NOx Reduction through Efficiency Gain

Robert Benz  Ryan Thompson  Marcel Staedter
President  Vice President, Operations  Project Manager

Benz Air Engineering, Co., Inc.
Las Vegas, NV | Austin, TX | Modesto, CA

ABSTRACT
Benz Air Engineering and the CompuNOx system focus on a controls approach to minimize emissions without exposing steam generation plants to an unbearable financial burden. With minimal system changes we use thorough system analysis in conjunction with a novel control design to deliver a comprehensive boiler controls retrofit that provides reductions in emissions as well as substantial cost savings. Combining mechanical engineering expertise with substantial experience in control engineering in over 200 retrofits this system achieves astonishing results with short payback time, making CompuNOx a feasible solution for emission mandates and cost savings.

INTRODUCTION
Rapid development in environmental policy as well as vulnerability to fluctuating fuel prices require industrial and utility steam generation to find feasible, reliable and cost-effective solutions. Rather than focusing on alternative fuel types and drastic changes in plant design we scrutinize existing steam generation plants to identify potential avenues for efficiency gain. Benz Air Engineering realizes that increases in efficiency are directly related to reductions in emissions. We therefore concentrate on the improvement of existing systems to achieve fuel savings as well as meeting regulatory standards in NOx emission. That is, rather than putting financial stress on steam generation plants to adhere to environmental regulations we provide an incentive to do so.

The simplicity and elegance of the CompuNOx system minimizes system changes. Control related changes consist of installation of variable frequency drives, control valves, actuators, transmitters and flow meters. System changes include the incorporation of flue gas recirculation (FGR) and the addition of heat exchangers if appropriate.

Control is achieved with a variety of Programmable Logic Controllers (PLCs) which are commonly used in processing plants and steam generation plants so that requests for specific platforms can be met. Customized programming allows for the control of any given system and to any extent that is required or necessary.

The results of this approach are unprecedented. Immensely reduced NOx levels, substantial cost savings due to increased efficiency and significantly increased turn down ratios, which provide valuable operational flexibility, are characteristic results of the CompuNOx approach.

METHODS
Control Parameters and Objectives
Our objective in controlling a steam generation system is to maximize efficiency while minimizing emissions. To obtain an optimal quality of combustion we consider the air/fuel ratio. The combustion reaction for a natural gas fueled boiler can be generally characterized with methane combustion described as follows:

\[
\text{CH}_4 + x(\text{O}_2 + 3.71\text{N}_2) \rightarrow \text{CO}_2 + 2\text{H}_2\text{O} + (x3.71)\text{N}_2 + y\text{O}_2 + \text{heat}
\]

Equation (1),
where \( y \) denotes the mole fraction of excess oxygen. The presence of nitrogen and excess oxygen radicals in this hot combustion environment promotes the formation of nitrogen oxides, or NOx. Using air mass flow and fuel mass flow as main control parameters and maintaining their ratio as suggested by the reaction in equation (1) we are able to limit the amount of excess oxygen in flue gases and eliminate the possibility of unburned fuel.

Overall boiler efficiency consists of a variety of heat loss terms and may require dozens of pieces of variable input. Concentrating on major terms boiler efficiency can be expressed as

\[
E = 100 \left[ 1 - 10^{-3} \left( 0.22 + \frac{K^* y}{1 - y} \right) (T_s - T_a) - \frac{\Delta H_f}{H_C} \right]
\]

Equation (2),

where \( K^* \) is a fuel dependent coefficient (1.01 for natural gas, 1.03 for oil, 1.01 for coal) and \( y \) denotes the mole fraction of excess oxygen. \( \Delta H_f / H_C \) is fuel dependent as well (0.02, 0.05 and 0.09 for coal, oil and natural gas respectively). \( T_s \) is stack temperature and \( T_a \) is ambient temperature. The significance of excess oxygen for overall boiler efficiency becomes apparent. In fact, a 1% increase in boiler efficiency is achieved by lowering excess oxygen in flue gases by 2%. Unnecessarily high excess oxygen due to poor process control systems, reveals a vast potential for both, NOx reduction as well as efficiency gain by merely applying an accurate process control system.

Airflow characteristics of a steam generating system are not a linear function of fuel flow; i.e. the air/fuel ratio does not exhibit a linear behavior over the entire firing range, especially if one desires to take advantage of the full capacity of the boiler and if one demands high turndown. Moreover, possible changes in fuel type (in dual fire applications), the introduction of Flue Gas Recirculation and system characteristics such as burner properties introduce further nonlinearities to the air/fuel ratio. Since these system characteristics have to be determined empirically over the whole firing range such inconsistencies are addressed and compensated for in customized controls programming and, adequate field tuning, and further underline the necessity of proper control.

To further lower NOx levels the precise control of Flue Gas Recirculation (FGR) flow becomes significant. The control of mass flow of flue gas in relation to mass flow of air is governed by the objective to achieve the maximum amount of preheating of combustion air and reduction of available oxygen radicals for NOx formation while ensuring sufficient mass flow of combustible air in order to maintain stable operation. As with the behavior of the air/fuel ratio, the amount of mass flow of flue gas is dependent on firing rate and combustion air supply but their rate of change is not directly coupled throughout the rate of change of fuel flow. This behavior is also controlled with control programming and field tuning.

Well-designed drum level control is highly important in order to compensate for peculiarities that arise from shrink/swell effects. An increase in load contradicts typical control anticipation in that volume displacement due to increased boiling volume occurs and drum level increases. Likewise, shrinking leads to a disproportional high drum level drop. This level swinging limits the ability to change load over short time spans and requires delicate control.

Further control parameters include steam flow, and, if applicable, steam temperature, deaerator pressure and system parameters such as feed water temperature.

The recognition of pertinent control parameters points to the needs for the right choice of instrumentation and sensors to have the ability to control these parameters.

Control Components

Having established the necessary control parameters, we have to incorporate an appropriate array of control components to make an adequate control of these parameters feasible.

As the Air/Fuel ratio is a crucial to our control the degree of accuracy of this ratio is dependent on the accuracy of both of these two parameters. We need to be able to achieve control of these parameters to within 1% of their desired set points. Fuel flow is monitored with the measurement of a pressure differential across an orifice plate and is controlled with a flow regulator consisting of an actuator and control valve. Depending on the performance of the actuator, implementation of this method has shown reliable and accurate results.

Combustion air flow is controlled with the most vital components of our control approach, Variable Frequency Drives (VFDs). These drives function under the premise that a change in frequency of an
AC-current supplied to an AC motor will change its speed by the relation:

\[
\text{RPM} = \frac{120 \times f}{p}
\]

Equation (3),

where \( f \) is AC frequency and \( p \) is the number of poles.

A VFD speed feedback provides a direct measurement of combustion air flow, due to the direct relation of fan speed to air flow, as opposed to having an indirect and inferred parameter as it would be with dampers.

![Fig. 1. Fixed fan curve and changing system curve with damper control](image1)

**Fig. 1. Fixed fan curve and changing system curve with damper control**

**Fig. 2. Variable fan curve with fixed system curve with VFD control**

Figure 1 shows the fan characteristic with damper control; i.e. a fixed fan curve with varying system characteristic. Typically, this characteristic shows a positive slope at loads less than 50%, which causes a pressure-flow instability and a control situation that is impossible to manage. Figure 2 shows the fan characteristics incorporating a VFD. The system curve remains constant while the fan curve can be easily altered to meet optimal control at any given load. In addition to significant advantages in control, changing fan characteristics due to VFD yields substantial reduction in power consumption caused by the cubic relationship between load and power versus a fixed speed fan scenario.

With precise flow control management and reduction in fan power consumption being essential advantages, the use of a VFD also provides several other positive effects. A VFD eliminates the necessity of linkages and cams to actuate dampers. Those components commonly exhibit hysteresis as well as wear and tear and have causes maintain inefficiently high excess oxygen levels for safety reasons. Moreover, unnecessary high airflow has been the cause of NOx formation due to a high abundance of oxygen radicals and high flame temperatures. At low loads, high air flow in damper systems causes unstable flame behavior, even higher NOx levels and more inefficiency since the efficiency of a boiler tends to be lower at load operation. These issues have severely limited system turndown ratios. Also, the inability to perform adequate field tuning over the entire firing range inherently causes inefficient operation. The elimination of dampers, linkages and cams allows for much tighter boiler control with more efficient excess oxygen trim.

The increase in possible operating range is accomplished by unprecedented high turndown ratios, which is a significant progress in the industry. High turn down ratios allow plants to run a boiler in banked conditions during its off-line state. The extremely low fuel consumption, with minimum firing rates of less than 2% provides the possibility to eliminate start up related fuel costs as well as post-purge and pre-purge losses since a boiler in banked condition stays warm and pressurized, and can go online virtually immediately. Start up fuel savings as well as high flexibility are powerful incentives for utility steam generation as well as industrial steam generation. It becomes clear that the utilization of VFD technology provides several layers of efficiency gain and NOx reduction.

Besides controlling forced draft combustion air fans, VFDs can also be used to control induced draft combustion air fans, flue gas recirculation fans, and cooling tower pumps.

Steam flow and feed water flow are also determined with orifice plate pressure changes. The DP orifice plate approach has been a reliable method but the caused pressure drop is ultimately a loss and can be compensated for by implementing Coriolis mass flow meters for liquids.

The control of feed water flow and boiler drum level control is increasingly accomplished by utilizing VFDs rather than using the less efficient method of a control valve to block flow at constant pump speed. The accuracy of this feed water flow ought to be within 1%. Transmitters acquire all relevant data for the system over the entire firing range. K-type thermocouples are implemented to obtain temperatures at relevant locations in the
process. Data acquisition should be accurate within 1\% for all control parameters and system variables. The central component of system control is a Programmable Logic Controller that is commonly used in industrial automation. The processor analyzes field inputs in real-time to generate real-time responses. Signals are delivered in digital or analog form to address status information as well as position of control components. Clearly, the performance of the PLC is strongly dependent on the time needed to execute these tasks, or, as it is commonly known, the scan time. Good performance in PLCs is necessary to eliminate the possibility of false control and to ensure reliable and accurate performance of the process control system.

**Control Programming**

The PLC programming environment is usually based on relay schematics in series emphasizing sequential significance, which makes it an ideal process control.

**Fig. 3. Typical sequential “ladder logic” in a PLC programming environment**

An essential part of its programming power is the ability to use the common proportional-integral-derivative feedback loop (PID loop). Taking into account the history and the rate of change of the error of a process variable to a given set point provides a stable control for system parameters. Any control parameter may follow a PID to maintain its respective set point. In particular, commonly used PID loops are those for the process variable steam flow when firing rate is used as control variable and that for the process variable firing rate when fuel valve position is used as control variable. In fact, any modulating control parameter may be handled this way.

**Fig. 4. Block diagram of PID loop**

This control method leads to stable and reliable behavior of our control parameters, which allows for very accurate and tight system control. In combination with a VFD the PLCs PID loop can reliably operate at optimum air/fuel ratios allowing for direct control of combustion air supply at minimized excess oxygen present in flue gases. This indicates an efficient operation with low NOx levels while maintaining safety standards.

The power of PID control has been used for these applications for some time now. However, some systems depend on loop controllers that merely use the raw function of the PID loop with limited set point ability. System nonlinearity such as inconsistencies in air/fuel ratio behavior, burner behavior, reaction to flue gas injection and feed water drum level swelling are insufficiently addressed in those solutions. The processing and memory power of a PLC allows for a dynamic response over the firing range as necessary for an individual system.

**Oxygen Trim and System Tuning**

With control components and programming ability in place, oxygen trim and system tuning has to occur. Oxygen trim empirically establishes characteristic air/fuel ratio behavior over the whole firing range. This allows immediate and extremely high turndown as the boiler will have a prescribed path to follow for stable and efficient operation. With excess oxygen as an indicator the response of combustion air supply as a function of firing rate is established at a minimum of 10 points distributed over the entire range of fuel flow. The result of this procedure is a curve from which the system response is derived upon requesting a certain output. This graph generally follows a < 3\% excess oxygen path, which is significantly below excess oxygen levels of purely mechanical control system and PID loop controllers, illustrating a significant increase in efficiency and NOx reduction.
Further system tuning occurs by establishing a curve for FGR. This tuning affects the combustion behavior of the system; i.e. flame stability and excess oxygen. Tuning for all system parameters that are affected by this procedure has to occur simultaneously to account for feedback reactions.

Additional tuning parameters include separate behavior management for different fuels in dual fuel applications, incorporation of multiple fans, and control of any dampers that might remain in the system.

**Human Machine Interface**

The most visible component of CompuNOx is the human-machine-interface, or HMI. The goal of this interface is to provide a clear and organized overview of the process and to offer all necessary control inputs without compromising reliability, safety and its ability to control complex system and nonlinear behavior. Typically, an overview screen provides system schematics and process information such as flow rates, temperatures and components statuses.

**Fig. 5.** The CompuNOx tuning screen, which displays combustion air fan behavior as well as FGR fan behavior

**Fig. 6.** Typical HMI-overview screen, here at UT Austin Boiler 3, depicting system with status information and variable values

A control interface allows for requesting a PID control modes, such as manual or automatic. Automatic mode bases the system fuel flow on a specified steam flow output and manual mode controls fuel flow directly. Feed water control and emergency options complete the HMI.

**Fig. 7.** Control interface providing main control functions

The important aspect to notice is that any control execution via HMI is based on system tuning and PID operation, which had been established under the premise of optimal combustion and reduced NOx emission for the individual system.

Using the memory power of PLC programming in combination with HMI programming additional features such as trending and process history are readily available and allow for trouble shooting, system behavior observation and performance monitoring.
Changes in System Design and Further Efficiency Gain

Major changes in system design are unnecessary to implement our approach. However, as indicated earlier, Flue Gas Recirculation is an integral part of our approach. The required installation consists of an FGR fan, drive and an appropriately placed duct. The position of flue gas suction is determined after accurate analysis of the existing system to ensure optimal results. The position of flue gas withdrawal from the system changes depending on the presence of economizers and air pre-heater heat exchangers.

System analysis often reveals significant potential for further efficiency gain through heat recovery. Invoking the Carnot Efficiency the objective leads toward reducing stack temperature as much as possible. Placement of additional heat exchangers at appropriate locations can lead to further NOx reduction, as the boiler efficiency is increased, and less fuel is required to be combusted.

Additional NOx Reduction

Utilizing tight controls and appropriate heat recovery may not always provide NOx levels low enough to meet mandates. Aged systems in regions with strict mandates have to find an alternative to cost intensive system replacements. Incorporation of Selective Catalytic Reduction has shown remarkable results. This approach places catalyst modules in the flow path of flue gases to force a catalytic reaction and reduce unwanted gas emissions.
Ammonia injection occurs prior to catalyst modules and under appropriate temperature conditions. The catalysis results in the formation of N₂ and H₂O and the reduction of NOx from the ammonia reaction. This method has shown documented results providing single digit PPM levels for NOx. The CompuNOx system can be implemented on a boiler to drastically reduce the size and expense of the SCR system required to achieve ultra-low NOx levels by minimizing the Box concentration prior to catalysis.

The versatility of CompuNOx and PLC programming allows for control of ammonia injection, which is crucial to an accurately functioning SCR system. The amount of ammonia to be mixed into the flue gas is determined by the firing rate and controlled with PLC and follows a tuning procedure in CompuNOx.

To guarantee suitable mixing of ammonia and flue gas, the location and velocity of injection and injection velocity have to be designed appropriately.

Continuous Emission Monitoring System (CEMS)

Emphasis on emission reduction requires accurate monitoring of relevant pollutants leaving the system. Emission monitoring is part of the CompuNOx system and provides real time data. Data is obtained through the continuous analysis of stack samples delivered to a monitoring station. Gas sensors provide signals proportional to the concentration of the corresponding gas. Data acquisition is accomplished by a PLC to provide real time monitoring of stack gases on an HMI screen as seen in Figure 13.

The memory functions of a PLC in conjunction with HMI programming allow for powerful logging capabilities. Logging can occur in short time intervals to accumulate a representative data set of all stack gases.

Safety

The increased flexibility in control with the use of PLCs and VFDs leads to the decrease in unnecessary safety measures, which affects efficient operation. Safety of the operating system is a primary concern in our approach. The sequential character of PLC programming allows for adequate safety precautions. Field feedback from the system provides status information about all control components as well as information about other system variables. The PLC output is ultimately a conditional result of that information prohibiting undesired and unsafe control output. Alarm limits for certain control parameters such as drum level and feed water flow are part of CompuNOx and deliver corresponding error messages.

Air damper control does not guarantee sufficient air supply for a given fuel flow, which might lead to severe explosions inside the...
combustion chamber. Proper VFD programming for system operation always has the system operating on the safe side; as such our control cross-checks the fuel flow with air flow at all times. That is, upon increasing firing range combustion air supply is increased before fuel flow goes up. Likewise, if firing rate is decreased the fuel flow has to decrease before combustion air supply is reduced. Similarly, the incorporation of FGR requires the same approach to guarantee stable flame behavior.

Hardwire interlocks according to NFPA code prevent fatal system failures independently from any control software. A UV or IR flame scanner is wired in series and closes the control circuit if and only if a flame is detected to prevent fuel from entering the combustion chamber without being burned. Other interlocks include:

- Purge Interlock: Combustion chamber has to be sufficiently purged with fresh combustion air to remove possible combustible before fuel flow is permitted.
- Insufficient Air Interlock: If combustion air supply is interrupted any fuel supply is shut off.
- Insufficient Fuel Interlock: Fuel supply is shut off if fuel flow inconsistencies occur to prevent flame instabilities.
- Low Feed Water Interlock: Fuel flow is interrupted if insufficient water supply occurs.
- Fan Failure Interlock: System faults if induced draft fan and/or forced draft fan dysfunction causes dramatic changes in furnace pressure.
- Flue Gas Interlock: System is faulted upon detection of intolerable amount of combustibles in exhaust gas, i.e. carbon monoxide.

An array of shut off valves arranged in “block and bleed” as prescribed by NFPA code with appropriate venting is responsible for fuel interruption upon system fault.

The implementation of PLC control facilitates the execution of safety procedures upon start up and shut down of boilers. The Burner Management System with its detailed purge sequencing and interlocks provides a safe and efficient way to start the boiler and shut the system down.

The emphasis on boiler safety shows that this control approach yields a significant safety advantage over conventional purely mechanical control systems.

RESULTS

With over 200 installations Benz Air Engineering can draw from substantial experience in implementing CompuNOx. The following examples are merely a small fraction of our installation but are representative of our achievements in reducing emissions and increasing boiler efficiency and operability.

UT Austin Boiler 3

This 1950’s Babcock and Wilcox vintage boiler equipped with four ring burners and rated for a steam flow of 150 lbm/hr, received a CompuNOx retrofit in 2005. Installation resulted in NOx reduction from 220 PPM to 18 PPM with an increase in boiler efficiency from 76% to 85%. Significant increase in turndown ratio resulted in $6000/day savings due to the ability to bank the boiler. This led to a remarkably short payback time of 2.2 months.

Del Monte Foods, Modesto, CA

The CompuNOx retrofit of two 150,000 lb/hour Babcock and Wilcox boilers led to NOx levels below 22 PPM NOx. The payback for installation occurred within 8 months and steam output exceeded 160,000 lb/hour with the original burners.

Cal State University, Sacramento CA

Benz Air Engineering was challenged with two 40,000 lb/hour Trane Murray Boilers with 40 year old Coen DAZ ring burners. Our CompuNOx retrofit resulted in 20 PPM NOx and less than 1 PPM CO using the existing 25hp combustion air fan. The
installation provided CSUS a simple payback within 1 year.

**UC San Diego, CA**

CompuNOx was installed on three 50,000 lb/hour Erie City Boilers. These units had 35 year old standard ring burners. CompuNOx reduced NOx levels to less than 16 PPM. CO emission was measured at less than 10ppm. To illustrate the degree of combustion optimization, the Boiler was operating at less than 1.5% Oxygen.

**Signature Fruit, Modesto CA**

The CompuNOx retrofit now provides control for two 120,000 lb/hour Nebraska boilers. These units avoided low-NOx burner replacement of their 30 year old Coen DAZ burners. Emissions were reduced to 20 PPM NOx. Moreover, not only did this retrofit grant payback for installation within 9 months, the boiler is now able to be operated at its maximum capacity, combustion air fan consumption is reduced to 80 hp and the unit possesses a significantly increased turndown ratio.

**CONCLUSION**

We have outlined the necessity for engineering solutions that provide thorough scrutiny of existing steam generation plants to accurately assess their potential for efficiency gain and emission reduction. We established the immediate connection of efficiency gain to emission reduction and delivered an overview of a comprehensive boiler retrofit approach based on tight system control and minimal system design changes.

The implementation of this approach requires a solid understanding in control as well as mechanical system engineering and one can not compromise one for the other. Benz Air Engineering relies on expertise in both fields to successfully control the behavior of steam generation equipment.

The successful results of this method speak for themselves and show that there is a feasible, reliable and cost-effective solution to cope with rapid developments in environmental policy and fluctuating fuel prices.

**REFERENCES**


