
17 Burners for Industrial Boilers

Lev Tsirulnikov, Ph.D., John Guarco, and Timothy Webster

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17.1 INTRODUCTION

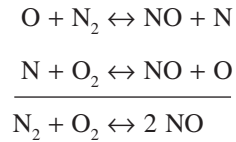
The purpose of a burner is to combine fuel and an oxidant (typically air) together and provide sufficient ignition energy to initiate and sustain the combustion process. This being the case, the main functions that a burner must address can be separated into the three categories: fuel injection, air introduction, and flame stabilization. Burners specifically designed for use in industrial boilers are most commonly of the circular register design, range in size from heat inputs of 20 to 400 million British thermal units (Btu) per hour, operate with forced-draft fans supplying the combustion air, and burn gas or liquid hydrocarbon fuels. These burners are generally classified by the amount of nitrogen oxide (NO_x) emissions they produce: conventional burners, low-NO_x burners, and ultra-low-NO_x burners.

17.2 NO_x FORMATION

To discuss NO_x reduction techniques, it is first necessary to briefly review the basic theory behind NO_x formation. Burning hydrocarbon fuels will form NO_x via three major processes: thermal NO_x formation, prompt NO_x formation, and fuel NO_x formation.

17.2.1 THERMAL NO_x FORMATION

Thermal NO_x formation is a route where high flame temperatures cause nitrogen molecules from the combustion air to break apart and combine with oxygen to form nitric oxide. The sequence is complicated, but the following two steps represent the essential features:



Combustion is a free-radical process whereby the reactions include intermediate species. In the above sequence, atomic oxygen attacks a nitrogen molecule to yield nitric oxide and a nitrogen radical. In the second step, the nitrogen radical attacks diatomic oxygen to produce another nitric oxide molecule and replenish the oxygen atom. The sequences sum to the overall reaction of one nitrogen and one oxygen molecule producing two nitric oxide molecules.

If we presume that the first step is rate limiting (disruption of the N–N triple bond) and that oxygen is in partial equilibrium ($\frac{1}{2} \text{O}_2 \leftrightarrow \text{O}$), then we generate the following integral kinetic rate equation:

$$[\text{NO}] = \int A e^{-\frac{b}{T}} [\text{N}_2] \sqrt{[\text{O}_2]} dt$$

where A and b are kinetic rate constants, T is the absolute temperature, square brackets denote the concentrations of the enclosed species, and t is the time.

From the rate equation, we deduce that “thermal NO_x” is primarily a function of temperature, but is also affected by oxygen concentration and the time at those conditions. [Figure 17.1](#) illustrates this relationship between thermal NO_x formation and flame temperature.

17.2.2 PROMPT NO_x FORMATION

Another way that NO_x is formed is called the prompt mechanism. As the fuel pyrolyzes, it generates fuel radicals, which combine with available nitrogen to produce carbon radicals. These carbon radicals oxidize promptly at the flame front to generate NO_x and other species. Under fuel-rich

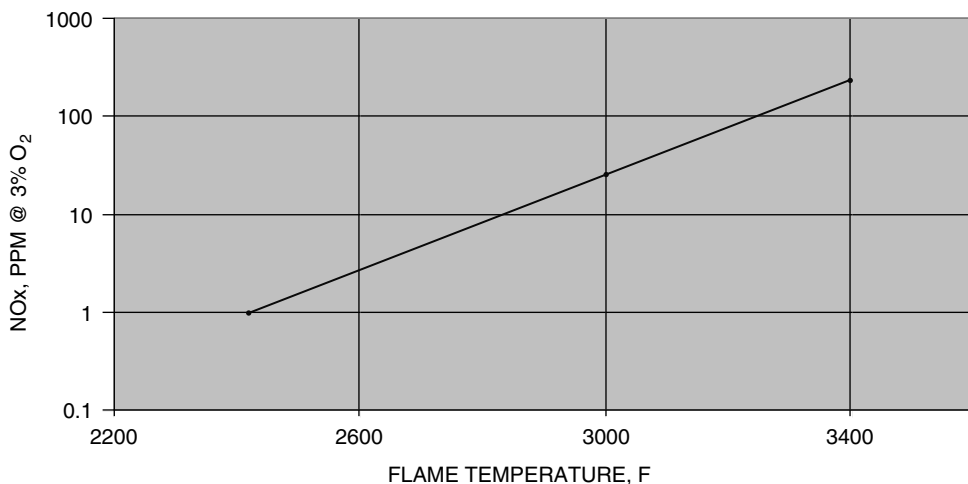
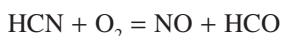
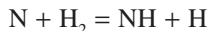
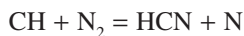
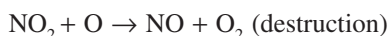
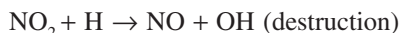
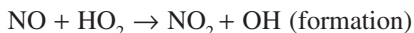


FIGURE 17.1 Thermal NO_x vs. flame temperature.

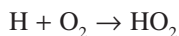
conditions, particularly when the stoichiometry is less than 0.6, both HCN and NH₃ can be formed through the rapid reaction of CH with N₂ to form HCN and N. As combustion continues, the HCN and NH₃ oxidize and result in the generation of NO_x. The following four reactions represent the basics of this process:



A part of the prompt NO formed is then converted into NO₂. A mechanism for this conversion is presented in the following reactions:



where the HO₂ radical is formed via:



Below a stoichiometry of 0.5, almost all NO_x formed is attributable to “prompt NO_x.” The rate of formation of prompt NO_x is very rapid, being complete in under 1 msec. Although prompt NO_x is temperature sensitive, the temperature sensitivity is not as great as with thermal NO_x. Unlike thermal NO_x, simply lowering the peak flame temperatures will not reduce prompt NO_x into the single digit range. Even if the reaction temperature is lowered to 2400°F, under fuel-rich conditions, significant amounts of prompt NO_x still remain, as seen in Figure 17.2. To control the formation of prompt NO_x, it is necessary to take steps in the burner design to minimize the formation of sub-stoichiometric regions within the flame.

17.2.3 FUEL NO_x FORMATION

The final NO_x formation mechanism is fuel specific and based on the level of nitrogen that is bound as part of the fuel molecule itself. If nitrogen is a part of the fuel molecule, once the molecular bonds are broken during the combustion process, this nitrogen is freed up as nitrogen radicals. These nitrogen radicals will now attack diatomic oxygen molecules, as described during the thermal NO_x formation process, to form NO_x. Natural gas and most other industrial gas fuels contain no

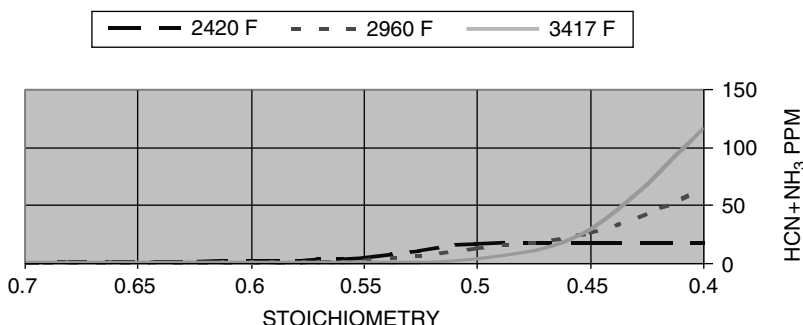


FIGURE 17.2 Prompt NO_x formation.

fuel-bound nitrogen and, therefore, form no “fuel NO_x.” However, most commonly used liquid hydrocarbon fuels, such as grades no. 2 through no. 6 fuel oil, contain between 0.01% and 0.50% by weight of fuel-bound nitrogen, which can contribute to between 20 and 80% of the total NO_x formed firing these fuels.

17.3 CONVENTIONAL BURNERS

Conventional burners, as seen in Figure 17.3, trace their lineage back to the days of ship-mounted boilers, where boilers had to be kept as small and light as possible thus making the requirement for short flames very important. The fact that without these boilers in operation, a ship could be left dead in the water, resulting in the need for the burners to reliably operate regardless of changes to the fuel or air supply. The maneuvering demands of the ship also required that these burners be able to operate across a wide range of firing rates and to be able to change firing rate quickly.

To accomplish all these goals, the design resulted in burners that typically mixed air and fuel as rapidly as possible to create a highly stable flame that was also as short as possible. Conventional burners commonly employ a series of vane-type louvers, called registers and shown in Figure 17.4, around the outer periphery of the burner to impart a swirling motion to the combustion air. The fuel was injected into this swirling vortex of air, as evenly as possible, right at the exit of the burner. The gas fuel injection was accomplished through a gas header that surrounded the burner exit, called a gas ring, which was drilled with a series of holes to inject the gas into the air stream as it exits the burner. The firing of liquid fuels was accomplished using a “gun-style” atomizer (see Figure 17.5) installed right down the center of the burners.

The absence of air in the center of the burner, caused by the swirling action of the burner, could result in fuel-rich pockets in the burner center when firing liquid fuels resulting in smoking. Therefore, in liquid fuel firing applications, a bluff body was commonly used at the end of the atomizer.

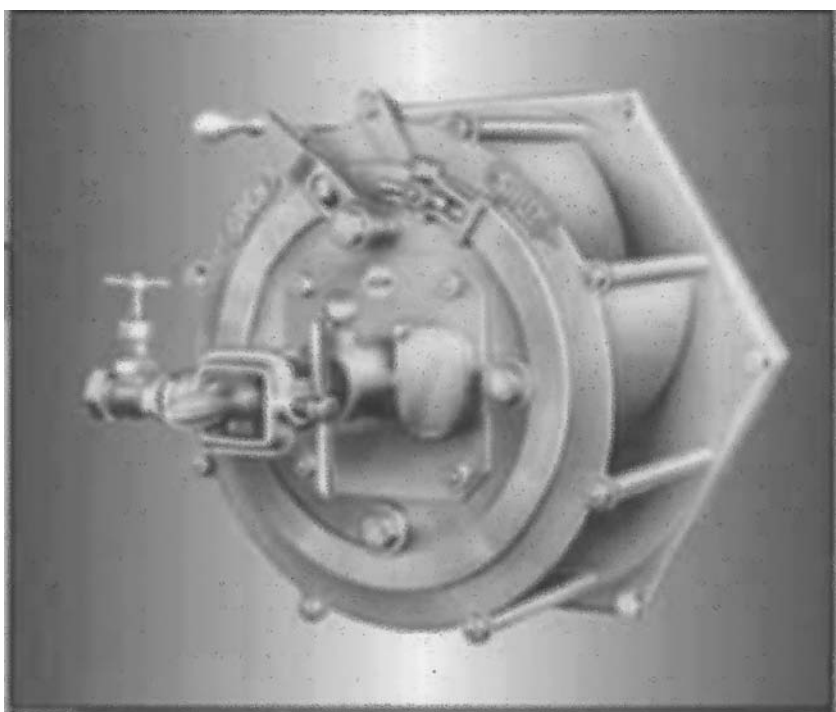


FIGURE 17.3 Conventional register-style burner.

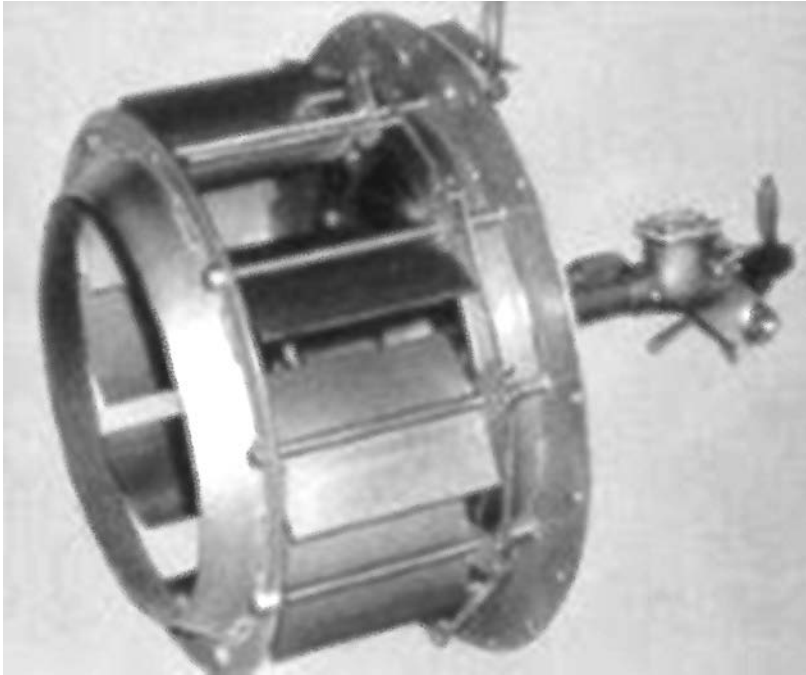


FIGURE 17.4 Register burner louver vanes.

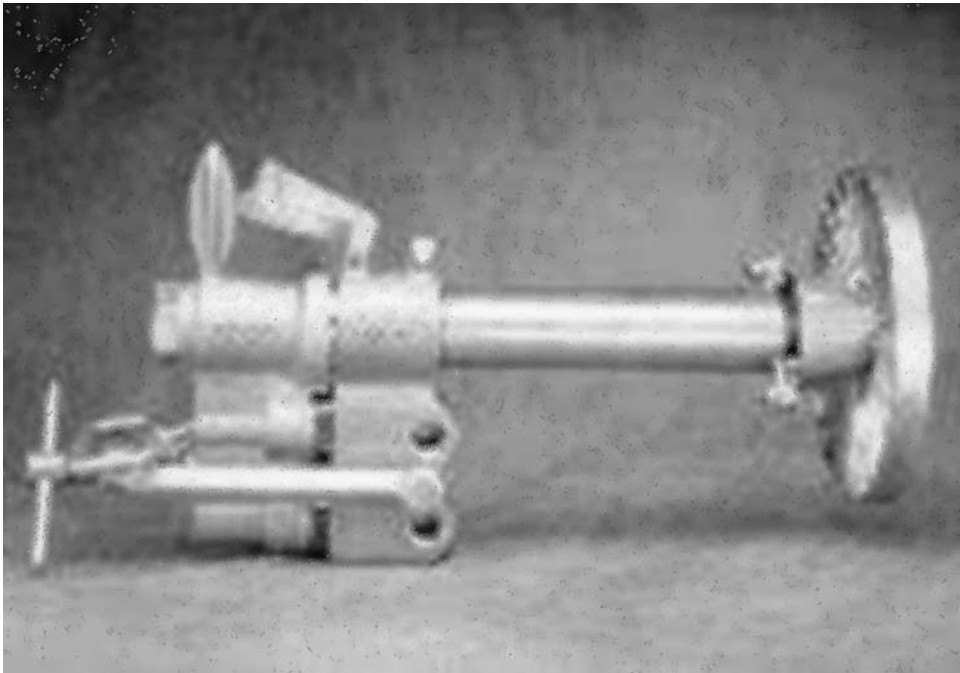


FIGURE 17.5 Oil atomizer gun assembly.

The purpose of the bluff body was to create a small recirculation zone in the center of the burner to help draw some of the combustion air back into the center of the burner to prevent the fuel-rich pockets. The positions of the air register louvers could also be adjusted to increase or decrease the amount of swirl added to the air, either speeding up or slowing down the mixing speed of the burner. The pressure drop on these burners was usually kept very low, with airside pressure drops of between 3 and 6 inches of water column (in. w.c.) and gas side pressures of 10 to 30 in. w.c.

The swirling fuel and air mixture exited the burner and entered the furnace through a refractory throat, conical in shape and ranging from 6 to 24 in. in depth. This throat helped stabilize the ignition process by providing a hot surface against which the rotational momentum of the burner “scrubbed” the fuel-air mixture. The result of this design was a burner that produced a short, hot, swirling flame that was extremely tolerant to rapid changes in firing rate and a wide range of excess air. The drawback to this design was that the intensity of the combustion produced extremely high thermal NO_x emissions, and the rapid fuel-air mixing also did nothing to retard fuel NO_x emissions while firing liquid fuels. However, these designs produced little or no prompt NO_x emissions.

17.4 FLUE GAS RECIRCULATION

One of the first methods of NO_x reduction was the use of flue gas recirculation (FGR), whereby a portion of the stack gases was returned and mixed with the combustion air to the burner. This added additional mass flow into the combustion zone across which the heat release was distributed, and thereby lowered the temperature and accompanying thermal NO_x formation. The introduction of FGR into the combustion air increases the overall mass of the reactants, and hence the products, in the combustion process. The increased mass, as well as the increased reactant diffusion time requirement, reduces the overall flame temperature. The fact that the flue gases being returned also have very low oxygen levels, typically 2 to 4%, resulted in a lowering of the volumetric oxygen concentration entering the combustion zone, which also helps to retard NO_x formation by limiting oxygen availability. FGR was added to many conventional burners, and could result in NO_x reduction ranging from 20 to 75%, depending on the amount added, the fuel being fired, and the initial NO_x level. The problems with FGR addition to conventional burners were three-fold: (1) additional fan capacity had to be used to transport the hot flue gases to the burner combustion air system, resulting in increased capital and operating costs; (2) very high levels of flue gases were often required to reduce NO_x emissions to acceptable levels; and (3) high rates of FGR, typically over 20%, decreased the flame temperature to the point where burner operation began to become unstable.

17.5 LOW-NO_x BURNERS

Low-NO_x burners were designed to eliminate or minimize the impact of these concerns by (1) reducing NO_x as much as possible without the use of FGR, (2) maximizing the NO_x reduction from FGR when required to minimize the amount needed, and (3) providing a burner design that was extremely stable with very high rates of FGR.

The first technique used in the design of low-NO_x burners was the concept of air staging. Instead of injecting all the combustion air at one point, burners began to separate the air into two or even three different streams that would be injected at various points.

17.5.1 AIR-STAGED, LOW-NO_x BURNERS

The basis of design is to develop a stratified flame structure with specific sections of the flame operating fuel-rich and other sections operating fuel-lean, as shown in [Figure 17.6](#). The burner design thus provides for the internal staging of the flame to achieve reductions in NO_x emissions while maintaining a stable flame. Controlling combustion stoichiometry to fuel-rich conditions

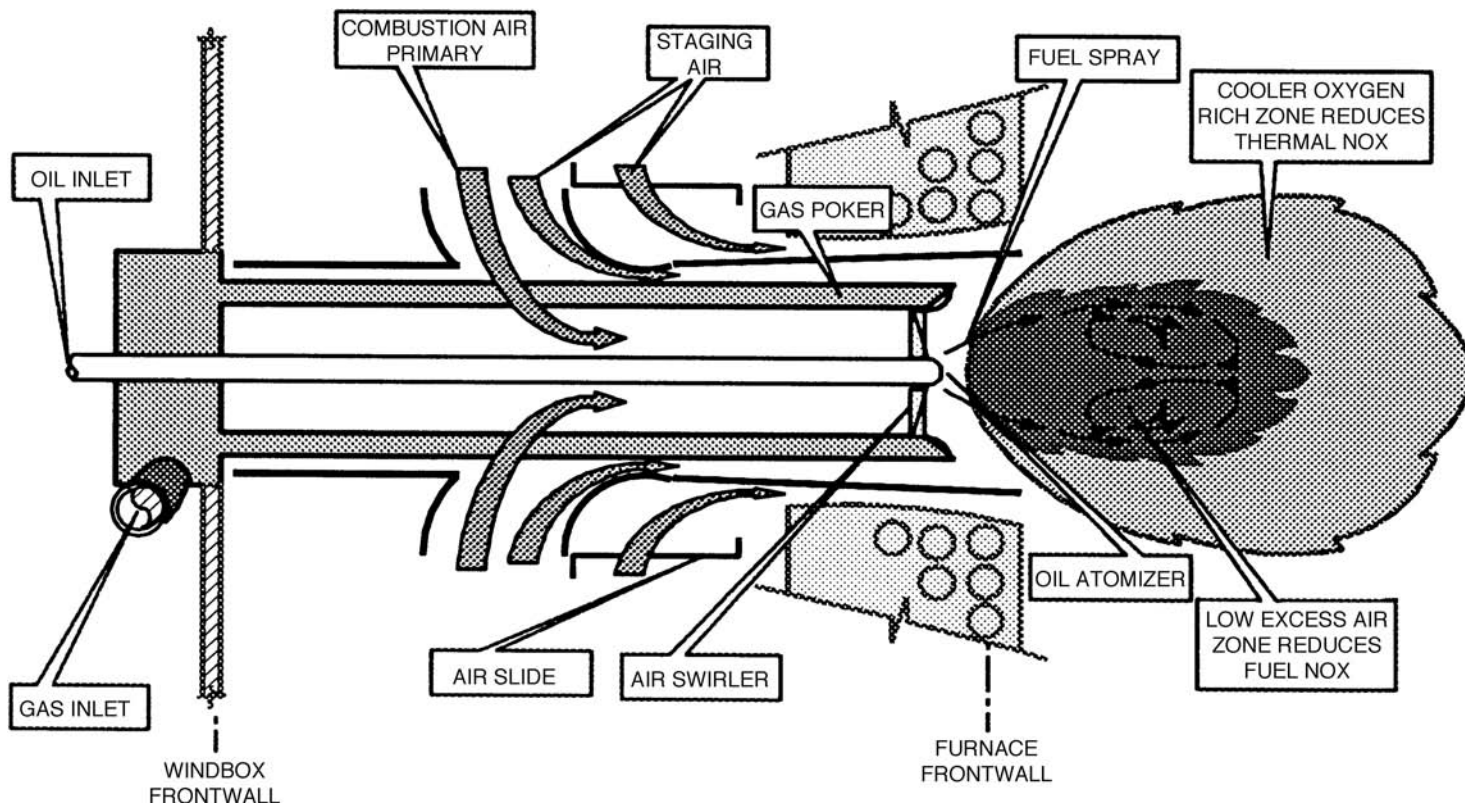


FIGURE 17.6 Staged-air, low combustion schematic.

inhibits NO_x production, especially in the burner's flame front. Operating the flame fuel-rich also reduces burner NO_x emissions dependence on the burner zone heat release (BZHR) characteristics of the boiler furnace. This is especially important in applications where very high BZHR near full load can result in an exponential increase in NO_x emissions.

Staging of the air into the combustion zone serves to slow down the combustion process and separate the flame into different zones, some that operate fuel-rich and some that operate fuel-lean. The fuel-rich and fuel-lean zones both combust at lower peak temperatures than a uniform fuel-air mixture, resulting in lower thermal NO_x formation. The combustion products from these two zones then combine to complete the combustion process and result in the completed oxidation of the fuel. By creating a fuel-rich zone in the front part of the flame, one can also reduce the conversion of fuel-bound nitrogen to NO_x and thereby lower fuel NO_x formation as well. However, the increase in sub-stoichiometric zones in the flame actually increases the prompt NO_x formation in these burners. The increase in prompt NO_x is more than offset by the large decreases in thermal and fuel NO_x, when applicable and, therefore, total NO_x production from these burners is still lower. The delayed mixing of fuel and air also leads to an increase in flame lengths, and staged burners can have flames that are 25 to 50% longer than conventional burners of the same heat input. This helps reduce NO_x by subjecting the flame to more of the furnace waterwall surface area, which also helps to draw heat from the combustion process and cool the flame. However, increasing the flame length must be carefully balanced with available furnace depth; otherwise, flame impingement can occur. Flame impingement will result in unburned fuel being emitted from the boilers in the form of both hydrocarbon emissions and carbon monoxide. This is an emissions problem, an efficiency problem, and can be detrimental to boiler tube life.

Staged air burners, such as the one shown in Figure 17.7, typically rely on little or no swirling of the combustion air in order to slow fuel-air mixing. A small amount of primary air, typically 10 to 20% of the total combustion air, is routed down the center of the burner. Most burner designs

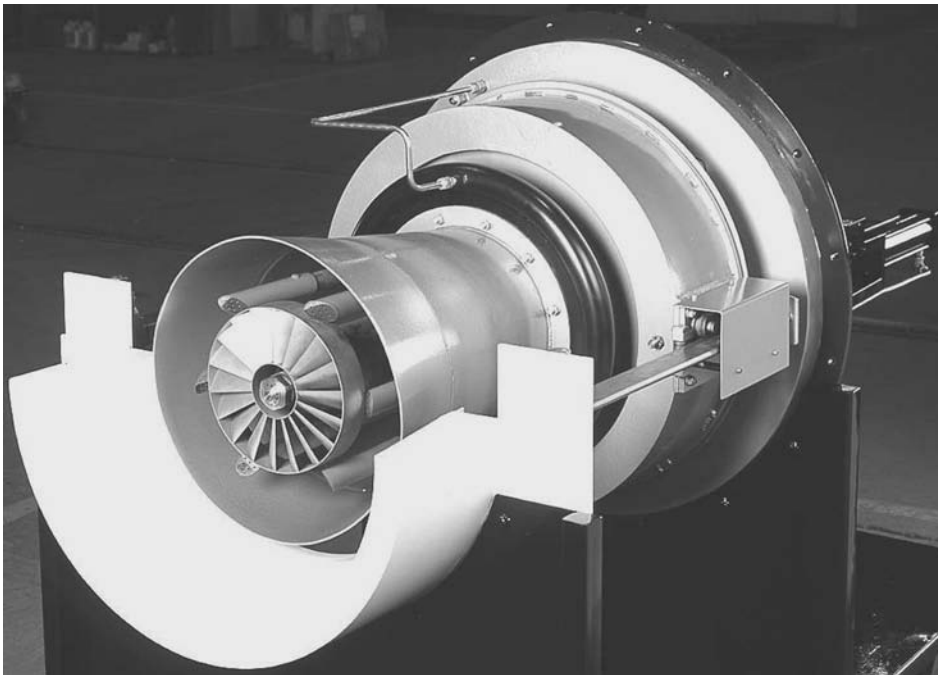


FIGURE 17.7 Staged-air low-NO_x burner.



FIGURE 17.8 Staged-air, low-NO_x burner swirler and gas injectors.

employ a curved bladed swirler, as depicted in Figure 17.8, to impart rotational momentum to this primary air. This swirled primary air creates a rotational vortex in the front of the burner, which serves several functions. It entrains a portion of fuel, creating a fuel-rich region immediately in front of the burner. This effect can be enhanced in some burners by designing fuel injectors that inject a portion of the fuel directly into this area. Because the burner flame front was established as a fuel-rich premixed flame, it results in increased flame speed and, in turn, flame stability. Combustion stoichiometry approaching a perfect premixed flame will broaden the flammability range of the fuel, ensure the maintenance of a flammable mixture over a broad range of burner throat velocities and fuel injection rates, and keep the burner operating reliably, even at extremely low flame temperatures.

This anchored base flame provides a location for the burner flame scanner to reliably sight the flame. The swirling primary air also generates a reverse flow in the form of a self-generating annular vortex that helps recirculate hot combustion gases from within the flame zone, thereby providing additional ignition energy to the fuel-air mixture and increasing the mass flow in this region to limit peak temperatures. In addition to controlling NO_x formation, operating under fuel-rich conditions results in the production of combustion intermediates that can result in the destruction of previously formed NO_x. In a reducing environment, NO can act as an oxidizer to react with these combustion intermediates, resulting in the reduction of NO to N₂. As such, NO,

necessarily formed to satisfy the requirements of establishing a strong flame front, can be scavenged by this mechanism.

To achieve complete fuel burnout at minimum excess air, the burner design must provide for fuel-lean zones to directly interact with the center fuel-rich sections. Creating a secondary air zone where the majority of the combustion air is introduced (65 to 90%) accomplishes this. The air injected into this zone is typically injected axially, with little or no swirl. Multiple gas fuel injectors are also located in this zone, and high-pressure fuel ranging from 5 to 15 psig is commonly used. The multiple high-pressure fuel jets allow for the free-jet entrainment of large amounts of air into the base of these flames. Separate air and fuel lanes are created, which eventually interact to provide the completely mixed fuel-lean combustion products from this zone. For liquid fuel firing applications, a center-mounted atomizer is used with specially drilled injection holes to direct the fuel into the secondary air flow. This secondary zone surrounds the fuel-rich primary zone, which ensures that the “rich” products of combustion from the center flame pass through the oxidizing zone for complete fuel burnout. The burner design typically allows control of the stoichiometry of the oxidizing zone from being pure air to having varying degrees of excess oxygen. This controls NO_x formation by causing the fuel burnout to occur in the form of a premixed flame rather than a diffusion flame.

To increase the flexibility of combustion staging and flame shaping capabilities, some low-NO_x burner designs are equipped with a tertiary air zone installed at the outer periphery of the burner throat. The tertiary air, which can be swirled or completely axial, is mixed in the furnace with the bulk furnace gas to achieve complete fuel burnout. This provides for the complete burnout of the fuel in the post-combustion zone where NO_x formation is inhibited by lower combustion temperature and reduced O₂ concentration. In cases when both the secondary and the tertiary air flows are straight, changes in the ratio between their flow rates actually do not visibly impact the combustion process, including NO_x generation. For such designs, the tertiary air flow is required, primarily to maintain flame dimensions.

The amount of air used in the tertiary zone can range from 10 to 15%; however, more tertiary air flow will increase the flame length because it adds an additional delay to the combustion process. The amount of tertiary air is commonly adjustable to allow maximum staging that can be tailored to the furnace geometry. Tertiary air flow also helps to cool the burner refractory throat by creating an air wall between the hot combustion gases and the refractory. This reduces the amount of heat that hot refractory will re-radiate back into the flame, lowering thermal NO_x formation, and helps to increase refractory life. However, because the burners no longer scrub the fuel-air mixture against the hot refractory, as was done on conventional burners, the refractory does little to aid in flame shaping or stability.

The register draft loss on low-NO_x burners is typically higher than that of conventional burners, with 6 to 8 in. w.c. of airside pressure drop being common. Air-staged, low-NO_x burners resulted in dramatic reductions in NO_x formation, and cut NO_x emissions from gas fuel firing by 50% or more. These burners can also be very effectively utilized in conjunction with FGR to achieve NO_x reductions as high as 85%, and have demonstrated operational stability with FGR rates greater than 40% in some cases.

Reductions from liquid fuel firing were also achieved; however, these reductions were not dramatic because much of the NO_x from those fuels was “fuel NO_x.” Reducing the amount of fuel NO_x formed can be achieved by taking further steps to create a fuel-rich primary combustion zone. In this case, the fuel-bound nitrogen, that is liberated as nitrogen radicals in the initial combustion process, cannot find sufficient oxygen to bond with and form NO_x. These nitrogen radicals will then recombine and form diatomic nitrogen. To accomplish this, staged-air, low-NO_x burners are often employed in conjunction with frontwall or sidewall NO_x ports for use during liquid firing. In this mode, the ports are opened during liquid firing and a portion of the combustion air, typically 15 to 35%, enters the furnace through the ports, bypassing the burner air register. This creates a fuel-rich flame across the entire burner front, and allows the port air to mix into the flame body

further down the furnace to complete combustion. As is the case with tertiary air, more staging of air to the ports does result in increased flame length.

17.5.2 FUEL-STAGED, LOW-NO_x BURNERS

In an effort to reduce the NO_x emissions firing gaseous fuels, without using FGR, several additional NO_x reduction techniques have been developed and applied to low-NO_x burners. The most common has been the use of fuel staging, whereby a portion of the fuel, anywhere from 50 to 90%, is injected directly into the furnace outside the air register. This process relies on the use of a highly stable center or core flame, which helps create and maintain a fuel-lean primary combustion zone at the burner front. Because all the combustion air is introduced through burner air register, but only a portion of the gas fuel is introduced here, the burner itself is operating at extremely high excess air levels. Without the use of the center-fired gas flame to provide a stable ignition source, the high excess air levels found in the primary combustion zone would not be able to reliably sustain stable combustion. By operating fuel-lean, both thermal NO_x and prompt NO_x formation is reduced in this zone.

The remainder of the gas fuel is introduced through gas injectors, inserted through the boiler furnace front wall, without any accompanying combustion air. Different designs for the gas injectors result in gas supply pressure requirements ranging from 6 to 22 psig for most applications. The center flame, containing a small amount of internally recirculated furnace gases, behaves like a regular high-temperature turbulent gas flame. The outer gas injectors supply the remaining fuel, which is a majority of the total gaseous fuel, into the secondary and tertiary air flows. The staged secondary flames are formed as the outside injector gas jets enter into the straight secondary and tertiary air flows and are ignited by the hot combustion products from the center flame. The injectors are located at a set distance from the center flame and divided from it by a layer of combustion products and air. This allows the gas jets to entrain additional amounts of inert, high-temperature furnace gases, prior to entering the combustion zone. The diluted fuel and furnace gas mixture limits the temperature rise resulting from the combustion process, dramatically reducing the formation of thermal NO_x. This outer gas injector fuel consumes the excess oxygen left over from the fuel-lean combustion zone, which has also generated its own combustion products. This method of internal furnace gas entrainment, combined with the fuel-lean primary zone combustion products, results in a secondary combustion zone that is equivalent to a burner operating with high levels of FGR. The NO_x reduction that can be achieved with this type of fuel staging can be equivalent to that of an air-staged, low-NO_x burner operating with FGR levels of 10 to 15%.

17.5.3 FUEL-INDUCED RECIRCULATION BURNERS

An alternate type of advanced low NO_x gas burner design utilizes flue gases mixed with the gas fuel, called fuel-induced recirculation (FIR), instead of with the combustion air to reduce NO_x. The burner uses the motive force of the fuel to inspirate flue gases from the boiler exhaust and mix them into the gas fuel prior to injection into the combustion zone. To provide sufficient motive force, fuel gas supply pressures ranging from 10 to 25 psig are usually required. The mixture of fuel and flue gas results in a diluted fuel, similar to a low Btu fuel gas, which generates lower NO_x emissions. The use of flue gases mixed with the fuel, instead of with the combustion air has proven to be 30 to 50% more effective at NO_x reduction. Substantial horsepower savings are also realized with this technology, through the use of available fuel pressure as the means of transporting the flue gases instead of fans. The burner design involves multiple gas nozzles supplied from a single fuel plenum to induce flue gases from an integral flue gas plenum. This requires only a single fuel gas and a single flue gas connection at the burner front. The design provides a large amount of burner nozzle area for maximum dilution, and stages the injection of both the fuel and air for added NO_x reduction. The high levels of dilution achieved by this burner design will reduce NO_x by 80 to 85% over the levels being achieved by a conventional burner.

17.6 LOW-NO_x OIL FIRING

Because the methods of fuel staging discussed previously are applied to gas firing only, they have no real effect on NO_x emissions while firing liquid fuels. When firing liquid fuels, these burners operate simply as air-staged, low-NO_x burners, with fuel staging provided only by advanced atomizer sprayer plate designs.

Boiler burners are designed to utilize many types of mechanical, dual fluid, and, occasionally, rotary cup oil atomizers. Most of these atomizers are fitted onto oil “guns” similar to the ones shown in Figure 17.9. For dual fluid atomizers, they are separated into “external mix” atomizers and “internal mix” atomizers, based on how the fuel and atomizing medium interact. The atomizing medium used is typically either steam or pressurized air; however, some tough-to-combust liquid fuels may utilize a gas fuel as the atomizing media.

17.6.1 INTERNAL MIX ATOMIZERS

Internal mix atomizers such as the “T-jet” typically require a relatively large amount of atomizing medium consumption, on the order of 0.1 to 0.3 pounds of medium per pound of fuel, but provide excellent atomization quality, with a typical Sauder mean diameter (SMD) of 75 μm at a fuel viscosity of 100 SSU. The supply pressure for the atomizing medium must be kept above the oil pressure to prevent oil from entering the atomizing medium supply lines. Operating pressures for internal mix atomizers range between 85 and 300 psig for the oil, with the atomizing medium pressure typically regulated to a differential pressure 15 to 30 psig higher than that of the oil. The turndown ratio for these atomizers, depending on the oil supply pressure, can be as high as 10:1.



FIGURE 17.9 Two oil atomizers.

17.6.2 EXTERNAL MIX ATOMIZERS

External mix atomizers such as the “Y-jet” require much less steam consumption than internal mix atomizers, on the order of 0.05 to 0.07 pounds of medium per pound of fuel; however, the atomization quality is slightly reduced, with a typical SMD of 125 μm at a fuel viscosity of 100 SSU. Due to the external mixing of these atomizers, there is very little chance for oil to enter the atomizing medium supply lines. Therefore, these atomizers do not require that the supply pressure for the atomizing medium be kept above the oil pressure. Operating pressures for Y-jet type atomizers range between 85 and 300 psig for the oil, with the atomizing medium pressure typically regulated to a constant pressure of 85 to 150 psig. The turndown ratio for these atomizers, depending on the oil supply pressure, can be as high as 10:1.

17.6.3 MECHANICAL ATOMIZERS

The two main types of mechanical atomizers are “simplex” and “spill-return” atomizers. Oil enters a mechanical atomizer through slots that expel the oil tangentially into a circular “whirling” chamber. The vortex created by the tangential entry into the whirling chamber is essential for good-quality atomization. For a spill-return flow atomizer, a portion of the supply flow will return back into the oil gun through a series of holes located at the back of the atomizer. The remaining oil exits the atomizer through either a single hole or a series of holes located at the front end (furnace side) of the atomizer. The “return” oil backpressure is controlled to adjust the firing rate, and the returned oil is recirculated back through the oil supply system. Simplex atomizers are simply a spill-return atomizer without the return flow, wherein the supply pressure to the atomizer is controlled to regulate the firing rate and no oil returns.

Burner performance has been improved using specially designed return-flow atomizers to maximize combustion efficiency and minimize NO_x. These atomizers produce good atomization quality at full load, with a typical SMD of 125 μm at a fuel viscosity of 100 SSU. However, atomization degrades rapidly with decreasing flow on these atomizer types, thereby limiting turndown. For this reason, to achieve satisfactory operating turndown, the oil pressures for simplex-type atomizers range between 300 and 600 psig. The turndown ratio for these atomizers, depending on the oil supply pressure, is very low (typically 2:1).

The delivered flow supplied by a spill-return atomizer depends on the return backpressure, which is essentially the same pressure as the atomizer would require if it were operating in simplex mode. The differential between the supply and return oil pressures, which can range between 100 and 350 psig, allows these atomizers a greater turndown range (up to 4:1). Operating pressures for spill-return atomizers typically range between 400 and 1000 psig.

17.7 ADDITIONAL NO_x REDUCTION TECHNIQUES

Some additional NO_x reduction techniques have been applied that affect both gas and liquid fuel NO_x emissions.

17.7.1 FURNACE GAS RECIRCULATION

One such technique is to use the burner air register, through the use of a venturi design, as a method of pulling furnace gases back into the burner and mixing them with the combustion air. In this design, ports in the boiler furnace front wall are ducted to the low pressure point in the air register venturi, as shown in [Figure 17.10](#), where the negative static pressure will create a suction that draws furnace gases back into the burner. The mixing of the combustion air with the high-temperature, incomplete combustion products, contained in the above internally recirculated flow, is highly effective in reducing thermal NO_x formation within the burner firing either gas or liquid fuel. It has also been established that introduction of the “hot” furnace gas flow, containing significant concentrations of

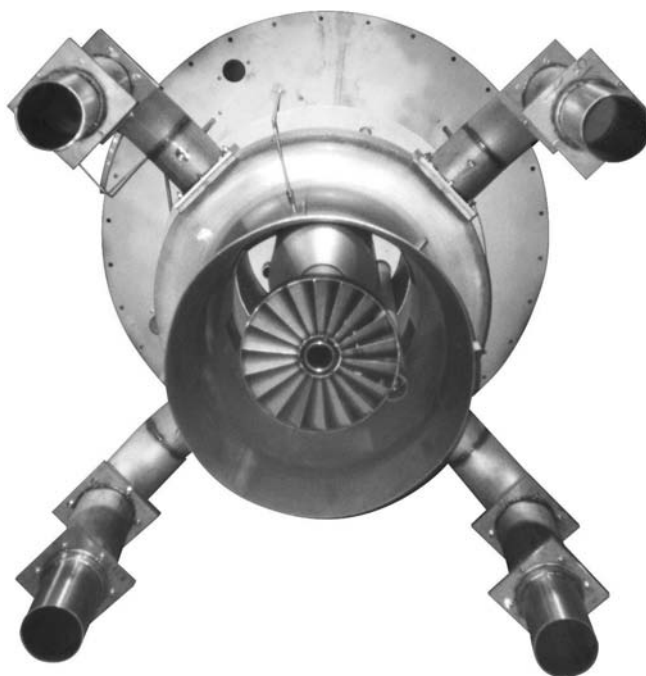


FIGURE 17.10 Burner equipped with furnace gas recirculation ducts.

incomplete combustion products into combustion air, reduces not only the thermal NO_x, but also the prompt NO_x concentrations. This effect distinguishes its impact from that of regular FGR, containing negligible concentrations of incomplete combustion products, which is capable of only reducing thermal NO_x emissions.

17.7.2 STEAM INJECTION

Another method that has been applied to reduce NO_x emissions from either gas or liquid fuel combustion has been the use of steam injection. Flue gas formed by the complete combustion of natural gas at low excess air levels contains at least 15% water vapor by weight. However, it is well known that introducing even a small additional amount of moisture into a burner flame usually brings a significant NO_x reduction, which depends not only on amount of moisture but also on the furnace and burner design, combustion air temperature, and excess air. In addition to these factors, the location where moisture is introduced into the furnace or flame is also very important. Steam acts to absorb heat from the combustion process and reduce thermal NO_x formation.

It has been established on a few industrial boilers that the NO_x reduction effectiveness of moisture injection is changed when FGR is used as well. Even in cases with the same combustion conditions, the same amount of the moisture introduced at the same point can provide different NO_x reductions, depending on whether the moisture is steam, water, or a mixture of both. However, because steam is also available at very high pressures, the energy of the steam jets can also be used as a method to increase fuel-air mixing within the burner and to entrain furnace gases into the flame front. However, the injection of steam always comes with the additional boiler operating costs associated with generating the steam for injection, unless a source of waste steam is available for use. Water treatment costs can also represent a significant impact in cases where high levels of chemical treatment of boiler feedwater is necessary. The use of water injection, in place of steam, also has operational costs associated with it, both with the power required for pumping and with the latent heat of vaporization that cannot be recovered by the boiler and, therefore, decreases the thermal efficiency of the unit.

17.8 ULTRA-LOW-NO_x BURNERS

Low-NO_x burners utilize staged combustion to delay the mixing of fuel and air, creating an initial fuel-rich combustion zone and adding air downstream to complete combustion. In this process, oxygen availability is limited, peak flame temperature is lowered, and thermal NO_x formation is reduced. Thermal NO_x can be further reduced through other techniques, such as the addition of flue gas recirculation (FGR) or steam injection. However, the prompt NO_x created in the initial fuel-rich zone remains, and it is this prompt NO_x formation that has prevented low-NO_x burners from achieving sub-10-ppm NO_x levels.

By “starting over” with NO_x formation fundamentals, it was determined that the most direct method of achieving ultra-low-NO_x emissions from a gas flame is to: (1) avoid fuel-rich regions with their corresponding potential for prompt NO_x, and (2) lower the flame temperature to reduce thermal NO_x to the desired level. To accomplish this, an ultra-low-NO_x burner design must first avoid fuel-rich regions, which can be accomplished in one of two ways.

17.8.1 PREMIX BURNERS

The first way to avoid fuel-rich regions is by premixing the fuel gas with some or all of the combustion air to ensure that the mixture contains at least 80% of the oxygen required for combustion. The drawback to this design is that a premixed volume of fuel and air can “flashback” to the point where the mixing occurs if the injection velocity is allowed to decrease below the flame speed. This becomes a concern as the burner firing rate is lowered, and commonly results in a limitation of only 3:1 or 4:1 turndown on premixed burner designs. One method to overcome this is through the use of a variable burner exit geometry, which decreases the size of the injection orifice as the firing rate is lowered, keeping the velocity above the flame speed and preventing flashback. Another method that has been successfully applied involves the introduction of the fuel-air mixture through a mesh-type surface combustor that also acts as a flame arrestor. Both methods have been shown to extend the operational turndown of these burners into the range required for typical industrial boiler applications; however, certain operational, reliability, and maintenance concerns still exist with both methods.

17.8.2 RAPID MIX BURNERS

The second method to accomplish the elimination of fuel-rich zones is by rapidly mixing gaseous fuel and air near the burner exit, as shown in [Figure 17.11](#). The rapid mixing results in a nearly uniform fuel/air mixture at the ignition point, which virtually eliminates prompt NO_x formation. In effect, the burner performs like a premix burner with one important distinction: because the fuel is added inside the burner, just upstream of the burner exit, the extremely small premixed volume eliminates the possibility of flashback inherent in premix burner designs. A couple of methods of initiating this rapid fuel/air mixing have been utilized. In the first method, swirler geometry, burner internal geometry, gas injector design, and quarl expansion are all matched to rapidly mix the fuel from a series of very fine gas injection orifices with the axially flowing combustion air. A portion of the combustion air/fuel mixture injected through the burner center is swirled to promote internal recirculation of a large amount of hot combustion gases. In an alternate method, high-pressure steam jets are used to provide rotational mixing momentum in the primary combustion zone for fuel/air mixing, as well as serving to reduce thermal NO_x.

17.8.3 ULTRA-LOW-NO_x BURNER OPERATION

Contrary to operation with staged combustion low-NO_x burners, where NO_x reductions are often accompanied by increases in other emissions, such as carbon monoxide (CO), unburned hydrocarbons (UBHCs), and volatile organic compounds (VOCs), ultra-low-NO_x burners, like the one shown

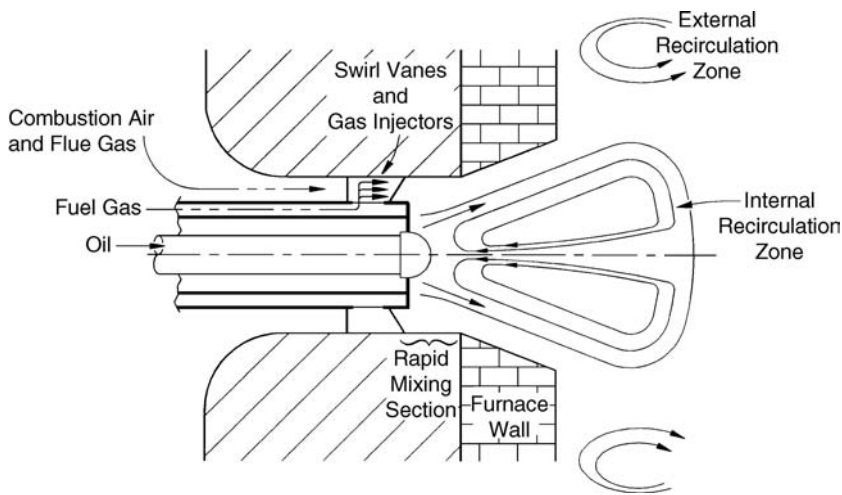


FIGURE 17.11 Rapid mix burner schematic.



FIGURE 17.12 Ultra-low-NOx burner.

in Figure 17.12, easily achieve reductions in all of these emissions simultaneously. The rapid and complete combustion that eliminates prompt NO_x also results in the virtual elimination of CO, UBHC, and VOC formation from ultra-low-NO_x burners.

Thermal NO_x is then minimized using FGR, which can also be combined with steam injection to lower the amount of FGR required to control flame temperature. A typical industrial boiler application will require the use of 25 to 30% FGR to reach sub-10 ppm NO_x operation. Some ultra-low-NO_x burners have shown that their flames remain stable at 60% FGR, which enables the burner to operate at lower flame temperatures and NO_x levels, with a “blowoff” point of about 3 ppm NO_x.

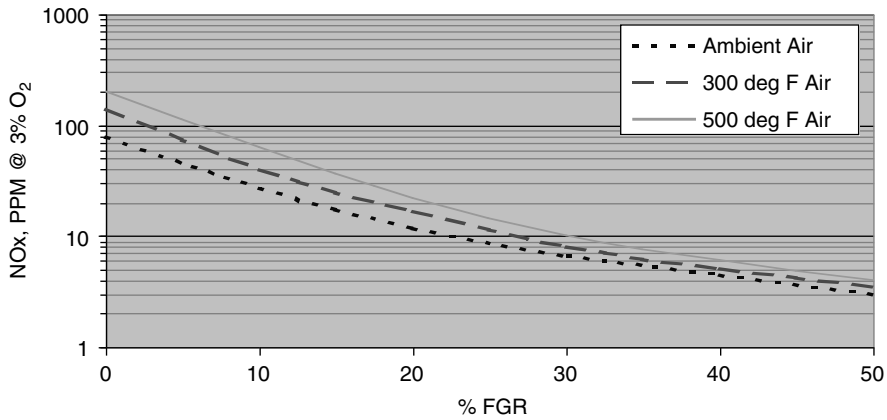


FIGURE 17.13 Effect of FGR vs. air preheat on ultra-low-NO_x burners.



FIGURE 17.14 Ultra-low-NO_x burner flame.

Contrary to conventional low-NO_x burner theory, increasing excess air reduces NO_x formation in ultra-low-NO_x burners. Because the burners employ premixing or near-perfect mixing, the fuel already has access to all of the oxygen required at the ignition point. Increasing excess air just serves to reduce the peak flame temperatures and, therefore, excess air has the same cooling effect as FGR. This provides major advantages in high excess-air combustion applications, such as dryers, where FGR is impractical or unavailable. In boiler applications, where FGR is available, it is preferred due to its lower impact on the boiler efficiency than high excess air, and its lower operating cost impact when compared to steam injection.

The ultra-low-NO_x design is also what allows the burner to operate with preheated combustion for increased efficiency, and still retain single-digit emissions performance by simply increasing

the FGR rate to compensate for the higher air temperature. For example, increasing the combustion air temperature from ambient (80°F) to an air preheat of 300°F would require an increase in FGR rate from 27 to 32% to maintain emissions at 9 ppm. Further increasing the air preheat to 500°F would require a respective increase in FGR rate to 43%, which can be seen in [Figure 17.13](#).

In addition to low emissions, another benefit of the ultra-low-NO_x burner design is an extremely stable and very short flame, as shown in [Figure 17.14](#). It is approximately half that of a staged air burner, which eliminates the potential for flame impingement, a common problem experienced with low-NO_x burner retrofits. The air-side pressure loss for most ultra-low-NO_x burners is typically higher than that for low-NO_x burners, at 8 to 12 in. w.c. The fuel pressure requirements, however, do not differ significantly from air-staged low-NO_x burners.

For oil firing, the ultra-low-NO_x burner utilizes a conventional center-mounted atomizer assembly. The burner operates as a staged-air low-NO_x burner when firing oil, with fuel staging provided by advanced atomizer designs and air staging provided by the burners primary and secondary air flows. This allows emissions performance on oil firing equivalent to other low-NO_x burners.