OPTIMIZATION OF SCR SYSTEM AT CAYUGA UNIT 1[1]

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Abstract

AES Cayuga Unit 1 is a 160 MW unit, equipped with a low-NO_x firing system and an anhydrous ammonia (NH_3), Selective Catalytic Reduction (SCR) system for NO_x emissions control. A combined boiler/SCR/air preheater (APH) optimization was performed to minimize the cost of NO_x emissions control. Boiler and low-NO_x system control settings, and SCR and air preheater (APH) operating conditions were included in a parametric test program. Information from a Breen Energy Solutions ammonium bisulfate (ABS) probe was also included for monitoring of ABS formation in real-time and as a constraint to the SCR optimization. The parametric test data were used as the basis for the optimization that consisted of an approach that incorporates accurate on-line support vector regression (AOSVR) modeling for adaptive learning, and genetic algorithms for implementation of the multi-objective optimization. The results indicate that optimal operating conditions can be achieved for a coordinated boiler/SCR/APH operation, and minimal NH_3 consumption, maximum SCR performance, and optimal net unit heat rate, subject to minimal impact on fly ash unburned carbon content, mitigated ABS formation, and other operational and environmental constraints. The optimal conditions resulted in reduced NH_3 usage of the order of 25 percent, with improved APH fouling management.

Introduction

Selective Catalytic Reduction (SCR) is a key component in utility company's plans for nitrogen oxides (NO_x) emissions control. Over 100 GW of coal-fired generation in the U.S. is expected to have SCR capabilities. SCR systems rely on the chemical reduction of NO_x with ammonia (NH_3) over the surface of a catalyst. A theoretical one-to-one NH_3/NO_x molar ratio would result in conversion of these reactants to environmentally benign molecular nitrogen and water vapor. However, this ideal condition is not always met, resulting in over-conditioning of NH_3, with associated operating cost penalties. The price of NH_3 has more than doubled in recent years. The SCR post-combustion NO_x control technology is usually retrofit on boilers equipped with low-NO_x firing systems and on high-

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dust, high-temperature configurations, with the SCR system located in front of the air preheater (APH) and the dust collection equipment. Many of these SCR systems are implemented and used for compliance with stringent NO_x regulations (year-round stack NO_x levels below the 0.15 lb/MBtu mark), hence, are designed and operated to achieve high NO_x reduction efficiencies of over 90 percent, while minimizing NH_3 slip to below 2 ppm. In coal-fired boilers, high NH_3 slip has an adverse impact on cold-end equipment located downstream of the SCR reactor. The concerns include ammonium bisulfate (ABS) deposition, and plugging and corrosion potential of APHs. Controlling and mitigating APH fouling is imperative in coal-fired boilers, since it precludes continued operation of the unit, requiring forced shutdowns for APH cleaning, with the associated lost in unit availability and financial penalty. The challenge of the SCR technology is to achieve cost-effective high levels of NO_x emissions performance, while constraining its detrimental impact at the boiler back-end. SCR process variables, such as flue gas temperature and residence time, and NO_x inlet concentration and the level of reagent conditioning all affect SCR performance, and are conditioned by the operating conditions of the boiler. An integrated approach to the optimization of the combustion and post-combustion systems offers an alternative to meet this challenge. Such approach should consider, in a coordinated fashion, the optimal operation of the boiler firing system, SCR reactor, sootblowing, APH and net unit thermal performance.

This paper reports the results of a combined boiler/SCR/APH optimization performed at AES Cayuga Unit 1, for cost-effective NO_x emissions control. Cayuga Unit 1 is a 160 MW cool-fired unit that fires Eastern U.S. bituminous coals and it is equipped with a two-layer SCR catalyst reactor. Parametric testing was performed at this unit to develop a representative database that characterizes the response of NO_x emissions, required NH_3 conditioning, SCR efficiency, ABS deposition and unit heat rate penalty to changes in boiler, SCR and APH control settings. The parametric test results were used to build functional relationships between independent and dependent parameters. These relationships were then used to perform mathematical optimizations. The optimization approach relies on having available monitoring tools for measurements of combustion-related parameters such as excess O_2 at the boiler outlet, pulverizer coal flow rates, overfire (OFA) register positions, etc., as well as SCR performance efficiency and ABS formation in the APH. The methodology used is based on modified accurate on-line support vector regression (AOSVR) modeling for adaptive learning, and genetic algorithms (GA's) for implementation of multi-objective optimization. AOSVR is a data-driven supervised learning method for classification and regression problems, based on statistic learning theory. This method overcomes some of the problems of artificial neural networks associated with slow training, local minima and poor interpretability of the results. GA is a class of stochastic search optimization technique, which derives its behavior from the evolutionary theory of natural selection. The combined boiler/SCR/APH optimization is a multi-objective optimization problem which it is well suited for the GA methodology.

Unit Description

Optimization, based on AOSVR for adaptive learning and GA for constrained optimization, was performed at Cayuga Unit 1. Cayuga Unit 1 is a tangentially-fired Combustion Engineering (CE) boiler, equipped with a low-NO_x concentric firing system (LNCFS) level III. The LNCFS-III system consists of four elevations of burners arranged in four corners (see Figure 1). Four pulverizers (1A1, 1B2, 1A3 and 1B4, from top to bottom) supply coal to the burner system, one mill per elevation. Cayuga Station typically fires Northern Appalachian coal; however, blending with lower quality fuels is common at this station. The windbox compartment at each corner is composed of fuel air registers (coaxial with the burner nozzle), auxiliary air registers and concentric fire system (CFS) air registers that are used to divert combustion secondary air at an offset, with respect to the burner centerline. In addition to the secondary air ports, the LNCFS-III arrangement at Cayuga Unit 1 incorporates OFA in two set of registers, a two-closed coupled overfire air (CCOFA) register set, and a separated OFA (SOFA) compartment with three registers. All the burner buckets and CCOFAs are connected to tilt in unison for controlling of steam temperatures. The SOFA compartments are also tiltable for combustion staging.

Cayuga Unit 1 is equipped with a 2-layer, anhydrous NH_3-based SCR system, with a $TiO_2/V_2O_5/WO_3$ formulation and a total catalyst volume of 5,890 ft^3 for additional NO_x control. The SCR system is equipped with NO_x analyzers at the inlet and outlet of the reactor, and an ABS monitoring sensor, manufactured by Breen Energy, Inc. The Breen Energy's AbSensor - AFP was retrofit after the SCR manufacturer installation, and it is a probe that measures the conduction of electrical current across the probe's tip that results from condensed hydrated ammonium bisulfate. The instrument reports both the ABS formation and evaporation temperature via OLE for process control (OPC). The AbSensor probe was installed at the inlet of the APH. The rest of the boiler back-end configuration includes two rotating APHs with air bypass dampers for average cold-end temperature control (average of APH gas out and air in temperature), an electrostatic precipitator for particulate removal, and a flue gas desulphurization unit.

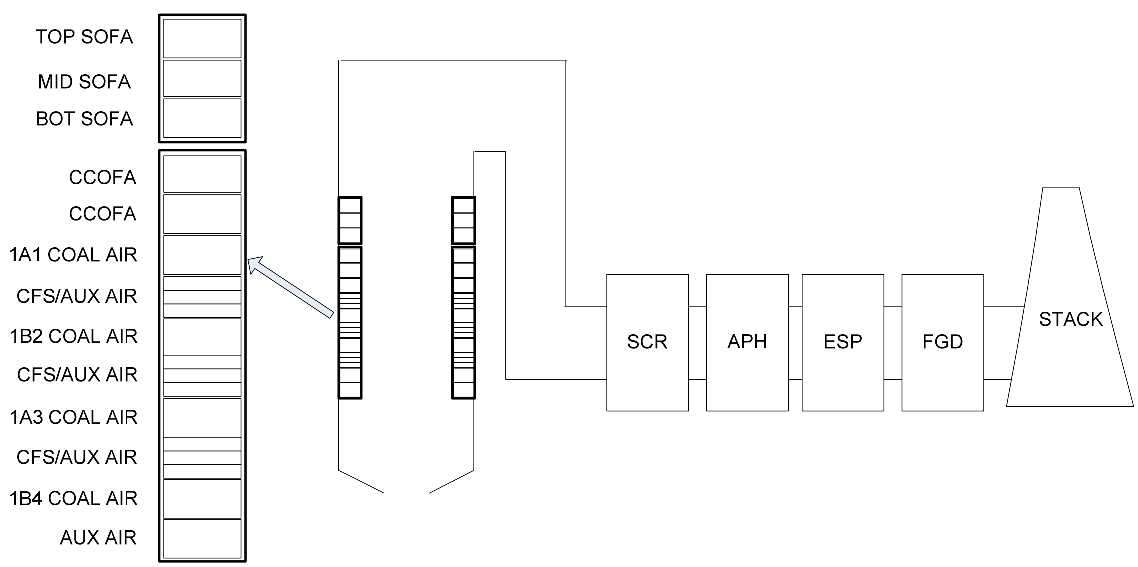


Figure 1: Cayuga Unit 1 – Boiler Configuration.

Parametric Field Tests

Parametric field tests were performed at Cayuga Unit 1, with data collected at different combinations of boiler firing system, SCR and APH operational settings. The tests reported in this paper are tests performed at full load;

however, testing was also performed over the load range. The parameters used for testing and their available operating ranges are included in Table 1. Economizer excess O_2, was used as an indication of the amount of excess air fed to the boiler, the average of the top and middle SOFA register openings was used as an indication of combustion staging. Additionally, the average burner and SOFA tilt angles, and the coal flow rate to the top 1A1 mill were included in the parametric list to characterize the relationship between boiler control settings and boiler outlet or SCR inlet NO_x and unit thermal performance. Other parameters used to characterize parametric relationships for the SCR and APH include the NH_3 flow rate and the APH bypass damper position, respectively. Parametric testing was conducted by changing individual parameters one at a time, while keeping the set-points of the other parameters constant during each test period. Coal and fly ash was sampled for each test run and analyzed off-line. Data on SCR inlet and outlet NO_x, and SCR NO_x removal efficiency (defined as the normalized NO_x reduction across the SCR with respect to the inlet NO_x), main steam and hot reheat steam temperatures, attemperating flow rates, boiler flue gas outlet temperature, flue gas and air temperatures across the APH, and fly ash loss on ignition (LOI) level were acquired for each test point. Indication of the net unit heat rate penalty for each test point, or combination of test parameters, with respect to design conditions, was estimated from a heat and mass balance model of the unit.

Table 1: List of Testing Parameters.

No.	Symbol	Variable description	Unit	Upper limit	Lower limit
1	O_2	Excess O_2	%	4.0	2.5
2	*SOFA*	Average top SOFA Opening	%	100	0
3	α_{ST}	SOFA Tilt	Deg.	25	-15
4	α_{BT}	Burner Tilt	Deg.	15	-15
5	F_{coal}	Coal flow rate of top mill	t/h	19	0 (OFF)
6	NH_3	Ammonia flow rate	lb/h	250	0
7	D_{APH}	APH bypass damper position	%	100	0

Constraints were imposed for the stack outlet NOx emissions level and for the APH to maintain the ABS axial deposition location in the APH at 2.5 ft. from the cold-end. This location set-point was chosen based on the known penetration distance of the APH sootblowers, which are located at the cold-end side of the APH. Any deposition of sticky ABS deposits on the APH baskets, beyond the chosen deposition set-point, would have a lower probability of being removed by sootblowing, increasing the risk of gradual fouling of the APH and further loss of generation for APH washing. The ABS deposition distance was calculated using the measured AbSensor evaporation temperature and an estimated APH metal temperature profile calculated from a heat transfer model of the rotating APH. The axial location of the APH metal temperature profile at which the metal temperature is equal to the ABS evaporation temperature establishes the ABS deposition axial distance from the APH cold-end. Two options are available when the ABS deposition distance is beyond the reach of the sootblowers (exceeds the 2.5 ft. set-point), viz, to lower the NH_3 injection rate to the lowest conditioning permitted to achieve the required outlet NO_x level, or manipulate the

APH air bypass damper to increase the metal temperatures. Opening the APH bypass damper is the least preferred option, since it results in heat rate penalties, due to the increase in stack losses associated higher flue gas temperatures exiting the boiler.

Results and Discussion

AOSVR was used to built artificial intelligence-based, functional relationships between the boiler outlet or SCR inlet NO_x level and heat rate penalty (with respect to the design heat rate level), and five of the parameters included in Table 1 (O_2, *SOFA*, α_{ST}, α_{BT} and F_{coal}). The AOSVR model was trained with the database obtained from the parametric tests, and adaptively updated with real-time data sets. Four thousand data points were extracted from real-time data at a 1-minute sample rate and used for AOSVR adapting. Figure 2 shows a comparison between the on-line data and the predicted model results for boiler outlet NO_x emissions rate. The AOSVR showed good convergence and acceptable learning efficiency. AOSVR accurate learning results from its efficient data updating and it is well suited for time-varying systems. The prediction performance of proposed AOSVR models was evaluated using a mean absolute percentage error (MAE) as validation criterion, which is defined as:

$$\text{MAE} = \frac{1}{n}\sum_{i=1}^{n}\frac{|y_i - \hat{y}_i|}{y_i}\times 100\%$$

Where n is the sample size, y_i denotes the sample data, and $\hat{y}_i$ is the modeling output value. The MAE value for the AOSVR boiler outlet NO_x and heat rate penalty was 1.65. Smaller values of MAE indicate better model predicting capabilities. Figure 3 shows AOSVR model trending results for the impact of the boiler parameters included in Table 1 and heat rate penalty, referenced to a design unit heat rate level.

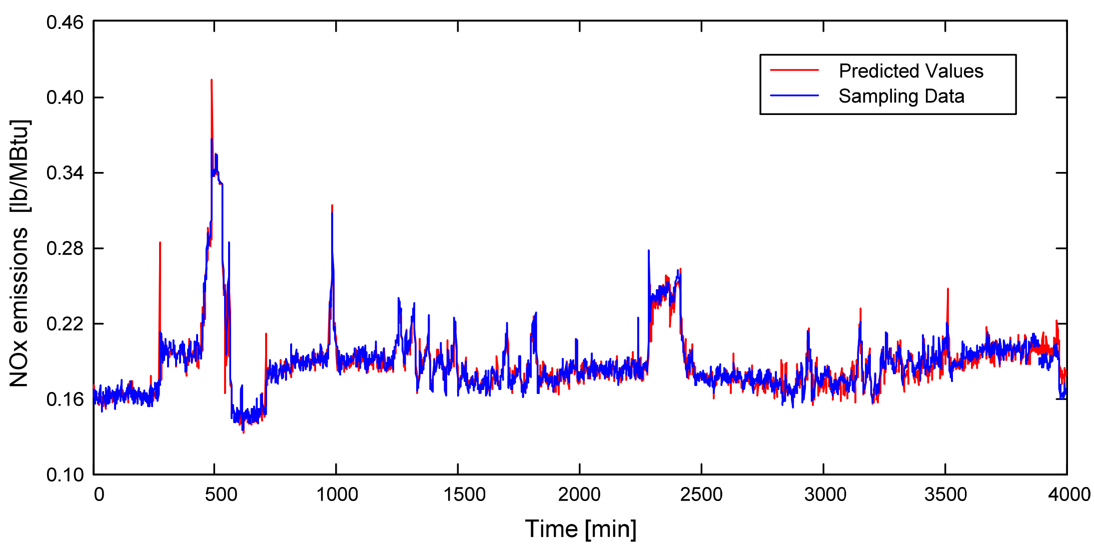


Figure 2: Modified AOSVR NO_x Emissions Model Prediction Results.

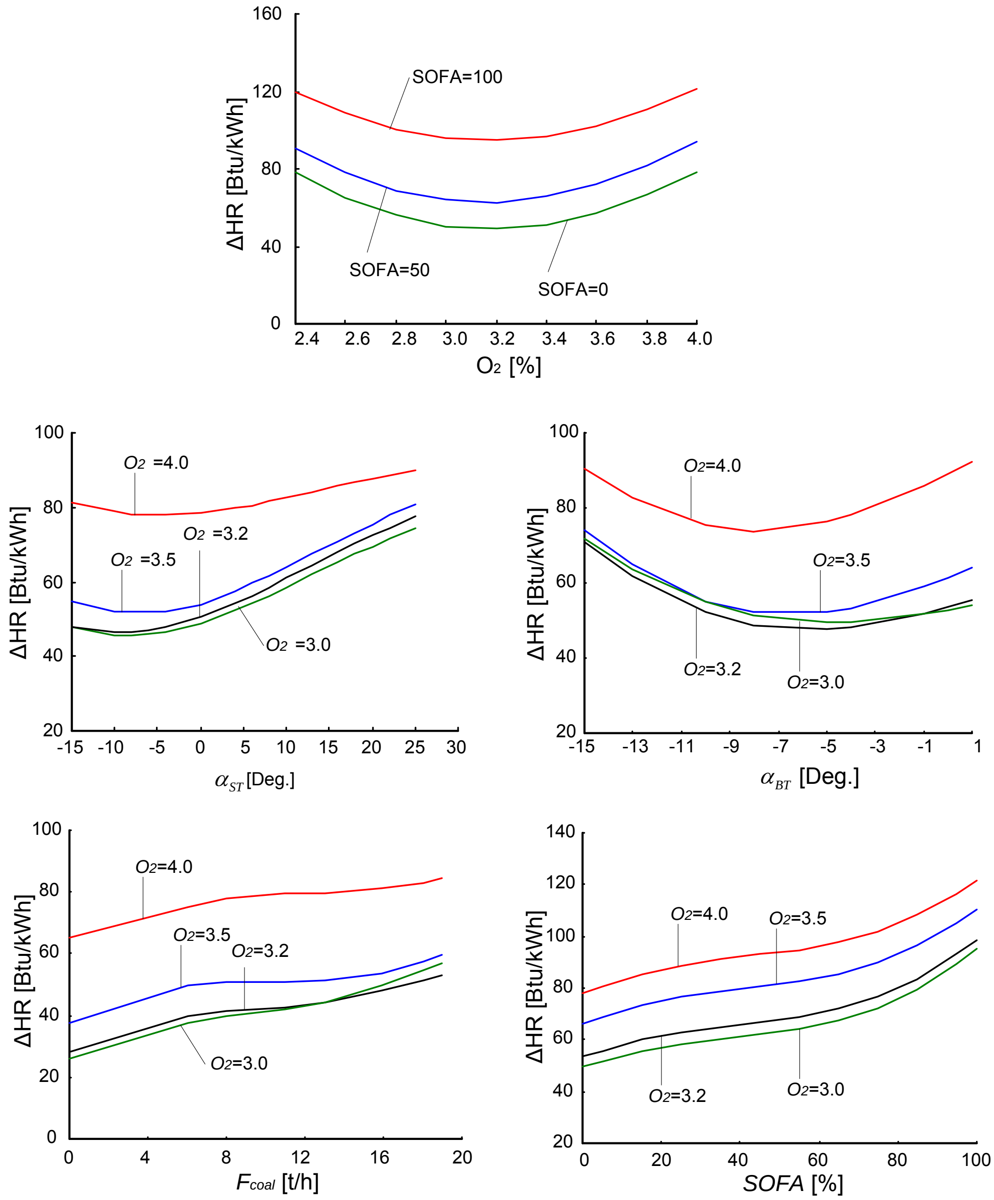


Figure 3: Trained AOSVR Model Results for Boiler Heat Rate Penalty.

The functional relationships obtained from the AOSVR models were then used to perform the boiler/SCR/APH mathematical optimization. Additionally, relationships for the lowest required NH_3 injection flow rate as a function of SCR inlet NO_x and for heat rate penalty as a function of the APH air bypass level were obtained from the parametric test data. Figure 4 shows a plot of minimal NH_3 flow rate vs. SCR inlet NO_x. The minimal NH_3 vs. SCR inlet NO_x curve shows a rapid increase when the SCR inlet NO_x level exceeds the 0.26 lb/MBtu, which is characteristic of the catalyzed NO_x reduction process in the SCR reactor. Maintaining the NH_3 injection rate with the same slope, as the one exhibited at low NO_x levels (< 0.26 lb/MBtu) would result in violation of the stack NO_x emissions constraint. An increase in NH_3 flow is required at larger SCR inlet NO_x levels. This increase in reagent requirement for elevated SCR inlet NO_x levels is what increases the risk of NH_3 slip and, subsequent formation of

ABS in the ducting and equipment, downstream of the SCR. The relationship between APH air bypass damper and unit heat rate penalty was obtained from the parametric field testing at different bypass damper opening positions, resulting in different APH metal temperature profiles, and ABS deposition depths. Figure 5 shows the heat rate deviation or penalty associated with the opening of the APH bypass damper, because of the increase in APH outlet gas temperature. Also included in Figure 5 are the ABS deposition depths (from the APH cold-end) vs. APH bypass damper position.

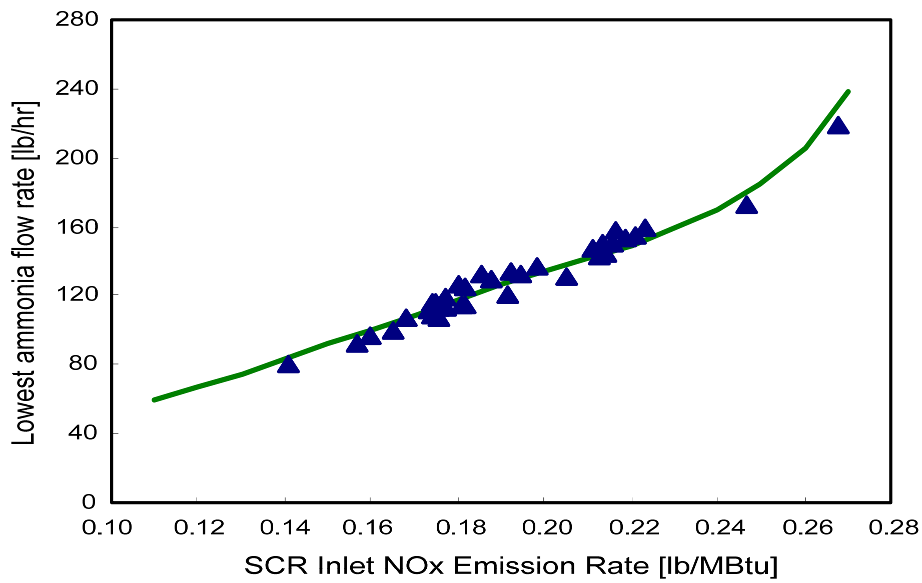


Figure 4: Lowest NH_3 Flow Rate vs. SCR inlet NO_x.

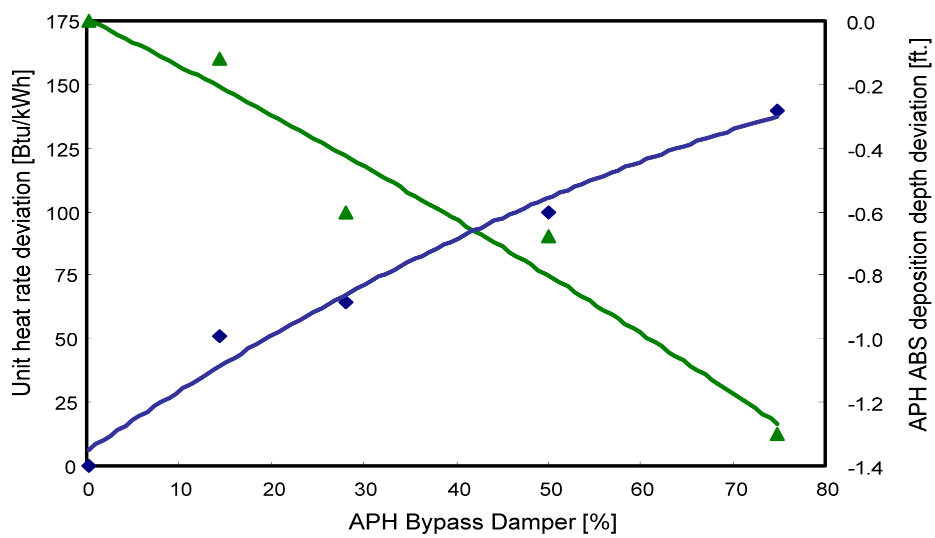


Figure 5: Heat Rate Deviation and ABS Deposition vs. APH Bypass Damper Opening.

The optimization was performed in two steps, using GA's. In the GA implementation, a population of candidate solutions was first used, based on the parametric test database. This population was then modified (recombined and randomly mutated) to form new iterative populations, from which better fitness or solutions were achieved, that fulfill the multi-objective optimization problem. The GA implementation was done in two steps. In the first step a GA was used to derive a functional relationship between the minimal or optimal boiler heat rate penalty as a function of target boiler outlet or SCR inlet NO_x. The constrained multi-objective optimization problem was defined by:

$$
\begin{aligned}
&\min NO_x = f_{NO_x}(O_2, SOFA, \alpha_{ST}, \alpha_{BT}, F_{coal}) \\
&\min q = f_q(O_2, SOFA, \alpha_{ST}, \alpha_{BT}, F_{coal}) \\
&s.t. \quad \theta \le \theta_{\max} \\
&\quad O_{2,\min} \le O_2 \le O_{2,\max} \\
&\quad SOFA_{\min} \le SOFA \le SOFA_{\max} \\
&\quad \alpha_{ST,\min} \le \alpha_{ST} \le \alpha_{ST,\max} \\
&\quad \alpha_{BT,\min} \le \alpha_{BT} \le \alpha_{BT,\max} \\
&\quad F_{coal,\min} \le F_{coal} \le F_{coal,\max}
\end{aligned}
$$

Where $f_{NO_x}(\cdot)$ and $f_q(\cdot)$ are the objective functions between the five boiler operating variables listed in Table 1, and boiler outlet NO_x emissions and heat rate penalty, q, respectively. The optimization was constrained by fly ash unburned carbon, θ, to be below a prescribed maximum of 4 percent, and the operating input parameters to be between minimum and maximum levels, representing their operational upper limit and lower limit, as indicated in Table 1. Figures 6a to 6d show different stages of the GA optimization for minimum boiler NO_x and heat rate penalty. The parametric test database is shown in Figure 6a. A sequence of data generation and best fitness selection is shown in Figures 6b to 6d. Converged optimal solutions are presented in Figure 6d after the 30^{th} generation. The heat rate penalty vs. SCR inlet NO_x trend in Figure 6d was fitted into a polynomial function to be used in the second step in the optimization.

The second step of the optimization consisted of minimizing an overall cost function that combines the costs of: (1) the heat rate penalty resulting from tuning of the boiler control settings to achieve an optimal boiler outlet or SCR inlet NO_x emissions rate; (2) reagent to produce highest SCR NO_x reduction performance; and (3) the heat rate penalty to operate the APH within the ABS deposition constraint. Savings due to avoidance of APH washes was not included in the optimizable cost function. The second step optimization was defined by:

$$
\begin{aligned}
&\min C_{total} = k_1 C_1(NO_x) + k_2 C_2(NH_3) + k_3 C_3(D_{APH}) \\
&s.t. \quad d_{\mathrm{ABS}} \le a_{depth} \\
&\quad NO_{\mathrm{x,outlet}} \le a_{NO_x,\mathrm{limit}} \\
&\quad NO_{\mathrm{x,min}} \le NO_x \le NO_{\mathrm{x,max}} \\
&\quad NH_{3,\min} \le NH_3 \le NH_{3,\max} \\
&\quad D_{APH,\min} \le D_{APH} \le D_{APH,\max}
\end{aligned}
$$

Where the total cost C_{total} is composed of the fuel cost, C_1, due to the boiler heat rate penalty; the NH_3 treatment cost, C_2, and the heat rate penalty cost, C_3, due to the manipulation of the APH bypass damper (D_{APH}). The coefficients, k_i, $i = 1,2,3$ were set with a value of 1.0. The deposition depth limit was set $< a_{depth} = 2.5$ ft.

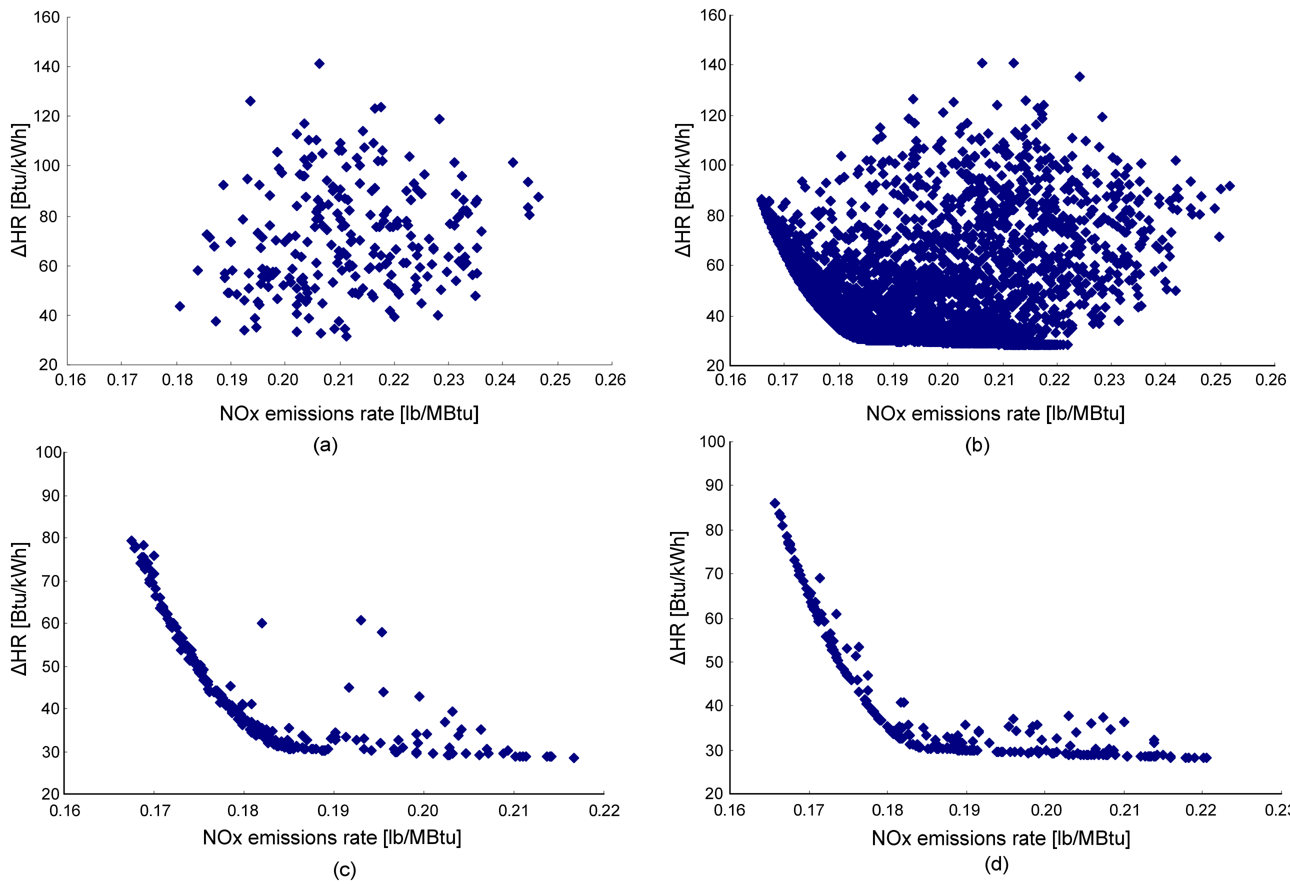
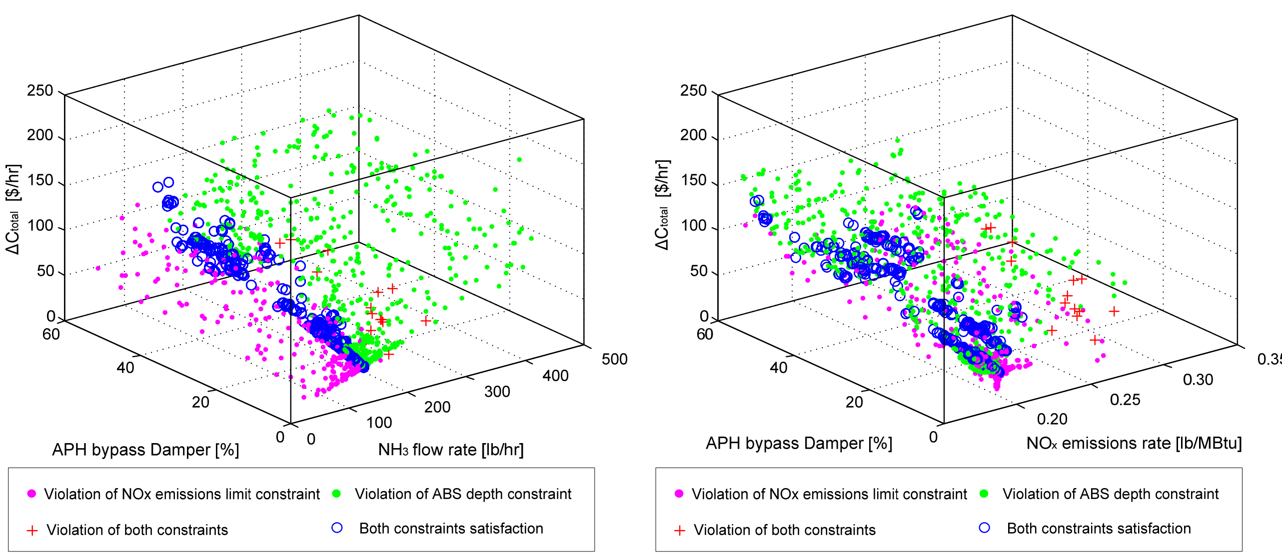


Figure 6: GA Optimization Results for Boiler Outlet NOx -
(a) Initialization Dataset, (b) 1st Generation, (c) 15th Generation, (d) 30th Generation.

The boiler/SCR/APH cost function was optimized using GA's. The following rates were used in the evaluation of the cost function: power generation cost of \$0.02/kwh and NH_3 cost of \$0.55/kg, to convert the objective function to units of dollars per hour. Figures 7a and 7b show a 3-D map of all searched solutions provided by the GA, expressed as differential costs with respect to design heat rate conditions. Also, included in these figures are the sets of SCR inlet NO_x, NH_3 injection rate and APH bypass damper positions that violate the ABS deposition distance constraint and the NO_x emissions rate limit. The set of feasible solutions, which satisfy both constraints are also shown in Figures 7a and 7b. These solutions were obtained after the 22nd generation of the GA algorithm. Figure 7a shows on the z-axis that a low NH_3 injection rates the stack NO_x emissions constraint is violated, while at high NH_3 injection rates the ABS deposition constraint is violated. Optimal solutions that satisfy both constraints are obtained in the NH_3 flow rate range between 120 and 195 lb/hr. The optimal solution for the lowest cost of compliance corresponds to the following control setting: O_2 =3.2 percent, average SOFA register opening = 51 percent, average burner tilt angle = -8 degrees, average SOFA tilt angle = +6 degrees, 1A1-mill coal flow rate = 6 t/hr, APH bypass damper = 0 percent, NH_3 injection rate = 125 lb/hr. The optimal NH_3 injection rate represents a reduction in NH_3 flow rate from baseline conditions of approximately 25 percent. The combination of optimal settings will result in NO_x emissions at the boiler outlet of 0.188 lb/MBtu, while complying with ABS deposition at less than 2.5 ft. and fly ash unburned carbon below 4 percent, at a differential cost of \$41.2/hr. Figure 8 shows costs associated with operation at optimal combinations of boiler control settings that result in a range of boiler outlet NO_x emissions levels. It can be inferred from Figure 8 that operation at the "knee" of the SCR inlet NO_x vs. heat rate penalty results in the lowest combined cost of operation. Operation at SCR inlet NO_x levels at the left of that "knee" results in a significant added cost, due to the contribution from the boiler heat rate penalty. Operation at the right of the knee results in a gradual moderate cost increase due to additional NH_3 consumption, until a point is reached (at around 0.25 lb/MBtu) where there is the need to manipulate the APH bypass damper to control the ABS deposition. This results in a steep heat rate penalty due to increased stack losses. As anticipated, the optimization model indicates that the total cost of compliance increases as the ABS deposition distance is tightly set, closer to the APH cold-end. A reduction in the ABS deposition depth setpoint below 2.5 ft. would require opening of the APH bypass damper, with the associated heat rate penalty from this component of the cost function.



(a) (b)

Figure 7: GA Optimization Solutions for the Total Cost Function.

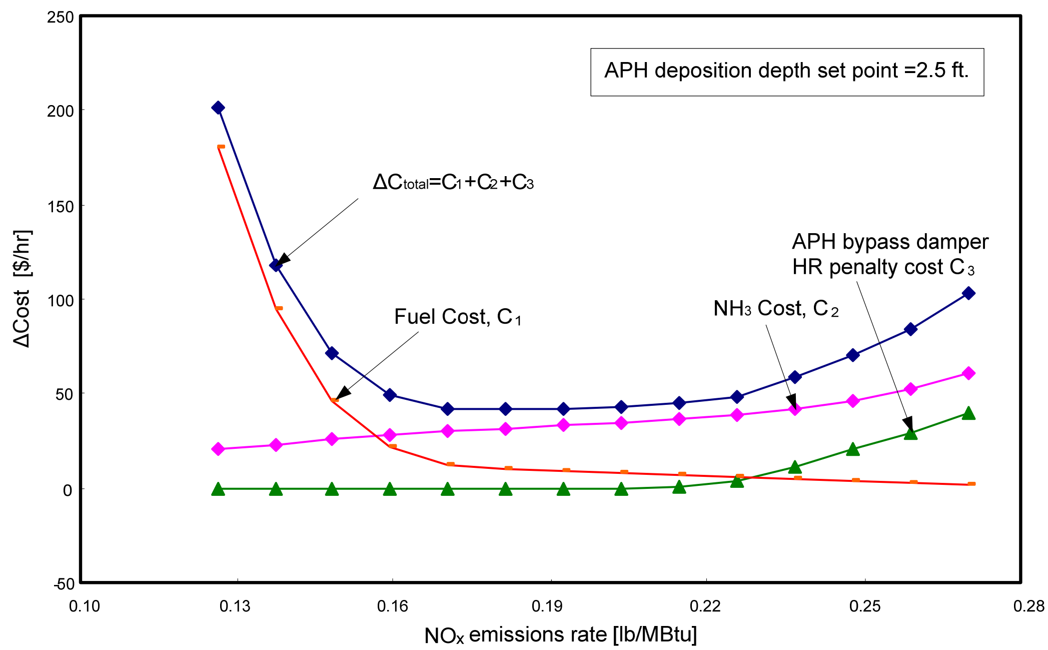


Figure 8: Cost Components as a Function of Boiler Outlet NO_x.

Conclusions

Process optimization is a cost-effective approach to improve the cost of NO_x compliance at coal-fired boilers, while meeting other operational constraints. In boilers equipped with SCR's, this is a classic multi-objective optimization problem to balance boiler thermal performance, NO_x emissions, the cost of reagent and APH maintenance costs. A modified artificial intelligent AOSVR model was implemented on parametric test data obtained from a 160 MW tangentially-fired boiler equipped with a low-NO_x firing system and SCR. An optimization model, based on GA's was used to solve the constrained optimization problem that provides boiler control, SCR and APH control settings that result in the minimal cost of compliance, subject to constraints on fly ash LOI, APH ABS deposition depth, and stack NO_x emissions level. The combined cost of compliance ranged from approximately $1.2 millions to $310,000 at optimal conditions.

Acknowledgements

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