ClearSign Core™ Process Burners and Boiler Burners - Burner Scaling and Field Results

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I. Abstract

During previous AFRC Industrial Combustion Symposia, ClearSign Technologies Corporation introduced its ClearSign Core technology currently used in our Ultra Low NO_x burner products. These ClearSign Core products have now been developed for different types of equipment applications to meet stringent performance and environmental requirements. In the past year, ClearSign successfully completed multiple unique and challenging projects that successfully demonstrate that ClearSign Core products are capable of meeting the requirements of some of the most challenging burner applications. In doing so, these completed projects have confirmed that the research and development efforts to develop the technology are transferrable to the challenges of existing operating facilities.

The ClearSign Core technology has been applied to Process Burners, Boiler Burners and Enclosed Combustors. The subject paper will discuss the scaling approach of the burners across various sizes, fuel compositions, and various furnace operating conditions. In addition, case studies will be presented from installed projects that successfully demonstrate the unique Ultra Low NOx and other capabilities of the ClearSign Core technology while also providing predictable, reliable, and stable operation demanded by our customers. Case studies and field certified results will be provided for both the ClearSign Core Process Burner, and the ClearSign Core Boiler Burner products.

II. Introduction

ClearSign's novel Core™ burners combine the benefits of lean Premixed Combustion and Internal Fuel Gas Recirculation to provide extremely low NOx emissions, on the order of those achieved by more complicated and costly Selective Catalytic Reduction (SCR) system, and without the use of expensive catalysts or chemicals. Premixing the fuel and air to form fuel-lean mixtures avoids high temperature stoichiometric conditions in the flame zone and prevents conditions conducive to both prompt and thermal NOx formation. Increasing the amount of excess air i.e., leaning the air-fuel mixture can help lower NOx even further with the ClearSign Core burners.

The ClearSign Core burner incorporates a flame holder positioned downstream from the air-fuel injection plane. Fuel and air are thoroughly mixed before reaching the flame holder. In addition, the momentum of the fuel jets and the air flow are utilized to internally entrain and recirculate the flue gases. The effect is dilution of the air-fuel mixture with inert flue gases – N_2, CO_2 and H_2O – which further lowers the flame temperature and reduces the formation of thermal NO_x. The mixture is then ignited by the flame anchored at the flame holder location where the bulk of the combustion occurs. Properly engineered mixing tubes are placed between the air-fuel injection plane and the flame holder to efficiently inspirate internal flue gases and thoroughly mix those flue gases, fuel, and combustion air. The flame holder is designed to provide flame confinement as well as enhanced radiant heat transfer to the desired surface. A schematic of the burner is shown in Figure 1.

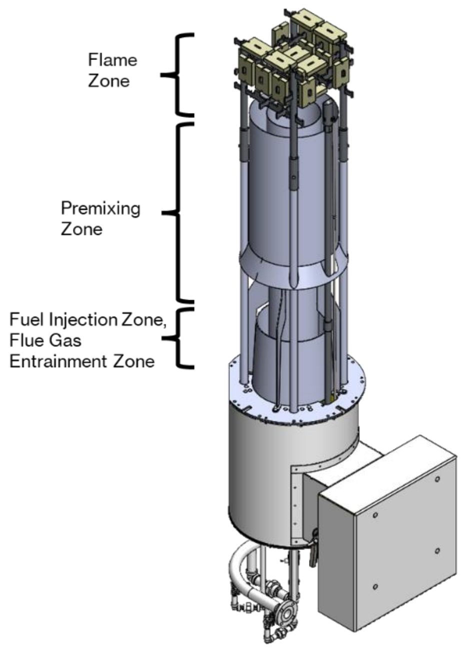

Figure 1 - Schematic of ClearSign Core™ Process Burner

The burner technology has already been successfully applied to three different applications – Boilers – both firetube and watertube, Process Heaters, and Enclosed Combustors. ClearSign Core Boiler Burners are forced draft while the Process Burners and Enclosed Combustors can be natural or forced draft.

III. Design Approaches for Diverse Operating Conditions

The ClearSign Core burner designs allow for flexibility to tailor to various firing rates, fuel compositions, and various furnace operating conditions. The following sections will discuss such applications tested and commissioned for several customers.

A. High-Hydrogen Fuel Application

Hydrogen is a remarkable fuel in terms of its physical and thermochemical properties and its reactivity. Yet, there are two main challenges with implementing a burner system to operate on high Hydrogen-content fuel: 1) The high adiabatic flame temperature of hydrogen produces high levels of thermal NO_x and is difficult to mitigate, and 2) hydrogen flames have a much higher flame speed and high fuel reactivity compared to other gaseous fuels; this increases the chance of upstream flame propagation or flashback in premixed burner systems. Figure 2 illustrates the multi-fold increase in NO_x emissions in diffusion flames for Hydrogen compared to Methane. This behavior is directly caused by the high adiabatic flame temperature of H_2 [Ref]. Prompt NO_x pathways are minimized in Hydrogen combustion due to the lack of hydrocarbon radicals. The flame speed of Hydrogen is an order of magnitude higher than that of Natural Gas or Methane [Ref]. In premixed systems like the ClearSign Core burner, this causes an increased propensity of the flame burning back at the fuel injection location if the mixture speed is not maintained above the flame speed. Burn back can cause damage to the burner components in the Premixing Zone, and result in reduced mixing leading to higher NO_x emissions. At turndown conditions, the reduced fuel velocity can further exacerbate flame burnback.

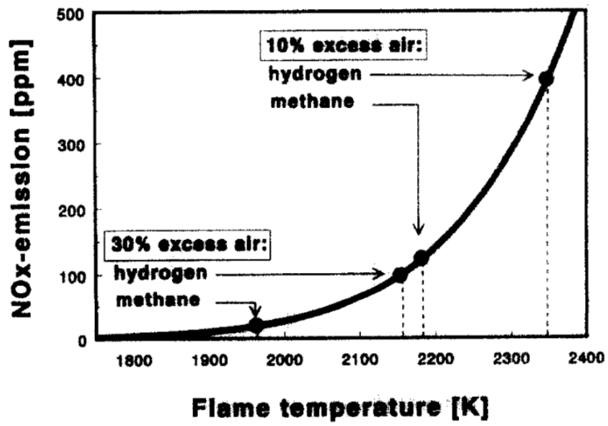

Figure 2 - NOx Emissions and Adiabatic Flame Temperature for H_2 and CH_4

In order to address the challenges with high-H_2 fuel, the ClearSign process burner was altered by creating physically separated regions within the premixing zone that are below flammability limits of the fuel-air mixtures. Also, the amount of flue gases inspirated in the Premixing zone were increased by appropriately sizing and positioning the mixing tubes. Finally, the velocities of mixtures in the premixing zone were maintained above the flame speed to prevent burnback under upset operating conditions. Partly delaying the mixing of air and fuel slightly stretched the flame lengths resulting in more flame surface area and thereby further lowering NOx emissions. In the referred application, the customer had a refinery fuel blend with H_2 levels up to and beyond 80% (by vol.). The modifications described above allowed the burners to operate on fuels ranging from Natural Gas to very high-H_2 fuel while retaining the low NOx emissions. The design was factory tested in a multi-burner configuration, had NOx emissions below 8 ppm (corrected to 3% O_2) and turndown of up to 4:1.

B. Low Furnace Temperature Application

Another challenging application in refining is applying NOx reducing technologies in furnaces that have de-rated. As demands within refineries change due to reconfiguring units, changes in demand for certain products or repurposing for use in a different service, a furnace's duty may be reduced yielding lower operating temperatures. Furnace with radiant sections operating at temperatures lower than 1200°F to 1400°F are generally considered challenging for low NOx burners increasing attention in the design to stability and reducing emissions such as CO and unburned hydrocarbons. Couple this with the challenge of trying to operate with reduced excess air to be more energy efficient, operating at lower firing rates can lower the radiant section temperature further and limit the ability to reduce operating oxygen below 6% - 8%. Tuning conventional ultra-low NOx burners can lead to higher NOx emissions to resolve stability and other emission issues.

ClearSign's Core process burner can be tuned to address stability, energy efficiency and maintain low emissions (NOx, CO and unburned hydrocarbons). The challenge in working in this cold environment is primarily the entrainment of internal flue gas. Achieving low NOx emissions relies heavily on the mixing of internal flue gas within the combustion chamber with the fuel gas injected by the burners gas tips. Each fuel jet entrains surrounding flue gas to inert the fuel stream thereby reducing peak flame temperatures. As the temperatures in the radiant section cool, the flue gas' density increases. Treating the flue gas entrainment as a constant volume, the lower the temperature the more effective the flue gas is at reducing NOx. Conversely, as the furnace temperature increase, the mass flow of flue gas is reduced increasing NOx.

Figure 3 - Single Burner Low Temperature Furnace Application

ClearSign's burner can be optimized or tuned to improve NOx, other emissions and allow more efficient operation (by reducing operating oxygen) by optimization techniques that control flue gas entrainment and mixing or residence time. This can be achieved by altering the mixing zones and changing the equivalence ratio in combustion zones, adjusting the flame holder location to reduce or increase residence time for mixing and adjusting the fuel injection's ability to entrain flue gas.

The result is being able to supply a burner for a challenging process capable of producing low pollutant levels and operating stability and achieving desired operating efficiency.

C. Application Requiring Increased Throughput and Compact Flame

Conversely to de-rating a furnace, another avenue often explored is increasing fired duty in a furnace. Unlike many emissions related projects, increasing the throughput of a heater can generate a profitable project realizing a return on investment unlike most burner projects where the sole purpose is to be in compliance with local regulatory requirements for emissions. Increasing fired duty can lead to higher emissions and flame impingement on the radiant tubes or shock tubes in the convection section. Also, economics factor into increasing fired duty. The ability to avoid modification to heater steel can make or break a project.

Depending on location, air permits typically require alteration to allow increased firing. Permitting could result in maintaining existing emission levels (tons/year) or reducing emissions to even lower levels. This challenge can be even greater if the application is already utilizing ultra-low NOx burner technology leading to more expensive solutions like post combustion, selective catalytic reduction. ClearSign's Core process burner can meet the emissions challenges utilizing the three pillars that the technology is based upon. They are lean premix strategies, maximizing internal flue gas entrainment and increased residence times to produce lower NOx levels to meet a more stringent permit.

Increased fired duty can result in flame impingement and higher fired density in the radiant section making NOx reduction challenging for combustion solutions. By increasing the firing rate, the intensity and temperatures in the radiant section increase leading the development of higher NOx emissions. API 560 recommends maintaining a heat release intensity ($Btu/hr/ft^2$) less than 300,000 $Btu/hr/ft^2$ to provide sufficient cross area for burner to produce predictable flame dimensions and NOx emissions. Firing a furnace beyond this value can lead to higher-than-expected NOx emissions and undesirable flame patterns with the potential to cause damage resulting in shortened run lengths or catastrophic damage to the furnace.

To take advantage of the increased heat input, API 560 recommends maintaining flame lengths less than 60% of the radiant section height. While visible flame may expend itself at that point, heat is still being released to the process tubes. Longer flames can result in higher bridgewall temperatures and loss of radiant efficiency. Unless the convection section can recover this duty, the overall performance of the furnace can suffer. Considering furnaces tend to be right sized, meeting flame lengths with additional firing rate is difficult. Compounding that furnaces that were designed for an original lower fired duty and API 560 recommending a more stringent maximum flame height (recent update of the document moved maximum recommended flame height from 67% of the radiant height to 60%) increasing fired duty will necessitate the need for flame lengths with shorter feet/MMBTU lengths than the existing burner.

Realizing higher firing rates can cause the owner to have to mitigate risk of higher-than-expected emissions or managing flame patterns with the potential to coalesce and stretch out impacting the shock tubes or short circuit the normal flow of flue gas recirculation pattern within the heater causing the flames to roll over into the radiant tubes.

Along with the technical and process risks are the added economic challenges associated with increasing fired duty. Normally, to increase fired duty with the same operating parameters (available draft and excess air requirements) the heater floor would need to have the burner openings enlarged to allow for a bigger burner due to the burner tile which serves as the metering device for the air flow through a burner. Modifications to the heater steel and floor refractory can kill a project as quickly as failing to obtain a new air permit.

In such an application, ClearSign's Core process burner achieved lower emissions and shorter flame than conventional low NOx burners, and also achieved the higher air flow rates needed to increase fired capacity by 25%. By altering the geometry of the flame holder, the flame pattern was reduced to allow for a more compact flame allowing the needed flame volume to fit within the existing heater volume. The Core process burner's utilization of premix allowed it to increase the air drawn into the burner as the fuel jets inspirate air on top of the air drawn into the furnace from the pressure differential between ambient conditions outside the furnace to the slight vacuum within the furnace chamber. Also, as the ClearSign core burner is more efficient at flue gas entrainment and mixing, the burner was still able to achieve lower emissions despite the more severe operating conditions brought on by the increase in fired duty.

Figure 4 - Photograph of multiple burners operating in the Increased Throughput, Compact Flame Application

D. Confined Furnaces / High Combustion Intensity Application (Firetube Boiler)

Firetube Boilers typically have a higher heat release per unit volume of the furnace compared to process burner applications. This characteristic combined with the high flow velocities and furnace confinement presented unique challenges for ClearSign's Core technology. However, these challenges were successfully overcome by utilizing the momentum generated by the forced-draft fan to achieve efficient mixing of fuel and air, as well as to effectively entrain internal flue gases into the air-fuel mixture. The ClearSign Core Firetube Boiler Burner architecture is shown in Figure 5. The burner was developed in ClearSign's Seattle test facility in a commercially available 125 HP, 4-pass, dry-back, firetube boiler. Measured NOx emissions were as low as sub-2 ppm NOx corrected to 3% excess O_2 for this burner at full firing rate. The NOx emissions as a function of excess O_2 follow a trend consistent with premix flame behavior as shown in Figure 6. The excess air dilution causes leaner air-fuel mixtures producing lower peak flame temperatures and hence, lower NOx emissions. The burner was stable across a wide range of operating conditions of O_2, firing rates, and available fuel pressures as low as 1 psig. The operation of the burner followed industry standard procedures as well. The burner itself is a self-contained unit comprising of the blower assembly, firing head, ignition system, and flame safeguards.

When scaling the firetube boiler burner from 5 MMBtu/hr size up to a 60 MMBtu/hr size, the approach involved maintaining the flow velocities through various burner sections, overall mixing lengths and residence times, and % FGR entrained internally. ClearSign's Core Firetube Boiler Burners have already been installed and independently source-tested for sizes ranging from 5 MMBtu/hr to 20 MMBtu/hr demonstrating sub-2.5 ppm NOx (corrected to 3% O_2).

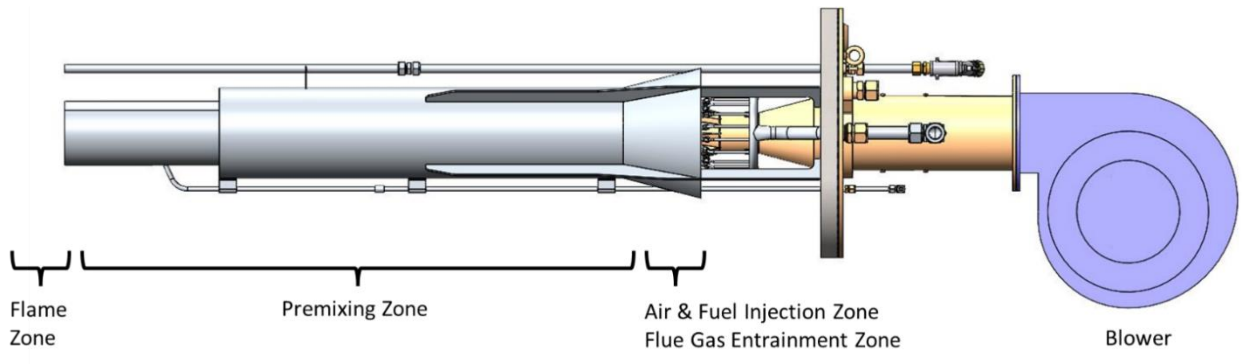

Figure 5 - ClearSign Core™ Firetube Boiler Burner

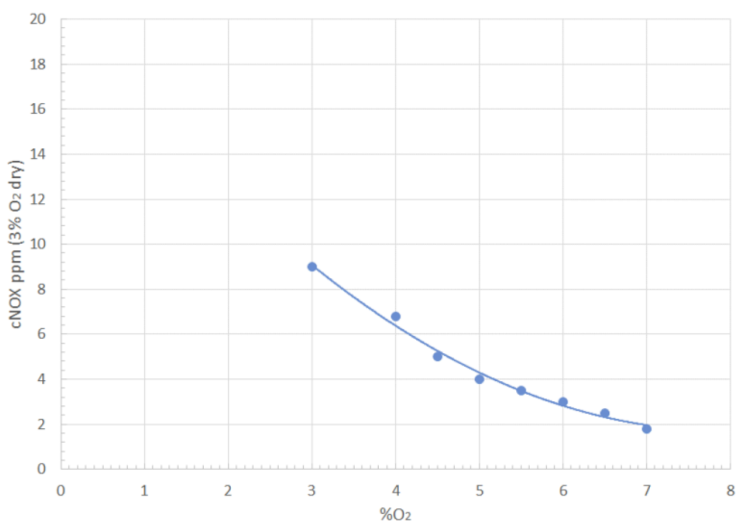

Figure 6 - NOx emissions (corrected to 3% O_2) at various operating O_2 levels

E. Enclosed Flare Application

ClearSign's Enclosed Flare burner employs a slightly different design approach compared to the process burner and boiler burner. The challenge in such enclosed flare applications is that, due to their high temperature from the lack of any process heat transfer, the flue gases have the potential to auto-ignite the premixed air-fuel or increase the propensity of flame burnback from the flame holder to the fuel tips. Given that enclosed flares typically operate at significantly higher combustor temperatures and are allowed to operate at high excess O_2 levels, the burner was designed to only utilize lean-premixed combustion but no internal flue gas recirculation to achieve low NOx.

Figure 7 shows one of four separate enclosed combustors installed at a small oil producer's sites in the Los Angeles area. These sites were disposing of well-head gas at volumes ranging from 2.5 to 30 MSCFD. The heating value of the gas ranged from 1452 to 1752 BTU/SCF HHV, depending upon the site. Emissions required were sub 15 ppm NOx, and sub 13 ppm CO, corrected to 3% excess O_2. In addition, no visible flames or emissions were permitted. The installations included the burner, flare stack, fuel gas train, burner management system, and controls. The combustors have been operating uninterrupted since November of 2020, and each unit has passed emissions tests successfully. Emissions for all units were sub 10 ppm NOx and sub 10 ppm CO, both corrected to 3% excess O_2.

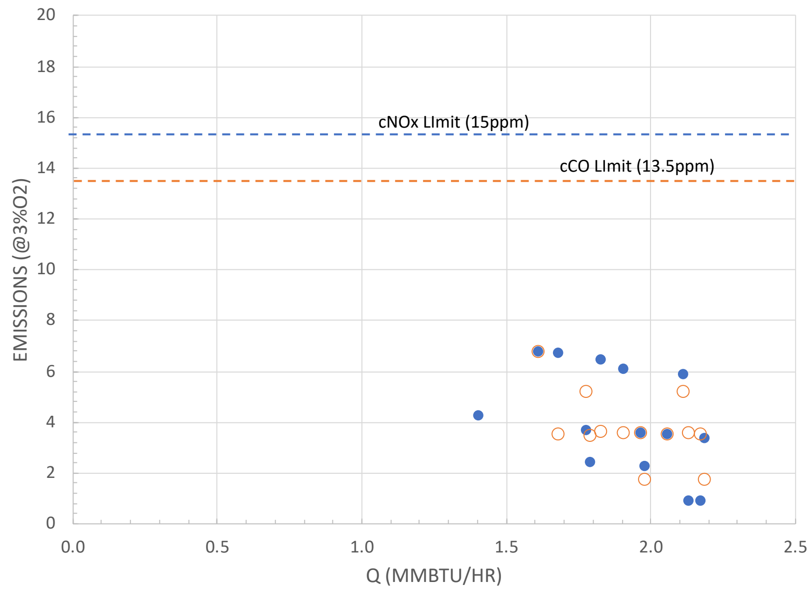

Figure 7 - NOx and CO emissions vs firing rate. Regulation permit levels shown as dashed lines.

IV. Conclusions

Like any emerging technologies, ClearSign's Core technology continues to evolve and find its place solving complex combustion applications and addressing ever tightening environmental regulations in different industries. With each development, the technology continues to expand in capability and application. The technology is proving adept at addressing different applications and each new application develops a greater understanding of the base technology and provides continuous improvement. Learnings in one application have proven useful on other projects. From utilizing forced air to natural draft, wide ranging fuel compositions, variable flowrates and different styles of combustion chambers, ClearSign's Core technology will continue to evolve and expand into serving far ranging applications to provide emissions solutions at a fraction of the cost of current emissions solutions.