuel) is injected to create locally fuel-rich zone in which hydrocarbon radicals (CHi) are generated. These hydrocarbon radicals are a well-known, key factor that promotes NOx reduction mechanism by forming HCN that reacts with NOx in the reburn zone to produce N2. Finally, additional air is added in the burnout zone, where the un-reacted fuel completes combustion. Air and fuel staging technology has also been demonstrated to be an effective technique for reducing NOx emission in many prior workers (Miller & Bowman, 1989).

In this study, the effect of air staging technique on NOx formation has been experimentally studied. Dry air and oxygen were used as an oxidizer, which was separately injected into two inlets part of the concentric pipe for supplying oxidizer. Air staging divides the combustion process into a run with a deficiency of oxidizer and a run with excess oxidizer in the primary zone. For this reason, radial flame stratification was formed and can reduce a degree of air/fuel mixing, thus decreasing gas temperature distribution and NO emission (Toqan et al., 1992). Apart, injected oxidizer may make slow down the reaction of the combustion process so that gas temperature distribution is decreased in the flame region. Through this process, thermal NOx
formation could be reduced by decreasing temperature distribution in the flame zone. In order to get the good reduction of efficiency, the process parameters like temperature, stoichiometry, and residence time have been carefully controlled.

SNCR has been proposed as another promising concept for NO$_x$ reduction. SNCR is one of the post-combustion methods for reducing NO$_x$ emission. It does not influence the thermal efficiency and is known as a conceptually simple process for NO$_x$ emission control. One or more chemical reagents are injected to the downstream of the primary combustion zone, and then the reagents selectively reacted with NO$_x$ rather than combined with oxygen. Generally, either ammonia or urea solution is chosen as the reagent. Many investigations (e.g., Tayyeb Javed et al., 2007) reported that the SNCR method may not only achieve high NO$_x$ conversion efficiency but also has a low capital and operating cost. However, there are some disadvantages of ammonia emissions (e.g., ammonia slip and a narrow operating temperature window).

In this study, the hybrid effects of reburning and SNCR with air staging combustion in oxygen-enhanced combustion on NO$_x$ reduction are examined. Using oxygen-enhanced combustion can increase thermal efficiency by increasing the oxygen ratio in the oxidizer. However, increasing thermal NO$_x$ formation caused by increasing flame temperature has to be considered. The aim of this study is obtaining knowledge of appropriate condition for achieving optimal NO$_x$ reduction. Another goal is to contribute to the understanding of chemical reaction characteristics in the hybrid De-NO$_x$ technique.

**EXPERIMENTAL SETUP**

Figure 1 shows an overall schematic description of the experimental apparatus. It can be divided into three parts. The first part is supplying the equipment with fuel and oxidizer. In this study, LPG is used as reburn as well as main fuel. As an oxidizer, dry air and oxygen are used. Pure ammonia (99.99%) is chosen as a reagent for the SNCR process. Fuel, oxidizer, and ammonia are provided and controlled by each mass flow controller. Before entering the mass flow controller, these gases are controlled with each regulator. The second part is an experimental furnace with a burner. The furnace is vertically oriented, while the burner is installed at the bottom of furnace so that the flame is established in upward direction. The furnace diameter is 0.5 m in diameter and 1.2 m in height. The furnace is made of stainless steel and has a thermal load of 15 kW/hr·m$^3$.

Figure 2a shows a detailed drawing of the furnace. To prevent heat loss through the furnace wall, the Cerakwool, a heat insulator, is installed along the inner furnace wall. The thickness of insulation is about 0.04 m around the furnace wall. Therefore, the effective diameter of the furnace is 0.42 m. On the outer wall of the furnace, eleven ports are installed with an interval of 0.1 m along the axial direction for measuring gas temperature distribution at the burner inlet region. Along the vertical direction, thirteen ports are also installed to check the furnace wall temperature variation. In order to measure wall temperature and gas temperature distribution, two types of thermocouple are used. The R-type thermocouple is used for measuring gas temperature up to 1600°C, while the K-type thermocouple is on the outside of the furnace up to 1200°C. In order to inject reburn fuel, burnout air, and ammonia,
Figure 1  Overall schematic description of the experimental apparatus.

Figure 2  (a) Schematic of the furnace. (b) Details of the furnace and location of the injection port.
six ports are installed around the furnace, and in order to examine the effect of reburn fuel injection location on NOx reduction, the axial location is varied along seven ports. These ports are also used for measuring the convective and radiative heat fluxes at the inner wall of the furnace. Figure 2b indicates the detailed dimension of furnace and location of the gas injection ports and measurement points.

For injecting reburn fuel, burnout air, and ammonia, flat type nozzles with a spray angle of 95° are used. Figure 3 shows the plane and side view of an injector for the reburn fuel and ammonia injection. Its nozzle size is 0.66 mm × 0.28 mm.

In order to establish a diffusion flame inside the furnace, coaxial burner is considered and fabricated. In addition, another two types of burner (i.e., single burner and air staged burner) are designed to investigate the effect of air staging on thermal characteristic and NOx reduction compared with the case for single burner. Detailed drawings of the two different burners are shown in Figure 4. The main fuel is supplied from the inner pipe with a diameter of 4 mm. In the single type of burner, only one concentric pipe is set up around the fuel pipe for supplying oxidizer, whereas there are two concentric pipes for air staged burner to control two separate oxidizer streams. The primary or secondary air ratio is defined by each primary or secondary air flow rate divided by stoichiometric oxidizer flow rate. Therefore, the total air ratio λ_T is the sum of the primary (λ_1) and secondary (λ_2) air ratio. In this study, λ_1 and λ_2 are set to be the same. Meanwhile, all burners are connected to a stabilizing chamber, because the oxidizer can be homogeneously supplied into the furnace. Each burner is equipped with a radial flow guide vane swirler to stabilize the flame using the swirl-induced recirculation zone. In this study, swirler vane angle is fixed at 45 degrees for the single burner, while it is 45 degrees for primary air for staged burner and 60 degrees for secondary air. The swirl number is defined as follows (Gupta et al., 1984):

\[ S = \frac{2}{3} \left[ \frac{1 - (D_h/D)^3}{1 - (D_h/D)^2} \right] \tan \theta \]  

where D is an inner diameter of the swirler, D_h is the herb diameter of the swirler, and θ is the swirler vane angle. Table 1 lists the swirl numbers for corresponding
experimental conditions. Also, a quarl is designed and attached to the burner tip to incur a stable flame.

In the meanwhile, when the oxygen enhanced combustion is examined, the diameter of the oxidizer pipe is varied according to the oxygen enrichment ratio \( \omega \) between \( \text{O}_2 \) and total oxidizer as follows (Baukal, 1998):

\[
\omega = \frac{\text{volume flow rate of } \text{O}_2 \text{ in the oxidizer}}{\text{total volume flow rate of oxidizer}}
\]

The last part in apparatus is the measurement section. As mentioned above, two types of thermocouple are used. The R-type thermocouple is made of a bare-wire Pt/13\% Rh-Pt thermocouple, which is sheathed in straight length of twin-bore ceramic cladding of 0.3 mm (o.d.). The thermocouple has an unavoidable error due to the radiative heat loss from the thermocouple bead. Therefore, the measured temperature is calibrated by using thermocouples with three different types of beads (0.3–0.5 mm). The local temperature at the same position is measured with thermocouples with different bead sizes. Then the results are extrapolated to the value at zero bead size (Baek et al., 2002).

<table>
<thead>
<tr>
<th>Oxygen enrichment ratio ([\omega])</th>
<th>(D_h) (mm)</th>
<th>(D) (mm)</th>
<th>Swirl vane angle (\theta) (degree)</th>
<th>Swirl number</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single burner</td>
<td>0.21</td>
<td>8</td>
<td>24</td>
<td>45</td>
</tr>
<tr>
<td></td>
<td>0.27</td>
<td>8</td>
<td>20</td>
<td>45</td>
</tr>
<tr>
<td></td>
<td>0.34</td>
<td>8</td>
<td>18</td>
<td>45</td>
</tr>
<tr>
<td></td>
<td>0.42</td>
<td>8</td>
<td>17</td>
<td>45</td>
</tr>
</tbody>
</table>

Figure 4 Detailed drawings of the single and staged burner.
The heat flux at the furnace wall is evaluated using a heat flux transducer, which is a Gardon (1960) gauge type with a diameter of 32 mm. It can measure the radiative and convective heat flux, respectively. In order to analyze composition of product gases, an electrochemical gas analyzer (Eurotron Green-line MK2) is utilized to measure the concentrations of CO, NO\textsubscript{x} (NO + NO\textsubscript{2}), and O\textsubscript{2} at the combustor exit section. Toxic gases (CO and NO\textsubscript{x}) pass through the diffusion barrier to the cell cathode, where it is electrochemically oxidized, thus generating a voltage proportional to the gas concentration. Then, a reverse of counter voltage proportional to the voltage at the air cathode is produced by the measurement circuit, and thereby the concentration is derived and displayed. The product gases are locally sampled by using a water-cooled stainless steel probe. The gathering port is located at 1.1 m away from the burner tip. The water tap in the gas analyzer has product gases dried. The accuracy of the gas analyzer is known to be about 95%.

**EXPERIMENTAL CONDITION**

All experiments are conducted when the thermal condition in the furnace reaches its steady state, which is determined by a variation in the furnace inner wall temperature. In order to examine the relative effectiveness of the reburning and SNCR with air staging hybrid system, four experimental cases are considered. As LPG is used as the main and reburn fuel in this study, the amount of main fuel is always fixed to maintain the thermal input condition of the primary zone so that the equivalence ratio in the primary zone is constant regardless of NO\textsubscript{x} reduction system. However, the equivalence ratio in the reburning zone is systematically changed depending on the amount of reburn fuel injected. In order to maintain the same equivalence ratio in the burnout zone, the amount of additional air injected is also varied in accordance with the reburn fuel fraction. While Case 1 examines the effects of reburning process only, Case 2 discusses the effects of air staging only or hybrid reburning with air staging. The effects of SNCR process only or hybrid reburning/SNCR are considered in Case 3. Finally, Case 4 investigates the effects of hybrid reburning/SNCR with air staging on NO\textsubscript{x} reduction.

To examine the effect of varying the amount of the reburn fuel on NO\textsubscript{x} reduction, Case 1-1 is conducted. In this case, the reburn fuel fraction is varied from 0 to 0.25 of the total heat input. The reburn fuel fraction \( f_{re} \) is here defined by

\[
 f_{re} = \frac{\text{the amount of the reburn fuel}}{\text{the amount of the main fuel} + \text{the amount of the reburn fuel}} \tag{3}
\]

For Case 1-2, the influence of the amount of additional air, which is injected to the burnout zone, is considered when the combustion is oxygen-enhanced. To evaluate the effect of oxygen-enhanced combustion on the heat transfer rate, the heat flux to the furnace wall is compared for two OER conditions of 0.21 and 0.35. Case 2 includes three sub-cases to show the effect of air staging. The objective of Case 2-1 is to show the thermal characteristics of the air staging in which the gas temperature distribution and heat flux to the furnace wall are measured in the oxygen enhanced combustion (\( \omega = 0.35 \)). To examine the effects of air staging on initial NO\textsubscript{x} formation for various oxygen enrichment ratio (\( \omega \)), Case 2-2 is considered. Case 2-3
<table>
<thead>
<tr>
<th>Case</th>
<th>Thermal input (kW)</th>
<th>Equivalence ratio (Φ)</th>
<th>Note</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>Primary fuel</td>
<td>Reburn fuel</td>
<td>Primary zone</td>
</tr>
<tr>
<td>1-1</td>
<td>15.00</td>
<td>0–5</td>
<td>0.91</td>
</tr>
<tr>
<td>1-2</td>
<td>15.00</td>
<td>3.75</td>
<td>0.91</td>
</tr>
<tr>
<td>2-1</td>
<td>15.00</td>
<td>—</td>
<td>0.91</td>
</tr>
<tr>
<td>2-2</td>
<td>15.00</td>
<td>—</td>
<td>0.91</td>
</tr>
<tr>
<td>2-3</td>
<td>15.00</td>
<td>0–5</td>
<td>0.91</td>
</tr>
<tr>
<td>3-1</td>
<td>15.00</td>
<td>—</td>
<td>0.91</td>
</tr>
<tr>
<td>3-2</td>
<td>15.00</td>
<td>—</td>
<td>0.86–0.94</td>
</tr>
<tr>
<td>3-3</td>
<td>15.00</td>
<td>3.75</td>
<td>0.91</td>
</tr>
<tr>
<td>4-1</td>
<td>15.00</td>
<td>0–3.75</td>
<td>0.91</td>
</tr>
</tbody>
</table>
explores the effects of the hybrid reburning with air staging on NO\textsubscript{x} reduction for various reburn fuel fractions. Case 3 includes three experimental conditions on hybrid reburning and SNCR process. Case 3-1 evaluates the effects of injection quantity of SNCR reagent on NO\textsubscript{x} reduction when the oxygen enrichment ratio is 0.35. Quantity of SNCR reagent is defined as the mass flow rate ratio between NH\textsubscript{3} and the reburn fuel when the reburn fuel fraction is 0.2 (Lee & Baek, 2007). To examine the relationship between the equivalence ratio in the primary zone and CO emission in the SNCR process, Case 3-2 is selected. Case 3-3 deals with the effects of hybrid reburning and SNCR process on NO\textsubscript{x} reduction, and its performance was compared with reburning and only SNCR process for the various oxygen enrichment ratio conditions. Finally, Case 4-1 considers a hybrid reburning/SNCR with air staging when the oxygen enrichment ratio is 0.35. The overall experimental conditions are listed in Table 2.

**EXPERIMENTAL RESULTS AND DISCUSSION**

**Reburning**

For the case of reference, experiments are conducted in the slightly fuel lean condition without reburning. The equivalence ratio in the primary zone is fixed at 0.91. Experimentally, a flame length is about 0.3–0.4 m away from the burner tip, and the reburn fuel is injected 0.4 m away from the burner tip while additional air is injected at 0.7 m. Based on this, the NO\textsubscript{x} reduction is represented for different reburn fuel fraction in Figure 5. When the reburn fuel is injected, the hydrocarbon radicals known as the key radical are generated. These hydrocarbon radicals react with NO to form N\textsubscript{2}. As seen in Figure 5, the NO\textsubscript{x} reduction steadily increases until the reburn fuel fraction reaches about 0.2. Afterward, there is no further reduction in NO\textsubscript{x}, even if more reburn fuel is injected. Under fuel rich condition, the following kinetics pathways control the efficiency of reburning process (Miller & Bowman,

![Figure 5](image-url)  
*Figure 5 Effect of reburn fuel fraction on NO\textsubscript{x} reduction and emission (Case 1-1).*
As shown in Eq. (4), the partial oxidation and pyrolysis of the reburn hydrocarbon fuel result in the formation of CH_i radicals, which react with NO, thereby generating HCN radicals. HCN radicals are known as the intermediate species to initiate NO_x removal reaction in the reburning zone. HCN radicals undergo several reactions, and then eventually nitrogen oxides are changed into nitrogen molecule. The formation of the HCN radicals extremely depends on concentration of hydrocarbon radical. Therefore, it is obvious that increasing injection of reburn fuel in the reburning zone could lead to more reduction of nitrogen oxides. However, as shown in Figure 5, the NO_x reduction does not occur any more when the reburn fuel fraction reaches 0.2. Because of limited mixing in the reburn fuel with nitrogen oxides, the NO_x reduction reaches a limitation. Another reason is that hydrocarbon radicals react with oxygen rather than NO. These two reactions competitively consume CH_i. Therefore, when the reburn fuel fraction exceeds 0.2, the reburning effectiveness is not enhanced anymore.

Injecting additional air into the burnout zone plays an important role in fully completing combustion. Generally, the equivalence ratio in the burnout zone is maintained at the same value in the primary combustion zone. Consequently, it is interesting to consider the influence of the varying amount of additional air in the burnout zone. In order to examine this point of view, Case 1-2 is experimentally accomplished using various amount of additional air under the condition of oxygen-enhanced combustion (\( w = 0.35 \)). Reburn fuel fraction is still fixed at 0.15. When the equivalence ratios in the primary and reburning zones are the same, the exit O_2 concentration in the product gas depends on the amount of additional air. Figure 6 shows that a decrease in exit O_2 concentration incurs the NO_x reduction. The NO_x reduction reaches 30% when the exit O_2 concentration is 4.0%. However, when the exit O_2 concentration is decreased, which means that less amount of additional air is used, the NO_x reduction increases up to 55%. In other words, a decrease in the amount of additional air can achieve more NO_x reduction. At the exit O_2, concentration decreases to as low as 1.5 percent, and the CO emission begins to increase. This phenomenon may result from a change in residence time of the reburn fuel. As the amount of additional air decreases, CH_i radical formed by injecting reburn fuel does not have time enough to completely burn, so that the CO emission increases and the reburn fuel has a greater chance to react with NO_x, which results in further NO_x reduction. As mentioned above, the oxygen-enhanced combustion gives rise to increasing thermal efficiency. To elucidate this effect, heat flux to the furnace wall is compared for experimental Cases 1-1 and 1-2. In Figure 7, the total heat flux
and radiative heat flux fraction are illustrated along the axial direction. Radiative heat flux fraction represents a ratio of radiative heat flux to total heat flux. The total heat flux as well as radiative heat flux fraction for the OER value of 0.35 is observed to be much higher than those when OER = 0.21. It is also noted that the radiative heat flux fraction ranges from 60–85% for OER = 0.35 but 30–45% for OER = 0.21. Therefore, the influence of the radiative heat flux is more dominant for the higher OER, as it is proportional to fourth power of temperature.

Figure 6 Effect of the amount of additional air on NO\textsubscript{x} reduction and CO emission (Case 1-2).

Figure 7 Total heat flux (THF) and radiative heat flux (RHF) fraction along the wall for different oxygen enrichment ratios (\(\omega\)) (Cases 1-1 and 1-2).
Air Staging

In order to examine the effect of air staging on heat flux to the wall and temperature distribution in the furnace under various oxygen enrichment ratios (\(w\)) conditions, Case 2 is experimentally performed. As shown in Figure 8, when air staged burner is used, the incident total heat flux to the furnace wall becomes smaller than that for single burner. This is because the chemical reaction at the primary zone is attenuated for the case of air staging (Spliethoff et al., 1996). Also, due to the effect of air staging, the flame shape is observed to be radially more expanded than for the single burner. Thereby, the gas temperature for air staging becomes lowered in most of region by a diminishing hot spot in the reaction zone, as shown in Figure 9.

Figure 8: Total and radiative heat flux along the wall for different burner type (Case 2-1).

Figure 9: Axial temperature distribution for different burner type (Case 2-1).
For air staging, a complete combustion of remaining fuel takes place downstream of the primary combustion zone. Figure 8 also shows that the radiative heat flux to the wall is smaller for the air staged burner similar to total heat flux. However, its reduction for the air staged burner is larger, as the radiative heat flux is more dependent on temperature than the total heat flux. Although two different burners show a different behavior in temperature distribution and heat flux, no measurable amount of carbon monoxide is produced in the experiment. The fuel supplied by two types of burner is supposed to be completely burned. Especially in air staging, secondary air supplied is considered to well mix with the fuel-rich core, which leads to completing fuel consumption (Toqan et al., 1992).

According to Figure 9, the gas temperature for air staged burner at the edge line from 0.4 m to 0.6 m is observed to be higher than that for single burner. This is because the flame zone radially widens for air staged burner than single burner while the flame length reaches about 0.3–0.4 m from burner tip. Figure 10 indicates the experimental results on NOx emission level for various oxygen enrichment ratios for Case 2-2. Theoretically, it is anticipated that NOx emission for air staged burner is lower than that for single burner as the NOx formation rate significantly depends on temperature distribution. When OER is higher that 0.27, a difference in initial NOx emission level between single burner and air staged burner increases. However, when OER is lower than 0.27, NOx emission level for air staged burner is higher than that for single burner. This is due to the formation characteristics of NOx through the temperature distribution.

It is well known that the formation of thermal NOx is significant at high temperatures (above 1520°C) as for higher OER (Bilbao et al., 1994). For the lower OER conditions smaller than 0.27, the temperature distribution becomes lower so that prompt NOx formation plays a more important role. Prompt NOx formation usually takes place at the flame surface region, which becomes wider for air staged burner.

![Figure 10](image)  
Figure 10 NOx emission level versus oxygen enrichment ratio (ω) for different burner type (Case 2-2).
Hybrid Reburning with Air Staging

Case 2-3 examines the effects of hybrid reburning with air staging on initial NO\(_x\) formation and NO\(_x\) reduction. Reburn fuel fraction is varied from 0 to 0.25, while OER value is fixed at 0.35. Its experimental results are shown in Figure 11. Similar to the experimental results for Case 1-1, NO\(_x\) reduction for hybrid reburning with air staging is saturated once the reburn fuel fraction reaches about 0.2. However, the hybrid method can achieve more NO\(_x\) reduction than the reburning-only process by way of air staging. The maximum NO\(_x\) reduction attains 65% when the hybrid reburning with air staging process is used.

Figure 12 shows the effect of the oxygen-enhanced combustion on NO\(_x\) reduction for three De-NO\(_x\) processes. In order to show the characteristic of the air staging process in oxygen-enhanced combustion, Case 2-2 is used. Oxygen enrichment ratio is varied from 0.21 to 0.45, while the reburn fuel fraction is fixed at 0.2 for hybrid reburning and reburning only. When single burner only with reburning is used, NO\(_x\) reduction is not significantly changed under the whole OER conditions. However, NO\(_x\) reduction for air staging only, by contrast, increases as OER value increases except for lower OER condition, for which prompt NO\(_x\) formation is more dominant than thermal NO\(_x\) formation. This is because the gas temperature is not sufficiently high to promote the generation of thermal NO\(_x\). Therefore, in the low OER value (about 0.21–0.25), NO\(_x\) reduction is recorded as negative, which means that more NO\(_x\) is generated. NO\(_x\) reduction for hybrid reburning is observed to steadily increase, when OER value increases. In summary, the hybrid reburning with air staging becomes more effective when OER value is larger than 0.3, as the hybrid process is better than reburning only for NO\(_x\) reduction.
Hybrid Reburning and Selective Non-Catalytic Reduction (SNCR)

In this study, pure ammonia (NH₃) is chosen as the SNCR chemical reagent. Many investigators (e.g., Tayyeb Javed et al., 2007) have discussed the effect of the temperature on SNCR process and shown that a suitable performance by SNCR process can be achieved at temperature between 850°C and 1175°C. This is a narrow temperature interval, because the reaction below 850°C is too slow to yield any NOx reduction, so that most of the injected NH₃ remains unreacted. At a temperature higher than 1200°C, the NH₃ oxidation becomes significantly dominant so that SNCR process may result in a net increase in NO. The major reaction for SNCR process is as follows (Lee & Baek, 2007; Tayyeb Javed et al., 2007):

\[
\text{NH}_3 + \text{OH}, \text{O} \leftrightarrow \text{NH}_2 + \text{H}_2\text{O}, \text{OH} \\
\text{NH}_2 + \text{NO} \leftrightarrow \text{N}_2 + \text{H}_2\text{O}
\]

As shown in the above equations, amidogen (NH₂) radical, which is a key factor to reducing NOx, is produced by the reaction NH₃ with hydroxyl (OH) radical or oxygen atom (O). Even in a fuel-lean environment, amidogen reacts almost solely with NOx when gas temperature maintains optimum temperature range between 850°C and 1175°C. Consequently, significant reduction in NOx can be achieved.

However, the problem of the generation of carbon monoxide is another formidable one. Usually, both CO and NH₃ competitively consume hydroxyl radical or oxygen atom. But the NH₃ + OH, O reaction is faster than CO oxidation reaction. For this reason, there are insufficient hydroxyl radical and oxygen atoms to oxidize carbon monoxide. This is because NH₃ injected in SNCR might behave as an inhibitor of CO oxidation, as mentioned by Lee (2008).

Figure 13 indicates results of the experimental Case 3-1. Ammonia is injected at an axial distance of 0.6 m from the burner tip, where the flow field in the inner furnace region reaches a stable state. As shown in Figure 14, a radial temperature

![Figure 12](image_url)
distribution is not significantly changed at 0.6 m from the burner tip where ammonia is injected. Because the flame length extends about 0.4 m from the burner tip, the influence from the flame and internal recirculation of product gas is expected to be minor at this location.

However, as mentioned above, it is important to keep an optimal temperature range for SNCR process. Because radial gas temperature measured at the injection point of ammonia is observed to range from 900 to 1000°C, as in Figure 14, the optimal temperature condition is well satisfied at this region. According to Figure 13, the more the NH₃ fraction increases, the more the NOₓ reduction rapidly increases.

Figure 13 Effect of NH₃ fraction on NOₓ reduction and product gases emission level (Case 3-1).

Figure 14 Radial temperature distribution at the various SNCR chemical reagent injection point (Case 3-1).
However, simultaneously, more unreacted CO and ammonia are emitted. When the NH$_3$ fraction reaches about 0.2, the NO$_x$ reduction attains a maximum value of about 75%. However, ammonia slip as well as CO emission also reach a maximum (NH$_3$ > 10 ppm, CO > 30 ppm). Consequently, a prevention of ammonia slip phenomenon is one of critical problems in the SNCR process. In order to avoid remnant ammonia emitted together with product gases, an optimal NH$_3$ fraction is selected as 0.1 in this study for which NO$_x$ reduction can still accomplish about 52%. Thereby, the ammonia slip problem can be avoided.

Meanwhile, CO emission is another problem while using SNCR process. The experimental Case 3-2 is conducted to examine CO emission level against the equivalence ratio in the primary zone. First, when SNCR process is not applied, exit O$_2$ concentration in the product gas is measured by changing the equivalence ratio in the primary combustion zone. Then, NH$_3$ fraction is fixed at 0.2. As shown in Figure 15, even though oxygen concentration is increased, NO$_x$ reduction is not influenced as much. Due to this, NH$_2$ radical in the optimal temperature range is considered to selectively react with NO rather than combine with oxygen atom or hydroxyl radical. In other words, increased O$_2$ concentration does not disturb chemical reaction for NO$_x$ reduction, so that more oxygen supplied is positively used to reduce CO emission, as observed in Figure 15.

Experimental Case 3-3 is performed to seek the effect of hybrid reburning and SNCR process on NO$_x$ reduction, compared with reburning-only or SNCR-only processes for various oxygen enrichment ratio conditions. While the reburn fuel fraction is fixed at 0.2, NH$_3$ fraction value is 0.1. As shown in the Figure 16, for the case of reburning-only, the NO$_x$ reduction slowly increases with oxygen enrichment ratio. For the case of SNCR only, although NH$_3$ fraction is fixed at 0.1, NO$_x$ reduction rapidly increases with oxygen enrichment ratio. That is because an increase in OER incurs a temperature rise in the furnace. In the low-temperature region for

![Figure 15](https://example.com/figure15.png)

**Figure 15** Effect of O$_2$ concentration on exit CO level and NO$_x$ reduction (Case 3-2).
which OER value is between 0.21 and 0.25, the reburning-only process is better than SNCR-only for NO\textsubscript{x} reduction. However, when OER value ranges from 0.30 to 0.45, the gas temperature distribution at the injection point of ammonia resides in the optimal temperature range (about 830–970°C) so that SNCR process performs better, accomplishing NO\textsubscript{x} reduction of 65%. For the case of hybrid reburning with SNCR system, NO\textsubscript{x} reduction varies from 45% up to 75% for various OER conditions sought here. Another primary advantage for hybrid system is that CO emission is easily restricted by supplying additional air as mentioned above.

**Hybrid Reburning and SNCR with Air Staging for NO\textsubscript{x} Reduction**

The ultimate goal of this study is to investigate the effectiveness of a hybrid system of reburning/SNCR with air staging on NO\textsubscript{x} reduction. This final experiment pertains to Case 4-1. To avoid ammonia slip based on preliminary tests, NH\textsubscript{3} fraction is maintained at 0.1 and its performance is compared with the other De-NO\textsubscript{x} processes. Figure 17 shows a variation of NO\textsubscript{x} reduction with reburn fuel fraction for four types of De-NO\textsubscript{x} process. As might be expected, De-NO\textsubscript{x} processes with SNCR yields a higher NO\textsubscript{x} reduction than otherwise. In general, the hybrid reburning with air staging process performs better in NO\textsubscript{x} reduction than reburning-only process by 15%. As shown in Figure 17, even with reburn fuel fraction of 0.05, the hybrid reburning process with SNCR accomplishes about 65% in NO\textsubscript{x} reduction. When the reburn fuel fraction is 0.2, NO\textsubscript{x} reduction becomes about 73%. Moreover, it has the advantage of avoiding ammonia slip problem with a small amount of ammonia for which NH\textsubscript{3} fraction is 0.1. The problem of CO emission problem can be easily solved by supplying additional air, as observed above.

Finally, a hybrid reburning with SNCR and air staging process comprises individual merit of each De-NO\textsubscript{x} process. Whereas the air staging process provides a chance to suppress initial thermal NO\textsubscript{x} formation by decreasing temperature
distribution, a higher NOx reduction can be achieved by using SNCR process. Therefore, the hybrid reburning with SNCR and air staging process can achieve a significant NOx reduction with a maximum of 81% for the conditions in this study. These results conclude that the hybrid reburning with SNCR and air staging system is more efficient in reducing NOx emission than the other De-NOx processes.

CONCLUSIONS

In this paper, experimental investigation was performed to predict and understand the thermo-chemical characteristics for the hybrid reburning system with SNCR and air staging in oxygen-enhanced LPG flame. Its effectiveness was discussed and compared with other De-NOx processes. The important conclusions were as follows:

- In the reburning process, NOx reduction was saturated when the reburn fuel fraction reached 0.2. Also, NOx emission could be reduced up to 45% for experimental conditions given here.
- NOx reduction in reburning process was influenced by the amount of additional air supplied in the burnout zone. As the amount of additional air decreased, NOx reduction was found to increase. Because CHi radical formed by injecting reburn fuel did not instantly react with NOx, less use of air led to increasing reaction time between CHi radical and NOx, which resulted in further NOx reduction.
- Gas temperature and heat flux to the wall of the furnace decreased when air staged burner was used. Therefore, a formation of thermal NOx was suppressed by using air staging. But the lower OER conditions (ω = 0.21 – 0.30) with air staged burner contributed to increasing prompt NOx by extending flame surface in a radial direction.
SNCR process could achieve a significant NO\textsubscript{x} reduction even if oxygen was sufficient in the flow field of the furnace. There was sufficient air to be advantageous to reducing CO emission.

Hybrid reburning system with SNCR had many advantages in comparison with reburning-only or SNCR-only process. Even though gas temperature did not reach an optimal range for promoting SNCR process, the reburning-only process attained a maximum of 45% in NO\textsubscript{x} reduction. Also a usage of additional air successfully restricted CO emission. Moreover, the hybrid reburning process with SNCR, even with small NH\textsubscript{3} fraction of 0.1, achieved a maximum of 75% in NO\textsubscript{x} reduction.

Hybrid reburning process with SNCR and air staging comprised each advantage of reburning, SNCR, and air staging processes. The reburning process provided a chance to reduce NO\textsubscript{x} at a wide temperature range rather than SNCR process. Air staging process could limit an initial NO\textsubscript{x} emission level by decreasing gas temperature. Finally, SNCR process could achieve a significant NO\textsubscript{x} reduction even with a small NH\textsubscript{3} fraction. In summation, the hybrid system could achieve about 81% of NO\textsubscript{x} reduction with almost zero CO and ammonia emission.

**NOMENCLATURE**

- D : nozzle diameter
- D\textsubscript{h} : vane hub diameter
- f\textsubscript{re} : reburn fuel fraction
- s : swirl number
- \Theta : vane angle
- \omega : oxygen enrichment ratio
- \lambda\textsubscript{T} : total air ratio
- \lambda\textsubscript{1} : primary air ratio
- \lambda\textsubscript{2} : secondary air ratio

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**REFERENCES**


