Enhanced Burner Design for Legacy Furnace Retrofits: A Comprehensive Approach

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Abstract

As NO_x regulations continue to tighten in areas like California and Texas, a need for a cost-efficient retrofit combustion solution for refinery applications exists. In recent years newly constructed furnaces are few and far between. In the early 1990s and into the 2000s, furnaces were retrofitted with early-generation low NO_x technology burners. These furnaces were not designed with these ultra-low NO_x burners in mind, especially with the increased flame volumes generally associated with lower NO_x emissions. With flame lengths increased up to double the length of conventional and early-staged fuel burners, there is a risk of problems occurring following these installations that may hamper operation and the ability to meet emissions or make full production rates.

Utilizing single-burner factory testing, burner technology could be shown to meet the emissions regulations, however following those retrofits flame interaction either with each other, or the flue gas flow patterns in the operating furnaces often resulted in elevated NO_x levels or non-optimal heating patterns on the radiant process tubes. A lot of time was spent making modifications in the field to achieve the desired result. At that time, bolstered by this need, Computational Fluid Dynamics (CFD) modeling was becoming more prevalent in the industry and started being utilized to better understand the flue gas currents in furnaces and how burners interacted with each other.

Today, with regulations on the West Coast and in Texas becoming more stringent and often requiring down to 5 ppm NO_x solutions, burner technology is again being challenged and consequently the tools available to validate the function of the overall combustion solution require additional consideration. ClearSign utilizes several tools such as multiple-burner testing and CFD prior to a heater retrofit to ensure the highest chance of success in a multiple-burner installation. This paper will outline how to approach a complex application by applying multiple, industry accepted tools that result in a better product and application success.

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I. Introduction

The refining industry heavily relies on the American Petroleum Institute's (API) standard 560, Fired Heaters for General Refinery Service, as a guiding document. API 560, first published in 1986, provides essential requirements and recommendations for refinery applications, including fired heaters, air preheaters, fans, and burners. However, retrofitting older units with new ultra-low NO_x burner technologies pose unique challenges due to design constraints.

While API 560 has continued to evolve to keep up with advancements in technology, legacy units present unique challenges for a retrofit due to design parameters such as burner-to-tube spacing, height of the firebox, and burner-to-burner spacing.

As ultra-low NO_x technologies have been introduced, the need for increased flue gas recirculation within the firebox has become critical to performance. Many of these legacy units still in service do not meet the revised API 560 guidelines for burner to tube spacing. New heater builds are encouraged to address this by enlarging the cross-sectional area of a furnace to allow for increased internal flue gas recirculation.

In addition to increasing the burner to tube spacing, burner-to-burner spacing, for ultra-low NO_x burners, also should be increased to help enhance flue gas recirculation and larger flame volumes. Increasing the burner-to-burner spacing also inherently requires an increase in the burner circle diameter. This makes it challenging to retrofit these units effectively without the need for floor modifications.

API 560 guidelines for maximum allowable flame length have decreased from 66% of the firebox height to 60% of the firebox. Ultra-low NO_x burner technology tends to form longer flame lengths than traditional burners, so this guideline requires careful consideration and may be challenging when retrofitting with traditional ultra-low NO_x burners.

The essence of these realizations is also presented in the API 560 recommendation that maximum hearth heat intensity (HHI) guidelines are also decreased. Increasing the HHI in a heater inhibits the ability to achieve low NO_x emissions, or to achieve proper functioning of the heat transfer surfaces and heater performance when flame volumes are enlarged. Although the decrease in recommended maximum HHI in API 560 is not the main driver of this challenge but rather the design of the legacy units prior to the need to accommodate low NO_x burners. These legacy units tend to have HHI's higher than the current recommended levels.

Retrofitting a heater, with low NO_x burners, without the need for floor modifications can be challenging. Floor modifications could include modification to structural steel, refractory installation or repair, and modification to fuel piping to the burners. The primary disadvantage is the cost involved for modifications, but refractory work and the required curing period also extend downtime that is also undesirable. Ultra-low NO_x burner installations tend to be driven by regulatory requirements, and generally do not provide throughput or efficiency gains, therefore, often not providing a direct financial payback.

With the challenges outlined above, the question arises on how to design a solution for legacy furnaces with the greatest chance of success. Traditional tools include scaled and full-scale physical testing of burners, multiple burner testing, and CFD studies of the burners and the intended heater. While each tool has its benefits, they all come with some limitations. The consequence of not using an integrated approach can yield problems in the field.

The benefits of multi-burner testing provide invaluable data as to the interaction between burners such as flame propagation in both the vertical and horizontal directions. CFD, in addition to multi-burner testing, provides insight into the performance of the burners within the client's heater. Utilization of both services, as an upfront cost, can provide valuable cost savings to the customer in the long run.

Burners that have not been optimized for use in the destination heater in addition to individual performance can cause a variety of problems. These can include stability issues limiting total fired duty caused by burner-to-burner interactions. Another issue could be furnace currents forcing the burner flames to recirculate back onto the process tubes caused by burner-to-burner spacing and proximity to the radiant tubes, this can lead to local overheating of the process tubes. If the burner-to-burner spacing is too close, the flames can merge and run together causing long flames and potentially causing impingement on the shock tubes. Recognizing warning signs in the project can provide insight on what tools to bring to bear to provide a well-designed solution mitigating problems from occurring with resulting potential damage to equipment and loss of run time.

To address these challenges with confidence, a systematic approach integrating multiple tools, such as physical burner testing, CFD, and scaled multi-burner testing, is proposed. These complementary methods offer invaluable insights into burner interactions, flame propagation, and heat distribution. By using both CFD and physical testing, the risk of problems in the field can be significantly reduced, ensuring successful implementation.

The project's timeline benefits from a coordinated approach, with CFD analysis preceding physical testing, optimizing the burner's design. Iterative CFD simulations help identify potential improvements before costly physical tests, enhancing cost savings and reducing testing time.

Employing an integrated approach with advanced tools and rigorous testing leads to a well-designed and successful solution for retrofitting legacy furnaces.

II. Advancing Combustion Technology - Research & Development

The early stages of developing the ClearSign Core Process Burner were marked by a commitment to innovation and a vision of revolutionizing combustion technology. The process began with small-scale single-burner testing in a 5 MMBtu/hr size furnace equipped with a premix natural draft process burner. These tests explored a limited range of fuel blends, flame holder materials, geometries, and mixing lengths to achieve the desired ultra-low NO_x levels.

As the technology progressed during the pilot scale testing, the challenge of scaling the burner to industry standard sizes emerged due to constraints like test furnace availability, costs, fuel options, and time limitations. Consequently, an exhaustive combination of geometries and fuel blends could not be tested directly. To address this, data extrapolation was employed to extend insights beyond available data points, fostering a comprehensive understanding of trends and patterns. This enabled the team to make well-informed decisions and predictions with greater confidence. Continued research, including physical testing and CFD, broadened the range of data validation and reduced uncertainties.

Collaboration played a pivotal role in the development process, as the ClearSign team actively engaged with industry partners, research institutions, and regulatory bodies. This collaboration facilitated valuable feedback and insights into practical challenges faced by industries, ensuring that the ClearSign Core Process Burner aligns with industry needs and standards. Once the core technology was validated and the burner's potential was demonstrated through single and multi-burner testing, ClearSign embarked on commercialization efforts. Close collaboration with industrial clients allowed for seamless integration of the new burner technology into their processes and facilities, with optimization driven by real-world applications.

The novel ClearSign Core^{TM} burners combine lean premixed combustion with internal fuel gas recirculation (iFGR) to achieve impressively low NO_x emissions comparable to complicated and costly selective catalytic reduction (SCR) systems without the use of expensive catalysts, chemicals, or large blowers. The premixing of fuel and air creates fuel-lean mixtures, preventing high-temperature, stoichiometric conditions in the flame zone and minimizing both prompt and thermal NO_x formation. Further reduction in NO_x emissions is achieved by increasing the amount of excess air, leaning the air-fuel mixture with the ClearSign Core burners.

The design of the pre-mix ultra-low NO_x burner prioritizes efficient fuel combustion with minimal NO_x formation. Precise control of the fuel-air mixture, flame stability, and incorporation of flue gas recirculation techniques collectively enable the ClearSign Core burners to achieve ultra-low levels of NO_x emissions, aligning with stringent emission regulations and environmentally friendly practices.

The ClearSign Core burner design incorporates a strategically positioned flame holder downstream from the air-fuel injection plane. The momentum of fuel jets and air flow entrains and internally recirculates the flue gases, and thorough mixing of fuel, air, and flue gases occurs before reaching the flame holder. The resulting dilution of the air-fuel mixture with inert flue gases (N_2, CO_2, and H_2O) further lowers the flame temperature and reduces the formation of thermal NO_x. The combustion takes place at the location of the flame holder, designed to confine the flame and enhance radiant heat transfer to the intended surface. Figure 1 presents a schematic of the ClearSign Core^{TM} Natural Draft Process Burner.

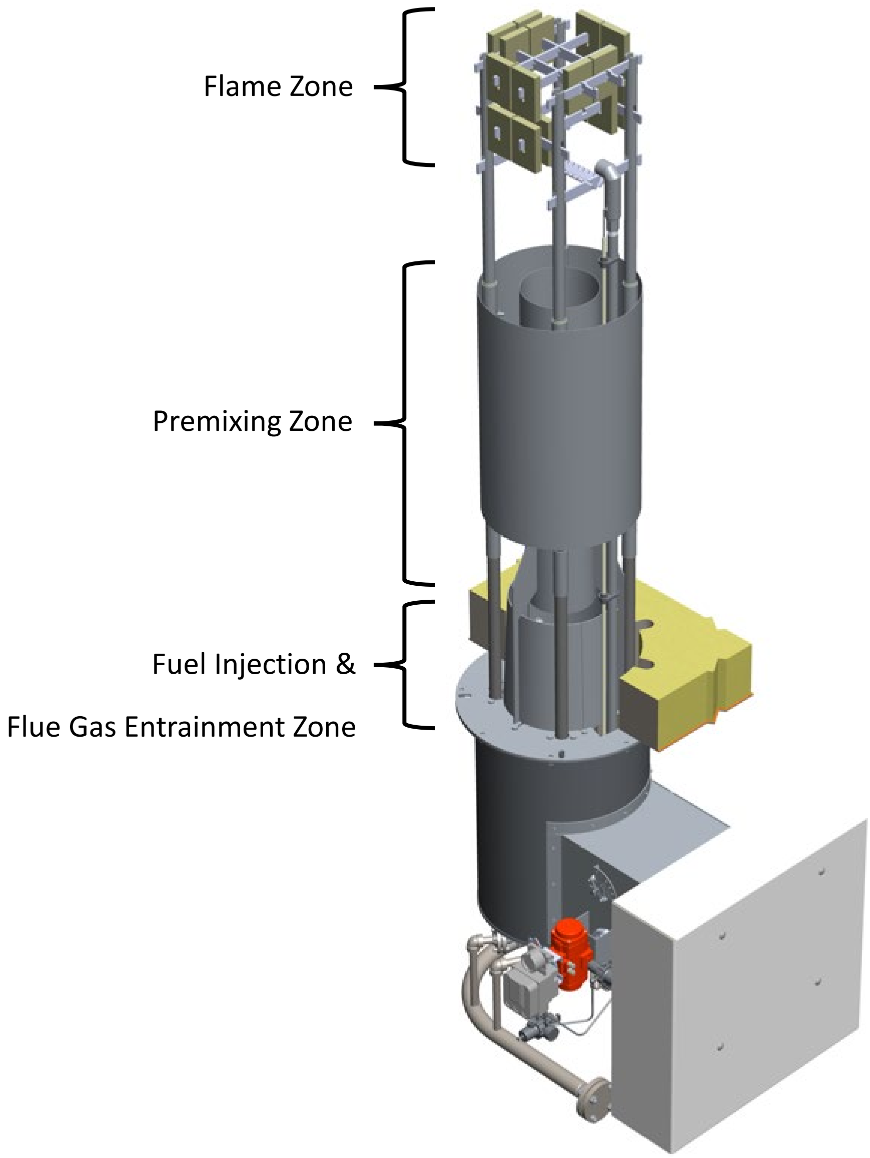

Figure 1 - Schematic of ClearSign Core™ Natural Draft Process Burner

The burner technology has found successful application in boilers (both firetube and watertube), process heaters, and enclosed combustors. ClearSign Core Boiler Burners operate with forced draft, while the process burners and enclosed combustors can be configured for either natural or forced draft systems. The ClearSign Core multi-burner combustion system is designed to cater to both fired and process heater applications. Fired heaters come in various types, such as vertical cylindrical, horizontal cylindrical, and box type, and play a vital role in refineries for heating crude oil, intermediate products, and various hydrocarbon streams. Process heaters are used in preheating feedstocks, heating utility streams, or providing heat for diverse refining processes.

III. Project Design Considerations

The project timeline dilemma arises when deciding whether to complete CFD or physical testing first—a classic "chicken and egg" scenario. Typically, CFD is performed initially to identify system issues, followed by fabrication and physical testing of the as-modeled burner to verify performance variables. Physical testing complements CFD by identifying issues that CFD may not capture, such as burner instability or additional issues that may alter the burner's original design. In cases of significant design impact, it may be necessary to re-run the CFD with an adapted model that matches the physical changes made to the burner to verify the furnace system has not been adversely impacted. This iterative process can be costly, but an additional CFD run is faster and more cost-effective than re-running physical tests. A typical design flow is illustrated in Figure 2 below.

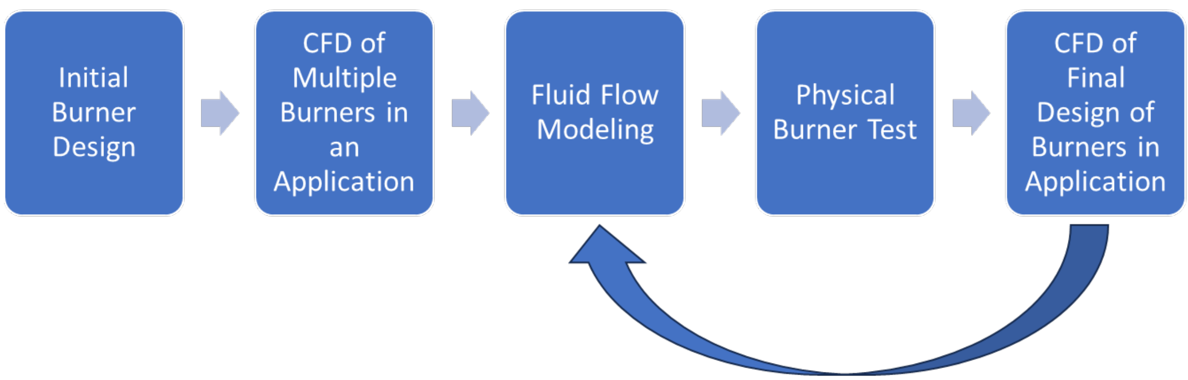

Figure 2 - Flow chart of ClearSign Core burner project design scenario timeline.

ClearSign currently utilizes both physical testing and CFD as complementary tools that each have limitations but when paired together can yield superior results. Single burner testing offers valuable insights into stability, airside capacity, fuel pressure, flame envelope, maximum turndown, NO_x, and CO emissions under multiple fuel and operating conditions (including turndown, O_2 adjustments, etc.). Multiple burner testing considers burner-to-burner interactions and provides NO_x data closer to real-world values but may underestimate results due to differences in furnace geometry. For example, the target heater or application could have a much tighter burner-to-tube clearance which could impact flue gas recirculation patterns, NO_x and flame patterns. CFD excels in evaluating complex combustion systems with exact heater geometries, enabling the assessment of single and multi-burner configurations.

Physical testing faces limitations due to the expense and the limited number of available furnaces in test facilities. Test furnaces may match correct geometry—vertical, horizontal, down fired, etc.—typically allowing the burners to be tested in the correct orientation; however, the relative cross-sectional area, furnace volume, or available draft may not correlate to the actual customer furnace, leading to differing emissions performance and furnace currents impacting the flame envelope. In such cases, CFD can effectively reproduce exact heater geometries, facilitating the evaluation of both single and multi-burner configurations in complex combustion systems.

CFD simulations help to model and analyze flow patterns, flame impingement on tubes, heat flux and temperature distribution profiles, furnace currents, and how they impact flame geometry and burner-to-burner interaction. When modeling the customer's actual furnace, points of interest like radiant efficiency, process tube metal temperatures, flame impingement on process and shock tubes can be evaluated both quantitatively and qualitatively. In retrofitting older furnaces, understanding how burners will interact and the impact on the performance of the unit can uncover problems during the design phase and prevent rework in the field causing a loss of operation. While CFD cannot always accurately predict the flame front (or point of ignition), incomplete combustion, or burner instability, its capacity to look at an application from a system perspective is unmatched. CFD provides insight for optimal burner-to-burner spacing and positioning, considering factors such as flame overlap prevention, efficient heat distribution to the tubes, optimization of the flameholder arrangement, and the pressure drop created.

IV. Burner Optimization Using CFD

Full heater geometries with multiple burners are completed using software with the capability to model combustion; however, these simulations can take weeks to converge due to the complexity and computing power needed. Another option is to utilize non-reacting CFD software with the capability to rapidly model burner designs. Although this form of modeling cannot predict the downstream combustion contours, scalar air-fuel mixing profiles can be evaluated. This resource proves useful during testing as a minor physical change to the burner can be modeled ahead of time and run to completion in a matter of hours. This ability not only provides cost savings but contributes to reduced testing time.

The image in Figure 3 presents the velocity field obtained from CFD simulations of a ClearSign Core multi-burner setup. The study revealed an opportunity to optimize the flameholder design, aiming to narrow the flame diameter and reduce potential flame interactions between adjacent burners. In this example, the flameholder "V" anchors were narrowed to reduce pressure drop while maintaining their flame-stabilizing capabilities. The resulting lowered flameholder pressure drop also eliminated local recirculation zones, leading to lower floor temperatures and lower NO_x emissions. Figure 4 illustrates the resulting improvement in the flow field. This behavior was successfully validated during subsequent burner testing.

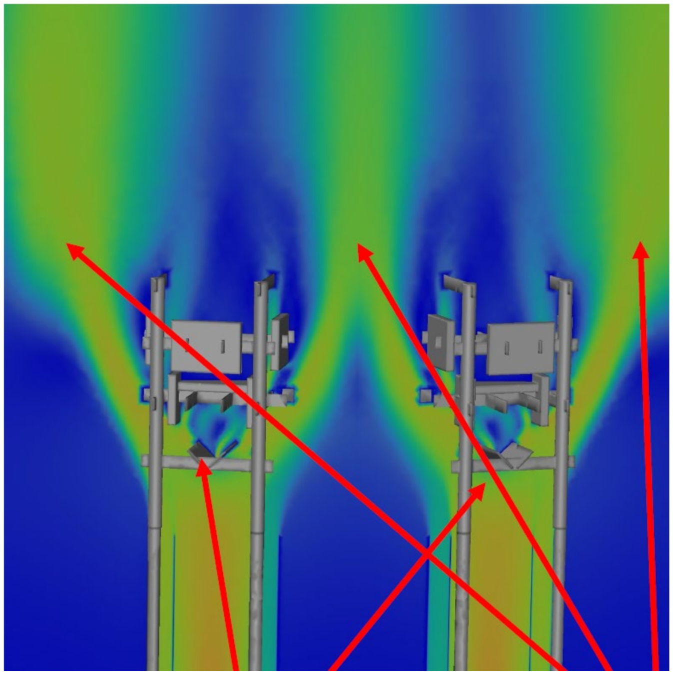

Figure 3 - The initial flame anchoring points, located at the base of the flame holder, led to flow diversion, and created the potential of flames merging.

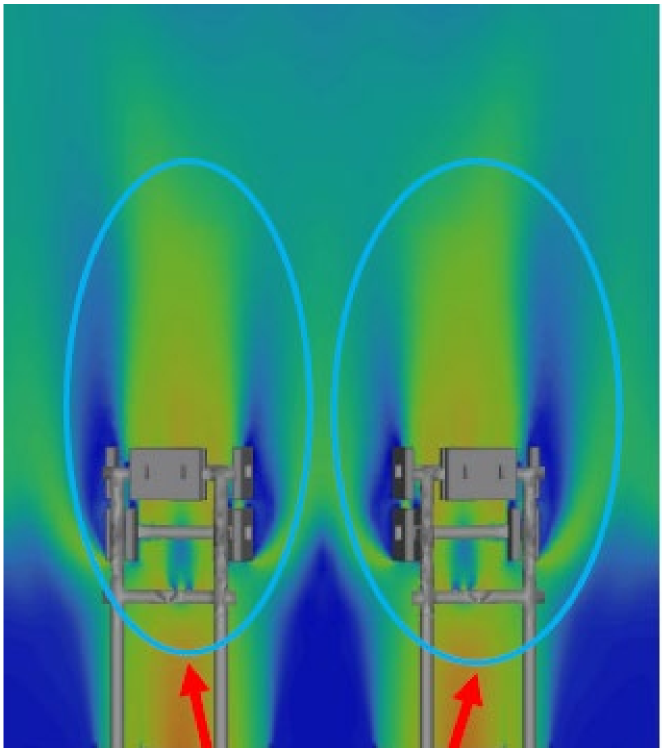

Figure 4 - By reducing the width of the flame anchor and eliminating internal tiles, the flow was successfully redirected axially.

V. Verification through Physical Burner Testing

Initial testing commences with a single burner to thoroughly fine-tune and optimize its design, including aspects like fuel staging and efficient flue gas entrainment. The objective is to achieve the targeted ultra-low NO_x value and ensure stable operation. This focused approach on a single burner allows for early identification and resolution of potential issues and limitations before scaling up to a multi-burner configuration. By adopting this strategy, associated fuel costs and the need for burner test changes are minimized.

Once ClearSign successfully demonstrates performance in the single burner test, multi-burner testing follows, enabling validation of flame stability and assessment of burner-to-burner interactions, providing a more realistic representation of the technology's capabilities in practical operating conditions.

Testing is conducted with various fuel compositions, involving intermediate blends between 100% natural gas and 100% hydrogen. The aim is to establish a suitable test fuel composition equivalent to the customer's fuel's Lower Heating Value (LHV) while also matching the hydrogen level of the fuel. The available fuels lend to only a certain combination of blends that can be created which can pose an issue if the LHV value is not within tolerance of the desired fuel.

During the single burner testing phase of ClearSign's recent project, several critical findings emerged, shedding light on various aspects of the burner's performance. Notably, the testing showed that narrowing the flameholder base, as identified as a crucial outcome from initial CFD analysis, led to a reduction in the overall flame diameter. Additionally, optimizing mixing tube diameters enhanced flue gas entrainment while maintaining high flow velocities above the flame speed. Height adjustments of the flame holder were also explored and optimized to maximize burner operability and stability and minimize NO_x emissions.

Adding to the complexity of testing is accurately measuring ultra-low NO_x emissions. The instrumentation used for NO_x measurement introduces inherent errors and tolerances, and at such low NO_x levels, even small errors can significantly impact the results. Achieving reliable and consistent measurements requires meticulous calibration and rigorous control of experimental conditions to minimize uncertainties.

In addition, measuring and evaluating compact flames poses unique challenges. Premixed flames tend to have short flame heights compared to their raw gas counterparts which are mixing limited and rely on diffusion. The CO probe positioned a foot above the flameholder, at an elevation of eight feet from the floor of the heater, recorded ~2000 ppm CO concentration. Above this elevation, CO concentrations were much lower indicating near-complete oxidation of the fuel. Even though premixed flames are compact, heat transfer from the hot flue gases to the process tubes continues at higher elevations via gas radiation. Since soot produced in premixed flames is minimal, no significant increase in radiant heat transfer is seen near the flameholder.

Subsequent multiple burner testing, incorporating the optimization made following the CFD analysis, revealed significant key findings with implications for emissions control and burner stability. Notably, the tests consistently achieved sub-5 ppm (parts per million) NO_x emissions throughout the entire turndown range. Moreover, the burner demonstrated the ability to maintain sub-5 ppm NO_x emissions across a wide spectrum of fuels, showcasing its versatility and reliability in handling various fuel compositions. Results from multi-burner testing for two target heaters are shown in Figures 5 and 6. As seen below, NO_x vs O_2 trends followed the behavior of premixed flames. It was interesting to note that although the same burner design was used, barring a change in fuel tips and throat nozzle, for the two application heaters which differed in total maximum firing rate by nearly 15%, the heater with the lower firing rate showed a markedly lower NO_x emissions at the same O_2 levels. The difference was attributed to the slightly elevated fuel gas pressure, slightly higher air velocity at the throat, and the lower combustion intensity/heat release per unit volume at the flameholder location. A photograph of the burners in operation is shown in Figure 7. Furthermore, the burner exhibited remarkable stability even under stoichiometric conditions, emphasizing its resilience and robust design, ensuring smooth and efficient operation, even during upset conditions.

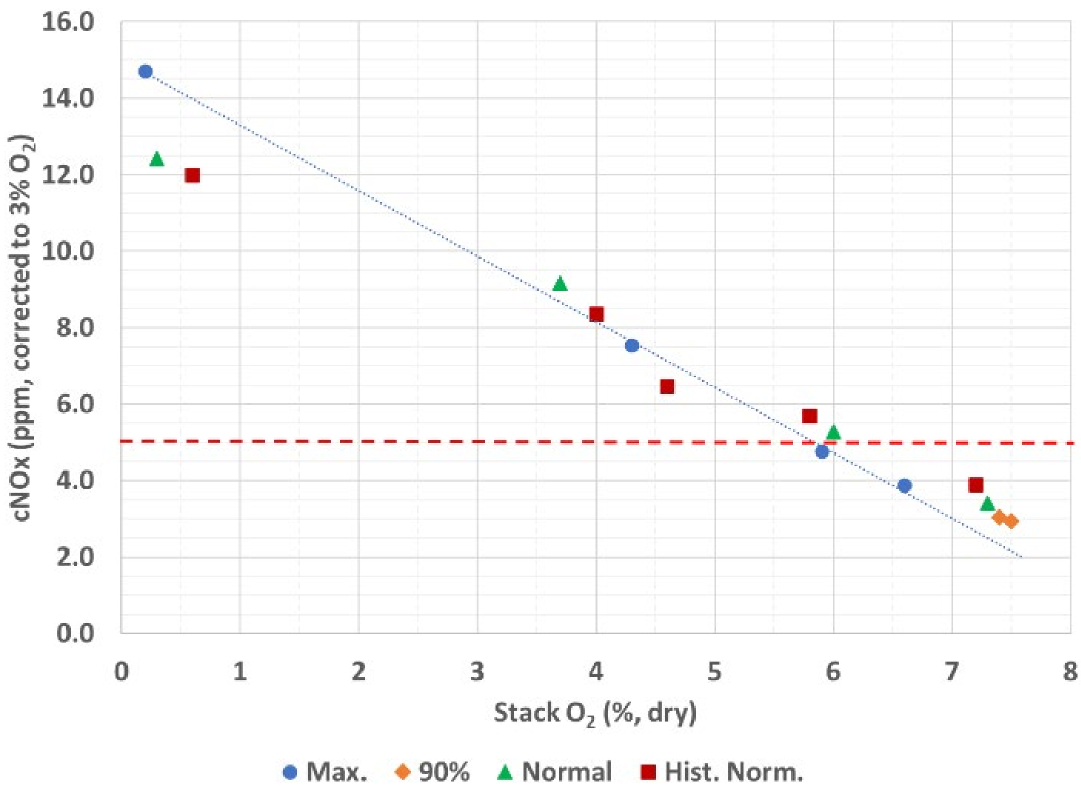

Figure 5 - Stack oxygen versus corrected NO_x for Heater 1.

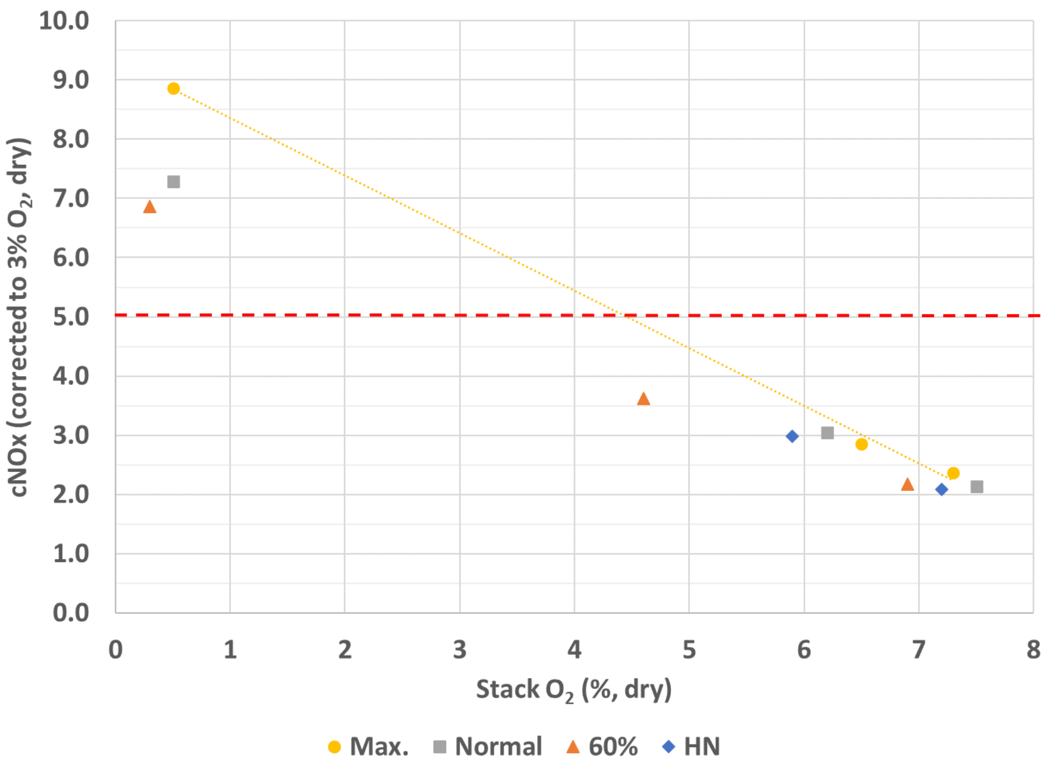

Figure 6 - Stack oxygen versus corrected NO_x for Heater 2.

Figure 7 - Multi-burner configuration, showing the flame holder portion of the burner, within the furnace.

VI. Concluding CFD Analysis

Once physical testing was completed, a final simulation of CFD was utilized to validate the as-tested burner geometry against the original burner CFD results. CFD studies typically characterize flue gas flows within the radiant section of the heater, analyzing flue gas recirculation patterns, velocity profiles, CO contours (e.g., 500 ppm, 2000 ppm) to define the flame envelope, temperature distribution, and heat flux contours.

The simulations play a crucial role in assessing potential flame impingement, flame merging, or rollover. The original and replacement burners are compared by evaluating parameters like radiant heat absorption, average and maximum heat flux, radiant efficiency, maximum process tube metal temperatures (TMT), overall flame height, and flame width.

VII. Field Implementation & Validation

Validation from the field typically comes from commissioning and tuning data, source test reports, and thermal imaging scans of the process tubes during operation. The emissions data help quantify the transition from the test furnaces to the customer furnaces and better understand the effects of varying furnace cross-section area, volume, and burner-to-tube spacing. The process tube scans can be used to validate the heat flux profile and tube metal temperatures predicted by the CFD simulations.

Field implementation results for the projects discussed above will be shared in a future paper following the commissioning of those projects in 2024. Instead, field data from a prior multi-burner field installation of ClearSign Core Process Burners, which have been in continuous operation for well over two years, is presented here. The burners were source tested at 6.2 ppm (corrected to 3% O_2) at 3.5% O_2 in the stack, easily meeting the sub-9 ppm NO_x air-quality district requirement. Figure 8 below shows an infrared (IR) image of process tubes from the same application conducted a year into service. The scan showed uniform temperature profiles on the tubes, no hot spots, and no signs of scaling or fouling.

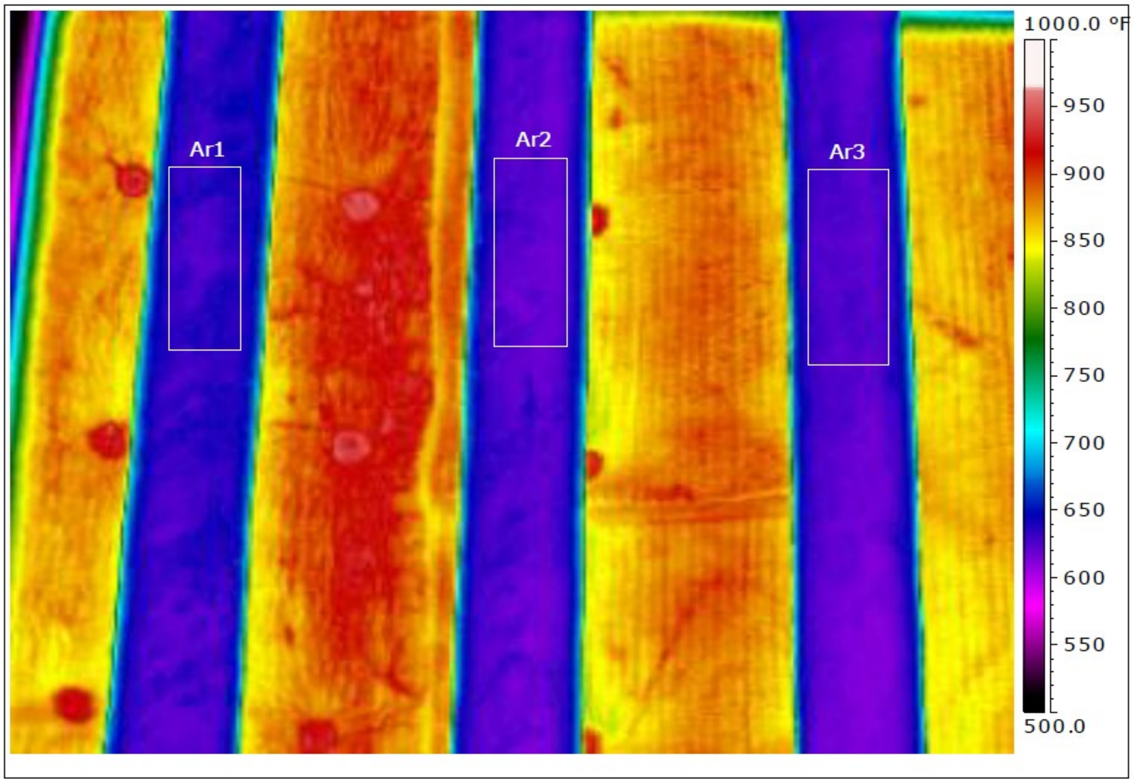

Figure 8 - Infrared (IR) scans of the process tubes in the heater.

VIII. Conclusion

The tools and techniques developed and made commonplace during the implantation of typical current low NO_x and ultra-low NO_x burners have a continuing place in the development and deployment of new and emerging technologies. As was the case during the introduction of the first highly staged ultra-low NO_x burners, as tools such as CFD and burner testing are employed with new burner technologies care should be taken to ensure that the features of the new technology that deliver their enhanced performance are also considered and accounted for when setting up the testing and modeling tools, and in the interpretation of their results.

By the implementation of a structured multifaceted burner development or commercial project optimization validation project, employing the tools and approaches described in this paper, a project's inherent risks can be mitigated, paving the way for successful project implementation and the attainment of its objectives—be it NO_x reduction, increased heater capacity, or the eradication of known challenges. Through testing and subsequent CFD, findings can have significant positive implications for multi-burner combustion systems and their application in refining and other growing sectors.