In the mid-1990s, a technology was developed that allowed burning natural gas in industrial boilers while producing nitrogen oxide (NOX) emissions less than nine parts per million by volume (ppm). This technology involves rapidly mixing fuel gas with air in a burner geometry that produces stable low temperature combustion. Such rapid mixing eliminated the conditions that cause formation of prompt NOX. To reduce flame temperature and control thermal NOX, the burner typically uses recirculated flue gases (FGR) from the boiler exhaust, but can also operate with high levels of excess air in lieu of FGR. For more than a decade, this burner design has operated in hundreds of installations, showing reliable performance can be achieved with NOX emissions maintained between 6 and 9 ppm.

But continuing pressure exists to drive emissions to even lower levels, especially in severe ozone non-attainment areas like the Central Valley of California. That's why research has been conducted into a modified version of this burner design, which would allow stable operation at even lower NOX levels. The goal of this research is to provide a burner that has a sufficiently wide stability range to allow reliable operation at NOX levels 50 percent lower than those achieved by the current design.

This article reviews the design philosophy of the modified burner, the results of full scale testing conducted at a customer’s facility and the commissioning of the first commercial installation of this technology.

**NOX Basics**

Minimizing NOX emissions from burners in gas-fired boilers requires controlling the two primary methods of NOX formation: thermal NOX and prompt NOX. The major source of NOX from natural gas is thermal NOX emissions created through high-temperature reactions of nitrogen and oxygen present in the combustion air. High temperatures within the flame zone cause atmospheric nitrogen molecules to break apart, creating nitrogen radicals. These nitrogen radicals then react with atmospheric oxygen molecules to form NO.

Although prompt NOX is temperature-sensitive, that sensitivity is not as great as with thermal NOX. Unlike thermal NOX, simply lowering the peak flame temperatures will not reduce the prompt NOX into the single-digit range. To control the formation of prompt NOX, it is necessary to take steps in the burner design to minimize the formation of fuel-rich regions within the flame.

Based on these two NOX formation pathways, the most direct method of achieving very low NOX emissions from a natural gas flame is to: 1) avoid fuel-rich regions with their corresponding potential for prompt NOX, and 2) lower the flame temperature to reduce thermal NOX to the desired level. To accomplish these goals, a burner design was developed that avoids fuel-rich regions by rapidly mixing gaseous fuel and air near the burner exit. The rapid mixing produces a nearly uniform fuel/air mixture at the

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**TABLE 1 OPERATING DATA FROM THE EMISSIONS SOURCE TEST**

<table>
<thead>
<tr>
<th>Boiler 1</th>
<th>Boiler 2</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Boiler Load</strong></td>
<td>%</td>
</tr>
<tr>
<td><strong>Stack O2</strong></td>
<td>%</td>
</tr>
<tr>
<td><strong>FGR rate</strong></td>
<td>%</td>
</tr>
<tr>
<td><strong>NOx ppm</strong></td>
<td>4.1</td>
</tr>
<tr>
<td><strong>CO ppm</strong></td>
<td>32</td>
</tr>
<tr>
<td><strong>Boiler Load</strong></td>
<td>%</td>
</tr>
<tr>
<td><strong>Stack O2</strong></td>
<td>%</td>
</tr>
<tr>
<td><strong>FGR rate</strong></td>
<td>%</td>
</tr>
<tr>
<td><strong>NOx ppm</strong></td>
<td>4.6</td>
</tr>
<tr>
<td><strong>CO ppm</strong></td>
<td>40</td>
</tr>
</tbody>
</table>
ignition point, which virtually eliminates prompt \( \text{NO}_x \) formation. Thermal \( \text{NO}_x \) is then minimized by using FGR, mixed with combustion air upstream of the burner to control flame temperature. The ability to reduce flame temperature with FGR is governed by the amount of flue gases that can be added to the burner while maintaining stable combustion and without generating unacceptable levels of CO through incomplete combustion. To achieve \( \text{NO}_x \) emissions of 7 ppm to 8 ppm in a typical ambient air-fired package boiler application, an FGR rate of around 30 percent is required.

**Original Burner Design**

The basic rapid mix burner consists of a parallel-flow air register. Combustion air pre-mixed with FGR is then mixed with combustion air upstream of the burner register and the entire mixture passes through a set of axial swirl vanes. These vanes, which are attached to a central gas reservoir, have air foils at the trailing edges that are perforated for gas injection. Thus, the swirl vanes also serve as the gas injectors and provide the burner’s near perfect fuel/air mixing. As the fuel, air and FGR exit the vanes, they are rapidly mixed by the high degree of swirl generated by the burner. The controlled expansion of this high-swirl combustion zone is contained by a refractory throat. The high swirl, along with the geometry of the burner throat and bluff body, is what allows the burner to operate reliably with the high levels of FGR required to reach single-digit \( \text{NO}_x \) emissions.

This high-swirl design works well for burners up to approximately 50 million Btu/hr heat input. However, as the heat input increases above this level, the required diameter for a burner of this type, while maintaining a reasonable air side pressure drop, becomes larger than many typical package boilers can accommodate. That’s why a second parallel-flow air zone surrounds the basic burner register on burners with higher heat inputs (Fig. 1). The outer sleeve contains a second set of gas injector vanes attached to an outer gas reservoir. However, these vanes do not impart any swirl to the airflow and therefore have a much lower pressure drop. Airflow through the inner and outer burners is designated as “primary” and “secondary” airflow, respectively. Both the primary/swirled and secondary/axial zones operate with the same near-perfect mixing. The primary zone, which provides the stabilizing central flame for the burner, represents 10 percent to 15 percent of the total burner heat input.

**Improved Burner Concept**

After more than a decade of operating both versions of the burner to meet \( \text{NO}_x \) levels of less than 9 ppm, a comparison of the performance showed a much wider stability range for the single zone burners. It was found that the single zone burners, with their completely swirled flow, could reliably operate with minimum \( \text{NO}_x \) levels of between 3 ppm and 5 ppm. The dual zone burners, with their high percentage of annular flow, would only reliably operate with minimum \( \text{NO}_x \) levels of between 6 ppm and 7 ppm.

The Central Valley region of California recently passed a regulation requiring many existing industrial boilers to be upgraded to meet a \( \text{NO}_x \) requirement of less than 9 ppm. As part of the rule’s implementation, an extension was given to users who agreed to meet a \( \text{NO}_x \) level of 6 ppm. The desire by many users to take this extension, but avoid having to install flue gas cleanup equipment to meet this level, created a demand for a burner that would comply with this limit. However, the heat input for most of the boilers that required this emissions limit was higher than could be provided using the single zone version of the burner.

The major limitation on the size of industrial package boiler furnaces comes from the need to ship these units by road or rail and the maximum allowable width this requires. As a boiler becomes larger, the furnace’s height and length increase much more rapidly than does the width. This width constraint limited the maximum applicable diameter of the burner. However, since the furnaces tended to get taller and more rectangular as the boiler capacity increased, multiple single zone burners applied in unison were proposed. In this way, combinations of smaller single zone registers could be used in configurations—like one-over-one, or three rows of two—to meet the required capacity, maintain the fully swirling flow through each burner and fit within the confines of the given furnace geometry.

**Burner Testing**

Validating the concept of using multiple burners in combination to meet \( \text{NO}_x \) levels of less than 6 ppm required
testing to ensure that no issues would be created by burner-to-burner interaction, such as high NO\textsubscript{x} emissions or reduced stability. An end user in central California agreed to allow the testing on a new boiler. The 30,000 lb/hr boiler was only required to meet NO\textsubscript{x} levels of 9 ppm, which could be accomplished by installing one single zone register, but which would be equipped with two burner “cells” and tested with higher FGR levels. Since the combustion air fan was sized to provide only enough FGR at full load to comply with the 9 ppm requirement, the testing with higher FGR levels would be conducted at a reduced maximum capacity. A drawing of the proposed cell burner arrangement is shown in Figure 2.

The demonstration would also test if any performance difference existed between swirling the flow of both burners in the same direction (co-current) and swirling them in opposite directions (counter-current). Therefore, three burner cells were built, two with clockwise swirl and one with counterclockwise swirl.

The testing goal was to demonstrate NO\textsubscript{x} levels of 5 ppm or less to allow operation with a comfortable margin to meet a 6 ppm emissions limit and CO levels of less than 50 ppm when operating between 25 percent and 100 percent load. Based on previous operating data collected on single zone burners operating independently, FGR rates of about 45 percent were needed to achieve NO\textsubscript{x} in the 4 ppm to 5 ppm range.

Boiler testing with the two cell burners was conducted and a certified emission testing company validated the emission measurements. The boiler was operated with NO\textsubscript{x} levels of between 4 ppm and 5 ppm when operating with two burners at boiler loads up to around 70 percent. The maximum capacity of the fan to run with the higher FGR rates required was reached at this load. When the boiler was tested with both co-current and counter-current designs, the boiler operated better when the burners were co-current. The FGR rate required to operate at this NO\textsubscript{x} level was consistent with the results from firing the burners independently—ranging from 40 percent to 45 percent—verifying that close coupling of multiple burners was not increasing the thermal NO\textsubscript{x}.

Commercial Installation

The burner was installed commercially, with the retrofit of two 80,000 lb/hr “D” style package watertube boilers. The customer had to meet an emission limit of 6 ppm NO\textsubscript{x} and 50 ppm CO on both boilers. However, since several air districts in California are proposing emission regulations that will require less than 5 ppm NO\textsubscript{x} on larger boilers, the goal was to demonstrate operation below 5 ppm NO\textsubscript{x} and 50 ppm CO.

The system design incorporated two burner cells, similar to the test installation, in a vertically stacked configuration, each cell with a heat release of 50 million Btu/hr. A new combustion air fan was supplied, sized to provide up to 25 percent excess air and 45 percent flue gas recirculation and was mounted directly above the burner wind box. No boiler modifications were required to allow operation at these ultra-low emission levels and the burners were installed into an existing wind box. A new burner management and combustion control system was installed to allow precise control of fuel, air and FGR during operation.

The larger burners performed the same as the smaller burners had during testing, with the ability to operate at less than 5 ppm NO\textsubscript{x} with between 35 percent and 45 percent FGR. This confirmed that increasing the diameter of the burner cells by 70 percent and their heat release by 170 percent had no effect on NO\textsubscript{x} performance. The burner excess air levels ranged from about 35 percent at low fire to 25 percent at high fire. Both units were set up to operate below 5 ppm NO\textsubscript{x} and have been operated in automatic with a ramp firing rate from 20 percent to 100 percent within three minutes. Operating data from the emissions source test is shown in Table 1 on page 1.

To test the burners’ operational limits, additional FGR and excess air were added until the CO exceeded the maximum level of 50 ppm. On Boiler 1, while firing at a 78 percent rate, the excess air was set at 22 percent (4.8 percent stack O\textsubscript{2}) and the FGR rate was set at 40 percent, giving a NO\textsubscript{x} level of 4.2 ppm and a CO level of 20 ppm. Excess air rate was then increased, while holding the FGR rate constant. By increasing the excess air rate to 35 percent (5.9 percent stack O\textsubscript{2}), NO\textsubscript{x} was reduced to as low as 3.3 ppm, with CO increasing to 55 ppm.

Firing at a 78 percent rate on Boiler 2, the excess air was set at 28 percent (5.0 percent stack O\textsubscript{2}) and the FGR rate was set at 35 percent, producing a NO\textsubscript{x} level of 4.7 ppm and a CO level of 37 ppm. The FGR rate was then increased, while holding the excess air level constant. By increasing the FGR rate to 40 percent, NO\textsubscript{x} was reduced to 3.5 ppm, with CO increasing to 52 ppm.

Both tests showed that burners were able to operate at NO\textsubscript{x} levels as low as 3.5 ppm before CO emissions would exceed 50 ppm. Since the rapid mixing design does not rely on delayed fuel-air mixing for NO\textsubscript{x} reduction, as with staged combustion burner designs, the use of either increased air or FGR are both equally effective at.
reducing NOX. The increased mass flow to the combustion zone only serves to reduce flame temperature. Reducing flame zone temperature producing 3.5 ppm of NOX was the point at which CO emissions would begin to exceed 50 ppm, regardless of whether it was achieved by increasing excess air or adding more FGR. This minimum NOX level was not a function of burner stability because the burners ran reliably at this extremely low NOX level with no rumble, pulsation or degradation of flame scanner signals.

The two-cell concept has proven extremely successful for operating at less than 5 ppm NOX and can accommodate boilers with heat inputs up to 120 million Btu/hr. The next step will be to install a four-cell (two over two) arrangement, which would allow boiler heat inputs extending to the range of 200 million Btu/hr.

Authors: Tim Webster is general manager for the Gordon-Piatt group of John Zink Co. and has 15 years in the boiler burner industry. He has a bachelor’s degree in mechanical engineering from San Jose State University, a Master of Engineering from the University of Wisconsin and is a licensed professional mechanical engineer. Steve Bortz is a principal engineer with URS Corp. He is been involved with ultra-low NOX gas combustion for the past 15 years and is the holder on the three Rapid Mix Burner patents.