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USE OF CFD MODELING TO GUIDE DESIGN AND IMPLEMENTATION OF OVERFIRE AIR FOR NOX CONTROL IN COAL-FIRED BOILERS

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ABSTRACT

CFD modeling has found increasing use among combustion engineers in the design and evaluation of utility boiler retrofits, combustion optimization and NOx reduction technologies. This paper reviews two recent examples of combustion engineers using CFD modeling in the design and implementation of NOx reduction technologies. Both examples involve the staging of furnace combustion through use of overfire air (OFA) to reduce NOx emission. The first is for a 265 MW_g B&W opposed-wall pulverized coal fired furnace. The second is for a 530 MW_g B&W opposed wall cyclone-fired boiler. Furnace simulations identified locations of highest flue gas mass flows and highest CO and O_2 concentrations and were used by the combustion engineers to identify OFA port placement for maximum NOx reduction with lowest increases in unburned carbon in fly ash and CO emission. Simulations with OFA additions predicted 34% and 80% reductions in NOx emissions, respectively, with minimal changes in CO concentration and unburned carbon. Plant CEMS data confirmed the accuracy of the modeling results for pre-retrofit and post-retrofit operation.

INTRODUCTION

In the past, technology for designing utility and industrial fossil fuel-fired furnaces has involved a large degree of empiricism. Empirical methods have been adequate for obtaining the design envelope, but frequently result in less than optimal designs, particularly when unique geometries, fuels or burners are involved either as initial designs outside a manufacturers experience range or as retrofits to existing systems. Computational Fluid Dynamics (CFD) based analysis has gained increasing acceptance in recent years as a tool in the evaluation of combustion systems. Although reacting CFD models involve varying degrees of approximation, they still provide valuable insight into the performance of furnaces. With the development of increasingly affordable and powerful computers, numerical simulation has become an engineering tool for evaluating furnace designs. Gibson and Morgan [1] introduced one of the first comprehensive numerical models for PC combustion. Since then, Lockwood, et al. [2], Fiveland et al. [3], Boyd and Kent [4], Bockelie, et al. [5], among others have employed increasingly more sophisticated models and have demonstrated the potential of such models as engineering tools.

Recently CFD modeling has found increasing use in the design and evaluation of utility boiler retrofits, combustion optimization and NOx reduction technologies. For example, over the past eight years Reaction Engineering International (REI) has performed CFD modeling using in-house software for over 90 fossil-fuel fired utility boilers to evaluate the performance and impact of NOx reduction technologies such as staging and overfire air, low NOx burners, visciated air and air preheating, co-firing of opportunity fuels, fuel blending, Rich Reagent Injection (RRI), Selective Non-catalytic Reduction (SNCR), gas reburning, and Fuel Lean Gas Reburning (FLGR). Boilers have ranged in size from 34 MW up to the largest U.S. boilers and include cyclone, tangential, wall and roof firing systems. Figure 1 shows the unit size distribution of cyclone, tangential and wall-fired units modeled by REI over the past eight years. The large majority of these units were coal-fired, requiring modeling software capable of accounting for the turbulent two-phase mixing, equilibrium (e.g., CO_2, O_2) and finite-rate (e.g., NOx) gas-phase chemical reactions, heterogeneous coal particle reactions (devolatilization and char oxidation) and radiant and convective heat transfer that comprise combustion processes.

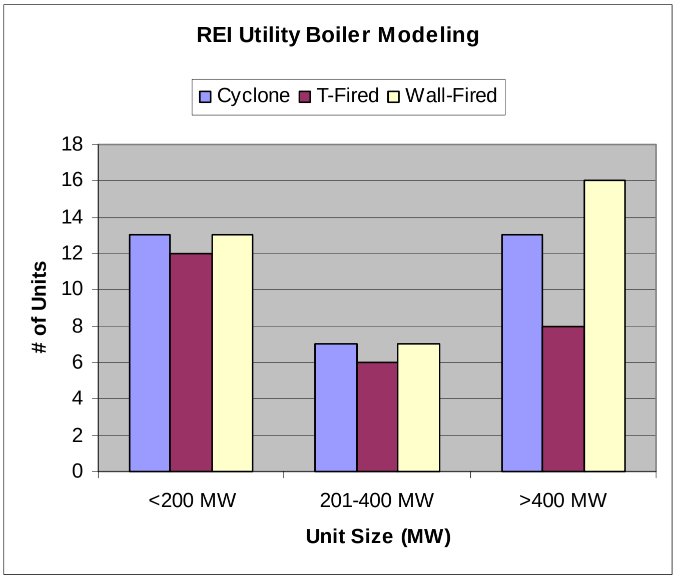

Figure 1. Distribution of utility boilers modeled by REI.

The REI combustion models employ a combination of Eulerian and Lagrangian reference frames. The flow field is assumed to be a steady-state, turbulent, reacting continuum field that can be described locally by general conservation equations. The governing equations for gas-phase fluid mechanics, heat transfer, thermal radiation and scalar transport are solved in an Eulerian framework. The governing equations for particle-phase mechanics are solved in a Lagrangian reference frame. The overall solution scheme is based on a particle-in-cell approach.

Gas properties are determined through local mixing calculations and are assumed to fluctuate randomly according to a statistical probability density function (PDF), which is characteristic of the turbulence. Turbulence is typically modeled with a two-equation non-linear k-ε model that can capture secondary recirculation zones in corners. Gas-phase reactions are assumed to be limited by mixing rates for the major species (local chemical equilibrium) as opposed to chemical kinetic rates for kinetically limited species such as oxides of nitrogen.

Particle mechanics are computed by following the mean path for a discretized group of particles, or particle cloud, in a Lagrangian reference frame. Particle reaction processes include coal devolatilization, char oxidation, and gas-particle interchange. The dispersion of the particle cloud is based on statistics gathered from the turbulent flow field. Heat, mass, and momentum transfer effects are included for each particle cloud. The properties of the particle cloud are computed from a statistical average over the particles within the cloud. The properties of the local gas field are computed with an analogous ensemble averaging procedure. Particle mass and momentum sources are converted from a Lagrangian to an Eulerian reference frame by considering the residence time of each particle cloud within the computational cells.

The radiative intensity field and surface heat fluxes are calculated using the discrete ordinates method. Effects of variable surface properties and participating media (gas, soot and particles) are included.

Modeling techniques and assumptions particular to cyclone-fired barrels and boilers have been implemented in the REI code and have been documented previously [6, 7, 8].

This paper reviews two recent examples of CFD modeling used in the design and implementation of overfire air NOx reduction technology for an opposed-wall PC unit and a cyclone-fired unit, respectively.

PC-FIRED BOILER OFA STUDY

CFD modeling was used to provide a conceptual design and to evaluate NOx reduction performance of an overfire air (OFA) system in a 265 MWg B&W, subcritical, opposed-wall, pulverized coal-fired furnace. The furnace is fitted with eighteen Babcock Borsig Power CCV low NOx burners and baseline NOx emissions are approximately 0.6 lb/MMBtu. It was expected that OFA ports would be installed on both the furnace front and rear walls. An elevation approximately ten feet above the top burners was suggested for OFA ports; this would provide adequate residence time above the ports for completion of combustion. Making use of symmetry, a 650,000 computational cell half-furnace model was developed. Basic features of the model are shown in Figure 2. Only three of the six front wall burners (for the half furnace model) are opposed by rear wall burners.

The goal of the CFD modeling study was the optimization of the overall OFA system design to maximize the reduction in furnace NOx emission while minimizing adverse effects such as increased CO emission and increased carbon in fly ash. OFA system design considerations were the horizontal plane OFA port placement, port geometry, air jet velocity, appropriate burner size adjustments, and the level of furnace staging. Before beginning modeling evaluations, AEP Pro Serv engineering worked with modeling engineers to identify feasible locations for the OFA ports on the unit.

An initial baseline simulation was performed to model the current operating condition and to verify the accuracy of the model. The baseline simulation predicted a furnace full load NOx emission of 0.58 lb/MMBtu, unburned carbon in fly ash (UBC) of 8%, and a model exit CO of 85 ppm. The CO level can be expected to decrease as it moves through the convective pass. With the exception of the unburned carbon level, which was a few percent higher than plant measurements, these values were in line with observed furnace operation.

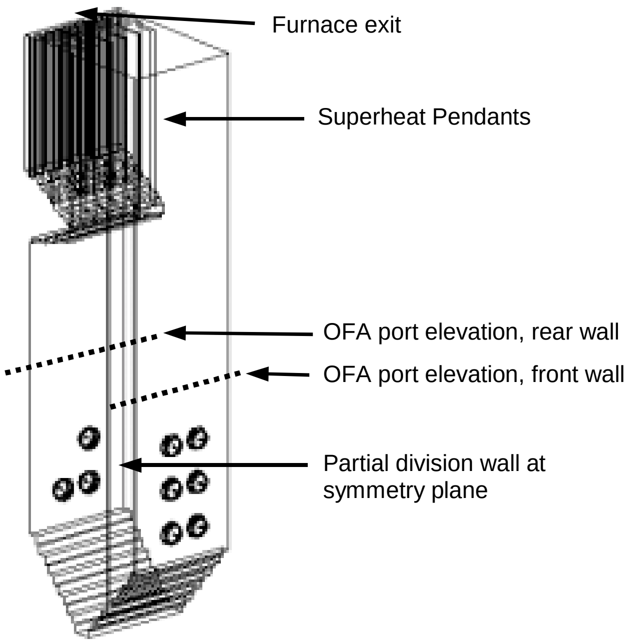

Figure 2. Schematic of half furnace model for opposed wall fired boiler showing OFA port elevations.

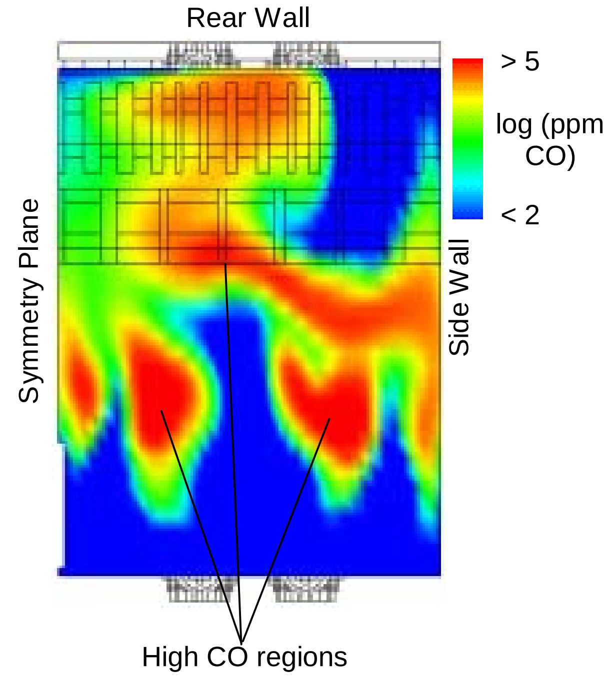

Figure 3. Plot of CO concentrations at proposed OFA elevation.

To evaluate placement of OFA ports in the horizontal plane ten feet above top burners, AEP Pro Serv engineering considered the baseline CO concentration and upward flue gas flow. If the CO and flue gas flow fields are not uniform at this elevation, OFA air will be most effective if concentrated in higher CO and flue gas mass flow regions. Although not considered here, in some cases effective distribution of OFA is provided by a combination of port location as well as biased air flow rates through the ports. The placement of the ports was instead used to effectively bias the OFA distribution in this case study.

Figures 3 and 4 show the location of high CO concentrations and upward flue gas mass flux, respectively, at the proposed OFA port elevation ten feet above top burners. High CO is present near the rear wall and near the furnace center. The two lobes nearest the front wall come from the top front wall burners below. The upward flue gas flow is highest in the rear half of the furnace, at least partially since there are no upper rear wall burners opposing the upper front wall burners. In the region above the upper front wall burners, the burner swirl results in downward mass flow at this elevation. Although the flow field shown in Figure 4 is for an unstaged furnace and could be expected to change somewhat with furnace staging, it provides a reasonable basis for locating OFA ports.

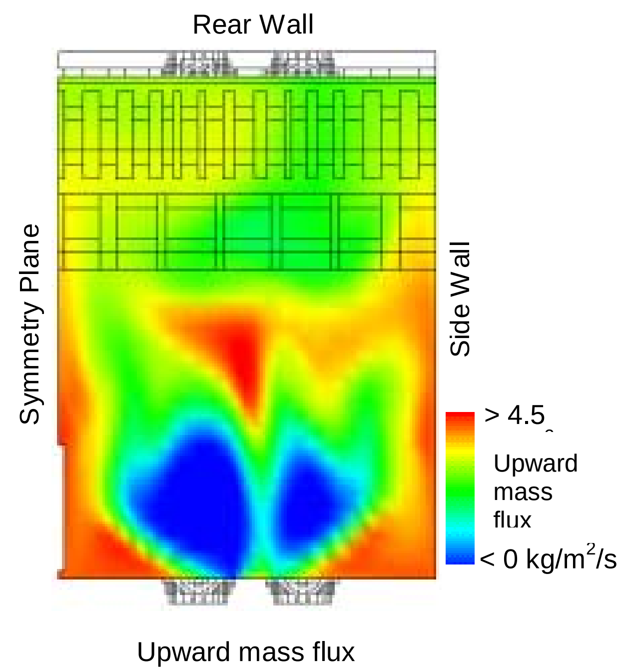

Figure 4. Plot of upward flue gas mass flux at proposed OFA elevation.

Based on the predicted flow field information above, AEP Pro Serv engineering determined a preliminary OFA port layout. The preliminary design is shown in Figure 5. Since high CO regions are nearer the rear wall than the front wall and the upward mass flow is higher in the rear half of the furnace than in the front half, more ports were located on the rear wall than on the front. In addition, it was felt that no OFA port was necessary in the center of the front wall where the predicted flue gas flow is downward, as this would result in the introduction of oxygen rich air into the burner zone. Ports were sized for an OFA jet velocity of 170 ft/s with the lower furnace staged to 0.9. Interlaced ports as in Figure 5 rather than directly opposed OFA jets often help penetration.

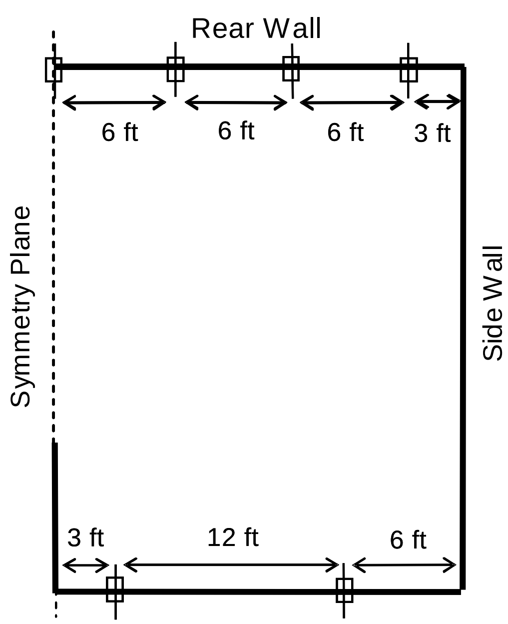

Figure 5. Schematic of proposed OFA port locations on front and rear walls.

Babcock Borsig Power recommends a specific secondary to primary burner air velocity ratio for the CCV burners in this furnace, so with some secondary burner air diverted to the OFA ports, burner modifications were included in the model. To achieve the desired secondary/primary burner air velocity ratio, diameters of the primary coal pipe and secondary air inlet were altered. A summary of predicted results for the baseline and initial OFA cases is shown in Table 1. Key parameters included are the level of furnace staging in the burner zone, burner modifications made to retain recommended fuel and air velocity ratios, and predicted NOx, UBC and CO concentrations. NOx reductions over 30% were predicted with OFA, but UBC and CO concentrations also increased significantly. Note that the NOx, UBC and CO concentrations are at the exit of the computational model, approximately after the first section of superheat pendants and directly above the rear wall of the radiant furnace. NOx concentrations will not change much beyond this point due to low flue gas temperatures, unburned carbon can decrease slightly, but CO concentrations can be expected to decrease significantly through the back pass of the boiler.

A second OFA simulation was performed in order to find a configuration that would produce less of an increase in carbon in fly ash. In the second OFA configuration, the level of furnace staging was decreased to a stoichiometric ratio of 0.95 (vs. 0.90 in the initial OFA simulation). This time only the primary burner diameter was altered to maintain the recommended secondary to primary air velocity ratio and the OFA ports were downsized to maintain a velocity of 170 ft/s. Predicted NOx remained low (0.38 lb/MMBtu) but the predicted increase in carbon in fly ash was more moderate (now 13% up from 8% in the baseline simulation). Although the simulations indicated that implementation of this configuration in the actual furnace would result in an increase in unburned carbon, the baseline UBC prediction appeared somewhat high suggesting that the final level could be lower than the prediction also, allowing the UBC to remain within acceptable levels.

Results from three CFD simulations of this furnace were used by AEP Pro Serv engineering to choose an appropriate OFA system design to reduced furnace NOx emissions. An overall summary of the simulations is shown in Table 1. Although NOx is reduced to the same level for both OFA configurations, the increase in carbon in fly ash is less severe for the revised OFA configuration. The furnace is less deeply staged in the revised OFA configuration, but burner modifications also have some impact on NOx. Although CO increased for both OFA configurations, much of the CO can be expected to burn to completion in the convective pass.

Table 1. Summary of simulation results showing the effect of different OFA designs.

	Baseline	**Initial OFA**	**Revised OFA**
Furnace Staging	None	0.90	0.95
Burner Modifications	None	Primary & Secondary	Primary
Predicted NOx (lb/MMBtu)	0.58	0.39	0.38
Predicted Carbon in Fly Ash	8%	20%	13%
Predicted CO (at furnace exit)	85 ppm	801 ppm	1000 ppm

The installation of the OFA design, as modeled, was completed in the Spring of 2002. Although AEP Pro Serv has not yet fully optimized the system, the NOx emission rates are in agreement with the modeling effort and both CO emissions (<50 ppm) and unburned carbon in flyash levels (5-10%) are within acceptable ranges. A comparison of the NOx emission rates, prior to and after the OFA retrofit is illustrated in Figure 6.

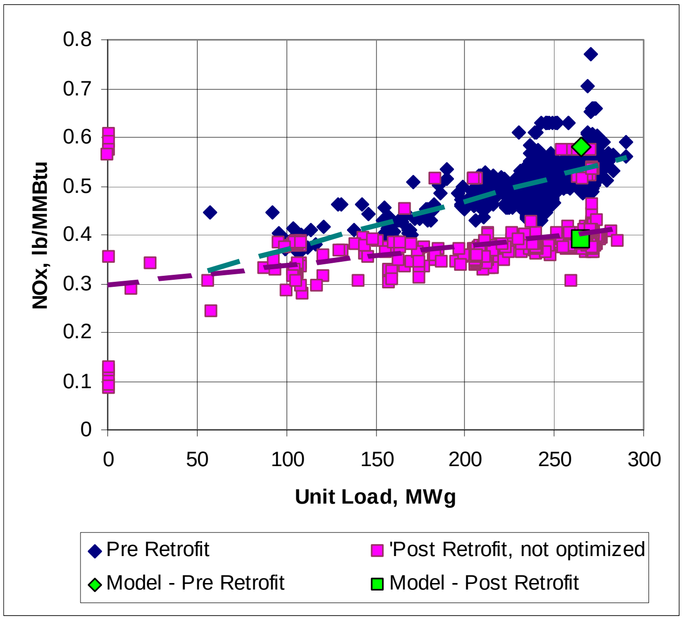

Figure 6. Comparison of predicted and reported NOx emission rates before and after OFA retrofit.

CYCLONE FURNACE OFA STUDY

CFD modeling was used by AEP Pro Serv engineering to provide a conceptual design and to evaluate NOx reduction performance of an overfire air (OFA) system in a 530 MWg B&W, supercritical, opposed-wall, cyclone-fired furnace. The furnace is fitted with eleven 10-foot diameter cyclones with radial primary burners. The cyclones are oriented 2 over 3 on the furnace front wall and 3 over 3 on the rear wall. The baseline NOx emissions were dependent upon the fuel source and the usage of water injection within the cyclone barrels. The CFD modeling effort was performed utilizing a current typical coal blend of 60% sub-bituminous PRB coal and 40% eastern bituminous coal. The baseline full load NOx emission for this fuel blend is approximately 1.8 to 1.9 lb/MMBtu. Prior to the application of OFA, this unit utilized water injection in the cyclone barrels to control visible opacity levels otherwise due to elevated NO_2 levels at the stack. Limited data was available with the specified fuel blend and without water injection.

As a result of previous changes the range of OFA elevation options were significantly greater than that limiting the OFA application for the previously discussed pc, wall-fired boiler, while still having sufficient residence times to achieve burnout above the OFA level. The selection of modeled OFA options were determined by practical limitations created by buckstay elevations. Two OFA elevation options, approximately nineteen and twenty-six feet above the top cyclone centerlines were considered. These options would provide adequate residence time above the ports for completion of combustion.

Normal operation of a cyclone furnace results in a layer of slag on the cyclone's barrel surfaces and the burning of nearly all of the coal on the surface of the slag layer. As such, the model study was conducted in two phases. First, the cyclone barrels were modeled with combusting particles. The cyclone barrel model consisted of ~350,000 computational cells. Secondly, the output of the cyclone barrel model, which included negligible organic solids, was then applied to a full furnace model as 100% gas phase. A 750,000 computational cell full-furnace model was developed. Basic features of the models are shown in Figures 7 and 8.

The goal of the CFD modeling study was the optimization of the overall OFA system design to maximize the reduction in furnace NOx emission while minimizing adverse effects such as increased CO emission and increased carbon in fly ash. OFA system design considerations were the horizontal plane OFA port placement, port geometry, air jet velocity, appropriate cyclone combustion airflow distribution adjustments, and the level of staging within the cyclone barrels.

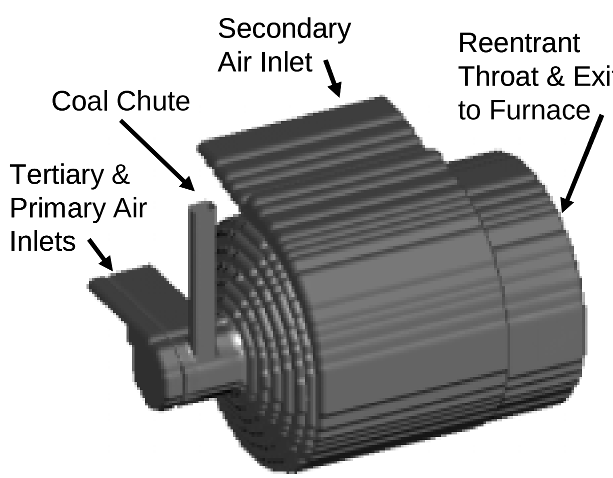

Figure 7. Schematic of cyclone barrel model.

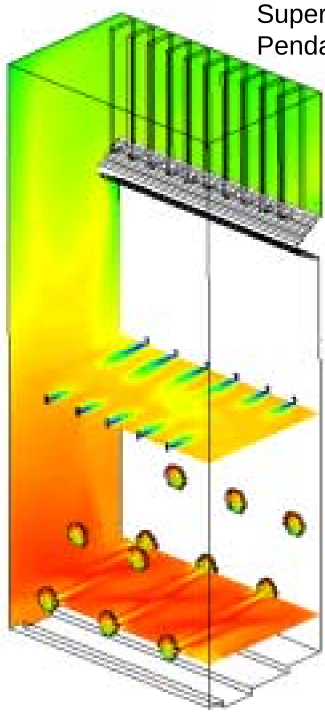

Figure 8. Schematic of full furnace model for opposed wall, cyclone-fired boiler showing one of three OFA options evaluated.

An initial baseline simulation was performed to model the current operating condition and to verify the accuracy of the model. The baseline simulation predicted a furnace full load NOx emission of 1.96 lb/MMBtu and a model exit CO of 217 ppm. The CO level can be expected to decrease as it moves through the convective pass. Because the furnace model considers only gas phase flows, no unburned carbon in ash predictions were provided. The predicted emission values were in line with observed furnace operation.

The staged cyclone barrel conditions were performed at a stoichiometric combustion air ratio of 0.9, while maintaining the flow in the primary burner at the same rates used under normal baseline, unstaged conditions. A comparison of the barrel model results is illustrated in Table 2. Notable are the predicted 13% reduction in the predicted cyclone barrel NOx production and the 97% increase in the CO concentration at the barrel exit plane. These results were then applied to the furnace model under each of three OFA port arrangements and OFA jet velocities of 300 ft/sec. The baseline furnace model mass flow distributions actually suggested that this front to rear wall port arrangement should be reversed; however, furnace structural concerns with such a configuration resulted in the ports being located above the cyclone barrel centerlines. The staggered OFA pattern was also incorporated to deeper jet penetrations and improved mixing patterns.

Table 2. Cyclone Barrel Model Results for Baseline and Staged Operation.

Parameters	Baseline	Staged
Furnace Exit Temp.(°F)	2897	2930
Furnace Exit CO (ppm)	36,680	72,214
O_2 (%, wet)	5.49	4.01
Burnout (%)	98	98
NO ppm @ 3% O_2	508	440
lb NOx / MMBtu	0.68	0.59

The results of the baseline and the staged furnace firing OFA options are presented in Table 3. The predicted average furnace exit NOx concentration for the baseline case was 1.96 lb-NOx/MMBtu. Figure 9 illustrates the NOx concentration profiles in the furnace under baseline operation and shows how the NOx concentration continues to increase as a function of furnace height from the barrel inlet region in the lower furnace to the nose region. This is due to the continued formation of thermal NO as the fuel lean, high temperature combustion products mix in the lower furnace. The highly stratified species concentrations present at the barrel exit mix in the lower furnace, providing a flue gas with more uniform characteristics, although some species concentration gradients continue to exist due to non-uniform flow patterns in the furnace. NOx formation rates are greatest in the lower regions of the furnace where temperatures are highest. As heat is extracted through the furnace walls, gas temperatures decrease resulting in lower thermal NO formation rates.

Table 3. Cyclone Furnace Model Results.

Case	Temp. (°F)	CO (dry, ppm)	O2 (dry, %)	NO@3%O2 (dry, ppm)	lb-NOx/ MMBtu
Baseline	2438	217	2.79	1467	1.96
OFA Case1	2299	2093	2.93	264	0.35
OFA Case2	2340	413	2.80	277	0.37
OFA Case3	2364	324	2.80	355	0.47

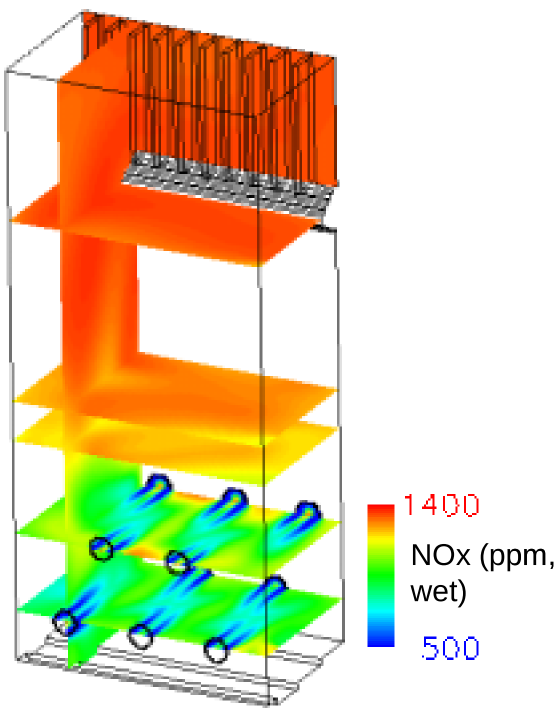

Figure 9. Predicted NOx concentration profiles for the baseline case.

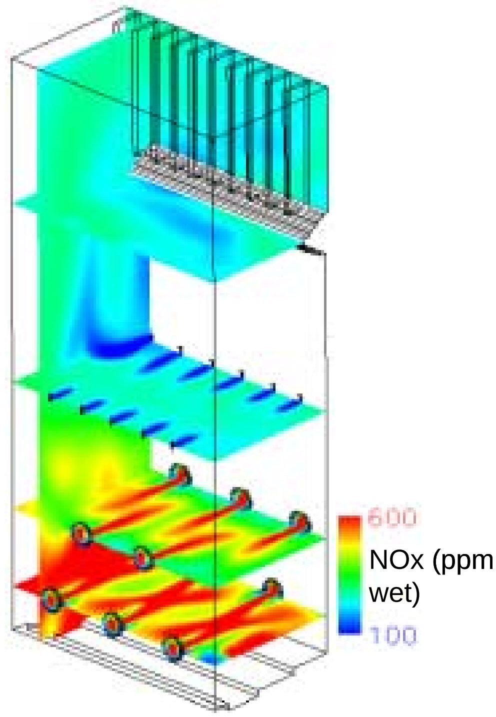

Figure 10. Predicted NOx concentration profiles for OFA Case1.

The initial staged furnace case evaluated (OFA Case1) resulted in a significant decrease in NOx emissions (~80%), but also a two-order of magnitude increase in predicted furnace exit CO concentrations. Note that this is not the expected furnace CO emission as the CO will continue to oxidize through the boiler backpass, but is significantly higher than the predicted baseline furnace CO levels. Staging also resulted in a predicted decrease in average flue gas temperature at the furnace exit.

Figure 10 illustrates the NOx concentration profiles in the boiler for OFA Case1. High NOx concentrations are evident in the lower portion of the boiler consistent with the concentrations exiting the cyclone barrels. However unlike the baseline case where NOx concentrations increased in the furnace, NOx concentrations in the staged case drop rapidly in the lower furnace. This is due to two factors. The first is that the fuel rich environment in the lower furnace inhibits NOx formation. The second is that the fuel rich environment also allows for reburning conditions to exist that reduce NOx formed in the cyclone barrels. The combination of these two effects results in significant drop in NOx concentrations at the furnace exit. It is interesting to note that the same high temperatures that contribute to NOx formation under fuel lean conditions also enhance the high NOx reduction rates under fuel rich conditions.

The simulation results of OFA Case1 indicated that there were CO pockets in the corners of the furnace that persisted through the furnace exit. As a result, the OFA injection scheme was changed to include four auxiliary ports near the corners on the side walls of the furnace (see Figure 11). The amount of flow introduced through the auxiliary OFA ports equated to 16% of the total OFA flow, 4% per port. The jet velocity through these ports was at a significantly lower velocity, 100 ft/sec, by utilizing different style port geometry. This produced reduced OFA jet penetrations from these ports in order to effectively reduce the predicted CO concentrations in the corners of the furnace. The front and rear wall jet velocities were proportionately reduced to 254 ft/sec (from 300 ft/sec).

The results of the OFA Case2 simulation are shown in Table 3 and indicate a significant reduction in predicted furnace exit CO concentration (2093 versus 413 ppm at the model's exit plane) with only a minimal change in NOx levels (0.35 versus 0.37 lb/MMBtu). The highest CO pockets still remained in the corners of the furnace (see Figure 12). These results were considered to be very positive and became the basis of the AEP Pro Serv OFA design that was installed in the Spring of 2002.

In order to assess the sensitivity of the unit CO and NOx concentrations, a third OFA design was also modeled. In OFA Case 3, the same OFA configuration used in OFA Case 2 was implemented at a lower elevation. The results summarized in

Table 3 indicate that the lower port configuration did further reduce furnace exit CO levels (413 versus 324 ppm), but at the expense of increased NOx levels (0.37 versus 0.47 lb/MMBtu). AEP Pro Serv engineering determined not to pursue this design in favor of the OFA Case2 design.

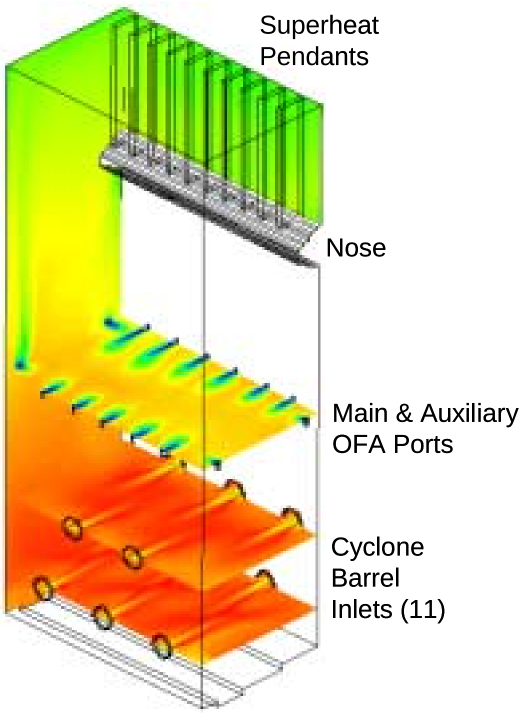

Figure 11. Schematic of cyclone furnace model showing main and auxiliary OFA ports.

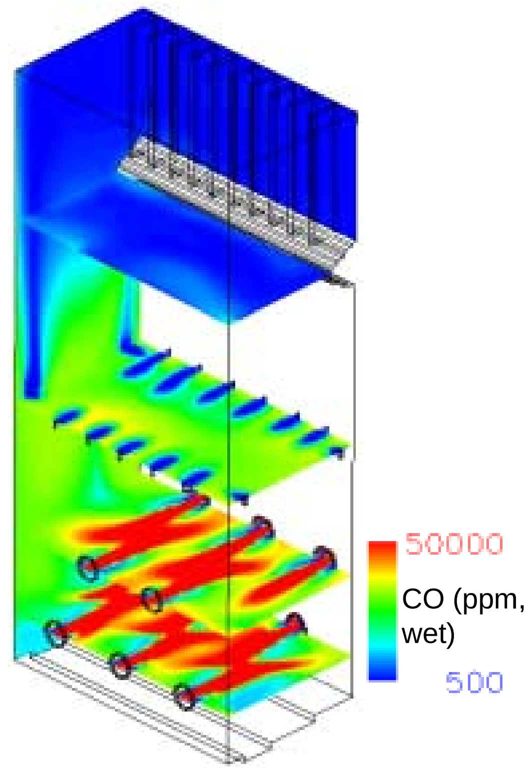

Figure 12. Plot of predicted CO concentrations for the OFA Case2 OFA port arrangement.

Figure 13 illustrates CEM's data representative of operation before and since the installation of the OFA system. While the modeling results had appeared to be somewhat optimistic, the resultant full load NOx emissions on the unit, while operating under the design conditions, have duplicated the model predictions for NOx emissions. This design has also resulted in stack CO concentrations of generally less than 50 ppm and average carbon in flyash levels on the order of 10% or less.

The actual OFA system was designed to achieve slightly deeper staging levels than the modeled 0.9 stoichiometric combustion air ratio. Firing under such conditions in the field has demonstrated some additional NOx control without adverse CO or carbon in ash effects.

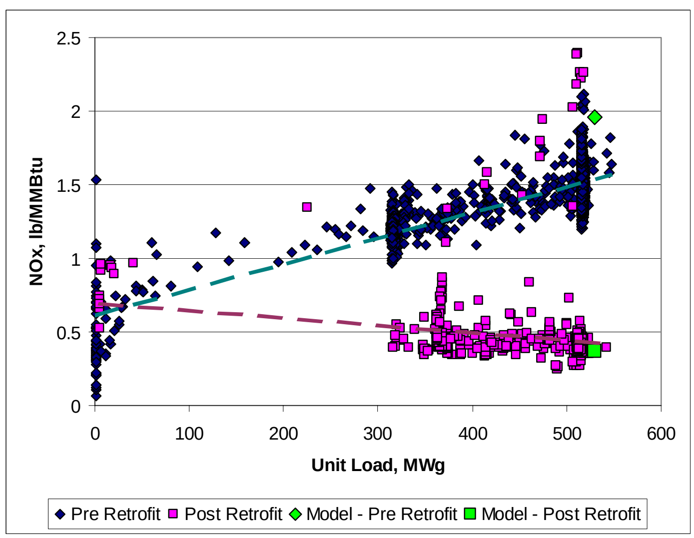

Figure 13. Comparison of predicted and reported NOx emission rates before and after OFA retrofit.

CONCLUSIONS

Two examples have been cited to illustrate the approach and effectiveness of using CFD in the design and implementation of the overfire air NOx reduction technologiy in coal-fired utility boilers. Both studies were conducted using REI's in-house CFD software specifically developed to account for all relevant combustion processes during coal combustion, including the formation and destruction of nitrogen oxides.

CFD simulations of a 265 MW_g B&W opposed-wall fired pulverized coal furnace fitted with Babcock Borsig Power CCV low NOx burners have been used by AEP Pro Serv to identify an OFA system design that will maximize the reduction in furnace NOx emission while minimizing adverse effects such as increased CO emission and increased carbon in fly ash. Modeling results showed NOx reductions over 30% could be achieved with either of two OFA designs, one with the boiler operating at a stoichiometric ratio of 0.90, the other at 0.95. Although NOx is reduced to the same level for both OFA configurations, the increase in carbon in fly ash is less severe for the higher stoichiometric ratio OFA configuration. The furnace is less deeply staged in this case, but burner modifications also have some impact on NOx and appear to compensate for the difference in furnace staging. Although predicted furnace exit CO increased for both OFA configurations over the baseline, much of this CO has been shown through field data to be oxidized in the boiler convective pass.

CFD simulations of a 530 MW_g B&W opposed-wall, cyclone-fired furnace with eleven 10 foot diameter cyclones have been used by AEP Pro Serv to identify an OFA system design that will significantly reduce in furnace NOx emission while minimizing adverse effects such as increased CO emission and increased carbon in fly ash. Modeling results showed NOx reductions over 75% could be achieved with the resultant OFA design with a 20% difference between two OFA elevation options. Although predicted furnace exit CO increased for the OFA configuration over the baseline, much of this CO differential has been shown through field data to be oxidized in the boiler convective pass.

Field-testing and optimization performed by AEP Pro Serv engineering confirmed the CFD predictions of NOx reduction and demonstrated the importance and value of accurate CFD modeling when combined with combustion engineering expertise to successful in-furnace NOx control designs. The CFD modeling results were shown to be very reliable, and are considered essential to optimal design development.

ACKNOWLEDGMENTS

The OFA modeling work described herein was supported by funding from American Electric Power (AEP). AEP Pro Serv provided engineering management, technical direction and optimization of the implemented OFA design. Some of the modeling results presented here for the pc-unit were previously published in an ASME paper by Adams et al. [9] and are used here with permission of ASME.

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