

Performance Testing and Modeling of an Advanced SNCR NO_x Control System

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ABSTRACT

This paper presents the results of an air-boosted SNCR NO_x control system installed on Progress Energy's L.V. Sutton Station Unit 3, a 1972 rear-wall-fired Riley boiler with low-NO_x burners (LNB) and over-fired air (OFA). The unit was originally designed to burn oil and was converted during construction to fire eastern-bituminous coal. There is insufficient residence time for complete coal combustion. Consequently, upper furnace temperature and CO concentration are variable and high, which made it challenging to design an SNCR system.

Mobotec's advanced SNCR system, Rotamix, uses boost air to carry urea deep into the furnace cross flow. High velocity air injection through multiple nozzles results in strong mixing and, therefore, high chemical utilization. NO_x was reduced from 0.54 lb/MMBtu at full load (410 MW_{net}) to 0.35 lb/MMBtu with an NSR of 1.0 while slip was maintained below 5 ppm. This equates to a 35% chemical utilization for NO_x reduction. Chemical utilization increased to 75% at lower loads due primarily to mixing. Computational fluid dynamic (CFD) modeling was performed for this boiler using advanced coal combustion and SNCR NO_x formation models. The fluid particle tracks clearly indicate significant mixing caused by high velocity air jets. The SNCR modeling shows similar NO_x reduction to field testing results at an NSR of 1.0, which demonstrated the potential to use modeling to optimize and design SNCR systems. The paper covers the system design, CFD modeling, and field-tuned results for this advanced SNCR system.

INTRODUCTION

Selective Non-Catalytic Reduction (SNCR) for further NO_x control is often applied to utility boilers that have already had low-NO_x burners (LNB) and/or over-fire air (OFA) systems.¹ SNCR systems typically use air injection to deliver the either urea or ammonia into the upper furnace as reducing agents for NO_x. Effective SNCR systems will depend largely on flue gas temperature, flue gas species, and mixing of the agent into the flue gas.

Mobotec's Rotamix with urea or ammonia injection is a third-generation SNCR system. The turbulent air injection and mixing provided by ROFA allows for the effective mixing of chemical reagents with the combustion products in the furnace. The result is the efficient introduction of chemicals directly into a well-distributed, rotating mixture. Through advanced feedback-control algorithms and on-site tuning, the Rotamix System adapts to changes in load and temperature in the furnace, and preferentially introduces chemicals where the temperature is most favorable for pollution reduction. This considerably reduces chemical consumption by increasing the efficiency of reactivity through mixing. Relative to other systems, Rotamix can decrease recurring chemical costs by up to 50%.

Mobotec has successfully applied ROFA and Rotamix technologies on many installations in the U.S. and Europe.^{2,3,4} This paper presents the details of a recent Rotamix installation on a 410 MW wall-fired unit. CFD modeling used to design the Rotamix system is also presented.

THE FURNACE DESCRIPTION

The furnace is a Riley rear-wall-fired unit. Originally this boiler was designed to burn oil, and as such, there is insufficient residence time for coal combustion. The unit routinely has upper furnace post-combustion, super heater tube temperature alarms, high CO, and overall poor combustion. For NO_x control, twenty eight B&W DRB-XCL Low-NO_x burners have been installed on the rear wall with seven B&W two chamber OFA ports on the front wall. Due to poor mixing between the OFA and the flue gas, deep staging for further NO_x reduction has been limited by post combustion leading to high upper furnace temperatures. Presently the unit burns eastern bituminous coal blended with bituminous coal delivered by barge from Venezuela. Coal quality further impedes efforts to stage for NO_x reduction.

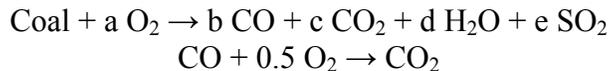
The geometric layout of the unit is unusual. Firstly, the rear-wall fired arrangement of the burners is not common. This arrangement puts the burners on the same side of the boiler as the nose and as such, does not benefit from the effect of the nose to increase in-furnace residence time. As shown in the CFD analysis, the coal leaving the second and third row of burners quickly traverses the furnace and proceeds up the front wall without sufficient in-furnace combustion residence time. Secondly, since the OFA ports are on the wall opposite the burners, much of the OFA misses the staged combustion that is moving up the front wall. This creates regions of high O₂ surrounded by regions of high CO (i.e., poor mixing), which in turn leads to post combustion in the upper furnace. Finally, the nose itself is more of an entry into a chimney section than a typical nose section. That is, there is a constriction in the furnace cross section at the nose which does not expand after the nose. This constriction coincides with the super heater pendants, creating high velocities (and short residence times) through the super heater pendants. In terms of designing an SNCR, the appropriate SNCR temperature window occurs very quickly within this chimney and complicates design.

CFD MODELLING

Computational Fluid Dynamics (CFD) modeling is used extensively in the Mobotec design process. The following section describes in detail the CFD modeling performed and the assumptions used.

Combustion Model Overview

FLUENT⁵ was chosen as the CFD code for this project because it is likely the best commercially available CFD package for this application and FLUENT has shown a continued commitment and support of the power generation industry. Grids (or meshes) used in the CFD simulations are first constructed using FLUENT's companion software, GAMBIT. Once realistic, high-quality grids have been created that match high local grid densities to regions where strongly dynamic physical processes are anticipated to occur and boundary types have been applied to appropriate surfaces, the grid/mesh is exported to FLUENT. A steady state solution is iteratively solved to determine the density, velocity, temperature, and species (including coal volatiles) concentration for gas and particle phases. The gas phase conservation equations are solved using a variable density, quasi-incompressible formulation embedded in an Eulerian reference frame. The governing equations are the gas phase continuity, momentum, turbulent kinetic energy, turbulent dissipation, enthalpy, and the species conservation equations for each gas species in the turbulent combustion model. These conservation laws have been described and formulated extensively in standard CFD textbooks. A k-ε turbulence model was chosen for our simulations. Standard Eddy-Breakup (EBU) turbulence combustion model was used. The following two step mechanism was utilized



where the stoichiometric coefficients (a, b, c, d, and e) were determined from the fuel proximate and ultimate analyses. For lower temperatures found in the back-pass, a rate-limited modification to the carbon monoxide reaction is also included to more accurately predict CO oxidation.

The CFD model solves the particle/liquid phase (coal and water/urea) in a Lagrangian reference frame. The gas phase and particle phase conservation equations are solved separately by FLUENT in order to make the calculation more tractable; however, these two phases are strongly coupled through iterative updates of the source terms that occur less often than the iterative updates of the gas phase variables. Particle motion is obtained through solutions of the bulk gas velocity. Turbulent dispersion of particles was modeled with the stochastic discrete-particle tracking approach. In the stochastic tracking approach, FLUENT predicts the turbulent dispersion of particles by integrating the trajectory equations for individual particles, using the instantaneous fluid velocity, along the particle path during the integration. By computing the trajectory in this manner for a sufficient

number of representative particles, the random effects of turbulence on the particle dispersion are well represented.

FLUENT (v6.2) provides the capability to model thermal-NO_x, prompt-NO_x, and fuel-NO_x formation. It is also capable of modeling NO_x reduction on char surface and by reburning with SNCR systems. The NO_x sub model involves sophisticated fuel-N conversion pathways. After fuel devolatilization, fuel-N is partitioned into volatiles-N and char-N. HCN is the dominant nitrogen species in volatile-N released from coal. Char-N is released into the gas phase at a rate that is proportional to the carbon burnout rate. Because char-N conversion chemistry is complex, we used a fixed fraction of char-N directly converted to NO with the rest of N converted to N₂. This assumption is used often.⁶ The gas phase NO can be reduced by CO, on the char surface, or through ammonia/urea injection.

Modeling of urea-based SNCR system has been performed by a number of groups over the last decade.^{7,8,9} There has been three typical approaches in SNCR NO_x chemistry modeling: 1) full chemistry modeling using Chemkin, 2) reduced mechanism, and 3) simplified chemistry modeling. The first and second approaches involve tremendous computational time, and therefore, are not practical to use for design. The simplified multi-step mechanism proposed by Brouwer et al.⁹ with kinetics determined by Rota et al.¹⁰ is used in our work. FLUENT (v6.3) has incorporated this SNCR urea chemistry. We have validated it against several full scale cases.

Geometry

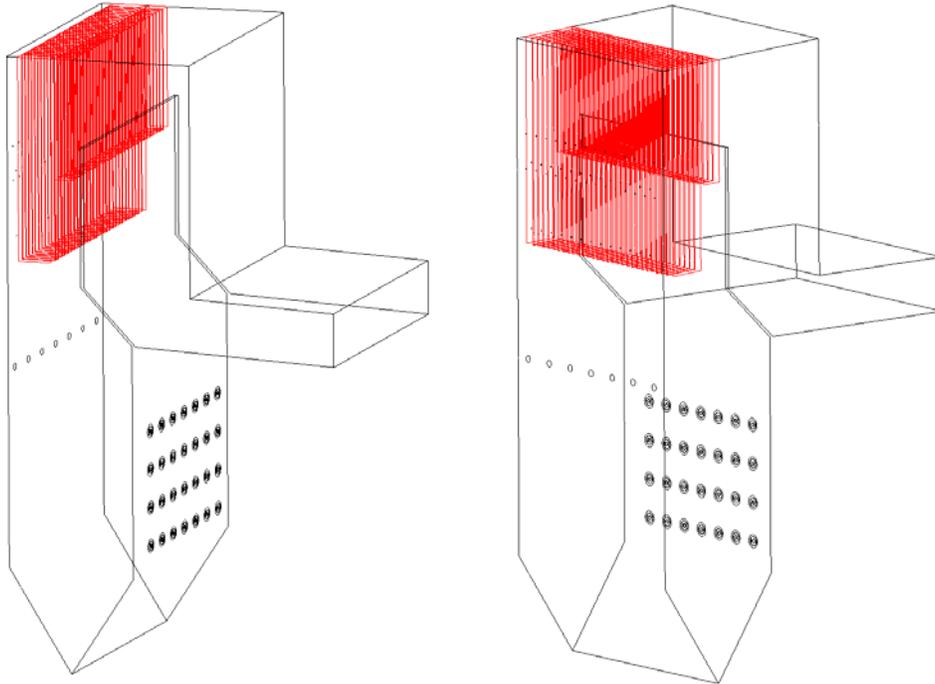
The unit geometry and CFD mesh are shown in Figure 1. Furnace geometries were taken from the original furnace drawings. The furnace geometry was represented in the computer model with approximately 780,000 computational cells in an unstructured, hybrid (tetrahedral and hexahedral) grid.

The radiant furnace is defined as beginning at the burner throat or OFA face (inlet boundary conditions) and ending at the vertical rear wall screen tubes at the top of the furnace (outlet boundary condition). The CFD model domain includes the entire radiant furnace (extending down to the ash hopper) and the grid structure is continued through the back pass, down to the economizer, and well into the duct work. This portion of the furnace is included to represent the correct fluid flow field in the upper furnace as well as to stabilize the numerical solution by preventing any reverse flow or recirculation at the exit boundary.

The superheat and reheat pendants are included in the model to account for heat absorption and flow stratification. Due to computational restraints (time and resolution) the superheat (SH) and reheat (RH) pendants are depicted by panels and not banks of individual tubes. The SH and RH panel wall temperatures are adjusted (within reason) to match the heat transfer rate indicated by the steam temperature change (enthalpy increase) measured by the plant. After the radiant furnace, no internal heat transfer surfaces are modeled (e.g., the

economizer). As such, results for NO_x are calculated at the exit of the radiant furnace (not the exit of the CFD model domain). We have conservatively assumed that the temperature at the exit of the radiant furnace has dropped sufficiently such that there is little ongoing NO_x reduction chemistry past this point.

Figure 1: The CFD domain (left) of the furnace and surface mesh (right).



Model Inputs

Key inputs for the furnace CFD simulations are listed in Table 1. The input coal composition, properties, and grind (fineness) are given in Table 2. The coal flow (318 kpph) and firing rate (3952 MMBtu/hr) were obtained from the heat rate, gross load (MWg), and the coal energy content (higher heating value) from a sample analysis.

The coal was assumed to be uniformly distributed to the burners. While spin vane and impellor differences were modeled, burner-to-burner coal and air imbalances were not modeled. Earlier modeling has shown that when burner-to-burner imbalances are modeled, it does not improve the SNCR prediction capabilities of the model. Inner and outer secondary air velocities, splits, and swirls were calculated based on the spin vane positions. Primary air swirl was based on impellor settings.

Table 1: System Data

| Parameter | | |
|------------------------------|------------|-------|
| System Firing Rate | [MMBtu/hr] | 3952 |
| System Load | [MW gross] | 425 |
| System Excess Air | [%] | 17.2 |
| System Excess O ₂ | [% dry] | 3.1 |
| System Coal Flow | [kpph] | 317.7 |
| System Air Flow | [kpph] | 3566 |
| Burners out of service | | None |

Table 2: Coal Analysis and Fineness

| | | |
|---------------------------|-----------|-------|
| <i>Proximate Analysis</i> | | |
| Volatiles Matter | [wt % ar] | 32.92 |
| Fixed Carbon | [wt % ar] | 50.12 |
| Moisture | [wt % ar] | 7.19 |
| Ash | [wt % ar] | 9.78 |
| HHV | [Btu/lb] | 12456 |
| <i>Ultimate analysis</i> | | |
| C | [wt % ar] | 69.75 |
| H | [wt % ar] | 4.72 |
| O | [wt % ar] | 6.28 |
| N | [wt % ar] | 1.42 |
| S | [wt % ar] | 0.87 |
| <i>Fineness</i> | | |
| < 297 um (50 mesh) | [wt %] | 98.9 |
| < 149 um (100 mesh) | [wt %] | 91.8 |
| < 74 um (200 mesh) | [wt %] | 69.9 |

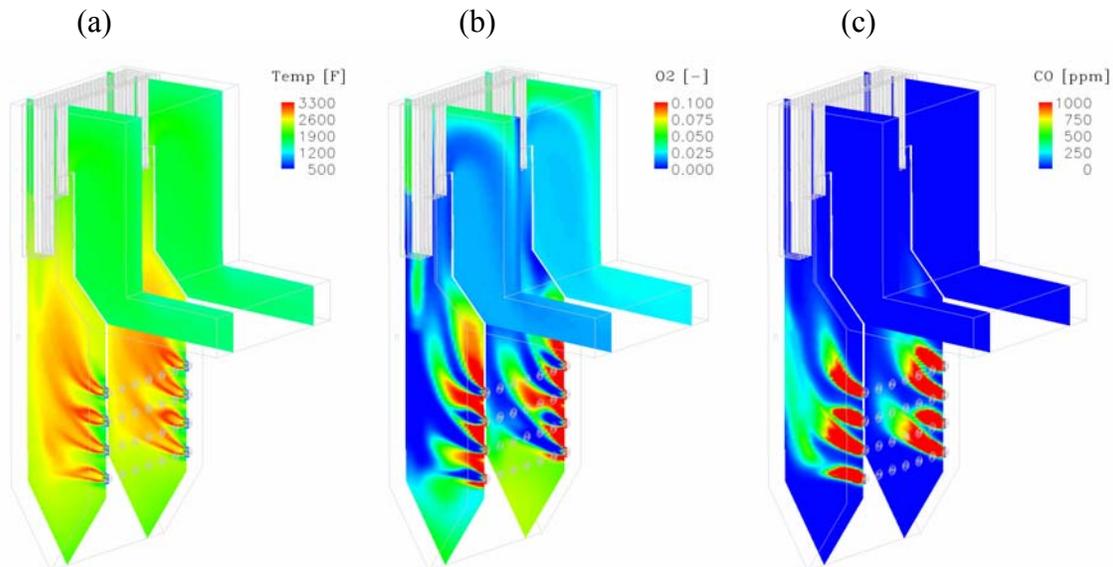
The total air flow (3556 kpph) at the given firing rate was calculated from the coal composition, coal flow rate, and an expected excess O₂ of 3.1% (dry). The coal carrier air (primary air) flow rate was based on a primary air to coal weight ratio of 1.4, which is 12.5% of the total air at 180°F. The resulting carrier air velocity was approximately 72 ft/s. The remainder of the combustion air, minus the OFA flow, was distributed to the secondary air registers at 622°F.

Burner swirl patterns and the firing configuration were implemented in the model by setting inlet boundary conditions. All coal nozzles were modeled with 25° coal spreader angles. The OFA flow was based on Pitot tube measurements. The distribution of air to the OFA system was assumed to be uniform to each port; i.e., OFA port biasing was not included in the model.

Modeling Results

The temperature distribution at two vertical planes appears in Fig. 2a. The maximum flame temperature in the baseline furnace is about 3300°F. The temperature distribution also indicates that coal ignites soon after being injected into the furnace, which is consistent with the observation of the furnace operation through view ports. Along the cross section of each burner, the ignition first occurs on the boundary between the primary flow and the surrounding flow. The flame then propagates and expands as flow continues into the center of the furnace. It is also observed that the center of the bulk coal flame is biased towards the front wall. Most of the coal combusts in the half of the furnace close to the front wall. This is due to relatively high secondary air (SA) and primary air (PA) velocities.

Figure 2: Gas temperature (a), O₂ (b) and CO (c) distributions at two vertical planes.



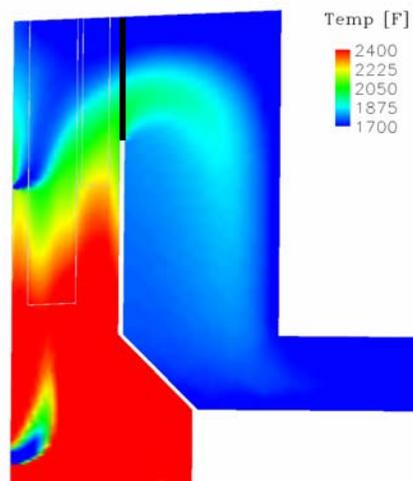
The biasing of the combustion to the front wall can also be seen from the O₂ distribution in Fig. 2b. In the region between the burner zone and the nose, the O₂ concentration is virtually zero along the front wall (opposite the burners and below the OFA).

Due to the O₂ distribution in the lower furnace, CO is burned slowly and persists downstream of the nose as shown in Fig. 2c. The formation of CO initiates near the burners, and the concentration persists along the fuel stream into the furnace. As secondary air mixes with the primary fuel stream, CO concentration reduces and dips. The average CO concentration at the furnace exit is approximately 20 ppm. There are zones of high CO between some of the pendants, in particular the pendant gaps that are not directly above an OFA port.

The upper furnace temperature is shown in Fig. 3 with a temperature scale from 1700°F to 2400°F. Since urea chemistry for NO_x reduction is best within a temperature window of

1700°F and 2000°F, this temperature scale best shows the region of the furnace that is available for SNCR NO_x reduction. Note that urea can be injected into temperatures exceeding 2000°F due to the time delay for mixing. In Fig. 3, the cooling effect of the Rotamix jet is clearly evident, as is the penetration of the jet.

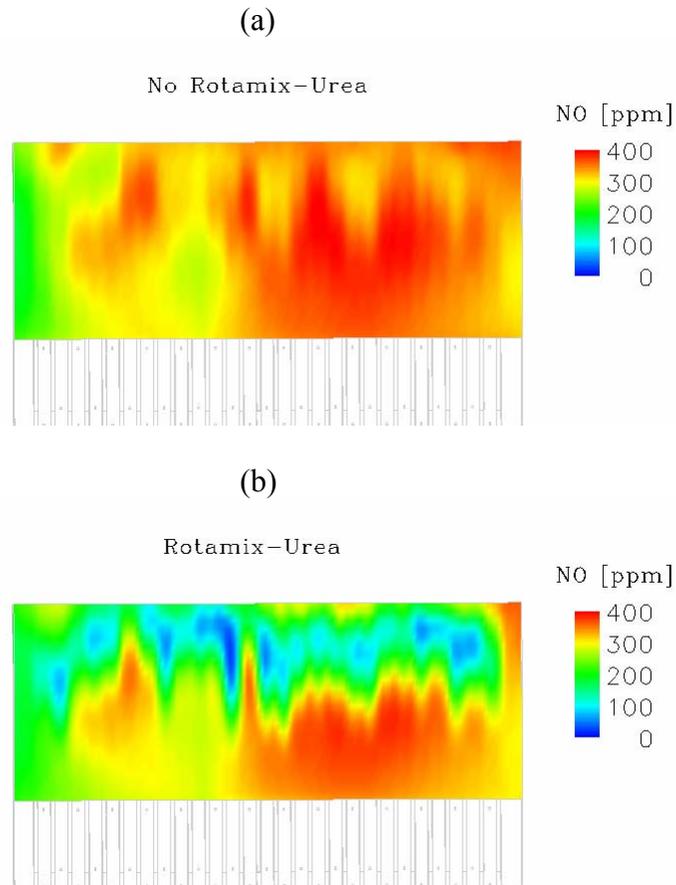
Figure 3: Predicted temperature distribution in the upper furnace. The vertical black line indicates the exit plane of the radiant furnace.



The SNCR chemical kinetic CFD NO_x calculation was performed and the results are presented in Fig. 4, where the NO concentration at the exit of the radiant furnace is compared with that without urea injection. In Fig. 4b, it is clear that NO_x has been reduced relative to Fig. 4a. Nowhere in Fig. 4b is the NO_x reduced to zero. Blue and teal coloring shows where the majority of the NO_x reduction occurs. Much of the green coloring also indicates significant localized NO_x reduction.

The total predicted NO_x reduction is 32% for this case. It is quite apparent that this 32% reduction is occurring across a localized area, representing less than 50% of the cross section of the boiler. This suggests that more NO_x reduction would be possible if the injection strategy could reach these locations. For this unit, the increased cost to pursue more NO_x reduction was not justified due to the difficulty of injecting urea into the back pass (around the nose and through the side walls within the super heater pendants); but this decision must be made on a unit-by-unit basis.

Figure 4: NO concentration without (a) and with (b) urea injection at the exit of the radiant furnace (indicated by the black line in Figure 3).



ROTAMIX SYSTEM

The Mobotec Rotamix system reduces NO_x emissions by injecting urea into the upper furnace. Urea is the preferred SNCR chemical for larger units as it preferentially vaporizes slower than water. When mixed with water and injected into the furnace, the urea is well mixed before becoming chemically active. While all urea SNCR systems utilize this feature, Rotamix contains several distinct advantages over other commercially available SNCR systems:

- 1) Rotamix uses a boosted-air delivery system to transport the urea deep into the furnace flue gas cross flow.
- 2) Rotamix uses lance-by-lance flow control, which is continuously biased by a computational feedback-control algorithm to continuously tune the system to reduce NO_x and slip simultaneously, reacting to coal changes, soot blowing, and load

- 3) Rotamix implements duct humidification of the boost air, which allows an additional control parameter for timing the chemical availability of the urea to the appropriate NOx reduction chemistry temperature window

These traits will be described in more detail in following sections.

Rotamix Design

In this section, Rotamix design challenges and details are reviewed for Mobotec's Rotamix system as applied to the Sutton Unit 3 boiler. Specifically, there are well known design parameters that affect the efficacy of an SNCR system; these include (among others): (1) reaction temperature, (2) chemical mixing or dispersion, (3) reaction residence time, (4) CO chemical interferences, and (5) transient operation.

Temperature

Urea, mixed with water, and injected into the furnace quickly heats up, preferentially vaporizing the water away from the droplet. When most of the water is gone, the urea vaporizes (or sublimates) to a gas phase and almost immediately thermally decomposes into HNCO and NH₃.¹⁰ These two species are the gas phase reducing species for NOx reduction. Ammonia (NH₃) is well known to reduce NOx. Isocyanic Acid (HNCO) also reduces NOx, but at a slightly higher temperature. Relative to ammonia alone, urea is a superior SNCR chemical on large hot units because the urea vaporizes after most of the water vaporizes. This delays the introduction of HNCO and NH₃ and allows for more mixing (and flue gas cooling) before becoming chemically reactive.

In SNCR design, the goal is to expose all of the urea to as much of the flue gas at temperatures between 1600°F and 2100°F. Above this temperature range, the urea will actually react to form NOx. Below this temperature range, the HNCO and/or NH₃ will "slip". Slip is when unreacted chemical escapes the hot furnace at high enough concentration to cause downstream problems. Problems from too much slip include binding with SO₃ to form ammonium bisulfate (which agglomerates in the air heater as pluggage), condensing into the ash (which causes ash odor and concrete problems), or forming a stack plume. Limiting the NH₃ slip to 5 ppm or even 2 ppm sufficiently eliminates these problems, but also limits the amount of NOx reduction that a given SNCR system can provide.

Mixing

While residence time and reaction temperature are clearly important, they are limited by mixing. A properly designed system that implements a high degree of mixing will inject the urea well upstream of the appropriate temperature window with enough water and humidification to allow superior mixing such that the urea becomes chemically available to reduce NOx (as NH₃ and HNCO) just as the appropriate temperature window as been

reached. A cursory glance at Figure 4 will clearly show that mixing is indeed important for increased NO_x reduction. However, even with the superior mixing provided by Rotamix, it is often impractical to exceed 40% or 50% NO_x reduction due to geometric challenges in the boiler.

Residence Time

In order to reduce NO_x, the reagent must certainly be well mixed and at the right temperature. Further, there must be sufficient residence time for the reaction to take place. In particular, at the lower end of the temperature window, if there is not sufficient residence time for reaction, the unreacted reagent will result in slip and not NO_x reduction, even if it was well mixed and within the design temperature window. This is particularly important for large units that have high quench rates through the appropriate SNCR reaction temperature window.

Carbon Monoxide

Carbon Monoxide (CO) disrupts urea/NO_x reduction chemistry⁹ and should be taken into account when designing an SNCR system. Mobotec chooses to do this through CFD modeling which includes CO chemistry effects for design and feedback control for tuning. Excessive CO concentrations in the vicinity of the urea chemistry will effectively reduce the reaction temperature window⁹. Variation in CO (puffs) will narrow the available temperature window for SNCR NO_x reduction (limited by slip on the cold side and effective NO_x reduction on the hot side). Rotamix further helps CO problems by providing localized air that can offset excessive CO by oxidizing the CO to CO₂ as the urea is mixing/reacting.

Transient Behavior

Any dynamic SNCR system needs to be able to respond to transient behavior in the boiler. Mobotec performs this through active feedback control on slip and NO_x to account for short term furnace changes such as soot blowing and through AI control on individual lances to account for longer term furnace temperature issues such as coal changes.

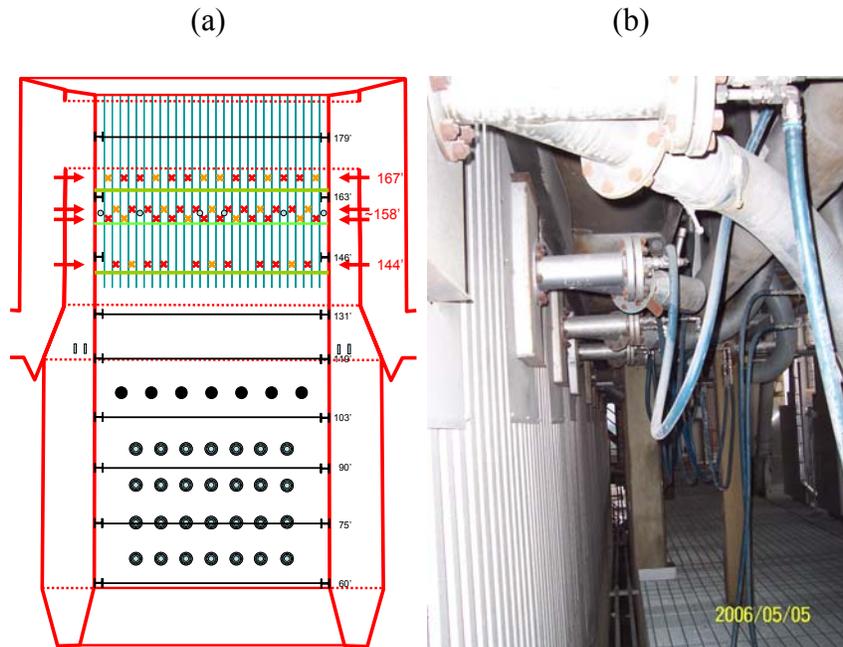
Key design components

Taking the above discussion into consideration, the key design components for Rotamix include (1) urea injection as opposed to ammonia, specifically for large, hot boilers, (2) boosted-air mixing for superior chemical dispersion and penetration into the flue gas, (3) high velocity carrying air with velocities sometimes exceeding 150 m/s, and (4) high kinetic energy to promote downstream mixing through turbulent dissipation. Each of these design components are analyzed using the CFD model.

Rotamix System Description

The Mobotec Rotamix system reduces NO_x emissions by injecting urea at a fixed concentration through a number of injection points on the furnace. On this unit, fifty injection locations along the front wall were installed. Often fewer nozzles are required; however, for this installation, there were many pendants near the front wall that resulted in more boiler penetrations. The location of the nozzles is shown in Fig. 5. Note that not all locations were installed during initial start up. The port colors (yellow and red) indicate which penetrations were used initially (red). During tuning many of the yellow ports were also tested. The final tuned locations included many more ports at the 158-ft elevation being used than at the 167-ft elevation due to the temperature. Fig.5b shows a photo of the Rotamix boxes along the 144-ft elevation.

Figure 5: Rotamix injectors on front wall (a) and an injector photo (b).



Urea flow to each lance is controlled as a function of boiler load. Anywhere from 8 to 25 lances can be in operation at a given load. A separate humidification water supply is delivered to any Rotamix box that is in service. A lance water rinse is performed whenever a urea lance is taken out of service. Urea is stored in two (redundant) 50,000 gallon vertical tanks at a urea concentration of 40% to 50%. The urea is further diluted with water to no less than 21% prior to being injected into the boiler. The mixing of the urea and water occurs online in the Rotamix cabinet prior to injection. Urea concentration is continuously measured with a density meter.

Air at ambient temperature is supplied to the Rotamix boxes from two (redundant) fans. The urea lances are also supplied with cooling air, separate from the Rotamix air, to provide cooling when the lance is out-of-service and urea isolation to prohibit leaking and corrosion.

Rotamix equipment controlled and monitored by the Mobotec process control system includes the following:

- 1) Rotamix fans (x2) pressure with modulating inlet dampers
- 2) Lance cooling air blowers (x2) pressure
- 3) Urea storage tank level
- 4) Urea feed pumps (on/off)
- 5) Dilution water holding tank level
- 6) Dilution water feed pumps (on/off)
- 7) Humidification water holding tank level
- 8) Humidification water pumps (on/off)
- 9) Rotamix cabinets for mixing, dilution, and individual lance metering of urea
- 10) Humidification cabinets for individual lance metering of humidification water

At each Rotamix box, the Rotamix air is first humidified and then injected with urea. The humidified Rotamix air transports the urea into the furnace and mixes well with the combustion products before the urea fully vaporizes. Varying the amount of humidification of the Rotamix air further controls the timing of the release of the urea through control of the vaporization of the water mixed with the urea.

Pressure that drives the flow of urea, dilution water, and humidification water comes from three different pump skids. Each pump skid has two (redundant) multi-stage centrifugal pumps. There are two (redundant) filters. Each pump skid has a back pressure regulator to provide a constant pressure and to provide recirculation during low flow operation to ensure that the pump does not stall. A differential pressure indicator has been provided across the filters to indicate when the filter element needs replacing.

RESULTS AND DISCUSSION

CFD Model versus Field Data

The CFD model prediction for SNCR NO_x reduction is compared with the full load field data in Table 3.

CFD Model. The CFD model was setup with a urea flow corresponding to an NSR of 1.0. Without urea, the NO_x was 0.50 lbs/MMBtu (338 ppm). With Urea this was reduced to 0.34 lb/MMBtu (232 ppm), which is a 32% NO_x reduction. Since the HNCO reaction

chemistry occurs at a slightly higher temperature than NH₃, the HNCO makes up most of the predicted slip (16.5 ppm).

Table 3: Comparison of SNCR Results between CFD Model and Field Data.

| <i>NOx Results</i> | | CFD Model | Field Data |
|--------------------|------------|-----------|------------|
| Baseline NOx | [lb/MMBtu] | 0.50 | 0.54 |
| SNCR-NOx | [lb/MMBtu] | 0.34 | 0.35 |
| NOx Reduction | [%] | 32 | 35 |
| <i>Urea Usage</i> | | | |
| NSR | [-] | 1.0 | 1.0 |
| Urea wt% | [%] | 21 | 21 |
| Slip | [ppm] | 16.5 | <10 |

Field Data. The tuned field results from the full-load Rotamix system achieved NOx reduction from 0.54 lb/MMBtu to 0.35 lb/MMBtu with a urea NSR of 1.0. This corresponds to 35% reduction, which is very close to the 32% reduction predicted by the CFD model. The NH₃ slip in field data was continuously monitored by a laser slip meter and the feedback control loop kept the NH₃ slip below 2 ppm at all times. The HNCO slip was likely higher than 2 ppm, but probably did not exceed 10 ppm. Measured slip and predicted slip were very similar.

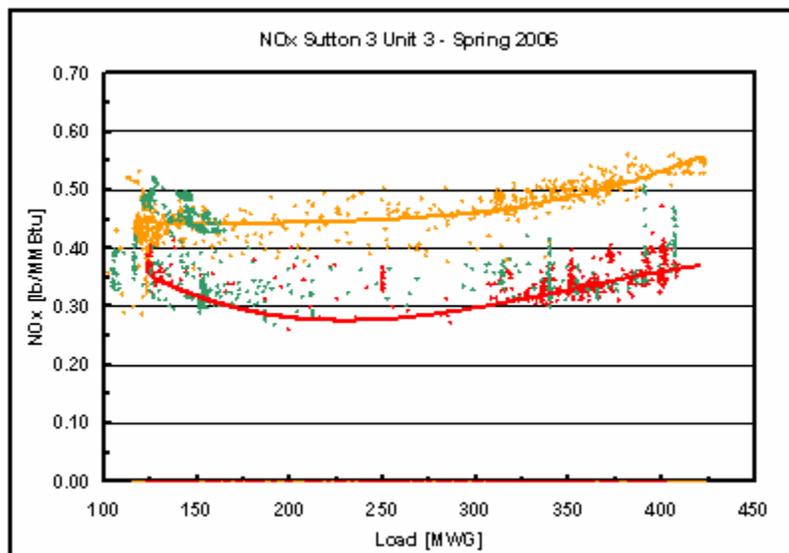
The CFD modeling results in Table 3 represents the “as tuned” Rotamix settings. Actual Rotamix air flow, urea flow, and water flow were modeled. During the design process, CFD modeling was performed with different settings and achieved similar results (though not as good). This is often the case where the tuners are able to perform better than the CFD model as they have many more design/tuning iterations available.

Field Performance Results

Figure 6 shows PI data from April and May 2006. Since the 2006 ozone season started the beginning of May, this data includes pre-ozone season (Rotamix out of service) and ozone season (Rotamix in service). Additionally, some start-of-the-season tuning was being performed during late April and early May.

When Rotamix was out of service, the NOx varied from 0.54 lb/MMBtu at full load to 0.45 lb/MMBtu at low load (150-200 MW) and is indicated in yellow on Fig. 6. When Rotamix was in service, the NOx reduction was maintained around 35% across load (as indicated in red) for all but below 200 MW. Green symbols indicate data taken during tuning.

Figure 6: Sutton 3 NOx emission versus load before and after Rotamix installation.



The lack of NOx reduction at low load was part of the design tradeoff to reduce costs and occurs since fewer ports were installed at the low load elevation. This is reasonable because regulations heavily favor high load NOx reduction over low load NOx reduction and this unit rarely runs at low load.

Chemical Utilization

Taking the yellow and red correlations (lines in Fig. 6) for NOx with Rotamix in (red) and out (yellow) of service from Fig. 6, and combining this information with urea flow rate, gives the data in Fig. 7, which shows the NSR, chemical utilization, and reduction percentage versus load. With similar reduction percent, the NSR at high load is 1.0, but is reduced to 0.5 at low load. The calculated urea chemical utilization is 35% at full load, and increased to a maximum of 75% at 230 MW load.

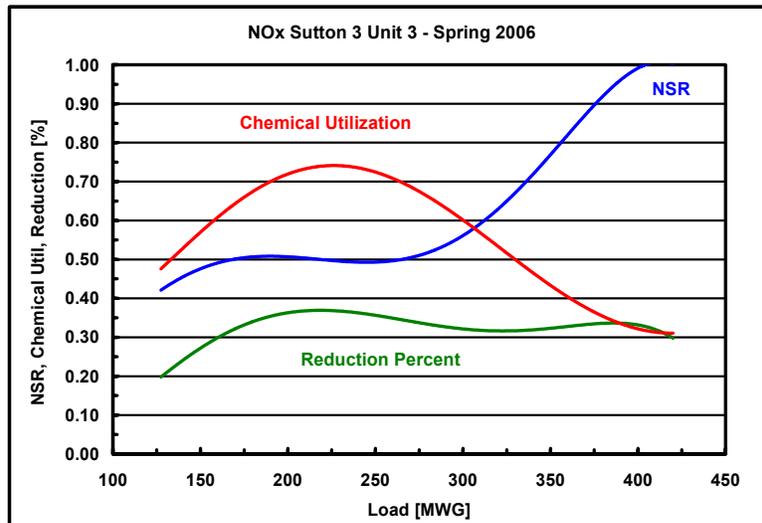
The better chemical utilization at lower loads is mainly attributed to longer chemical reaction time at the right temperature. Since the flue gas flow rate generally scales with load, at 50% load there is one-half the flue gas flow and the residence time of the flue gas through the pendants (near the SNCR system) is longer.

Financial Payback Analysis

At full load (3952 MMBtu/hr), Rotamix-SNCR reduced NOx from 0.54 lb/MMBtu to 0.35 lb/MMBtu. This is equal to 751 lb of NOx reduced per hour. Over the North Carolina 12-month ozone season (starting January 2007) with a capacity factor of 80%, this results

in 3426 tons of NOx reduced per year. With NOx credits trading at \$2000/ton, this generates \$6.9 million per year of revenue.

Figure 7: Sutton 3 Rotamix system NSR, chemical utilization and reduction versus load.



The recurring cost for Rotamix is primarily the chemical cost. Relative to the chemical, parasitic fan losses are negligible. With an average NSR of 0.9 across load and a delivered price for 50-wt% urea of \$0.62/gal, the chemical costs are equal to \$436 per ton of NOx removed, or \$1.5 million per year.

The capital (installation) cost associated with installing Rotamix as a stand-alone SNCR system can vary between \$5 and \$10/kW. For this installation, the payback was less than six months. Even at \$10/kW, the payback is less than a year.

Clearly there is a cost advantage to using an SNCR to reduce NOx. These advantages are even more pronounced when NOx credit costs climb to above \$3000/ton. Relative to other SNCR systems, Rotamix uses approximately one-half of the reagent, which results in a shorter payback period.

CONCLUSIONS

Mobotec installed Rotamix, an air-boosted SNCR NOx control system on Progress Energy's L.V. Sutton Station Unit 3. The unit has low-NOx burners (LNB) and over-fired air (OFA) and so Rotamix was installed as a stand-alone system. Rotamix uses high velocity boost air and multiple air nozzles to carry urea deep into the furnace cross flow.

NO_x was reduced 35% from 0.54 lb/MMBtu at full load to 0.35 lb/MMBtu. Slip was maintained below 5 ppm. Urea was injected at an NSR that varied from 0.5 at low load to 1.0 at high load. The low chemical usage results in a very low recurring chemical cost for continued NO_x reduction.

CFD modeling was used extensively during design. Results from an “as tuned” model are presented relative to the tuned NO_x data, with good correlation. This, and other validation studies, has helped us design SNCR systems resulting in low-risk, NO_x-reduction installations.

REFERENCES

1. Stallings, J., “Cardinal 1 Selective Non-Catalytic Reduction (SNCR) Demonstration Test Program.” EPRI Final Report, July 2000
2. Ralston, J., et al. “Injection of Urea through the Rotamix System to Obtain Improved NO_x Reduction – Summary”, presented at the 2003 DOE/NETL Conference on Selective Catalytic Reduction and Selective Non Catalytic Reduction Technologies.
3. Coombs, K., Crilley, J., Mark S., Higgins, B., “Installation and Operation of the ROFA/Rotamix MobotecSystem at Dynegy Midwest Generation's Vermilion Power Station Unit #1” 01/26/05 at the EUEC conference.
4. Haddad, Crilley, and Higgins, “The Viability and Economics of Adding a ROFA/Rotamix MobotecSystem to a Selective Catalytic Reduction (SCR) Installation,” NETL/DOE 2003 Conference on SCR and SNCR for NO_x Reduction, Pittsburgh, PA October 29-30, (2003)
5. FLUENT (v6.2) Manual, Fluent Inc.
6. Niksa, S., and Liu, G.-S., “Incorporating detailed reaction mechanisms into simulations of coal-nitrogen conversion in p.f. flames”, Fuel 81(18), pp. 2371-2385 (2002).
7. Han, X., Wei, X., Schnell, U., Hein, K.R.G., ”Detailed modeling of hybrid reburn/SNCR processes for Nox reduction in coal-fired furnaces.” Combustion and Flame, 132: 374-386 (2003)
8. Cremer, M.A., Montgomery, C.J., Wang, D.H., Heap, M.P., Chen, J-Y, Proceedings of the Combustion Institute, 28: 2427-2434 (2000)
9. Brouwer, J., Heap, M.P., Pershing, D. W., and Smith, P. J., Proceedings of the Combustion Institute, 26: 2117-2124 (1996)
10. Rota, R., Antos, D., Zanoelo, E., Morbidelli, M., “Experimental and modeling analysis of the NO_xOUT process.” Chemical Engineering Science, 57: 27-38

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