Combustion Management to Achieve Lower NO\textsubscript{x}

Innovative Combustion Technologies, Inc.
2367 Lakeside Drive, Suite A-1
Birmingham, AL 35244
205.453.0236
www.innovativecombustion.com
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THE MECHANICS OF NO\textsubscript{x} FORMATION

NO\textsubscript{x} generated by coal combustion is a combination of nitric oxide (NO) and nitrogen dioxide (NO\textsubscript{2}). NO\textsubscript{x} in flue gas from coal combustion is 90% to 95% NO.

Fuel bound nitrogen and oxygen in the combustion air react to form NO\textsubscript{x}. All mechanisms that form fuel NO\textsubscript{x} are not fully understood at this point in time. What is known is that nitrogen in coal is responsible for approximately 80% of the total NO\textsubscript{x} formed during coal combustion which makes this the largest source of NO\textsubscript{x} production on a PC boiler. American coals are typically between ~0.25% to 1.5% nitrogen. If complete conversion of all fuel nitrogen took place, this would result in NO\textsubscript{x} emissions of 0.4 to 2.6 lb/MBtu. During the normal combustion process only 20% to 30% of the N\textsubscript{2} content in fuel is converted to NO\textsubscript{x}. The conversion of fuel nitrogen is weakly temperature dependent but depends strongly upon local burner stoichiometry.
**Thermal NOx**

Molecular nitrogen (N₂) and oxygen (O₂) both in the combustion air react to form thermal NOx at the high temperatures of the flame core. Atmospheric air utilized to provide combustion air for a coal flame is ~20.9% O₂ and 78% N₂. Naturally occurring nitrogen in air is basically inert, however, temperatures above ~2800°F cause thermal dissociation of N₂ and O₂ allowing nitrogen to combine with oxygen, creating primarily NO molecules. The rate of reaction that forms thermal NOx is highly dependent upon peak flame temperature and the stoichiometric ratio in the primary combustion zone (i.e. @ burners). The maximum thermal NOx production occurs at a slightly fuel lean mixture due to the abundance of oxygen in the hottest regions of the coal flame. The rapid decrease in NOx formation for either fuel rich or lean combustion indicates that control of stoichiometry at the burners is critical to achieving reduction in thermal NOx. Flame temperature decreases rapidly along the length of the flame as heat is radiated away from the flame resulting in almost all of the thermal NOx generated at the flame core.

Figure 1 illustrates relative NOx emissions and the temperature dependence of the three (3) sources of NOx for coal combustion. These relationships make precise control of burner stoichiometry mandatory for optimization of NOx emissions.

![Figure 1](image-url)
Thermal NOx formation can also increase as furnace heat release increases. Non-optimum combustion results in lower boiler efficiency which in turn requires more fuel to be fired to maintain unit electrical generation or steam flow. Lower boiler efficiency and higher fuel flows result in higher furnace heat release, which in turn, increases furnace gas temperature, promoting the formation of thermal NOx. Consequently, it is important to maintain optimum combustion which reduces heat rate and increases boiler efficiency to achieve further reductions to NOx.

**Prompt NOx**

Prompt NOx is typically insignificant, producing <5% of the total NOx formed during coal combustion. Prompt NOx is only significant in very fuel rich flames, which are inherently low producers of NOx due to reduction in thermal and fuel NOx. Prompt NOx is formed during the earliest stages of combustion in the flame zone through intermediate formation of fixed species of nitrogen that oxidize to NO, such as hydrogen cyanide (HCN), nitrogen monohydride (NH), dihydrogen cyanide (H₂CN), etc.
NOx emissions on pulverized coal fired (PC) boilers are increasingly being managed through the use of flue gas treatment technologies (i.e. SCR and SNCR); however, opportunities exist for managing NOx by optimizing boiler side or “combustion” side parameters. Optimized combustion includes control and management of the secondary airflow, balancing the primary air and fuel flow to the burners, burner tuning and burner tilts (tangential fired boilers) and pulverizer performance. Managing the combustion inputs should be the first step towards NOx reduction.

Secondary Air Flow

NOx emissions can vary significantly under transient load conditions if primary and secondary air flows are not accurately controlled. Secondary (combustion) air distribution to each burner, burner compartment or burner corner should be balanced to within ±5% deviation from the mean. Precise, repeatable and predictable control of NOx requires accurate measurement and control of both pulverizer primary air and secondary air. Accurate on-line measurement of secondary air is only typically found on units with compartmentalized windboxes. When boiler design does include windbox compartmentalization and flow measurement elements, it is imperative that flow measurement devices, whether they be air foils, pitot arrays, flow nozzle or venturi(s), be periodically calibrated by local hot “K” factor traverses. Common mechanical, maintenance or operational variables that cause burner secondary air imbalances are:

- Air register settings
- Non-representative external indication of burner sleeve, shroud or register position
- Windbox damper stroking or actuator malfunction
- Windbox aerodynamics
- Windbox/casing leaks
- Non-optimum distribution of overfire, boundary or curtain air
- Balancing economizer exit O₂ by burner adjustment when O₂ split is caused by localized boiler setting air in-leakage
- Air heater leakage or partial pluggage
- Imbalances originating from F.D. fans
Primary Air Flow

Fuel flow to each burner should be balanced within ±10% deviation from the mean. Our experience has indicated that high primary air flow can both increase NOx emissions and contribute to non-optimum combustion. Increased NOx emissions caused by high primary air flow are often the result of the following:

- **Flame Detachment (ignition points far from burner nozzle tip).** The most critical part of a low NOx burner flame is the region of the flame close to the nozzle, as the near burner conditions control the flame’s overall NOx production. In the “near burner” region of the flame, the fuel N₂ (largest producer of NOx) in the volatile fraction of the coal must be released into an atmosphere lacking O₂. To ensure this occurs, the flame must be attached to the burner nozzle, since high primary air flow tends to push ignition points out into the furnace. Flame attachment not only controls the near burner air:fuel ratio, but enhances the devolatilization of coal hence the release of fuel N₂ into this critical reducing zone of the flame.

- **Injection of excess oxygen into the high temperature flame core.** High primary air flows force more O₂ into the flame core making more oxygen available for the conversion of nitrogen to nitric oxide.

- **Increases in primary airflow correlate to an increase in velocities at the classifier outlet of the pulverizer.** Higher velocity air at the classifier outlet has sufficient energy to entrap larger, more massive coal particles, which results in poor coal fineness. Lower velocities allow larger particles to be returned to the pulverizer grinding zones. High primary airflow also increases the velocity differential between primary air and secondary (combustion) air. This delays combustion, allowing a large percentage of heat to be released above the burner belt zone instead of being absorbed by the lower water walls. This high heat release elevates furnace exit gas temperatures which increases slagging propensity.
The importance of accurate measurement and control of the primary air cannot be emphasized enough. ICT prefers utilization of a flow nozzle (shown in figure 2) when possible. If flow nozzles are not installed, primary air flow measurement accuracy must be within ±5% of actual flow.

**Figure 2 -- PA Flow Nozzle Schematic**

Flow Nozzle Designed for 2” differential pressure at Full load airflow

**Low Excess Air Operation**

Optimum combustion or complete burnout of all oxygen to carbon monoxide and all hydrogen to water is at odds with NOx formation. Excess oxygen is required in the furnace to ensure stoichiometric combustion. However, too much oxygen will increase the formation of NOx. If the combustion air is reduced too much, it can result in poor fuel-air mixing creating CO and soot emissions. On high heat release units, NOx is often marginal and excess air must be lowered to the least possible quantities without excessive CO emissions or flyash loss on ignition (L.O.I.). The effects of reducing excess air on thermal NOx generation and unit performance is case specific with varying effects caused by furnace retention time (height of furnace cavity), furnace heat release, burner heat input and burner placement. Achieving the best possible balance in fuel and air will allow the lowest possible excess air level without unacceptable CO emissions, high carbon in ash and/or localized
furnace slagging. This means that opportunities to balance fuel and air flows is case specific and differs between individual boilers.

Burner Tilts

On tangentially fired boilers, burner tilt position sometimes significantly effects NOx emissions. Typically, NOx emissions increase as burner tilts are elevated due to increased interaction of fuel-rich streams with air through the close coupled overfire air compartments or upper auxiliary air compartments. Downward orientation in burner tilts also results in other favorable boiler performance factors, including:

- Lower slagging propensity with downward orientation of burner tilts at full load due to furnace exit gas temperature depression by increased lower water wall heat absorption
- Highest furnace retention time, allowing for enhanced carbon burn-out and improved flyash Loss on Ignition
- Increased homogenization of flue gases for uniform tube metal temperatures and flue gas O₂

Combustion conditions and heating surfaces must be evaluated and optimized if full load operation with acceptable steam temperatures can not be maintained at slight downward orientation of burner tilts. Often burner tilts are used as a means to balance furnace O₂ at the boiler or economizer exit. Employing tilts to balance O₂ is only masking a furnace oxygen imbalance and is not the corrective action that attains maximum boiler performance. When tilts are utilized to balance O₂, this is indicative of O₂ imbalances caused by localized boiler setting air in-leakage or fuel and/or air imbalances at the burners.

Staging of Combustion Air

Staging of combustion air includes methods for introducing combustion air into the boiler other than through the in-service burners. The intent is to separate the primary air from the secondary air to delay combustion and encourage the formation of N₂ rather than NOx and to also reduce oxygen at the hot burner flame core to discourage the formation of thermal NOx. Methods that have been used historically include overfire air, simulated overfire air and boundary air.
Overfire Air

Several types of low NOx systems for wall fired and tangentially fired boilers utilize overfire air to reduce NOx emissions. The configuration and delivery of overfire air is unit specific and varies greatly between different boilers; however, the principle and mechanisms through which NOx is reduced are essentially the same. Reduction in NOx with overfire air is facilitated by pyrolysis of coal in an oxygen deficient high temperature atmosphere in which fuel bound nitrogen evolved from the coal is converted to N\textsubscript{2} rather than NO combined with reduction in thermal NOx by ensuring an oxygen deficiency in the hot flame zone. This is followed by the introduction of the remaining air required to completely burn the coal without forming excessive amounts of NO because the bulk of oxidizable organic nitrogen has already been converted into innocuous molecular nitrogen. On systems that utilize overfire air, overfire air is typically 20% of the total air for combustion to attain maximum NOx reduction with acceptable combustion. Decreases in overfire air typically increase NOx emissions and decrease L.O.I. This is the result of allowing a higher proportion of air to pass through the burners where the exposure or retention time of coal derived carbon to excess air is maximized. Increases in overfire air often increase furnace exit gas temperature. This is caused by staging or delaying combustion which elevates the center of combustion in the furnace exposing less water wall heating surface to the active combustion zone, subsequently reducing total heat absorption by the walls. The heat unabsorbed by the water walls must be absorbed by de-superheating spray flows or raising boiler exit gas temperatures. Lower burner belt stoichiometry is also less forgiving to fuel and air imbalances in the lower furnace, exacerbating localized slagging in the burner zone which seasons water wall surface, leading to further increases in furnace exit gas temperature.

*Units are often found to be operating at NOx levels far below legally mandated levels due to higher than required overfire air flow. This is sometimes favorable when system averaging of NOx emissions is being exercised; however, it is often detrimental to the boiler and combustion efficiency. While excessive amounts of overfire air will reduce NOx, this comes at the expense of very low burner zone stoichiometry which can lead to tube wastage, slagging, aggravation of coal-ash corrosion, high carbon in ash, burner component overheating and excessive side to side O\textsubscript{2} or tube metal temperature variation and high de-superheating spray flows.*
On corner fired units, dissimilar proportioning of over fire air flow between separate corners must be avoided through careful control of measurement of overfire air flow to each corner. Disproportionate distribution of overfire air flow between separate corners will result in some burner corners operating at a different stoichiometry than the remaining corners. This could feasibly result in the bulk of NOx emissions originating from one burner corner. Lower NOx and improved combustion would be realized through more effective utilization of overfire air if it were equally distributed. Equal distribution of overfire air flow and uniform stoichiometry in each of the burner corners is critical to achieving optimum combustion as well as optimizing unit NOx emissions. **To prevent the adverse effects of overfire air, it is important that the overfire air be accurately measured and controlled precisely. This is facilitated by accurate flow measurement elements and frequent calibration by local traverse by proficient field test personnel. As a goal, overfire air should be accurately measured and controlled to within ±3% deviation from the mean.**

**Simulated Overfire Air**

On wall fired boilers that have not been retrofitted for overfire air, some plants have substituted the use of an out of service upper pulverizer to inject additional combustion air into the furnace. This technique involves shutting off the fuel flow to a top row of burners and maintaining air flow through the burner registers of the out of service burners in order to achieve a simulated overfire air effect. Just as with the retrofitted overfire air ports, the benefits are not without cost as low burner stoichiometry is still an issue. Additionally, generation requirements at most plants preclude the use of operating with pulverizers that are out of service for extended periods of time.

**Boundary (Curtain) Air**

Some low NOx burner systems utilize “Boundary” or “Curtain” air to reduce localized areas of reducing atmosphere that promote slagging, corrosion and tube wastage or as a NOx reduction technique. Boundary air is typically introduced through the boiler's lower dead air spaces or through openings below or around the burner zone periphery. Great care is usually taken to meter and control combustion air and pulverizer primary air with little attention to control quantity of boundary or curtain air flow. In some cases, excessive amounts of boundary or curtain air are experienced due to lack of measurement or control. This method of combustion air staging is not as
common due to the fact that if the boundary air is excessive, the burners can become combustion air starved leading to high carbon in the ash, localized slagging, excessive furnace O2 stratification, burner component overheating, as well as other adverse effects on performance.
Furnace Stoichiometry

Precise control of furnace stoichiometry is critical in any system that reduces NOx emissions through combustion controls. Furnace stoichiometry is typically controlled by oxygen analyzers at the boiler exit or economizer exit. Oxygen measurement at the boiler exit can often be inaccurate due to air in-leakage through the penthouse, nose arch dead air spaces, expansion joints and casing. Often boiler exit oxygen is 2.5% to 4% higher than furnace O$_2$ due to dilution of flue gas with ambient air in-leakage between the furnace exit and boiler exit. This results in 0% to 1% oxygen in the furnace cavity which is insufficient to facilitate complete combustion of carbon and can result in slagging, fouling, tube wastage, aggravation of coal-ash corrosion and other adverse effects. Quantifying air in-leakage or the relationship between furnace O$_2$ level and boiler exit oxygen should be considered of paramount performance on any unit utilizing low NOx burners. Furnace O$_2$ is usually ascertained using a water-cooled HVT probe at the furnace exit which is also used for accurate quantification of furnace exit gas temperature. Low NOx burners by design are fuel rich at the flame core. Test measurements within the flame envelope of a low NOx burner indicated that a short distance downstream on the burner, burner flue gas was 10% to 15% or 100,000 to 150,000 ppm carbon monoxide. An oxidizing furnace exit is mandatory for complete carbon burnout and the eradication of CO.
Burner Line Air and Fuel Imbalances

Combustion management and optimization naturally includes the pulverizer’s contribution of fuel and air to each burner. The primary air is responsible for drying the coal and pneumatically transporting the fuel to the burners. The resulting two-phase fuel / air mixture must be balanced in each individual burner line to facilitate proper mixing at the burners and to prevent imbalances in the furnace that would impede stoichiometric combustion. Primary air to each burner (dirty air flow) should be accurately measured and controlled to within ±5% deviation from the mean. Common mechanical, maintenance or operational variables that cause non-uniform combustion as a result of burner line fuel and/or primary air imbalances related to the pulverizer are:

- Non-synchronous opening of classifier blades on centrifugal classifiers
- Excessively worn classifier blades
- Excessive erosion or non-optimum length of the classifier outlet skirt or deflector
- Eroded through holes in classifier cones
- Excessively worn riffle
- Non-optimum riffle configuration or orientation
- Poor coal fineness
- Absence of coal line orifices to balance burner line air flow or worn orifices
- Obstructions in burner lines from repairs of eroded elbows
- Non-uniform or non-optimum spring force on grinding elements
Pulverizer Coal Fineness

Proper sizing of coal transported through the burner lines is mandatory to achieve low NOx formation with low NOx systems without unacceptable levels in unburned carbon in flyash. Fineness is a primary mechanism for controlling flyash L.O.I., however, it is also required to enhance rapid devolatilization of coal in which the burners depend upon to reduce NOx. Low NOx is facilitated through lower burner stoichiometry, less intense mixing of air and fuel at the burners, combustion staging or low excess air. All of these factors provide less abundance of O2 in close proximity to the coal, making complete combustion of char carbon more difficult. Due to this, previous fineness standards, which were typically 70% passing 200 Mesh and <1% remaining on 50 Mesh, must be increased to higher levels to compensate for less intense combustion associated with low NOx burner systems. Increases in coal fineness almost always results in more even distribution of coal between separate burner lines. More even distribution of coal results in more precise control of burner stoichiometry that is critical to reducing NOx and achieving the best possible burner performance. Some units are more or less forgiving to fineness depending on coal quality, furnace geometry and burner configuration. In all cases, a minimum of >75% passing 200 Mesh and less than 0.3% remaining on 50 Mesh should be maintained with low NOx firing.
Boiler Cleanliness

NOx emissions can vary greatly as ash or slag deposits build up on water walls or in the burner zone which increases furnace exit gas temperatures (FEGT) or local flame temperatures. All wall deslaggers and sootblowers should be operable with frequent maintenance and functional checks. Optimum sootblowing practices are also mandatory to prevent excessive furnace slagging or fouling. The following actions should be taken to ensure optimum furnace cleanliness:

- Ensure retractable (IK) sootblowers that clean the bottom side of the nose arch are operable and have a local steam blowing pressure of 200 to 225 PSIG. This is some of the most effective surface in the furnace. Sootblowers that clean the bottom of the nose arch are typically effective in reducing furnace exit temperature by 100 to 150°F (38-65°C). These blowers will also be effective in reducing reheater or superheater de-superheat spray flows.

- Ensure wall deslagger poppet valves are set to maintain a minimum blowing pressure at the blower of 200 PSI, 225 PSIG on wall deslaggers if slagging is apparent.

- Ensure all sootblowers and deslaggers are functional.

- If slagging or high furnace exit gas temperature is apparent, change wall deslagger gear drive limit pin setting from 360° rotation (1 revolution) to 720° rotation (2 revolutions).

- Ensure lances are not warped or misaligned. Misalignment or warped lances will cause binding. Binding will limit rotation and result in improper cleaning.

- Ensure lance nozzles or orifice(s) in the steam ports are not misaligned, missing, worn or coated with deposits. Misalignment or missing nozzles will handicap efficient removal of deposits.

- Verify blowing arcs. Sootblowers and wall blowers with one or two steam ports will usually release the blowing medium within a predetermined segment of rotation. Insure blowing medium is released when steam ports are facing tube surfaces.

- Ensure poppet valves and lance nozzles/orifices are of optimum sizing to deliver appropriate quantity of blowing medium.

- If aggressive sootblowing is required to reduce FEGT and slagging, ensure all thermal drains are operating properly, steam line insulation is intact and steam line slope is proper for effective condensate removal to prevent tube erosion.
Coal and Ash Quality

When evaluating the effect of coal quality on NOx emissions, fuel nitrogen content and fixed carbon/volatile matter content are often monitored closely without a great deal of attention to other factors. It is important to remember that other coal variables such as moisture, grindability index and ash fusion temperatures are also critical to unit performance and emissions. Changes in the Hardgrove Grindability Index (HGI) or fuel moisture will have significant impact on pulverizer capacity and fineness. Degradation in fineness as a result of lower H.G.I. coal or increased moisture can cause slagging problems, degradation in fuel balance and pulverizer surging which leads to less desirable NOx emissions and higher flyash L.O.I. Classifier changes, increased grinding element spring pressure, grinding surface “blue-printing” or other maintenance actions may be required to compensate for lower HGI coals. Differences in ash fusion temperature significantly changes furnace slagging propensity. A slagged furnace will result in less water wall absorption and higher furnace temperatures which can cause NOx emissions to demonstrate a gradual upward trend. When evaluating ash fusion temperatures, reducing and oxidizing fusion temperatures should be ascertained. Depending on ash constituents, primarily iron oxides and pyrites, oxidizing ash fusion temperature may be anywhere between 50°F and 300°F higher than reducing. For bituminous type coals there is typically a 100° to 175°F differential between reducing and oxidizing fusion temperatures. To prevent slagging, the furnace exit gas temperature at the nose arch should be well below the ash softening temperature. Accurate determination of furnace exit gas temperature requires use of a HVT Probe to quantify temperature peaks. Infrared and optical type pyrometers may be able to quantify average furnace exit gas temperature, but are unable to determine localized peaks in flue gas temperature. Utilization of the HVT Probe also allows quantification of oxygen to ensure no localized areas of reducing or near reducing atmosphere are present.

What is a Successful Low NOx Burner Retrofit?

A low NOx burner retrofit should not be considered successful unless good combustion efficiency, unit efficiency and operability are achieved. Combustion efficiency is usually gauged by flyash Loss on Ignition, while unit efficiency is measured by heat rate which is affected by numerous variables such as spray flows, cycle losses, dry gas losses, draft losses, etc. Operability would be regarded as unit response, unit capacity, flame stability, stack opacity, ease of operation and absence of “excursions” in unit load,
boiler pressure or steam temperatures. Achieving combustion uniformity in the burner zone is one of the most critical steps to achieving target NOx emissions and optimum performance; however, it is also one of the most difficult and time consuming endeavors. Achieving combustion uniformity in the burner zone includes the balancing of fuel, primary air and secondary air to each individual burner. Achieving high combustion efficiency with low NOx burners requires enhanced performance of each component in a combustion system. The combustion system includes burners, pulverizers, fans, all points of combustion air injection, boiler heating surface, the unit operators, and boiler maintenance personnel. Too often, boiler combustion is viewed from a macro perspective of total air to fuel ratio. Improvements are achieved by optimizing excess air and burner adjustments dictated by boiler exit gas species. Stratification at the boiler exit often show large variation in O\textsubscript{2}, NOx and CO levels. The large gradient in the products of combustion (O\textsubscript{2}, NOx and CO) is often caused by non-uniformity in combustion at the burners as a result of fuel and/or air imbalances. Individual burners create a multitude of local combustion zones that have vastly differing emission characteristics due to differing air to fuel ratios. Non-uniform combustion can lead to higher or non-repeatable NOx emissions. Maintaining uniform combustion requires uniformity in burner stoichiometry, which requires precise fuel and air balancing. Uniform combustion will result in similar heat release and emission characteristics of each individual burner. Non-uniform combustion can also result in other combustion related complications that lead to increased NOx emissions. Non-uniform combustion resulting from fuel and air imbalances in the burner zone are sometimes caused by mechanical or maintenance variables related to the pulverizers, burners, dampers or windbox. In other cases, non-optimum fuel balance or secondary air balance is inherent to the systems design and modifications must be made to reduce imbalances.