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Development of a High Performance Versatile Low NOx Burner

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ABSTRACT

The paper describes the development process of a new Coen low NOx high performance burners and the transition from a successfully tested prototype to a commercially available product . The performance data are illustrated by the results achieved at the test facility and in numerous package and field erected boilers. The burner was the first commercial product that could fire Natural Gas with NOx emissions below 30 ppm and low carbon monoxide emissions without the use of flue gas recirculation (FGR) in a wide variety of package boilers. For the boilers with low space heat release rates the burner achieves even lower NOx in the range 15-20 ppm.
The burner is specifically suited for industrial duty applications, as it does not impose any special requirements to the control system, like tight air fuel ratio, O2 trim, etc. The burner achieves 10 to 1 turn down and with some modifications allows turn down in the excess of 15 to 1. The burner can easily fire other gaseous fuels like refinery gas and does not require special gas preparation, as the typical minimum diameter for the gas discharge is more than 1/8”. The versatility of the burner is also enhanced by its ability to operate with induced or selective FGR as it allows NOx reduction down to the 12-15 ppm level.
While most of the burner performance can be realized when firing gaseous fuel, liquid fuels like #2 and #6 oil can also be fired separately or simultaneously with gas. Change over between fuel can be done on line.

INTRODUCTION

The development of this new low emission burner was prompted by new regulations requiring lower and lower NOx emission standards country wide. Until recently the only practical way to reduce NOx emissions from packaged boiler firing Natural Gas to the level of 30 ppm was to operate with a significant amount of FGR, that was resulting in an increase in capital and operational cost and in some instances reduction in the boiler efficiency, and capacity.
This paper describes the development of a new type of burner that achieves 60-80% NOx reduction, when firing gaseous fuels, and 20-30% lower emissions, when firing oil without using FGR. The burner was developed in various modifications that together comprise a unique class of fuel staged burners with one specific feature in common: combustion air and primary gaseous fuel are rapidly mixed together and discharged into the furnace through a series of radial slots. The trade name of these class of burners is QLN. The primarily applications for QLN burners are retrofit and OEM markets of packaged and field erected boilers.
The development of the burner was launched in late 1992. In 1993 numerous 40 and 50 MMBtu/Hr prototypes were extensively tested at the Coen company test facility. The first introduction to the market was in early 1994, when a 75,000pph B&W packaged boiler was retrofitted with model QLN-3.4, firing natural gas or jet fuel without the use of FGR. In this boiler the burner demonstrated less than 30 ppm NOx on gas. During 1994 and 1995 the development continued. The burners were designed and built in different sizes with the capacity ranging from 20 to 200 MMBtu/Hr. Modifications of the burner were developed to accommodate numerous specific applications: refinery gas type fuels, high combustion air temperature, selective FGR, extremely short furnaces. The result was an array of QLN burner designs that could be applied

for a wide variety of packaged and field erected boilers. By the end of 1995 there were over 100 burners operating in the United States and some in Europe.

QLN BURNER. PRINCIPLE OF OPERATION

There are three main mechanisms of NOx formation that have been extensively described in the literature: prompt NOx , thermal NOx and NOx originated from nitrogen content species in the fuel (fuel bound nitrogen). Formation of prompt NOx can be greatly reduced if the fuel burns under fuel lean conditions. Formation of thermal NOx is an exponential function of peak flame temperature and can be reduced, if the combustion region contains high amount of combustion products with temperatures much lower than the adiabatic flame, or again under fuel lean conditions when excess of air serves as a diluent. Formation of NOx from nitrogen in the fuel is typically a concern only when firing oil, as gaseous fuels seldom contain non molecular nitrogen components. Fuel rich environment is beneficial for the reduction of this source of NOx.

QLN burners effectively reduce formation of NOx from all there sources.
The basic burner design is shown on Fig.1. The main burner parts are primary, secondary and core gas headers with gas spuds that provide distribution of gaseous fuel. The burner body with the attached air distribution plate shapes air flow into a star pattern. The primary gas is injected into the air flow inside the burner through the radial spuds, so most of the mixing of gas and air is taking place upstream of the distribution plate. The axial part of the burner is reserved for the oil gun. The core gas header is typically positioned around the oil gun guide pipe. The burner is equipped with a short straight throat. The secondary gas spuds protrude through the ports in the throat. When firing oil, these ports are used for bringing a portion of air into the combustion area. A simple mechanism allows for closing or opening of all the ports at once. The same ports are sometimes used as the injection points for the flue gas recirculation, if brought selectively to the burner.

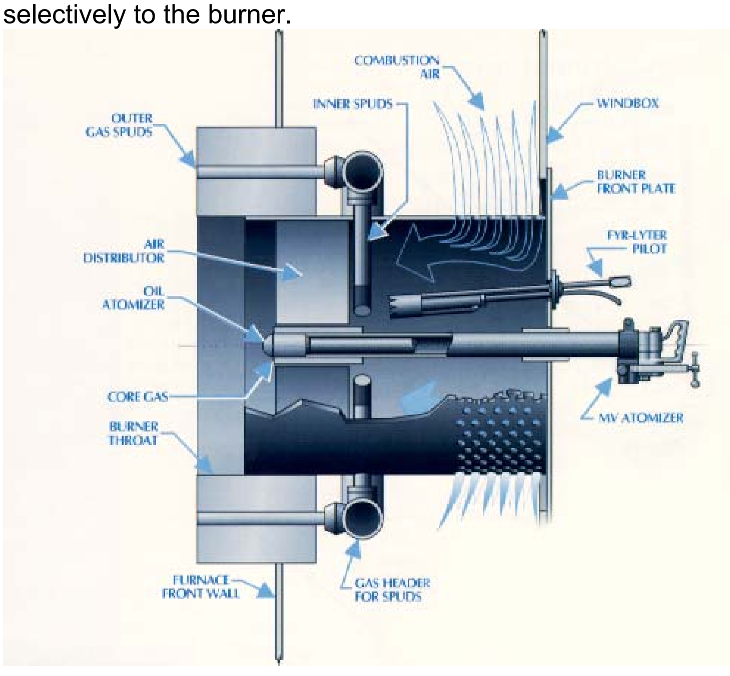


Figure 1. Basic QLN Burner

The flame structure of a QLN burner firing gaseous fuels is extremely complex and to some degree depends on the adjustments made to the burner. Typically the combustion process with QLN burners can be described as follows.

The mixture of primary gas and air is very lean. This mixture gradually burners in the furnace as it mixes with combustion products of the core, hot furnace gases and secondary fuel. This combustion process is mostly taking place at the lean limits of flammability, thus formation of both prompt and thermal NOx are greatly reduced.

The secondary fuel ignition point is also delayed as the furnace gases in the area around the burner has very low oxygen content. Gradual burning starts as the secondary fuel engages oxygen from the combustion air both prior and after the combustion of primary gas.

The core fuel is a small percentage of the overall fuel flow. It provides a reliable ignition source for the primary and secondary fuel.

An overall interleaving pattern of air and fuel distribution creates conditions for a sufficiently compact overall flame and low carbon monoxide emissions with low excess air.

As the mixing of primary gas and air takes place inside the burner, flash back can happen at low loads. This problem was addressed during the early development stage by simply allowing flash back to occur. This typically happens with one or two slots of air and primary gas flow at the loads below 20%. At these reduced loads flash back is continuous, but does not cause any damage to the burner. Each small flash back flame is surrounded by considerable amount of combustion air and is not in contact with the burner parts. The overall turn down of the burner is 1.2 to 1.3 times of the turn down in the combustion air flow. Typically turn down of 8:1 to 10:1 can be met with the basic QLN design without a significant increase in CO emissions. For special applications requiring wider turn downs a special modified QLN burner was developed that is capable of a turn down up to 2.5 times that of the turn down of the combustion air. With the adequate fuel controls this easily translates into the burner turn downs over 15:1. This higher turn down modification, however, shows slightly higher NOx.

The above description is based on the observations of the flame patterns generated by burners of different sizes operating under different conditions. CFD modeling was only moderately used in the burner design, as accurate predictions of ignition points flame fronts, etc. are still very difficult and not reliable for this complex three dimensional problem even with modern CFD codes like Fluent. Some useful results came from the mixing model between primary gas and air that helped in the optimization process. Most of the work, however, was done experimentally.

The burner also shows good NOx performance when firing oil. This is attributed to the effect of enhanced recirculation of combustion products in the part of the furnace adjacent to the burner and the effect of air staging. As the major portion of combustion air discharges into the furnace in a spoke star shaped pattern the entrainment of rate of furnace gas by combustion air is greatly enhanced, if compared with the entrainment by a single round jet. This creates reduction in the flame temperature and reduced thermal NOx production. At the same time, diverting a certain portion of air flow to the ports around the burner throat creates air staged combustion, when most of the fuel burns in reduced oxygen environment, thus reducing NOx formation from fuel bound nitrogen as well as thermal NOx.

BURNER PERFORMANCE AND OPERATING PARAMETERS

The first prototype of the burner was built with the throat diameter of 20". The second prototype had 26" diameter throat and was rated to 60 MMBtu/Hr. Test firings were performed in an eight feet diameter water cooled furnace partially lined with refractory. The furnace had numerous observation ports and ports for the flue gas sampling. The very first prototypes of the burner had limited stability range with respect to variations in the excess air. After the improvements to the design, however, combustion stability was reliably maintained up to 9-10% O2.

The test data shown in Fig. 2 were plotted versus excess air as it appeared to be the main parameter determining the NOx for any given burner modification within the wide range of loads. The effect of firing rate on NOx in the test furnace was relatively small. The deviation of data is primarily due to different burner adjustments.

The size of the visual flame body and CO emissions measured with a traversing probe at different distances from the furnace front were also a strong function of the overall excess air. At

3% O_2 in the flue gas for example the combustion was practically complete within the volume corresponding to the combustion intensity about 75-80 kBtu/ft3. When testing modifications of the burner designed to higher flame intensity (smaller flame diameter) NOx emissions were inevitably higher.

To be able to apply QLN burners to short boilers a version of QLN, called QLN/S (where "S" stands for "swirl") was developed. The flame was shortened and widened without any penalties on the NOx emission side.

Interesting results were achieved when operating with preheated air.. The initial data showed that the function of percentage of NOx increase with air temperature was practically identical to a conventional burner without staged combustion. However, with an adjustment was made to the fuel distribution, the rate of NOx increase was much slower, Fig. 3. This means that optimum settings of the fuel distribution is a function of air temperature.

The burner was also tested when operating with the flue gas bulk mixed with the combustion air and with the flue gas introduced into the furnace through the ports surrounding the secondary gas spuds separately from the combustion air. In the case of bulk mixed flue gas, the distribution of fuel had to be shifted to the primary gas and the effectiveness of flue gas on a percentage basis was slightly less, if compared with FGR brought selectively, Fig. 4. With either type of FGR NOx emissions could be reduced to 10-15 ppm with 15-25% FGR until the flame started showing signs of instability by increased fluctuations of pressure in the furnace. With higher FGR rates the stability range of the burner became more narrow with respect to the excess air. In order to maintain NOx below the 15 ppm level, both combustion air and FGR had to be very tightly controlled, and that was beyond the capabilities of most of the available control systems.

Deeper NOx reduction to 7-9 ppm was possible when firing a modified QLN burner with the induced FGR without the flow of gas through the secondary spuds, but again very tight controls were required. This level of NOx reduction with ambient combustion air was possible with up to 40% of FGR.

Fig.2 QLN Performance. COEN Test Facility

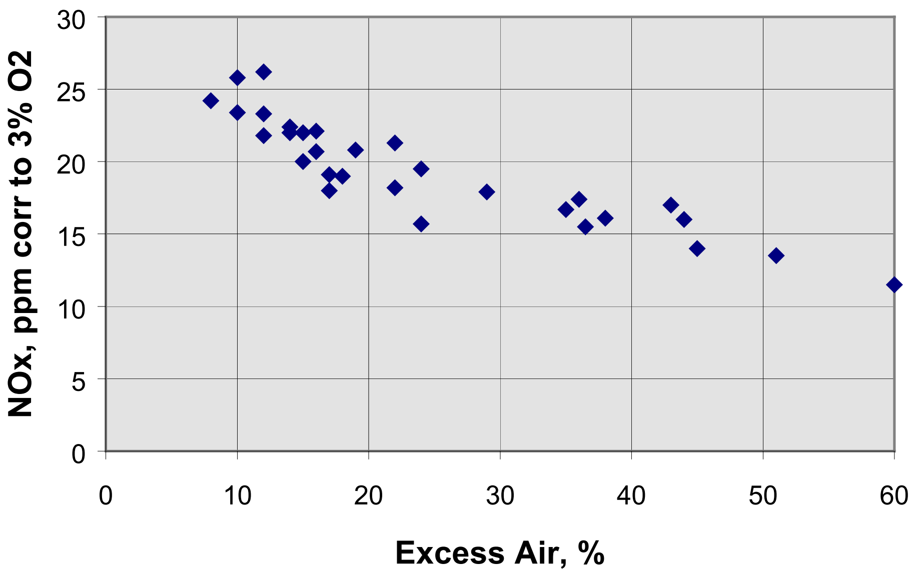


Fig. 3. Effect of Combustion air Temperature on NOx. QLN in the Test Facility

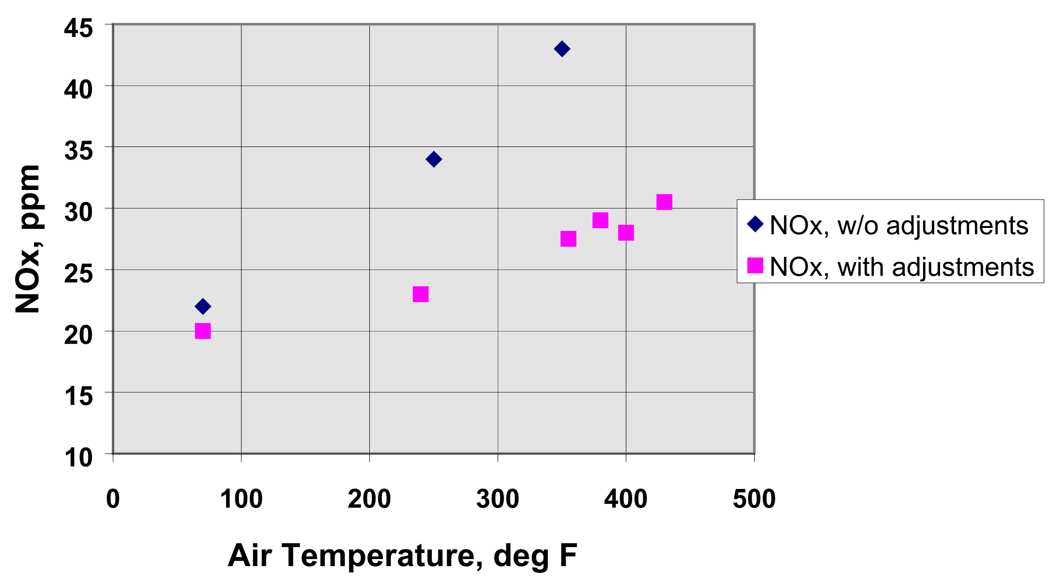
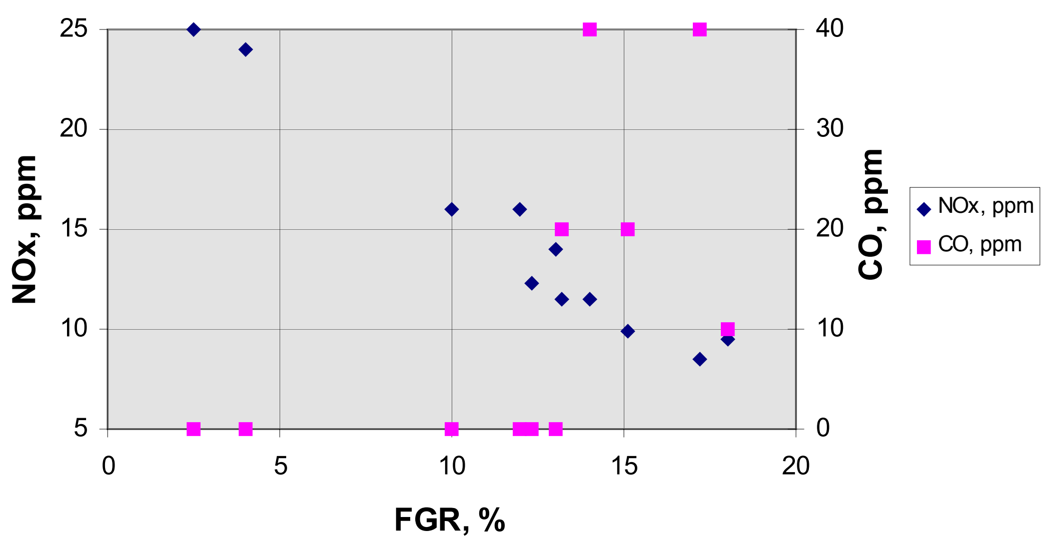


Fig. 4. Effect of FGR on NOx. QLN in the Test Facility



OUTLINE OF BENCHMARK INSTALLATIONS AND THE RESULTS

The following describes the results achieved with QLN burners in some applications that together present the overall picture of the burner performance.

1. United Airlines, San Francisco CA - retrofit of a 75,000 pph B&W packaged boiler. The burner was firing natural gas, and jet fuel with up to 95 MMBtu/hr capacity. This was the first field installation of QLN burner mentioned earlier. All of the existing combustion controls and the fan were reused. When firing Natural Gas, NOx emissions below 30 ppm were easily achieved with 15% excess air and no FGR, Fig. 5. Carbon Monoxide emissions at the back of the furnace were about 50 ppm, but reaching 300 -400 ppm at the stack due to short-circuiting . When firing jet fuel NOx was up to 75 ppm.

2. Nerefco, Netherlands - this was the first retrofit of a field erected boiler with two QLN burners, manufactured by COEN Dejong, a subsidiary of COEN in Holland. The boiler had relatively low space heat release, typical for European boilers. Overall firing rate was 235 MMBtu/hr. Combustion air was at slightly elevated temperature. The results were 26 ppm NOx, 13% excess air and insignificant CO emissions without FGR.

3. Gaylord Container, Antioch CA . This job is a good example of QLN performance in a large field erected boiler equipped with four QLN burners firing up to 480 MMBtu/Hr. The results were 42 ppm NOx, at 15% excess air and practically no CO emissions without FGR.

4. Extremely low NOx emissions of 14 ppm were achieved in this eight feet diameter Steam Flood Generator (Bakersfield, Ca) firing Natural Gas at up to 60 MMBtu/Hr. The furnace was almost equivalent to the Coen test facility where all the initial testing with QLN was performed. The reduction in NOx versus data at the test yard are attributed to the absence of refractory lining in the Steam Flood Generator.

5. An attempt was made to reach minimum possible NOx emissions in this 100,000 pph "A" type packaged boiler (Vernon, CA) by applying QLN and FGR. The unit was originally set to 15 ppm NOx with 25% FGR. Later on in order to control CO emissions the burner was reset to 22% FGR and 19 ppm NOx. The necessity of this reset was caused by deterioration of patchwork sealing gaps in the water tube walls of this old boiler and resulting increase in CO. This was the only job where a combination of bulk mixed and selective FGR was applied.

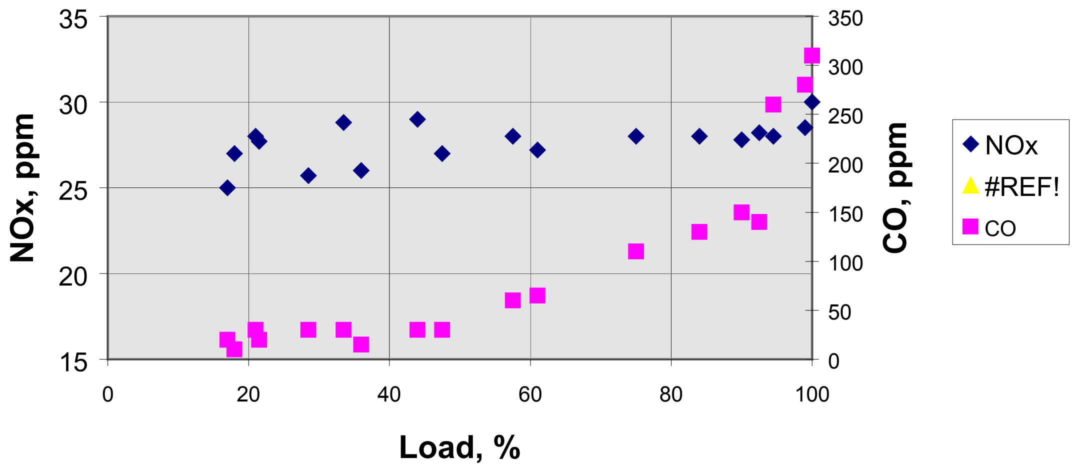
6. Retrofit of a 4 burner boiler, firing Natural Gas with the total maximum firing rate of 320 MMBtu/Hr (Orange, Texas). The application is also interesting by high combustion air temperature of 630 deg F. The boiler was outfitted with QLN/H burners - a modification of QLN designed to accommodate for smaller size openings in the boiler front wall. The achieved NOx emissions were 110 ppm without FGR. CO emissions were insignificant. If larger openings for the burners would be available, NOx emissions could of been reduced by an additional 15%.

7. Retrofit of a 250,000 pph boiler firing Refinery Gas. Four QLN burners were furnished for this boiler in Texas. The achieved NOx emissions were 58 ppm without FGR. CO emissions were insignificant. The refinery gas adiabatic flame temperature was 120 deg F higher than of Natural Gas. This caused an estimated NOx increased by about 50%. Another specific of this application is that the Refinery Gas contained some liquids, so the design of the burner was changed to provide for the maintenance convenience.

8. Retrofit of a 150,000 pph B&W packaged boiler with a single QLN firing up to 185MMbtu/Hr, Huron, Ca. As noted earlier, NOx emissions with QLN burners are higher in high space heat release furnaces. Actually for packaged boilers with steam production over 100,000 pph the main parameter that determines NOx with a given amount of FGR is the heat release per the unit of furnace cross section. This 150,000 pph was equipped with the maximum size QLN burner. The achieved emissions were 70 ppm NOx without FGR. It hardly be matched with any other existing equipment. To meet 30 ppm NOx 10% FGR was required. Conventional burners would require 15-18% to meet 30 ppm NOx.

9. Oil Firing With QLN burners. A special type of oil cap drilling was designed for firing #2 oil and #6 oil with QLN burners. Coupled with Coen MV type oil atomizers QLN burners were typically showing NOx ranging from 75 to 90 ppm when firing in packaged boilers without using the FGR. This is about 20-30% less than with the conventional burners. Statistical data firing #6 oil with QLN are still insufficient to claim any significant NOx reduction.

Fig. 5. QLN Performance.
75,000 pph B&W Packaged Boiler



ENCOUNTERED DIFFICULTIES

With the increased number of applications we encountered several problems that are likely common to fuel staged burners. The first was high CO emissions in old narrow and leaky boilers. The second problem was low frequency pulsation.

The problem with CO emissions was anticipated, as high concentrations of CO are present in the area around the flame and the furnace gas escapes through the gaps in the partition between the furnace and the convection section. The CO emissions were reaching sometime 1500 ppm at the stack, while readings at the rear of the furnace were below 50 ppm. The problem was typically solved, first, by sealing the gaps between the water tubes, second, by adjusting the regime of the firing and, third, by modifying some parts of the burner. Steps two and three, however, result in deviation from the optimum NOx performance.

The problem with low frequency pulsation was not expected, as it did not occur during the test yard firing or within the initial group of applications. Yet it happened in some furnaces with different degree of severity, mostly at lower loads, and was difficult to overcome without a substantial increase of NOx. On some of the pulsation jobs the problem could be solved simply with reduced deviations in fuel to air ratio, like O2 trim. With the given simplistic controls, however, it would impose additional requirements to the tuning and maintenance and was never used as a permanent solution.
A one dimensional acoustical analysis was performed in the attempt to identify applications that are prone to the pulsation. The system that was considered encompassed all the volumes and resistances to the flow of air and combustion products starting from combustion air fan up to the discharge into the atmosphere. Never the less, it was difficult to explain all the differences in the response of seemingly identical systems.
Eventually an effective way was found to eliminate flame pulsation with the minimum impact on the burner performance and no additional requirements to the combustion controls. The controls still might be as simple as single point positioning even for outdoor installations.

Another difficulty that was solved while working on the pulsation problem was online fuel change over. In order to maintain smokeless operation during change over from gas to oil the atomizing steam shall be introduced through the oil gun prior to oil. This steam was adversely affecting the stability of gas combustion of QLN burner, even with the burner pilots brought on. With the modification made to the gas injection pattern and to the gas train both low and high fire change over can be reliably and safely accomplished.

TRADE OFFS BETWEEN DIFFERENT PERFORMANCE PARAMETERS

Extensive tests and field data on QLN burner operations reviled relations between the system operating parameters, furnace geometry and performance parameters of the burner. Furnace size and its tightness are of the greatest importance to the level of NOx, CO and excess air that can be achieved in the application. It was also found, that higher gas pressure of up to 25 psig at the burner, and higher differential air pressure of up to 10" water column, if properly utilized in the burner design, are beneficial for lower NOx and CO. Good air distribution by the wind box is important for both NOx and CO reduction. There is also strong tradeoff between NOx and CO. By adjusting the burner firing regime and making the flame narrower CO emissions typically can be reduced. At the same time NOx emissions go up.

In practical applications, however, available gas pressure, air pressure, furnace geometry and furnace condition are often fixed and a typical task for a burner company is to offer the most effective combustion device that meets the required emission standards and limitations to the system. This task is difficult, as even identical boilers differ with respect to the available gas pressure, condition of the boiler, requirements to NOx and CO. Retrofit jobs sometimes impose additional limitations to stay within the size existing wind boxes or to reuse the existing fans.

In order to utilize properly all the available resources the design of the burner shall be properly tailored to the parameters and requirements of each application. To make this tailoring process easier special computer programs were developed that for each case compute expected performance and design parameters.

CONCLUSION

A unique class of fuel staged combustion low NOx burners was developed for a wide range of industrial applications. When firing gaseous fuels the burner shows NOx emissions that were achievable in the past only with high amounts of FGR. There was a large distance from the original successful prototype to a commercial product that might be safely used by the industry. Special attention was given to the compatibility of the burner with simple combustion controls. Some difficulties reviled itself when the scale and variety of applications had increased. The burner appeared to be very adaptable to different fuels, air preheat, FGR. Development of various modifications and important improvements to the design continued over the period of two years. At the same time the burner proved itself in the industry with over 100 of installations.