Design and Demonstration of Rich Reagent Injection (RRI) for NOx Reduction at Conectiv's B.L. England Station

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ABSTRACT

This paper summarizes the design and application of Rich Reagent Injection (RRI) at Conectiv's B.L. England Unit 1, a 138 MW cyclone-fired boiler. Installation of overfire air (OFA) has reduced uncontrolled NOx emissions from ~1.2 lb/MMBtu to ~0.5 lb/MMBtu. An existing SNCR system reduces these emissions an additional 30%. Based on previous modeling of the OFA system, REI's combustion simulation software was used to design an amine-based injection system for the staged lower furnace and to evaluate NOx reduction performance of the RRI system. Field-testing confirmed modeling predictions and demonstrated that the RRI system alone could achieve 25-30% NOx reduction beyond OFA levels with less than 1 ppm ammonia slip and that RRI in combination with SNCR could achieve 50-55% NOx reduction with less than 5 ppm slip. The capital costs associated with an RRI system are consistent with those of SNCR.

INTRODUCTION

Previous research has shown that the injection of NH_3 or urea into the high temperature NOx-containing flue gases, using normalized stoichiometric ratios (NSR) of 1 to 4, can lead to noncatalytic NOx reductions of 80% under idealized conditions[1,2]. With support from and direction from EPRI's Cyclone NOx Control Interest Group (CNCIG), Reaction Engineering International (REI) has developed, implemented, and tested an enhanced chemistry model with their proprietary Computational Fluid Dynamics (CFD) code *GLACIER* to simulate this process, named Rich Reagent Injection (RRI). Numerical and experimental investigations have shown the potential for significant NOx reductions, with little to no ammonia slip, in cyclone fired furnaces utilizing RRI.

Studies carried out by CNCIG suggest that the staging the cyclone barrels to operate the lower furnace fuel rich reduces NOx that is formed in the barrel, within the lower furnace. This is in contrast to normal unstaged operation where NOx is formed, not destroyed, in the furnace. When the barrel is operated fuel rich, NOx reduction rates are high near the barrel outlet but in the vast majority of the lower furnace volume they become very slow. Consequently, there is a small benefit in NOx reduction if the vertical distance between the OFA ports and the top row of barrels is increased. The concept of RRI, applied to staged cyclone fired furnaces, is to use a nitrogen-containing additive to increase the NOx reduction rate in the lower furnace (See Fig. 1). The conditions in the lower furnace of a staged cyclone furnace are within the range that could make the concept very attractive.

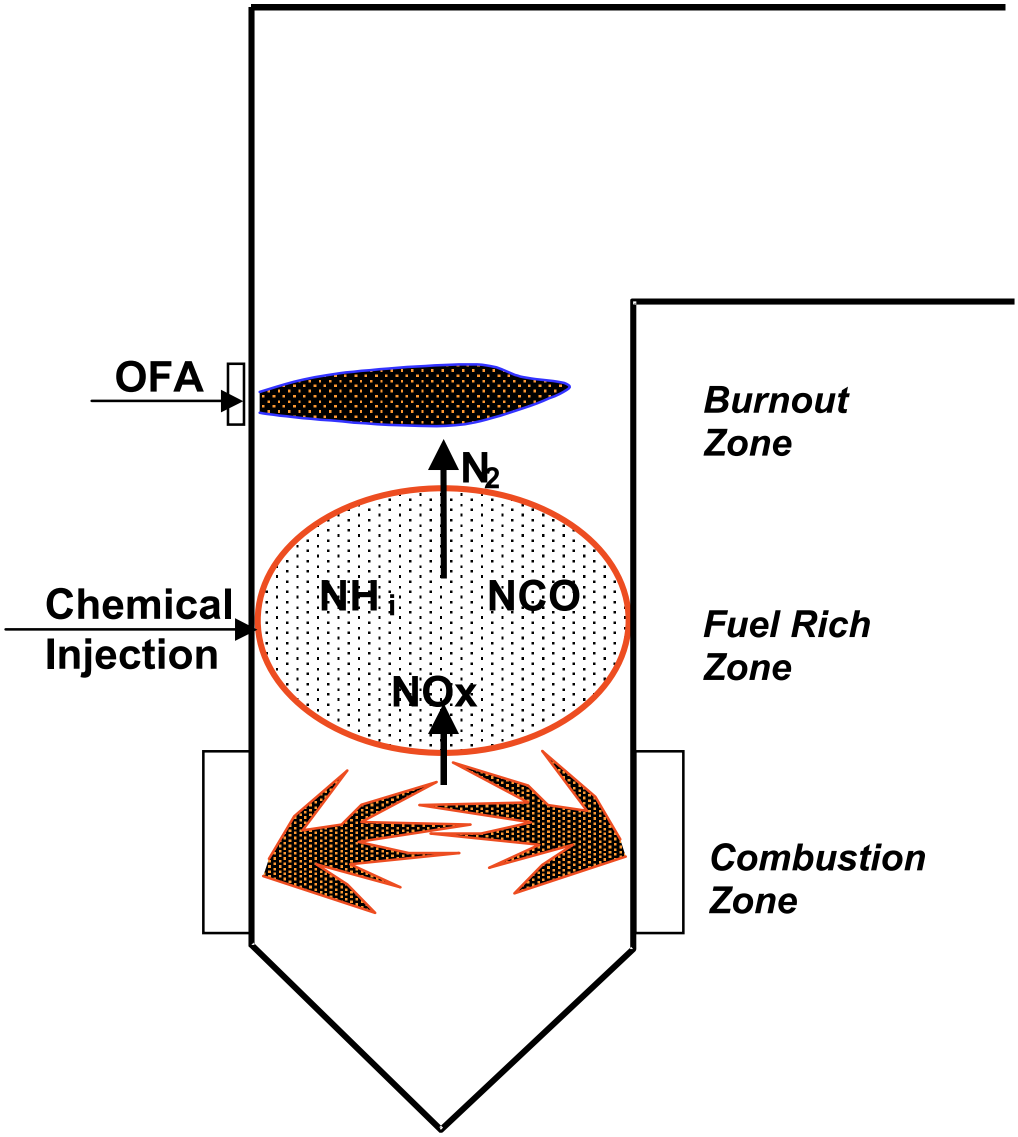
Prior to the full scale demonstration discussed in this paper, REI carried out several investigations to determine the potential for significant NOx reduction in cyclone fired boilers. These investigations included:

- Detailed chemical kinetic calculations under perfectly mixed conditions
- Bench scale testing in a 0.1 MMBtu/hr facility
- Pilot-scale testing in a 5 MMBtu/hr facility

The bench scale testing was conducted in the University of Utah's 0.1 MMBtu/hr "U-furnace" facility using anhydrous ammonia reagent at burner stoichiometric ratios of 0.90, 0.95, and 1.0[3]. The furnace was fired with a fast mixing natural gas burner. Measured reductions in NOx of up to 68% were measured. The detailed chemical kinetic calculations that were performed[3] showed that as the stoichiometric ratio increases, the optimal gas temperature decreases. In all U-furnace cases, the gas temperatures were most likely too low for maximum effectiveness.

Pilot scale testing of the RRI process in a 5 MMBtu/hr facility (L1500) at the University of Utah showed reductions in furnace outlet NOx of up to 90% by injection of either aqueous ammonia or urea. Rich zone stoichiometric ratios from 0.90 to 0.99 were tested in these experiments. Within this facility, higher rich zone gas temperatures were achievable, and efforts were made to provide the most effective reagent mixing scenario possible. The increased NOx removals in these experiments were most likely a result of the ideal mixing conditions and the higher, more optimal injection zone temperatures that were achievable in the L1500 as compared to the smaller U-furnace.

Figure 1: Schematic illustrating the application of RRI in a staged furnace.



METHODS

Development of CFD Model of RRI Process

To assess the expected performance of RRI in reducing NOx emissions in a full-scale boiler, REI has developed a CFD model of this process. In order to model this process, chemical kinetic rates describing the rates of reaction of the ammonia and/or urea in the presence of NOx in the hot, fuel rich region needed to be identified for inclusion in the CFD model. This has been accomplished by using conventional reduced mechanism approaches that have been implemented in a tool named the Computer Assisted Reduced Mechanism (CARM) method[4]. A 10-specie reduced mechanism was developed and implemented as a post process to REI's three-dimensional, multiphase CFD code, *Glacier*, to model the reduction and oxidation reactions governing NOx formation/destruction. This chemistry model development has been described elsewhere[5]. The new model was applied to:

- U-furnace
- 160 MW, wall fired cyclone furnace
- 540 MW, opposed wall fired cyclone furnace

In the U-furnace calculations, both qualitative and quantitative agreement with the measurements was quite good[5]. For both full scale cyclone fired furnaces that were investigated, the simulations indicated that NOx reductions of approximately 40%, in addition to the reductions already obtained with OFA, could be achievable using anhydrous ammonia. It was also noted that poor reagent placement in the full scale furnaces could limit NOx reductions to 10% or less. This result underscores the value of using modeling results to optimize the RRI process for full-scale installations, thereby achieving consistently high levels of NOx reduction.

Application of CFD Model to BL England Unit 1

In order to evaluate the performance of RRI in a full scale cyclone fired furnace, CNCIG chose to support a demonstration of this technology in Conectiv's B.L England Unit 1. B.L. England Station is located in the town of Beesley's Point, New Jersey, south of Atlantic City. It consists of three units, two coal fired units (1 & 2) and one oil-fired unit (3), with a total rated capacity of 468 MW. Unit 1 is a 138 MW unit fired by 3 cyclones. The NOx emissions from Units 1 & 2 are currently controlled using selective non-catalytic reduction (SNCR) and recently installed overfire air (OFA) systems. The overfire air systems are based on CFD analyses previously performed by REI. Operation with the OFA system has demonstrated reductions of NOx emissions from the uncontrolled baseline of 1.2 lb/MMBtu to approximately 0.5 lb/MMBtu with less than 50-ppm CO stack emissions. The existing SNCR system, installed in 1995, reduces NOx emissions an additional 30% with less than 5-ppm ammonia slip. The existing aqueous urea SNCR and OFA systems on Unit 1 made this a cost effective site for a demonstration of the RRI technology since the existing SNCR infrastructure could be used for the test.

REI's three-dimensional turbulent reacting flow code *GLACIER,* with additions to represent the RRI chemistry, was used for all of the simulations of RRI in B.L. England Unit 1 (BLE1). These simulations were carried out in two parts:

- Cyclone Barrel Model
- Furnace RRI Model

Cyclone Model

The original cyclone barrel CFD model utilized for the BLE1 cyclone barrel cases was developed as part of a previously funded program sponsored by CNCIG. Details concerning this model are included in papers by Adams[6] and Stuckmeyer[7]. Barrel simulations for BLE1 were performed for stoichiometric ratios of 1.09 (baseline) and 0.90 (staged). All RRI predictions were based on the staged barrel results.

Furnace RRI Model

The results of the cyclone barrel model were interpolated at the barrel exit into the inlet of the furnace model as shown in Fig. 2. Within the *GLACIER* simulations of the furnace, the dynamics of the injected aqueous urea droplets were modeled as in previously completed studies to evaluate SNCR[8,9]. The initial direction and velocity of the droplets was specified according to the assumed spray pattern and initial droplet velocities. The model accounts for the coupling between the particle and gas phases in terms of mass, momentum, and energy. The release of the urea into the gas phase and the subsequent chemical reactions between the urea products and the local flue gas species were accounted for based on the new reduced chemistry. This approach allows complete coupling of all the relevant physical processes involved including heat transfer, turbulent mixing, and chemistry so that objective estimates of RRI performance can be obtained.

RESULTS AND DISCUSSION

CFD Model Predictions

The enhanced CFD model was utilized to aid in the design of an RRI injection system for BLE1 as well as to predict RRI performance in the field demonstration. An assessment of the boiler showed that the number of feasible locations for injector nozzle penetrations was limited for a number of reasons including:

- The short elevational distance between the cyclone barrels and the OFA ports
- Lack of access to the front wall (cyclone barrels, risers)
- Location of the windbox

Feasible locations that were identified and subsequently considered in the CFD modeling are shown in Fig. 3. The locations included 6 side wall injectors at the elevation of the bottom row of cyclone barrels, and 2 side wall and 2 rear wall injectors at the elevation directly above the top cyclone barrel. The parameters that were considered in the evaluation included:

- Reagent distribution between the injectors
- Droplet size and velocity distribution
- Spray pattern
- Reagent concentration

CFD predictions of RRI performance showed NOx reduction varying between 10 and 35% (beyond reductions obtained with OFA) utilizing equivalent reagent flow rates. Simulations showed that due to the highly stratified flow in the lower furnace, improper reagent injection could result in little to no reduction in NOx emissions, and even a net increase in certain circumstances. Through proper placement of injectors and specification of nozzle characteristics, NOx reductions up to 33% were predicted with less than 1-ppm ammonia slip, utilizing eight injectors and a normalized stoichiometric ratio of approximately 2.

Figure 2: The computed results at the barrel exit are interpolated onto the inlets of the furnace model where the RRI predictions are obtained.

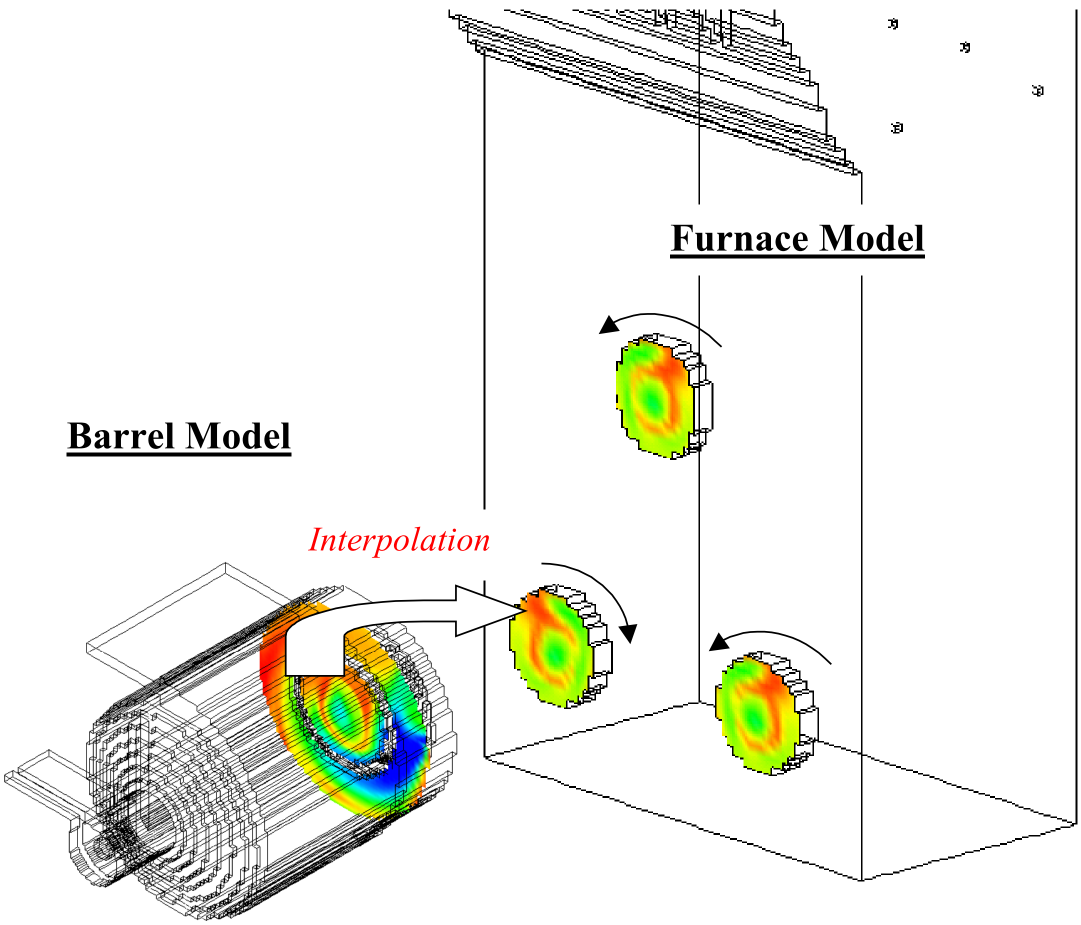
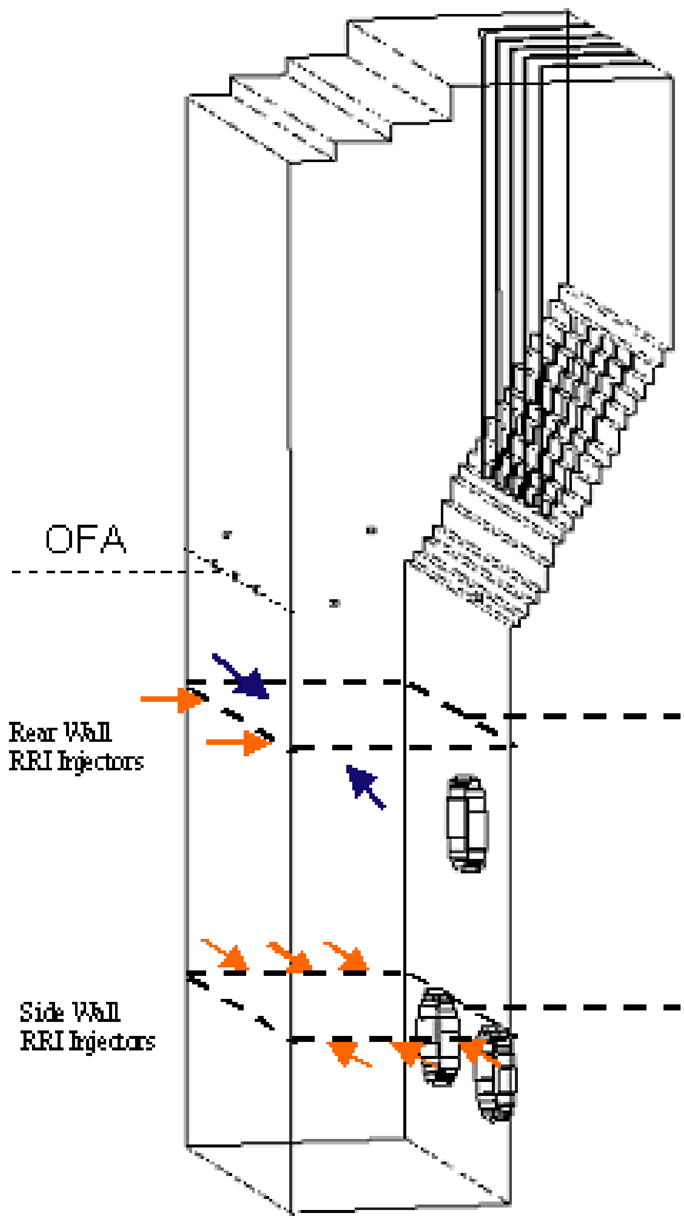


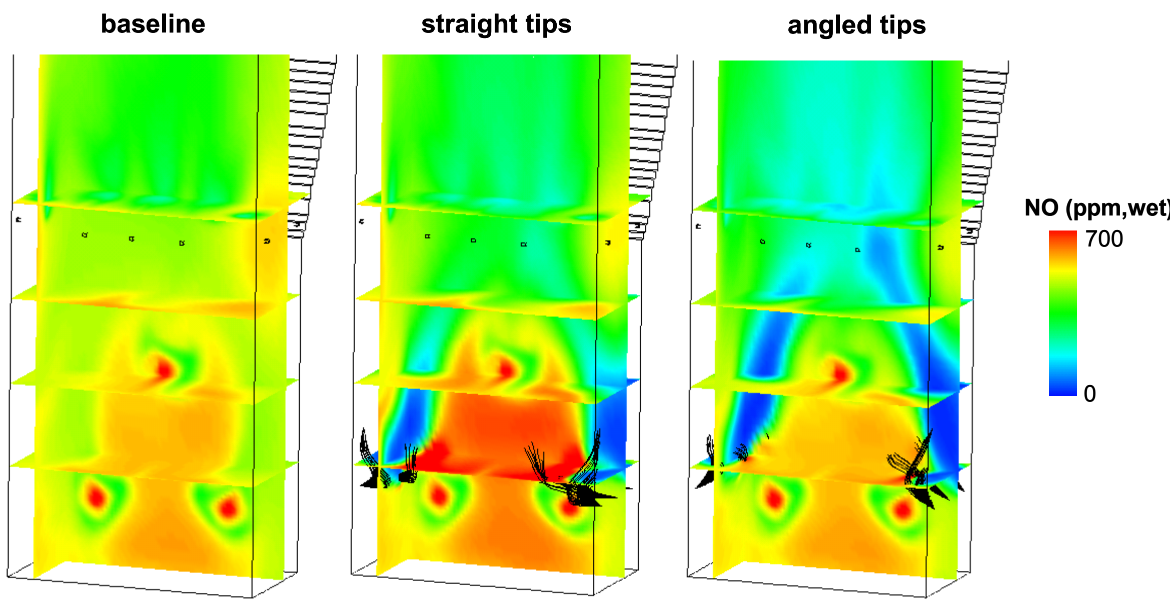
Fig. 4 illustrates the predicted effect of injection strategy on the NO distribution. The three profiles show the predicted NO distribution in the absence of reagent injection, injection using straight injectors, and injection using angled injectors. Due to the stratified nature of the gas flows exiting the cyclone barrels, the predictions suggest that significant quantities of NO will be formed if the reagent penetrates into these gases. Angling the injectors upward to reduce the penetration results in much better overall NO reduction. Other cases indicated that increased penetration of reagent in the region of the cyclone barrels resulted in limited performance.

Figure 3: Schematic of BLE1 showing the extent of the furnace model and the approximate nozzle locations that were evaluated in the CFD model.



This analysis indicated that if the existing SNCR nozzles were utilized for RRI injection, NO reduction would be significantly limited. The modeling suggested that it would be advisable to modify both the droplet size distribution and the nozzle capacities.

Figure 4: Predicted NO distribution showing the impact of penetration of reagent into the BL England Unit 1 lower furnace. The black lines illustrate typical droplet trajectories. Penetration of reagent into the stratified gas flow exit the cyclone barrels results in significant levels of NO formation. By angling the injectors upward, much less NO is formed, and high NO destruction rates near the walls result in significant overall NO reduction.



Results of RRI Installation and Field Testing

Based on the CFD analysis, eight RRI injection ports were installed. The locations are shown in Fig. 3 (gray arrows). The ports in Fig. 3 that were not installed are the two upper level side wall locations (black arrows). RJM Corporation who had installed the original SNCR equipment led the installation of the temporary RRI equipment. The installation was designed to allow testing of the new RRI system in combination with the existing SNCR system in unit 1. As suggested by the CFD analysis, significant modifications to the existing SNCR injectors were warranted in order to achieve the predicted RRI performance. These modifications were made as specified by REI. However, no significant modifications were made to upgrade the nozzle materials or cooling design to take into account the severe lower furnace conditions.

The majority of the tests were conducted at nominally 120 MW. The intent of the testing was to:

- Evaluate the effectiveness of RRI as a NOx reduction technology in BLE1
- Determine how well performance can be predicted
- Assess NOx reduction achievable by layering OFA, RRI, and SNCR

Since a large number of injector and boiler parameters were varied to assess sensitivity of RRI, the individual tests were relatively short, each lasting less than one hour. Furnace exit NO levels were based on the continuous emissions monitors (CEMs). NH_3 measurements were taken in two separate ducts upstream of the air heaters.

The parameters that were evaluated included:

- Injector spray pattern
- Normalized stoichiometric ratio (NSR)
- Reagent Concentration
- Nozzles out of service (NOOS) and reagent flow biasing
- Cyclone barrel SR
- Injector atomization air pressure

Fig. 5 shows a scatter plot of the test results showing furnace exit NO for the tests. The plot shows measured values for OFA only, for OFA combined with RRI, and OFA combined with both RRI and SNCR. Baseline testing was at a lower furnace SR of 0.9, but there was some computed variation around that level. Fig. 6 shows the same test data computing percent NOx reduction due to application of RRI or RRI in combination with SNCR. The line passing through the data in Fig. 6 indicates the NO reductions with RRI in which optimal injection strategies were utilized. As seen in Fig. 5, NO emissions under staged conditions with OFA were approximately 0.55 lb/MMBtu. Addition of RRI to the OFA system reduced the exit NO by approximately 25-30% (Fig. 6). Combining RRI with SNCR was observed to achieve approximately 55% reduction beyond OFA levels to reduce the NO emissions to approximately 0.25 lb/MMBtu. These levels of NO reduction were achieved utilizing NSRs of approximately 1 and 2 for SNCR and RRI, respectively. This demonstrates a remarkable reduction in NO of approximately 80% through the combination of OFA/RRI/SNCR from baseline NOx emissions of 1.2 lb/MMBtu.

NH_3 measurements during the RRI testing showed < 1 ppm slip for all tests. The results shown in Figs. 5 and 6 for the combined application of RRI and SNCR yielded average NH_3 slips of < 5 ppm. No significant increase in furnace CO emissions was observed due to RRI testing.

Figure 5: Measured NO emissions from BLE1 during RRI and combined RRI and SNCR testing.

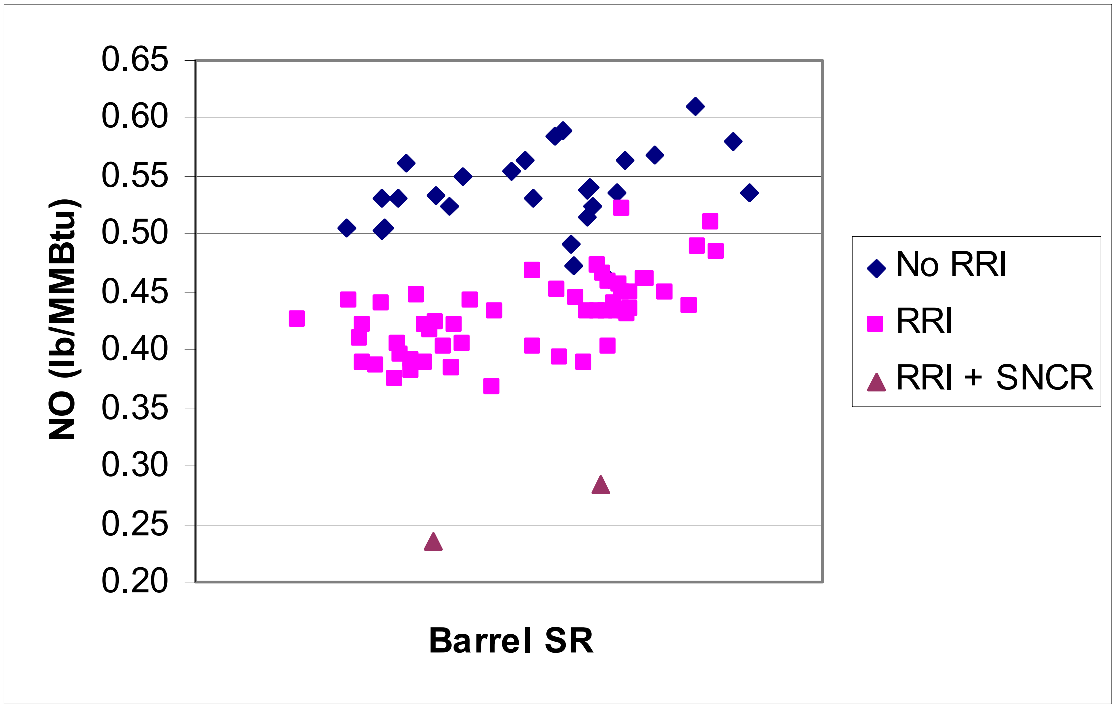
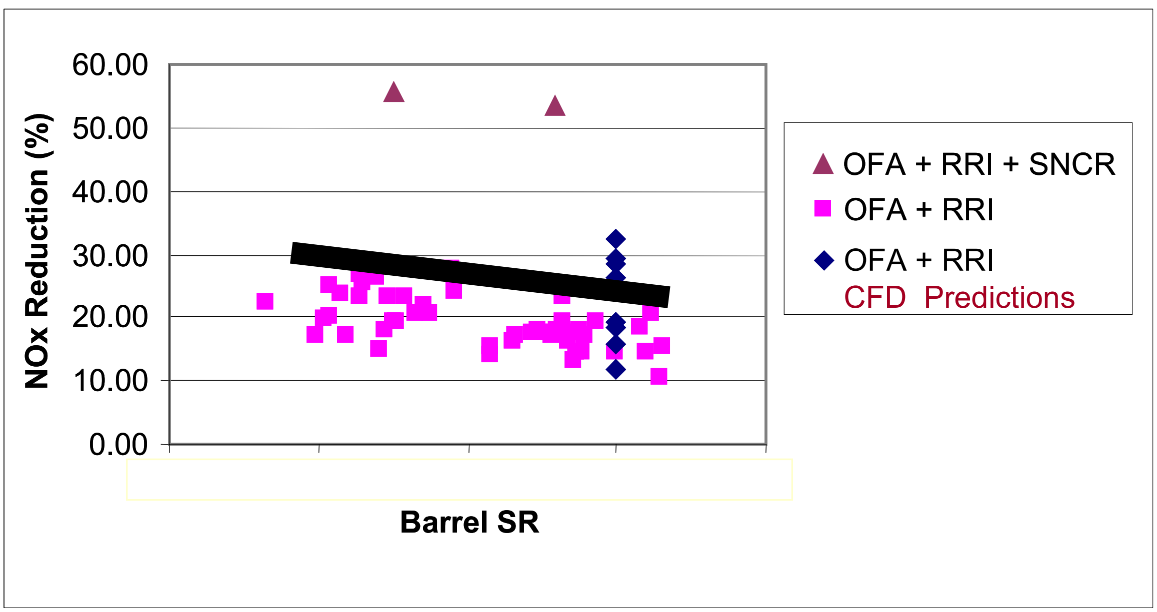


Figure 6: Computed % reduction based on measurements from Fig. 5.



CONCLUSIONS

The ability of the RRI process to significantly reduce NOx emissions from a staged cyclone fired furnace operating with overfire air has been demonstrated. NOx reductions of 30% with less than 1-ppm ammonia were obtained with RRI under full load conditions in Conectiv's B.L. England Unit 1, a three barrel, 138 MW cyclone fired furnace. RRI in combination with SNCR was found to yield up to 55% NOx reduction under full load conditions, to reduce NOx emissions from this unit to as low as 0.23 lb/MMBtu, with less than 5 ppm ammonia slip. The field testing confirmed the CFD model predictions and demonstrated the importance of accurate CFD modeling to a successful RRI design. Data suggests that in other units possessing increased residence times in the lower furnace, RRI performance should be higher than those achieved in B.L. England Unit 1. The CFD modeling results have proven to be very reliable, and are considered essential to proper location and configuration of the injectors.

An additional demonstration of RRI is planned in a 480 MW cyclone fired furnace during the summer of 2000. The applicability of RRI to other furnace types is currently under evaluation.

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ACKNOWLEDGMENTS

This work was supported in part by the Electric Power Research Institute (EPRI) and their Cyclone NOx Control Interest Group (CNCIG), Conectiv, and the U.S. Department of Energy (USDOE) under contract number DE-FC26-00NT40753.

Key Words

CFD

Modeling

NOx

Boiler

Cyclone

Staging

SNCR

Urea