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Energy Research and Development Division

FINAL PROJECT REPORT

Demonstration of a Novel Ultra-Low Oxides of Nitrogen Boiler for Commercial Buildings

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PREFACE

The California Energy Commission's (CEC) Energy Research and Development Division manages the Natural Gas Research and Development Program, which supports energy-related research, development, and demonstration not adequately provided by competitive and regulated markets. These natural gas research investments spur innovation in energy efficiency, renewable energy and advanced clean generation, energy-related environmental protection, energy transmission and distribution and transportation.

The Energy Research and Development Division conducts this public interest natural gas-related energy research by partnering with research, development, and demonstration entities, including individuals, businesses, utilities and public and private research institutions. This program promotes greater natural gas reliability, lower costs and increases safety for Californians and is focused in these areas:

- Buildings End-Use Energy Efficiency.
- Industrial, Agriculture and Water Efficiency.
- Renewable Energy and Advanced Generation.
- Natural Gas Infrastructure Safety and Integrity.
- Energy-Related Environmental Research.
- Natural Gas-Related Transportation.

Demonstration of a Novel Ultra-Low Oxides of Nitrogen Boiler for Commercial Buildings is the final report for the Demonstration of a Novel Ultra-Low Oxides of Nitrogen Boiler for Commercial Buildings project (Contract Number: PIR-14-004) conducted by the Gas Technology Institute. The information from this project contributes to Energy Research and Development Division's Natural Gas Research and Development Program.

For more information about the Energy Research and Development Division, please visit the CEC's research website (www.energy.ca.gov/research/) or contact the CEC at ERDD@energy.ca.gov.

ABSTRACT

The Gas Technology Institute, along with Power Flame, Inc.; Tetra Tech, Inc.; Southern California Gas Company; and Mission Linen Supply, demonstrated an emerging efficient low oxides of nitrogen burner technology, termed *dynamic staged entrainment*. The burner incorporates dynamic flow geometry that induces entrainment of cooled products of combustion to provide greater spatial uniformity in the distribution of the reacting species, heat release rates, and temperatures. In addition, the technology allows for staging of combustion reactants within the combustion chamber, providing further thermal distribution within the chamber. These features minimize localized high-temperature regions within the flame thereby limiting production of thermal oxides of nitrogen.

The project team installed the dynamic staged entrainment burner demonstration with a commercial fire tube boiler at Mission Linen Supply in Santa Barbara, California. The technology offers a simple design well-suited for application to commercial water heating/steam generation. The burner consistently achieved emissions below 9 volumetric parts per million oxides of nitrogen (NO_x) without the need for costly and complex selective catalytic reduction applied downstream of the boiler to remove NO_x from the exhaust stream. The technology also offers advantages over other alternatives for NO_x reduction including external flue gas recirculation, whereby exhaust products from the boiler stack are returned to the burner inlet or burner operation at high excess air levels. Compared to flue gas recirculation systems, the dynamic staged entrainment burner achieves similar or improved efficiency, with further reductions in air blower power. In comparison to high excess air burners, the dynamic staged entrainment burner is 2 percent more efficient and requires significantly less electric power to drive the combustion air blower. The dynamic staged entrainment technology offers a cost-competitive alternative to currently available equipment for the commercial hot water/steam generation market in California in an easy-to-operate and simple design.

Extensive evaluation of the technology for more than 10,000 hours of real-world conditions have proven this burner is capable of meeting low NO_x levels while operating with relatively low excess air and high efficiency levels. The demonstration documented 9 percent savings in fuel usage compared to the baseline conventional boiler. This result highlights the benefits of applying a newer reliable boiler/burner technology, which can provide significant energy and cost savings to commercial buildings.

Keywords: High-efficiency, low-emission, commercial buildings, boiler, firetube, steam, NO_x

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EXECUTIVE SUMMARY

The dynamic staged entrainment burner developed by the Gas Technology Institute was installed with a commercial fire tube boiler at Mission Linen Supply to provide steam for commercial laundry use. The technology design specifically addresses commercial heating applications to achieve compliance with stringent oxides of nitrogen (NO_x) regulations while improving efficiency. Deployment of the technology could reduce the demand for natural gas at many different commercial sites, and consequently the overall natural gas demand in California. Natural gas ratepayers will benefit from increased efficiency of natural gas-fired equipment, more efficient use of gas, and reduced gas use for heating and hot water. Commercial facilities will benefit from energy efficiency and environmental stewardship, sustainable energy use, good citizenship, lower natural gas costs, and increased profits. Given the alignment of the project with Public Interest Energy Research program goals, grant funding was a suitable resource for furthering the advancement of the technology towards market deployment. Benefits of this program accrue primarily to the California ratepayers in the form of energy savings, reduced energy cost, reduced carbon dioxide (CO_2) and NO_x emissions. While laboratory testing performed by the project team members has proven the performance of the system, a high-visibility demonstration of the dynamic staged entrainment technology at a California host site under real world conditions was necessary to transfer knowledge of the technology to California markets.

The costs associated with NO_x mitigation strategies represent a major economic burden for California boiler operators, especially for smaller-scale commercial installations. Retrofit costs associated with bringing commercial-scale boilers into compliance are 50 percent greater than costs for large-industrial scale retrofits, on a cost-per-ton-of-NO_x-reduced basis. Thus, there is a significant need for low-cost NO_x control strategies that can allow California-based commercial boiler operations to achieve regulatory compliance, without reducing efficiency, and increasing gas consumption. The only technologies which are currently commercially available to achieve NO_x emissions <9 volumetric parts per million (vppm) are selective catalytic reduction, external flue gas recirculation, and high excess air burners. All of these technologies incur penalties to operating efficiency and can add significantly to the cost of operation. The selective catalytic reduction systems require substantial investment in ancillary downstream equipment and qualified personnel for operation and maintenance. These factors make selective catalytic reduction economically unviable for most commercial heating distributions systems. Similarly, external flue gas recirculation systems require additional equipment and controls, adding to capital costs, reducing overall system efficiency, and making them unattractive for the commercial heating market. The high excess air burners operate with substantially elevated air levels, resulting in significant losses to boiler efficiency and hence, increased fuel consumption, operating costs, and greenhouse gas (GHG) emissions. Moreover, the increased blower sizes required for the high excess air burners further add to capital costs and electrical demands. Thus, dynamic staged entrainment technology has the potential to emerge as a cost-effective, high efficiency alternative for the commercial boiler market.

The scale of the demonstration system, although it is at an industrial site, is well positioned in commercial building heating and hot water load range. This allows data from the demonstration tests to be used with confidence across a broad range of commercial applications. The team estimated that dynamic staged entrainment technology would be capable of replacing 40,625 boiler horsepower (BHP worth) of California commercial boiler capacity within 10 years of market commercialization. In comparison to competing high excess air high excess air high excess air technologies which currently dominate the California commercial market segment, this will provide an annual reduction of 119,600 million British thermal units (MMBtu) and 928,850 kilowatt-hours (kWh) of natural gas and electricity consumption, respectively. This equates to a combined savings of more than $930,000 in annual energy costs for California commercial boiler operators. Annually, this will reduce California CO_2 and NO_x emissions by 7,380 tons and 1,315 pounds, respectively. These substantial benefits to California will continue to extend even further as dynamic staged entrainment technology gains market share within the commercial building sector.

The dynamic staged entrainment burner technology developed within this project has satisfied all performance targets set forth, demonstrating the ability to achieve <9 vppm NO_x emissions. The host site demonstration documented a 9 percent savings in fuel usage as compared to the baseline conventional boiler. This highlights the benefits of applying a newer reliable boiler/burner technology, which can provide significant energy and cost savings to commercial buildings. Successful completion of this demonstration project has built confidence and awareness of the dynamic staged entrainment technology, furthering commercialization efforts, and ultimately helping to bring to market a cost-competitive, efficient alternative for California commercial boiler operators seeking to reduce operating costs and greenhouse gas emissions, while maintaining regulatory compliance.

Beyond this, the technology demonstrated a wide range of operational latitude, with the ability to achieve NOx emissions from less than 20 vppm to less than 9 vppm, allowing the burner to adapt to a broad set of markets with varying regulatory requirements. This operational flexibility was achieved without need for modification to the burner equipment, allowing the burner to be tuned for different applications with simple operating adjustments made during commissioning.

Widespread deployment of the dynamic staged entrainment burner will provide several environmental, performance and life cycle cost benefits to California ratepayers including:

- Reduced operating costs through reduced gas and electricity consumption resulting from higher system efficiency in comparison to currently deployed technologies.
- Reduced CO_2 and NO_x emissions resulting from reduced energy consumption.
- Reduced equipment cost for commercial-scale NO_x mitigation — the costs for the technology are anticipated to be less than competing alternative control measures.
- Cost-effective path for air quality compliance in commercial boiler applications — the capital and operating costs associated with currently available NO_x mitigation strategies represent a significant economic burden to California boiler operators, especially for smaller commercial scale operations. The technology provides cost-effective solution for NO_x reduction, especially for the commercial building sector.
- Reliable operation and equipment longevity — the technology applies fundamental NOx reduction strategies in a simple design without the complicating elements of selective catalytic reduction or external flue gas recirculation; thus, system reliability and longevity are expected to be high, with an anticipated equipment lifetime of more than 30 years.

To bring the technology to market, Gas Technology Institute has partnered with Power Flame Inc., a leading manufacturer in the United States of burners for commercial and industrial applications. Power Flame has been actively engaged in the burner development efforts to date and continues to express great enthusiasm for the technology. Given the high performance of the technology and the straightforward, low-cost design, the team is confident they will be able to offer the product to market with competitive pricing, ultimately enabling broad deployment.

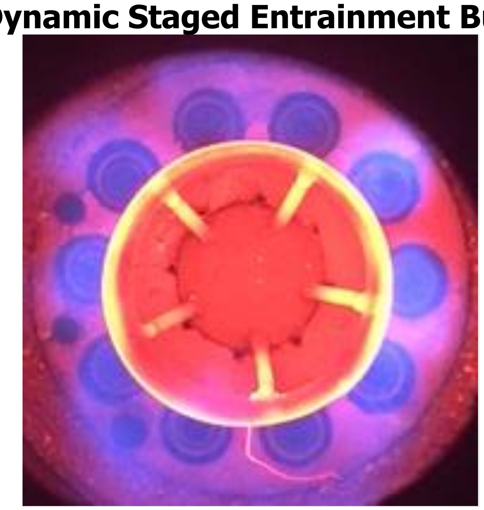
CHAPTER 1: Technical Merit and Need

Importance and Barriers

Emissions of nitrogen oxides (NO_x) from combustion sources are a leading cause of air quality degradation, posing serious environmental and health risks. As a result, this criteria pollutant is heavily regulated based on source specific standards. In Southern California, commercial boilers are required to emit less than 9 volumetric parts per million (vppm) NO_x. Currently, the only commercially available technologies capable of meeting these emissions are exhaust cleanup systems, such as selective catalytic reduction (SCR), or burner enhancements such as external flue gas recirculation (FGR) and high excess air (HEA) firing. All of these options incur significant efficiency, operating cost, and/or capital cost penalties in comparison to conventional fire tube boiler systems.

The costs associated with NO_x mitigation strategies represent a major economic burden for California boiler operators, especially for smaller-scale commercial installations.[1] Retrofit costs associated with bringing commercial-scale boilers into compliance are 50% greater than costs for large-industrial scale retrofits, on a cost-per-ton-of-NO_x-reduced basis. Thus, there is a significant need for low-cost NO_x control strategies that can allow California-based commercial boiler operators to achieve regulatory compliance, without reducing efficiency, and increasing gas consumption. This project demonstrated a novel high efficiency low emission commercial boiler/burner technology, based on the dynamic staged entrainment (DSE) combustion concept. Laboratory testing of the DSE technology by GTI has proven the ability to achieve NO_x emissions below 9 vppm without the use of SCR, FGR, or HEA. Figure 1 shows a view of the burner flame using the DSE concept. The DSE technology offers a simple, robust design that is well-suited for application to the commercial water heating/steam generation segment.

Figure 1: Dynamic Staged Entrainment Burner Flame



Source: Gas Technology Institute

[1] "Rule 1146.1. Emissions of Oxides of Nitrogen from Small Industrial, Institutional, and Commercial Boilers, Steam Generators, and Process Heaters," South Coast Air Quality Management District, 2013.

The DSE technology was developed by GTI in cooperation with Power Flame Inc., a major U.S. burner manufacturer, for use in commercial boiler applications to meet the requirements of commercial heating and hot water demands. The demonstration effort allowed the team to effectively transition the technology towards a commercial product offering for the California commercial building sector. Following successful demonstration and validation of the DSE boiler system, the team is better positioned to deploy this breakthrough technology throughout the California commercial boiler segment, ultimately reducing end-user costs and energy consumption.

By operating without the use of SCR, FGR, or HEA, the DSE technology offers a new pathway for commercial boiler operators to achieve regulatory compliance at a lower cost and with higher energy efficiency than is possible with currently available NO_x mitigation strategies. Demonstration of the DSE technology strongly supports PIER program goals of "advanced efficiency solutions, including technologies and approaches for more affordable and comfortable buildings" and broader California statewide goals of "increased energy efficiency in buildings." This project aimed to provide an environmentally sound, safe, reliable, and affordable energy product while satisfying the unique California requirement of smog mitigation through NO_x reduction. The DSE system increases the overall efficiency of natural gas-fired equipment, while decreasing natural gas and electricity demand, with an associated decrease in NO_x and GHG emissions.

This project addressed key issues with current low NO_x systems by demonstrating a cost effective, high efficiency technology based on a unique, but proven concept at a host site facility. The project advanced the scientific and economic understanding of the DSE technology, while proving cost effectiveness, safety, and reliability, and widely transferring the results to the California's commercial sector.

CHAPTER 2: Burner Development Considerations

Performance Targets

The objective was to develop a burner for commercial and industrial steam and hot water boiler applications that achieves <9 vppm NO_x without the need for SCR, FGR, or HEA operation. To achieve broad market appeal, the burner must maintain adequate reliability, turndown, and efficiency, and be capable of deployment in other boiler markets that have less stringent NO_x regulations. Additionally, the combustion air blower pressure and power requirements must be satisfactory with respect to conventional blower equipment capabilities and burner manufacturer expectations. The key performance targets are summarized as follows:

1. <9 vppm NOx across full operational turndown
2. <400 vppm carbon monoxide (CO) across full operational turndown
3. 4:1 turndown in firing rate
4. SCR, FGR, and/or HEA not required for operation
5. Manufacturer-acceptable combustion air blower requirements

Burner Design Concept

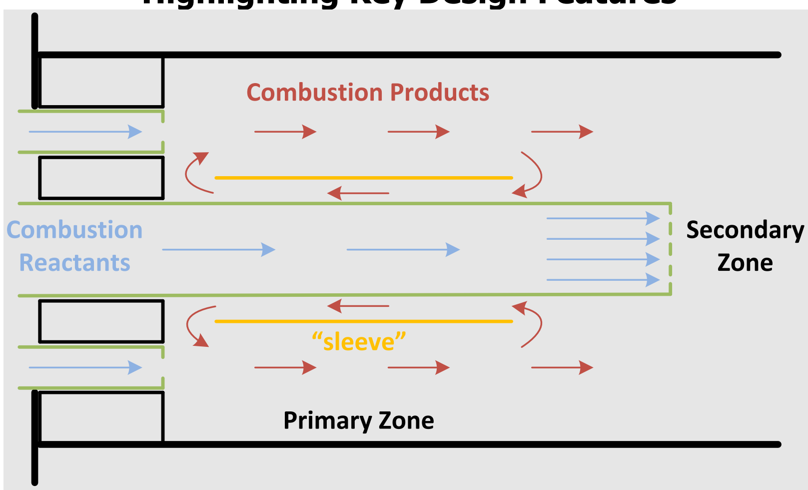
The dominant mode of NO_x formation during natural gas combustion results from the reaction of oxygen and nitrogen at high temperatures. Low NO_x combustion strategies seek to mitigate this "thermal" NO_x formation by reducing peak temperatures within the flame. However, when flame temperatures get too low, flame ignition and stability can become problematic, leading to increased carbon monoxide (CO) and total unburned hydrocarbon (THC) emissions. The envelope between achieving low NO_x production and maintaining complete combustion becomes narrower as the requirements for low NO_x become more stringent. Achieving satisfactory flame stability and turndown, while also maintaining NO_x emissions below 9 vppm was one of the main challenges addressed during the project.

To achieve the required performance targets, GTI developed an advanced burner concept as shown in Figure 2, which maintains flame stability while reducing NO_x levels. The DSE burner technology employs four distinct NO_x mitigation strategies, all of which serve to reduce peak flame temperatures and inhibit thermal NO_x formation.

1. Premixing of Fuel and Air — Natural gas and air are thoroughly mixed upstream of the burner nozzles. This serves to ensure that the reactions taking place throughout the flame zone occur at the desired combustion stoichiometry, and therefore at the desired reaction temperatures.—2. Recirculation of Cooled Combustion Products – The dynamic flow geometry of the burner promotes recirculation and entrainment of cooled combustion products from the primary combustion zone. This serves to dilute the combustion mixture in the same fashion as FGR, reducing peak flame temperatures and NO_x formation.

3. Radiant Burner Surfaces — The components of the DSE burner are located within a "sleeve" that is designed and situated within the burner at an optimal configuration to allow for sufficient heating. This promotes strong thermal radiation to the boiler walls without elevating temperatures to critical levels for NO_x formation. This thermal radiation serves to both stabilize the flame and extract heat from the combustion zone.
4. Staging of Combustion Reactants — A portion of the combustion reactants are delivered further downstream in the combustion chamber. This provides a larger volume for heat release within the boiler fire tube chamber and allows for optimal combustion stoichiometries to be applied in the primary and secondary zone of the burner to minimize NO_x formation.

Figure 2: Schematic of Dynamic Staged Entrainment Burner Highlighting Key Design Features



Source: Gas Technology Institute

Previous development of the DSE technology showed that <9 vppm NO_x could be achieved at full load conditions, but limitations in startup, turndown, and hydrocarbon burnout at low firing rates were encountered. Throughout those prior technology development activities, considerable effort was made towards understanding these limitations, including the application of computational fluid dynamic (CFD) modeling. Several key burner design factors were found to have significant impact, including the combustion heat release profile, the recirculation flow patterns within the chamber, and the combustion chamber geometry.

The initial design approach applied for achieving low emissions utilized staging of combustion products. While this approach adds another level of sophistication to the burner, prior studies indicated that staging had good potential for achieving ultra-low NO_x levels with operation at low excess air levels, and hence high efficiency. A burner design package was generated with the staging concept included, but with flexibility to allow for operation of the burner without staging. The burner was fabricated by the manufacturing partner, Power Flame Inc., providing a means for engaging them in the development process.

Burner Capacity and Geometric Constraints

Prior investigations into the DSE burner technology had found that the boiler combustion geometry played a key role in the performance of the burner, especially in regard to the cross-sectional area per unit fuel energy input. To ensure that the burner was appropriately sized in terms of firing rate and boiler chamber dimensions, a survey of commercial boiler products was performed. Table 1 outlines the nominal combustion chamber tube diameter in inches (in.) for different boiler manufacturers along with their respective capacities expressed in boiler horsepower (BHP).

Table 1: Nominal Boiler Combustion Chamber Diameters for Varying Boiler Sizes by Manufacturer

Fire Tube Boiler Manufacturer	Chamber Diameter, in.	Rated Boiler Capacity, BHP
York-Shipley	15.25	25-50
	20	60-80
	24	100-150
	29	175-200
	33.5	250-350
Cleaver Brooks	19	50-100
	23	125-200
	33	250-350
Kewanee	17	60-80
	20	100-125
	23	150-200
	25	250
	30	300-350
	34	400-500
Dixon	26.5	60-150
	30.5	120-180
	32.5	150-225
	34.5	150-225
	36.5	200-300
	42.5	250-375
	46	300-450
	50	350-750
Burnham	27	60-70
	30	80-100
	27.6	150
	27.5	200
	33.4	250
	42	300
	45	350-400

Source: Gas Technology Institute

Priority was given to the evaluation of the Hurst boiler product line, as the DSE burner technology would likely first be deployed to their products given that Power Flame Inc. (GTI's manufacturing partner for the burner technology) is the primary supplier of burners for Hurst boilers. Table 2 shows the different Hurst boiler outputs by (BHP) along with their corresponding combustion chamber dimensions.

Table 2: Hurst Boiler Combustion Chamber Dimensions

Rated Boiler Capacity, BHP	Chamber Diameter, in.	Chamber Length, in.
15	16	71
20	16	86
25	18	78
30	18	89
40	20	99
50	20	119
60	20	135
70	24	115
80	24	127
100	24	151
125	26	175
150	26	195
200	34	163
250	34	194
300	34	215
350	42	177
400	42	187
500	42	223
600	48	239
700	48	271
800	48	307

Source: Gas Technology Institute

To enable flexibility during testing and evaluation of the prototype burner technology, GTI's boiler simulator test facility was utilized. This state-of-the-art facility has advanced controls and instrumentation, access ports for probe and optical measurements, and flexibility in combustion chamber dimensions, with diameters from 20-inch to 40-inch. Initial efforts for development of the burner were focused at smaller load scales, where the costs and time for fabricating, retrofitting, and testing burner components are lower. The initial design of the burner was targeted for operation with a 100 BHP boiler (4 MMBtu/hr) having a 24-inch chamber. To further add flexibility during testing, the burner was designed to also enable installation on GTI's 20-inch simulator.

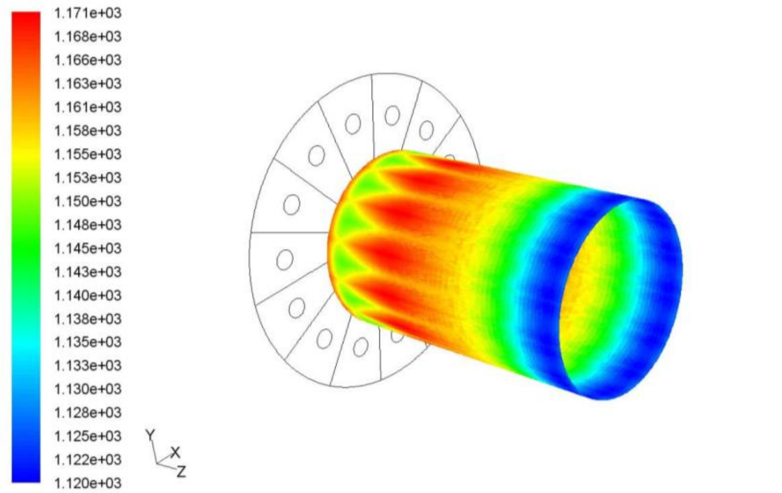
Initial development was performed with full load testing at 4 MMBtu/hr. As the development activities progressed, the project team was successful in securing funding from the California Energy Commission and Southern California Gas Company to demonstrate the burner technology at a customer facility under real-world conditions. Under this demonstration effort, the host customer required full load steam generating capability at 125 BHP, such that the burner must achieve the desired performance with firing rates up to 5.25 MMBtu/hr. Therefore, the team selected a Hurst 125 BHP boiler.

CHAPTER 3: Development Approach

Computational Modelling Approach

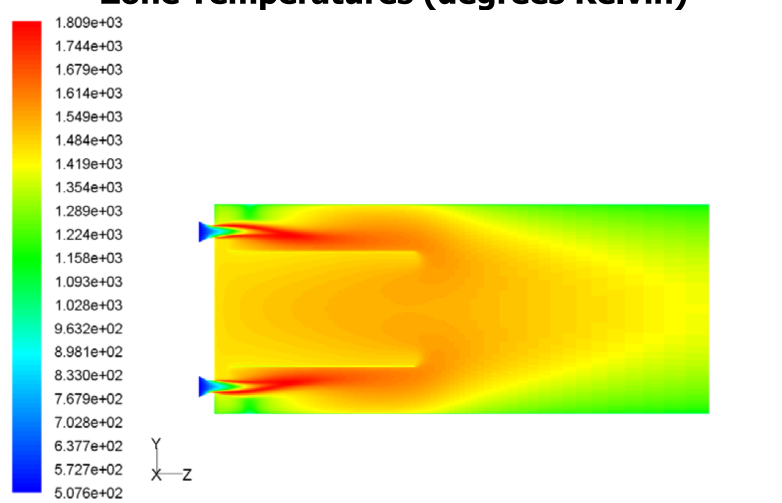
Computational fluid dynamics (CFD) modelling was used to estimate burner performance for varying geometric configurations and operational conditions. An initial CFD model was prepared based on knowledge of prior burner designs and results. This initial model was used to provide a preliminary characterization of the burner performance to help guide the design of the prototype for experimental testing. Sample results from this preliminary model are shown in Figures 3 to 6.

Figure 3: Preliminary Computational Fluid Dynamics Results of the Recirculation Sleeve Temperatures (degrees Kelvin)



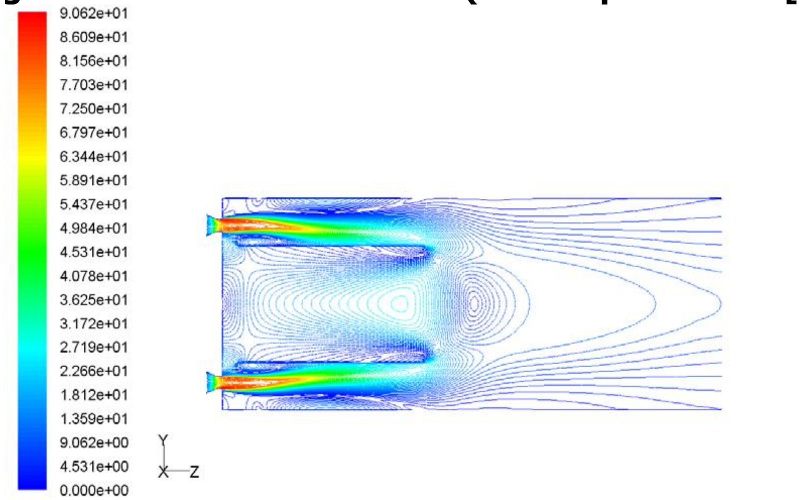
Source: Gas Technology Institute

Figure 4: Preliminary Computational Fluid Dynamics Results of the Combustion Zone Temperatures (degrees Kelvin)



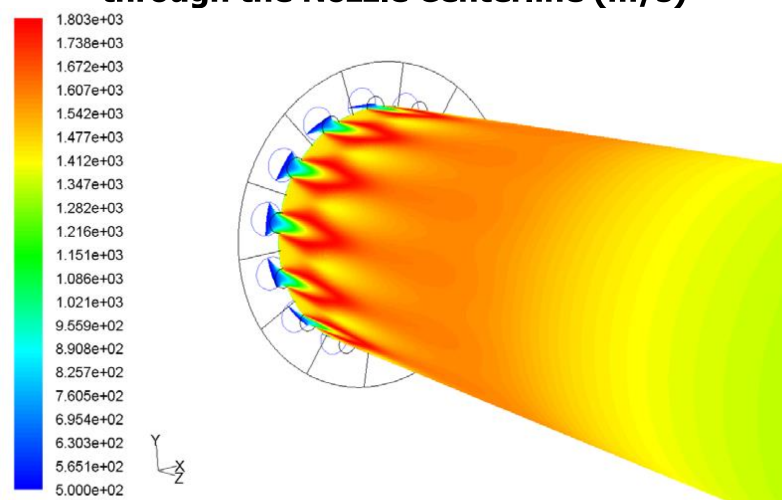
Source: Gas Technology Institute

Figure 5: Preliminary Computational Fluid Dynamics Results of the Velocity Profiles through the Burner Cross-Section (meters per second [m/s])



Source: Gas Technology Institute

Figure 6: Preliminary Computational Fluid Dynamics Results of the Velocity Profiles through the Nozzle Centerline (m/s)



Source: Gas Technology Institute

An initial prototype burner was designed and fabricated based on information from the preliminary CFD model and results of GTI's extensive development and experimental studies throughout prior efforts. The prototype burner was then installed on GTI's boiler simulator test facility and initial experimental data was gathered. The preliminary CFD model was then revised until it agreed with the initial experimental results. Once validated, the revised CFD model was used to perform parametric studies of varying burner configurations and operational characteristics. These computational modelling studies provided key insights into the flame behavior and operational characteristics, serving as a powerful tool for guiding design and development decisions. Moreover, these studies reduced the number of burner geometric design parameters to be evaluated, focusing experimental studies on parameters of greatest interest.

Experimental Testing Approach

The prototype DSE burner was installed on GTI's boiler simulator facility, and integrated with the existing supply, controls and instrumentation infrastructure as shown in Figure 7. Desired performance data was collected and analyzed using advanced instrumentation including combustion air flow, natural gas flow, temperature, pressure, emissions analysis (both within the flame zone and in the exhaust), and acoustic diagnostics. A data acquisition system was used to collect test data sets into a single data file for analysis and reporting. A full set of continuous emissions gas analyzers are used to measure NO_x, oxygen (O_2), CO, CO_2 and THC. The boiler simulator test facility has advanced controls, enabling precise control to target conditions and flexible operation across a wide domain.

Figure 7: Prototype Dynamic Staged Entrainment Burner Installed on Gas Technology Inc.'s Boiler Simulator Facility

Source: Gas Technology Institute

Testing was performed across a vast operational space in order to fully characterize the performance of the burner in satisfying varying steam load and emissions requirements. Geometric parameters of greatest significance were identified using the computational model, and physical changes to the burner were implemented and tested to characterize performance.

Commercialization Approach

To ensure that the DSE burner technology has a clear path to market, effort was expended early in the development stage to secure a robust and capable commercialization partner. After discussing the technology with multiple potential manufacturing partners, GTI teamed with Power Flame Inc., a leading manufacturer in the United States of burners for commercial and industrial applications with a strong presence in the packaged boiler market. Power Flame has a solid reputation in the industry, with significant market share throughout the United States and abroad, and a large presence in the low-NO_x boiler market.

The project team made an active effort to engage Power Flame from the earliest stages of the development process. Power Flame's input was sought on the initial prototype design package, to ensure that they would be capable of fabricating the unit at costs comparable to conventional burner designs. Once the design was established, Power Flame fabricated the initial unit to further identify and address issues related to its manufacturability. As the project team progressed further into the testing and refinement of the burner, Power Flame was engaged to provide additional clarity regarding their desired performance and operating characteristics, including turndown and air blower requirements.

The project team packaged the burner with a commercial boiler and controls system and demonstrated the boiler/burner system for continued operation under real-world conditions at a customer facility located in Santa Barbara, California. These activities allowed the project team, including Power Flame, to address practical issues that arise, ensure that the system achieves required reliability, and build confidence in the value and performance of the technology. Following successful field demonstration of the technology, it is anticipated that a licensing agreement will be executed with Power Flame for the burner technology, providing a clear path to market.

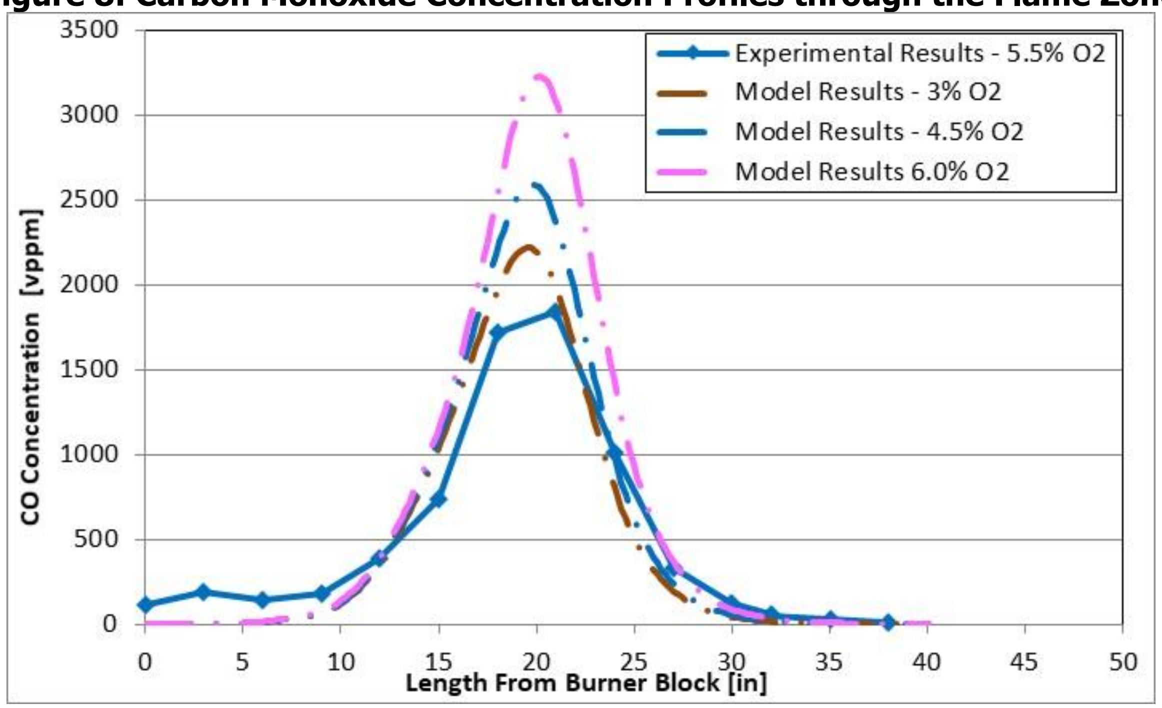
CHAPTER 4: Results and Discussion

Computational Model Results

A CFD model of the burner was used to guide the preliminary design of the prototype burner. Once the prototype burner was installed at GTI and initial experimental test results were attained, the CFD model was revised. The project team performed detailed studies of the model assumptions and level of refinement, allowing the team to achieve solid agreement between experimental and model results. Ultimately, the CFD model enabled the project team to evaluate a wide range of geometric designs through simulation rather than experimentation.

During experimental testing, data was collected within the flame by traversing a water-cooled sampling probe through the combustion zone. With these measurements, flame species and temperatures could be characterized, generating a one-dimensional mapping of the flame. Carbon monoxide (CO) concentration levels are particularly useful for providing a rough estimate of the flame location and as such, CO concentration profiles were compared between the CFD model and experimental results. As the model assumptions were revised, good agreement between the experimental and model results was attained. As shown in Figure 8, the CFD model accurately predicts the trend in CO concentration, and therefore accurately predicts the approximate location of the flame zone.

Figure 8: Carbon Monoxide Concentration Profiles through the Flame Zone

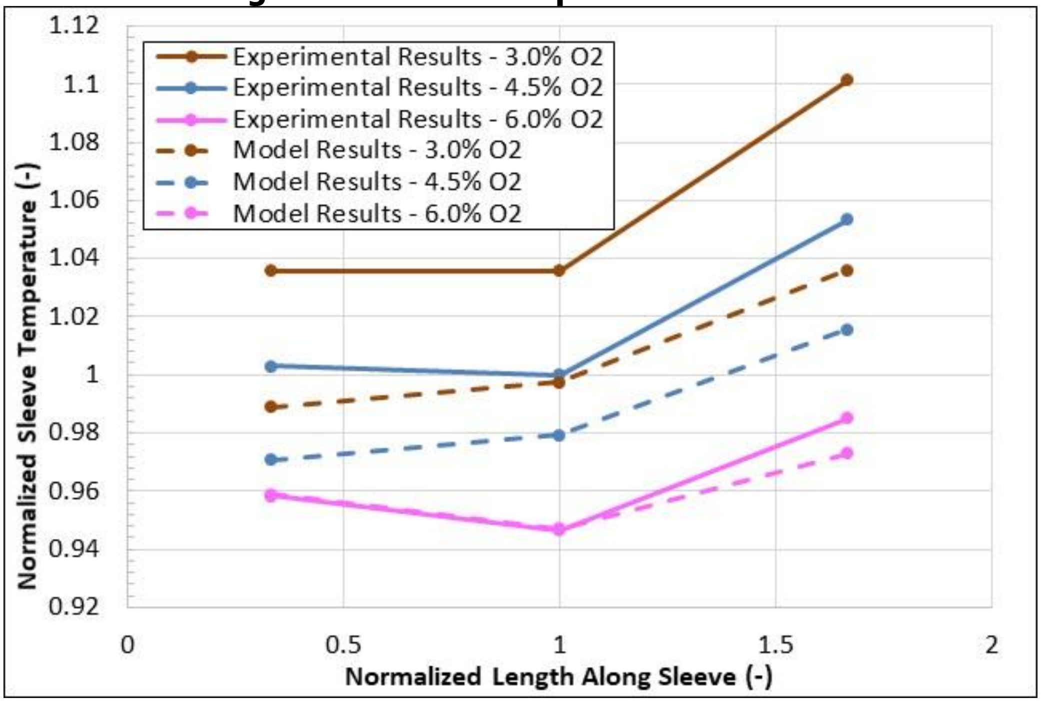


Source: Gas Technology Institute

A second key variable of interest is that of the temperatures along the sleeve in the burner. Thermocouples were installed along the sleeve at three different locations. As shown in Figure 9, the CFD model results show good qualitative agreement in the sleeve temperature trends.

For operation at 6% excess oxygen, the model results agree very well with test data. At 4.5 and 3% excess oxygen level, the agreement is slightly reduced; however, the trends still show comparable behavior.

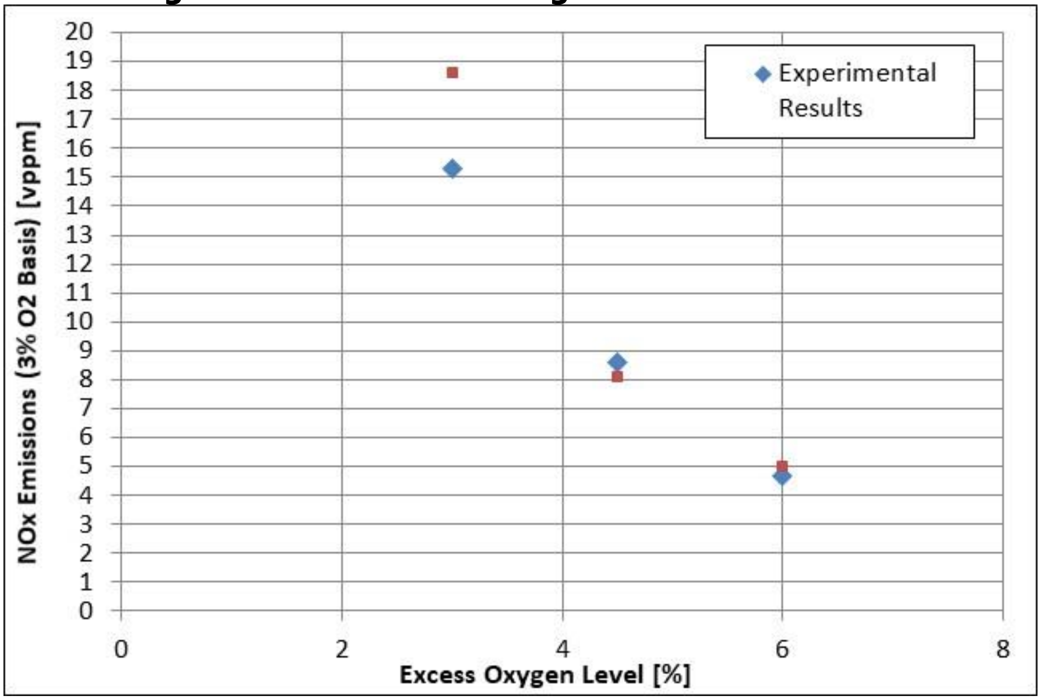
Figure 9: Sleeve Temperature Results



Source: Gas Technology Institute

Once CFD model was validated with respect to CO concentrations and sleeve temperature results, efforts turned towards evaluating NO_x emissions. In using the CFD software, the NO_x calculations are performed after the model solution is obtained. Given that there are additional assumptions and inputs that are required when running the NO_x calculations, further effort was required to ensure that an adequate level of refinement was achieved for the NO_x simulations. Good qualitative agreement was attained between experimental and model results for NO_x emissions, as shown in Figure 10. At 4.5 and 6% excess oxygen levels, the model achieved good quantitative agreement as well. At 3% excess oxygen, the CFD model slightly under-predicted NO_x levels.

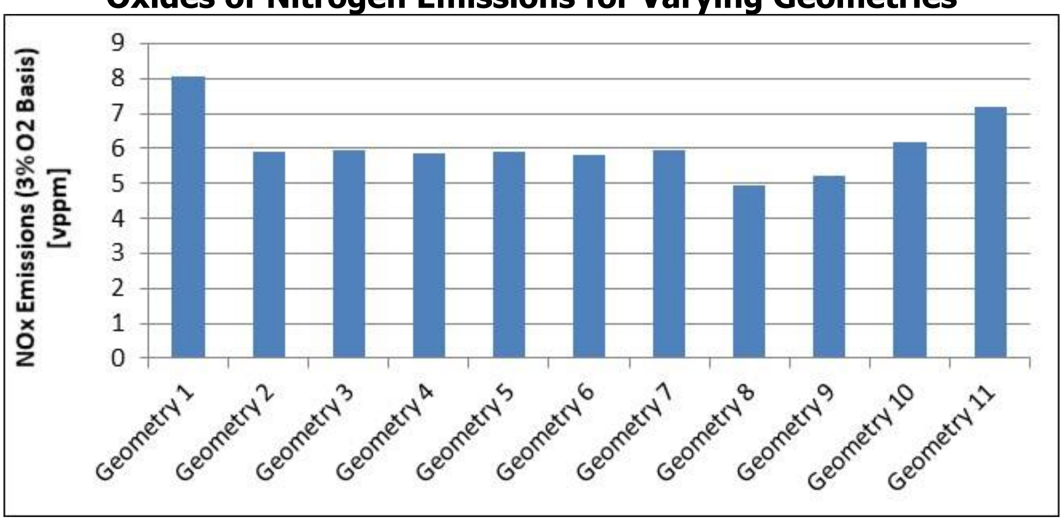
Figure 10: Oxides of Nitrogen Emissions Results



Source: Gas Technology Institute

Once experimental and model results were in agreement, the CFD model was used to estimate the performance of burner for varying geometries. A wide range of geometric parameters were evaluated to estimate their effects of flame behavior, heat release, and NO_x emissions (Figure 11). From these results, the project team could identify variables of greatest interest, focusing experimental test efforts on the variables of highest potential impact.

Figure 11: Computational Fluid Dynamics Model Predictions of Oxides of Nitrogen Emissions for Varying Geometries

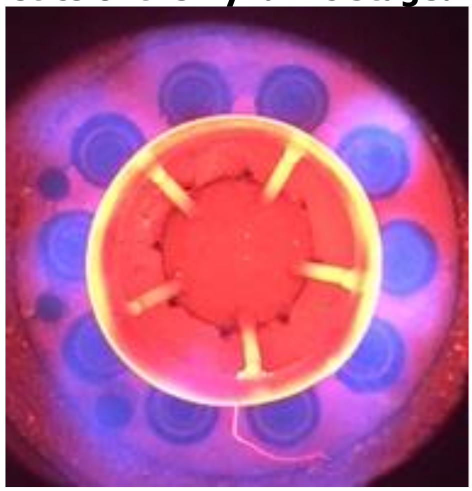


Source: Gas Technology Institute

Experimental Test Results

Experimental studies of the DSE burner were carried out with GTI's boiler simulator facility. An image of the burner flame zone for the final burner designs with operation at full fire is shown in Figure 12. Studies were performed both with and without staging of combustion reactants within the burner across a wide range of firing rates and combustion stoichiometries.

Figure 12: Flame Characteristics of the Dynamic Staged Entrainment Burner Design



Source: Gas Technology Institute

By adjusting the excess oxygen level at which the burner operates, NO_x emission levels could be varied significantly. The target level of <9 vppm NO_x could be achieved at ~4.5% excess oxygen. Note, that while CO emissions increase slightly at higher excess oxygen levels, these levels are still very low (<15 vppm) in comparison to regulated limit of <400 vppm CO.[2] This lower excess air firing will directly increase overall efficiency.

Beyond the low NO_x emissions attained, the advanced DSE burner has also demonstrated a wide degree of operational latitude. By operating at reduced excess oxygen levels, the burner can operate at conditions to satisfy NO_x levels of <9, <12, and <20 vppm, as representative of a range of regulated air quality districts. As such, this burner is capable of being deployed over a broad set of boiler markets throughout the United States, without requiring any physical modifications to the burner. The required adjustments to the operating parameters of the burner can be made with simple modifications to the burner control settings during commissioning of the system.

While the initial performance of the burner with respect to NO_x and CO emissions was very positive, the turndown and air blower demands of the technology required some improvement. Based on discussions with the manufacturing partner, Power Flame Inc., the combustion air pressure required for the initial burner design was determined to be too high. This was especially relevant as the burner operation was scaled up from 4 to 5 MMBtu/hr to satisfy the demands of the host site facility. Design modifications were made to bring the air blower pressure and power requirements to acceptable levels. These changes; however, resulted in a slight reduction in low-fire stability, negatively impacting turndown.

Efforts were then made to evaluate modifications to the burner aimed at improving turndown. While the initial performance target for the technology was a 4:1 turndown, Power Flame

[2] "Rule 1146. Emissions of Oxides of Nitrogen from Industrial, Institutional, and Commercial Boilers, Steam Generators, and Process Heaters" and "Rule 1146.1. Emissions of Oxides of Nitrogen from Small Industrial, Institutional, and Commercial Boilers, Steam Generators, and Process Heaters," South Coast Air Quality Management District, 2013.

indicated that a higher turndown level would be desirable. To enhance the turndown capability, geometric changes were needed to enhance stability at low fire. However, such changes tend to have an opposing effect on NO_x emissions, and as such, thorough studies were performed to optimize the design to achieve the required turndown targets without sacrificing performance with respect to NO_x and CO emissions.

While the NO_x and CO emissions for the final burner design are somewhat higher in comparison to the results for the initial design for a given excess oxygen level, the turndown and air blower demands are significantly improved. Further, the final burner configuration still exhibits a wide range of operational latitude for satisfying varying regulatory NO_x levels. Additionally, CO levels remain very low across the operational range. Across the wide operating domain, CO emissions are below 15 vppm for nearly all conditions.

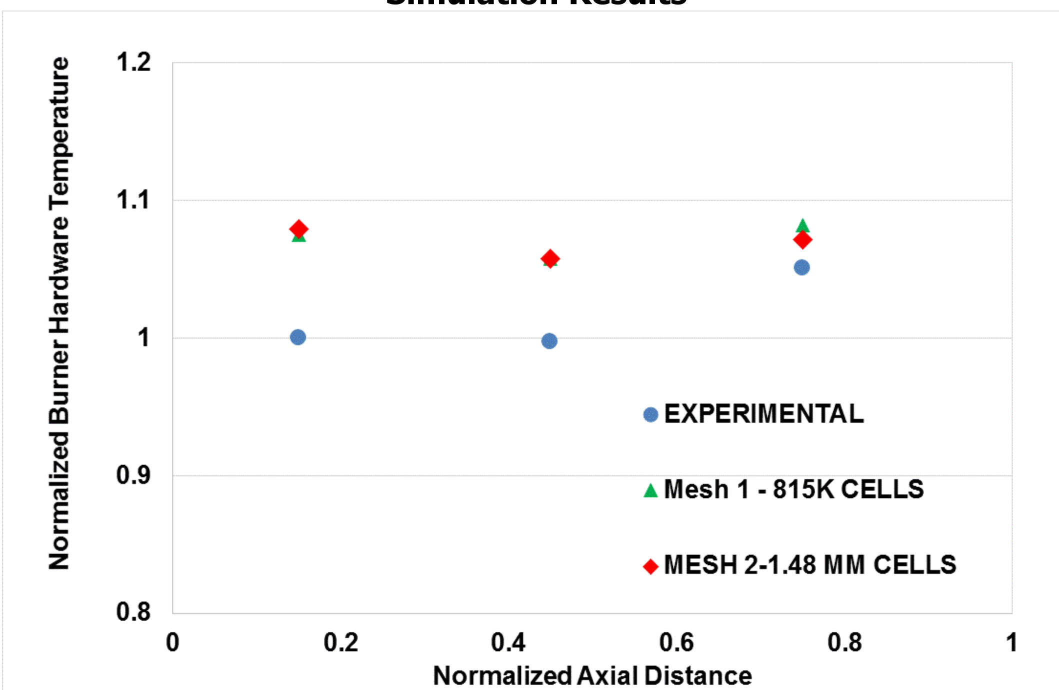
The performance of the burner in the boiler simulator directly translated to the performance of the burner in the commercial boiler, both at GTI and at the host facility. GTI's DSE burner was coupled with the commercial boiler as shown in Figure 13. Thermocouples were installed on the burner sleeve to provide temperature measurements for comparison with simulation data. CO emissions were measured with a probe that was traversed along the axial length of the burner to provide emissions along the flame length. NO_x emissions were measured at a single location downstream of the burner exit plane. A NO_x analyzer and a paramagnetic oxygen analyzer were calibrated and used for emissions measurement. Performance test data was collected for several burner test conditions. The initial tests evaluated performance of the conventionally designed burner (baseline tests) and subsequent testing efforts focused on evaluation of different operating parameters and designs for comparison with the results of CFD simulations. Each design condition was evaluated for its effect on CO and NO_x emissions and burner hardware temperature.

Figure 13: Performance Evaluation and Validation at Gas Technology Institute

Source: Gas Technology Institute

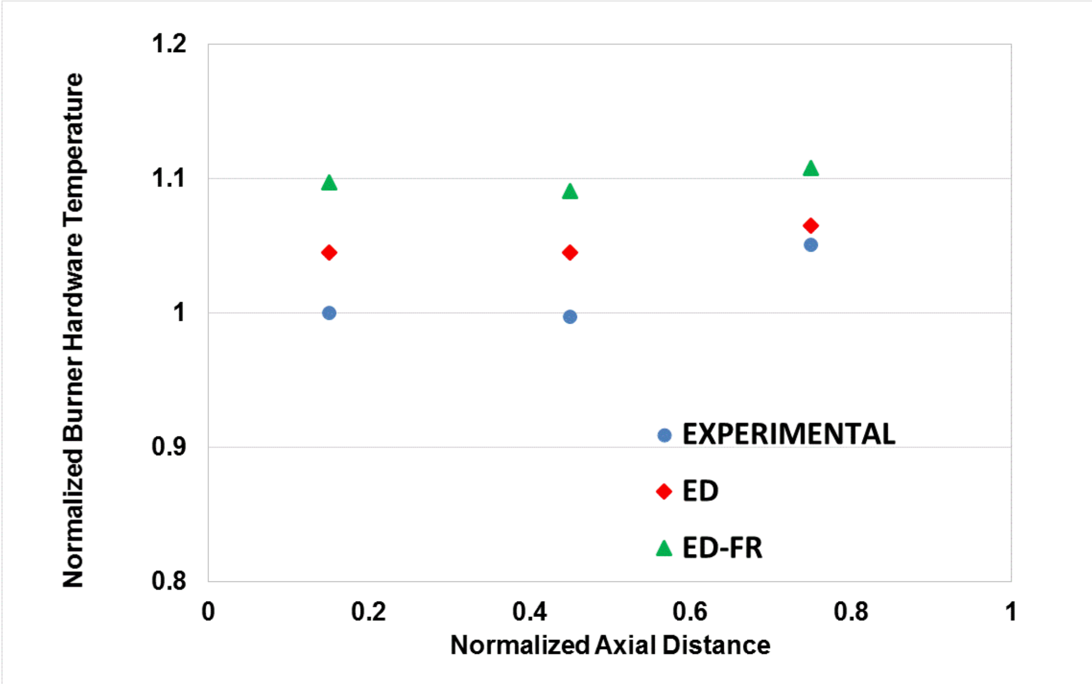
Figure 14 shows the grid independence study performed. Two different mesh sizes with increased cell count were simulated to see the impact of the mesh quality on the results. The burner hardware temperature was considered as the parameter to be compared with the experimental results to evaluate grid independence. Nearly doubling the cell count from 815,000 cells to 1.48 million, did not improve the accuracy of the results. This showed that the mesh was sufficiently refined to provide reliable results and hence the mesh with 815,000 cells was chosen for further simulation. Multiple turbulence-chemistry interactions were chosen from the commercial code. For premixed combustion, eddy dissipation-finite rate (ED-FR) combination is best suited for the current burner configuration. In addition, the eddy dissipation (ED) model was also evaluated. These two models were evaluated in comparison to the experimental data for the burner hardware temperature and CO emissions. Figure 15 shows the comparison of the hardware temperature with the experimental results along the axial length of the burner for the two different models. ED model performs better than the ED-FR model. This, however, does not mean the ED is the right choice as this is based on mixing and not suitable for cases where the mixture is already in a mixed or partially mixed condition. That will lead to premature combustion and erroneous results.

Figure 14: Grid Independence Study to Evaluate Mesh and its Impact on the Simulation Results



Source: Gas Technology Institute

Figure 15: Two Different Turbulence-Chemistry Interaction Models to Evaluate Model Validation

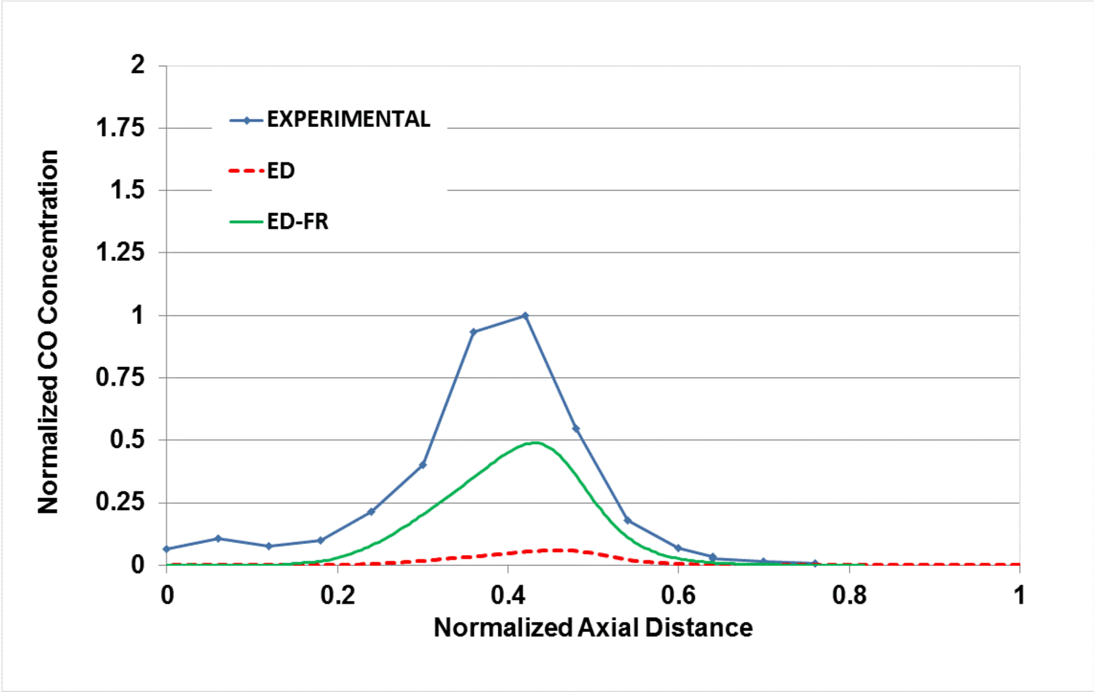


Source: Gas Technology Institute

Figure 16 shows the CO emission profile for the two models. As shown, the CO emissions peak and relative magnitude for the ED-FR model was much closer to the experimental results than the ED model. This was primarily because the ED model leads to combustion if the air-fuel mixture is within the flammability limits. However, with ED-FR, the kinetics were also considered and hence the flame location and the CO burnout was more accurate and reliable as compared to the ED model. Hence the ED-FR turbulence-chemistry model was chosen for further simulations.

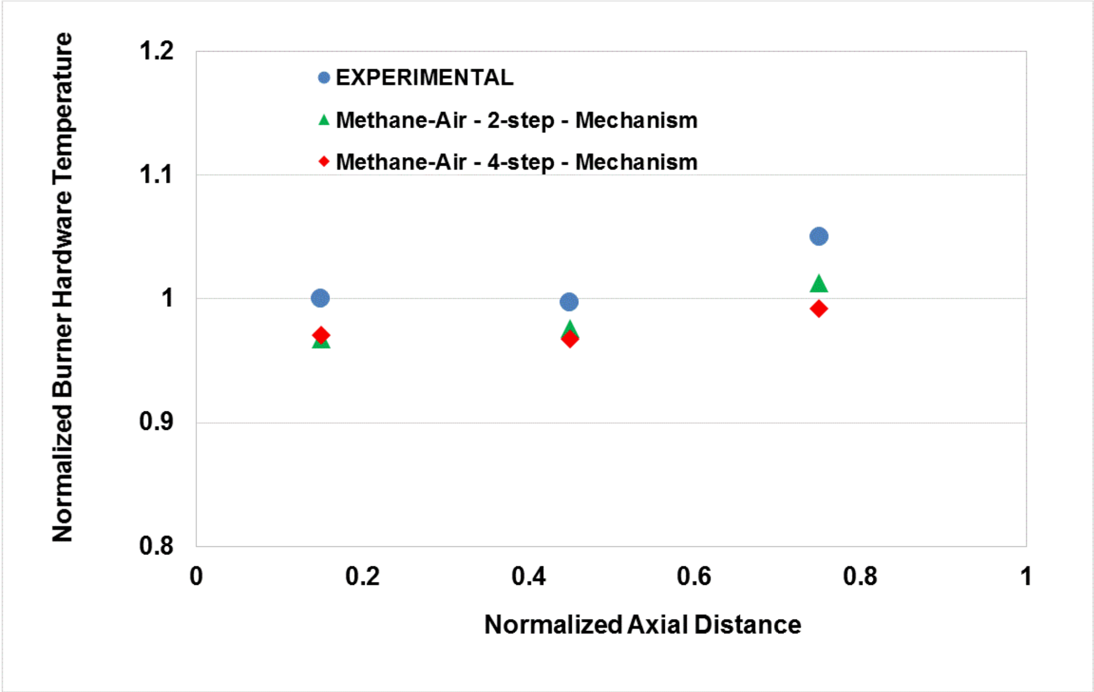
For natural gas combustion chemistry, a one-step, two-step, or a four-step global mechanism can be used as a trade-off between reliable results and reduced computational resources. The one-step mechanism is a global mechanism that does not account for CO emissions and flame temperature changes due to production of CO and hydrogen gas (H_2) in the flame zone. Hence a two-step and a four-step mechanism were used to evaluate the results and compare to the experimental data for hardware temperature as shown in Figure 17. Both mechanisms showed good trend agreement with the experimental results. Figure 18 shows the CO emissions profile in comparison to the experimental results. As shown, the CO emissions profile/flame location matches well for the two-step mechanism, while shifted to the right for the 4-step mechanism. This could be due to a delayed reaction within the 4-step mechanism.

Figure 16: Two Different Turbulence-Chemistry Interaction Models to Evaluate Model Validation



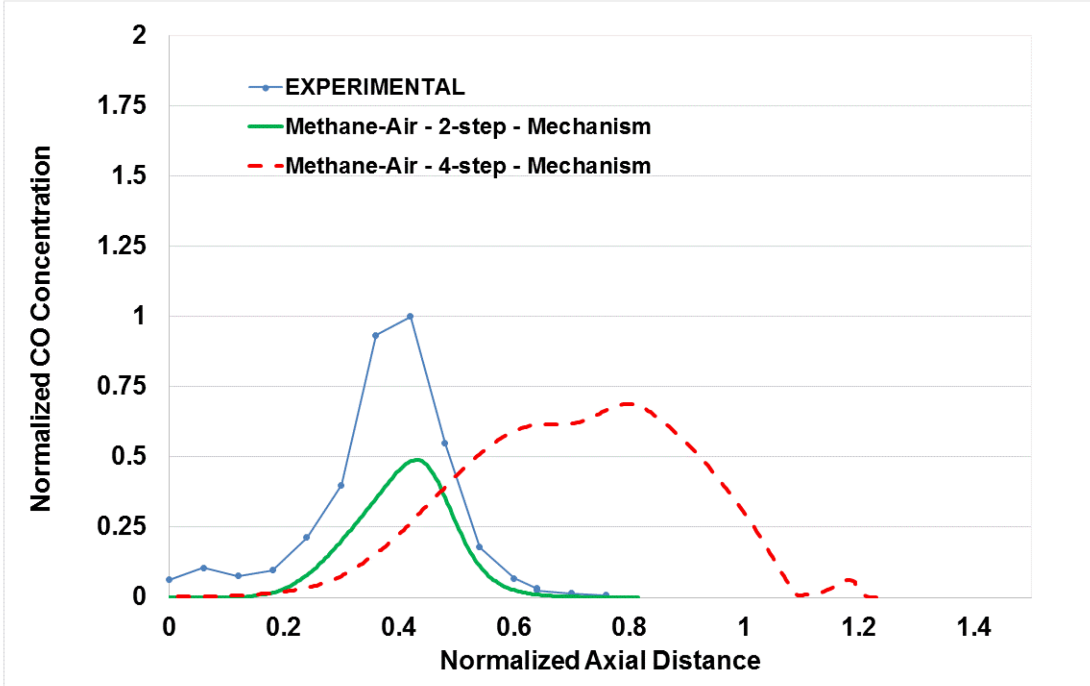
Source: Gas Technology Institute

Figure 17: Two Different Reaction Mechanisms to Evaluate Burner Simulation Results



Source: Gas Technology Institute

Figure 18: Two Different Reaction Mechanisms to Evaluate Burner Simulation Results



Source: Gas Technology Institute

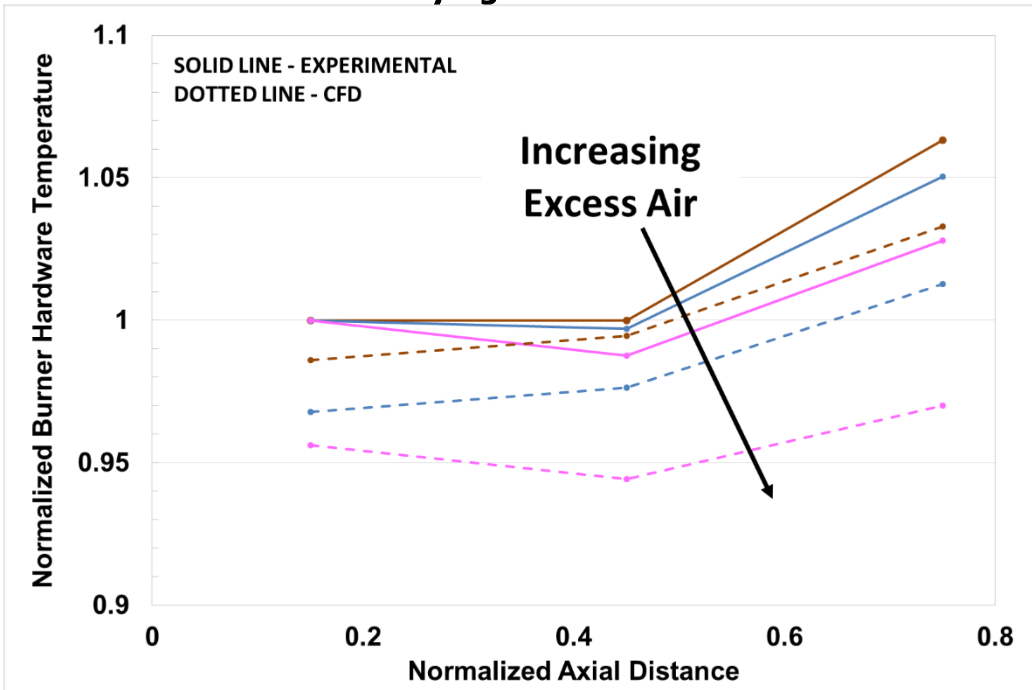
After evaluating and selecting the model settings, simulations were performed for different excess air conditions. The excess air was based on the minimum and maximum design conditions for both NO_x emissions and operational optimization. Figure 19 shows the burner hardware temperature for the simulation and experimental data with variable excess air. Results indicate the trends for excess air match that of the experimental data, however, absolute values were lower than the experimental values. This was attributed to variations in the radiation properties, measurement method used in the experimental testing with thermocouples, and material properties being different in the simulation. The slight variability may not impact the overall results of the simulation.

Figure 20 shows the NO_x emissions with variable excess air. As the excess air was increased the NO_x emissions decrease which was expected due to reduced flame temperature. In comparison to experimental results the CFD results show good trend agreement.

Figure 21 shows the CO emission profiles for the different excess air factors and in comparison to the experimental results. The peak CO emissions were at the same region indicating that the peak flame temperature and the flame profile match well with the experimental data. Quantitatively, the CO emissions were lower compared to the experimental data. This could be associated with a two-step mechanism that does not account for the detailed CO chemistry. A more detailed mechanism, such as Augmented Reduced Mechanism-19 or a full set of reactions such as Gas Research Institute-Mech 3.0, could give better quantitative results.

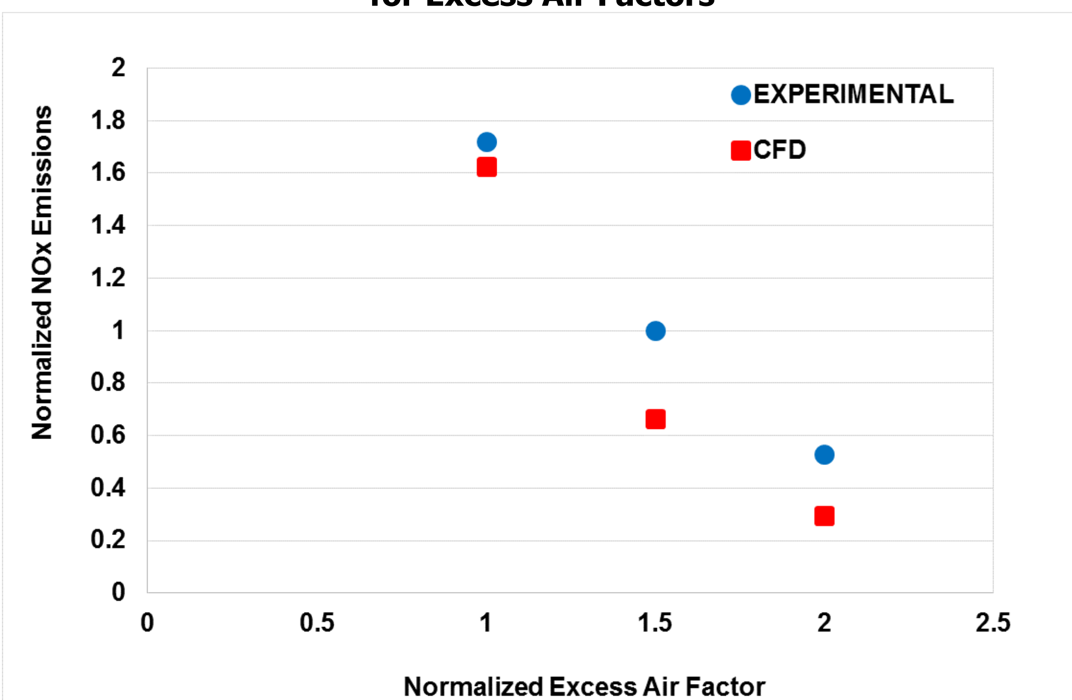
Figure 22 shows the effect of simulating NO_x emissions for different firing rates. For the lower firing rates there was greater difference in NO_x emissions, while as the firing rate was increased the CFD and experimental values show good agreement. However, this difference was not conclusive since at low NO_x levels the mathematical tolerance can be of the same order of magnitude. It was difficult to predict very low levels of NO_x.

Figure 19: Burner Hardware Temperature Compared to Experimental Data for Varying Excess Air



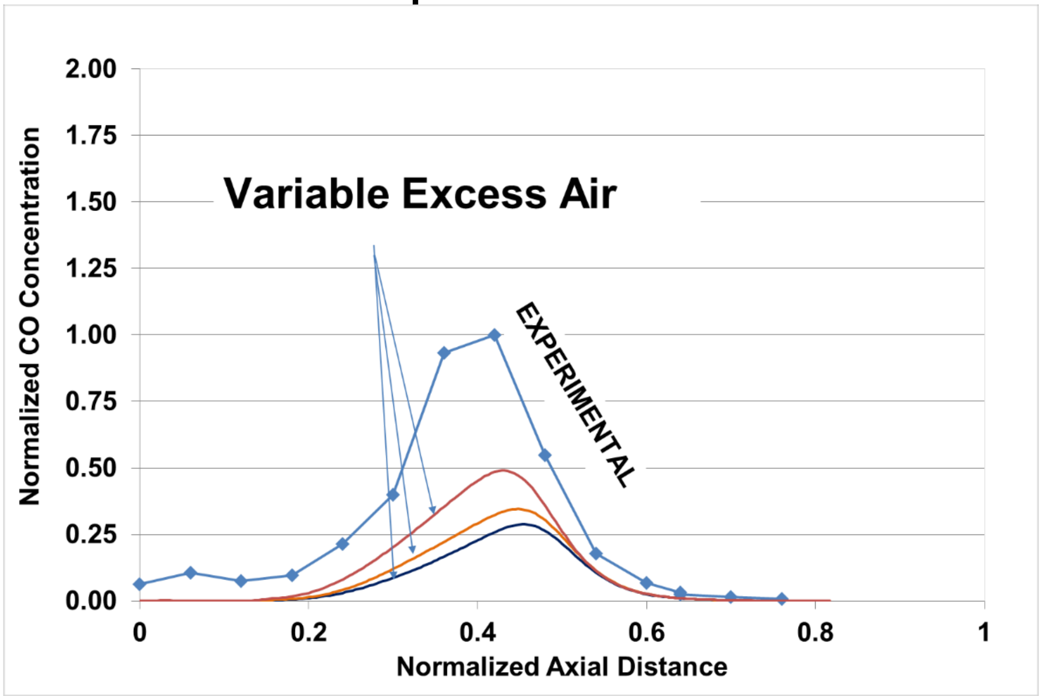
Source: Gas Technology Institute

Figure 20: Comparison of Oxides of Nitrogen Emissions with Experimental Results for Excess Air Factors



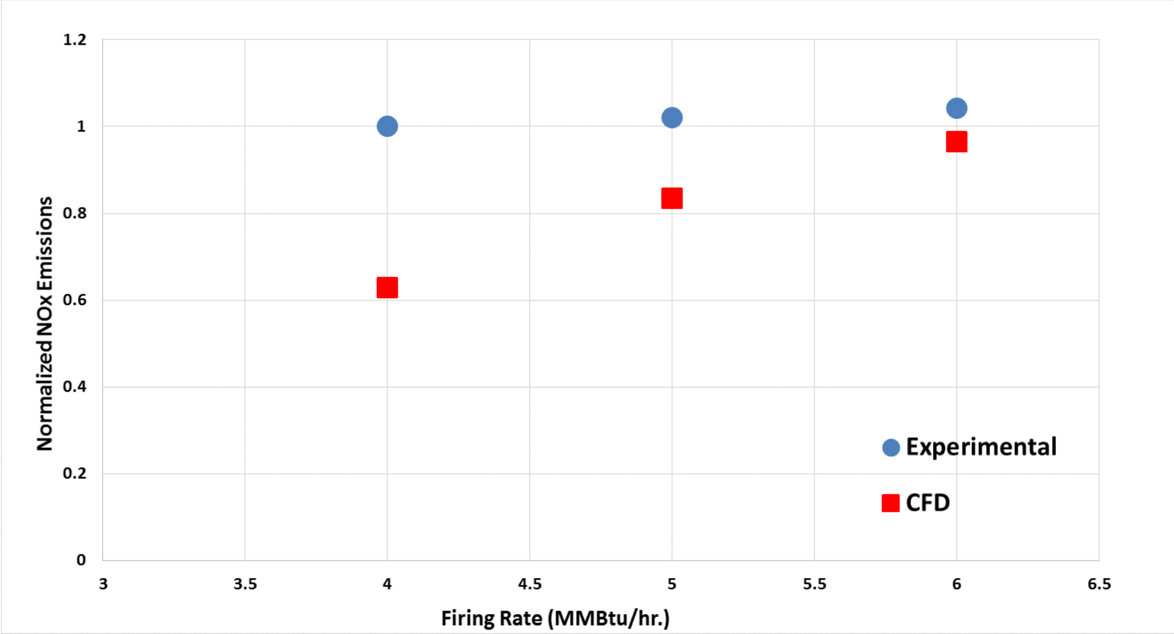
Source: Gas Technology Institute

Figure 21: Carbon Monoxide Emissions Profile along Burner Length in Comparison to Experimental Results



Source: Gas Technology Institute

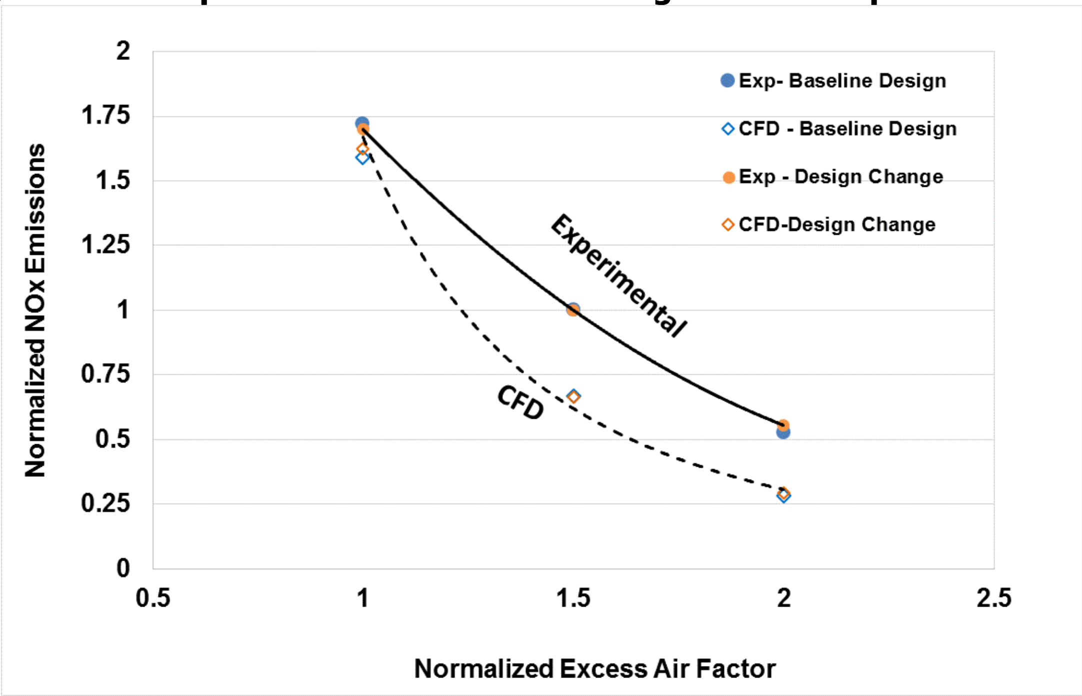
Figure 22: Oxides of Nitrogen Emissions as a Function of Firing Rate



Source: Gas Technology Institute

Figure 23 shows the comparison of the experimental data to the baseline data and design change that was made to the CFD model followed by experimental testing. Results show good trend agreement with CFD results which provided confidence in the CFD model.

Figure 23: Comparison of Baseline and Design Data to Experimental Data



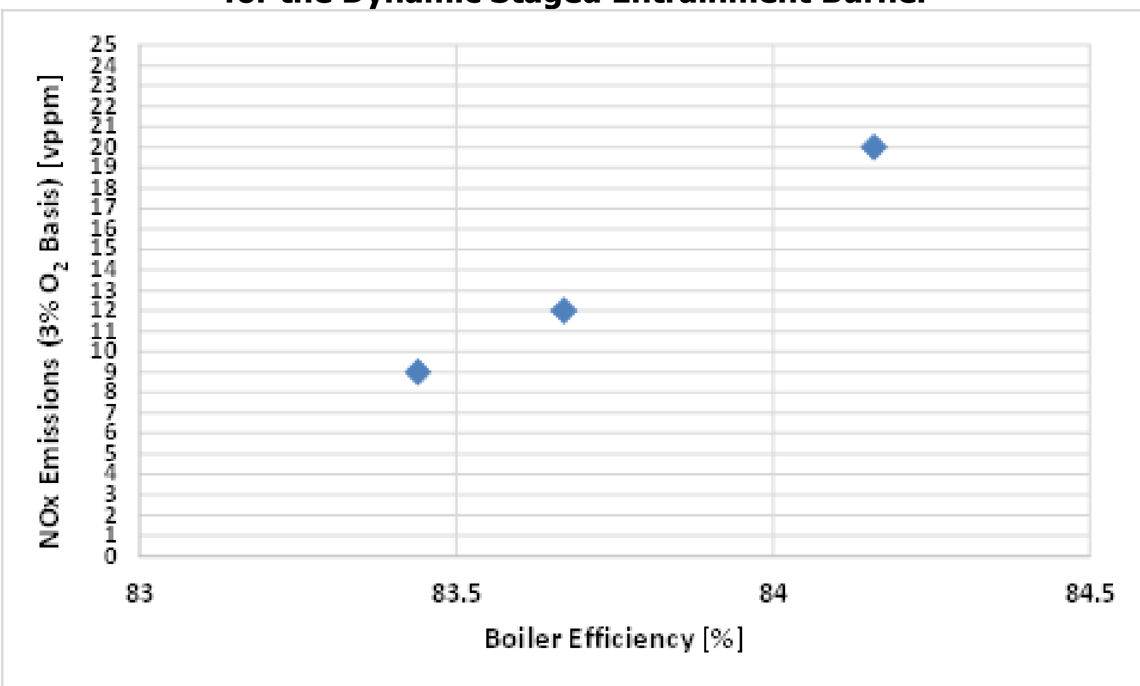
Source: Gas Technology Institute

CHAPTER 5: Benefits of the Technology

Laboratory testing of the DSE burner technology has demonstrated the ability to achieve NO_x emissions below 9 vppm without the use of SCR, FGR, or HEA. The technology therefore offers a new pathway for commercial and industrial boiler operators to achieve NOx emission reductions mandated by current and future regulations at a lower cost and with higher energy efficiency than is possible with current commercially available NO_x mitigation strategies.

The DSE burner offers a simple, robust design for application to commercial and industrial boiler markets. The technology has demonstrated wide operational latitude in satisfying market needs, with the ability to satisfy requirements for <9, <12, and <20 vppm NO_x. As the burner is tuned to satisfy varying NO_x criteria, the excess air level of the burner is adjusted, optimizing the efficiency of the technology for a given NO_x level (Figure 24).

Figure 24: Exhaust Oxides of Nitrogen Emission Level versus Achievable Efficiency for the Dynamic Staged Entrainment Burner



All boiler efficiency values reported here are based on a stack-loss methodology, assuming an exhaust temperature of 400°F, unless otherwise noted.

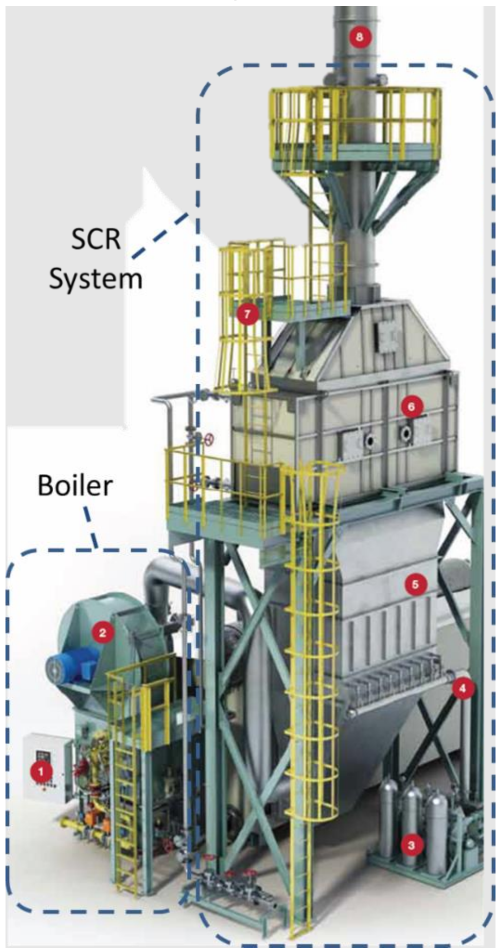
Source: Gas Technology Institute

Beyond the target emissions level, the DSE burner technology has demonstrated the ability to achieve stable operation at lower firing rates, a factor important to boiler operators. While stability and operational reliability of the burner at low NO_x levels has not yet been fully validated, this suggests that it may indeed be possible to achieve compliance at even lower levels, as regulations continue to tighten. Given that some large-scale boiler installations in California have already begun to seek operability at lower levels, this potential is highly relevant.

Benefits in Comparison to Selective Catalytic Reduction Technologies

At present, the only commercially available approach for reliably achieving lower NO_x emissions is SCR, which is applied downstream of the boiler to remove NO_x from the exhaust stream. Figure 1725 shows a typical SCR system as integrated with a conventional boiler. Although these systems are well proven for achieving ultra-low NO_x levels, they are costly, complicated to implement, reduce boiler efficiency, and not economically feasible for small industrial and commercial users. SCR systems also require significant resources in terms of qualified maintenance personnel, supporting equipment, and space required for system installation.

Figure 25: Selective Catalytic Reduction System Integrated with a Conventional Boiler



Source: Figure adapted from Cleaver-Brooks Selective Catalytic Reduction product brochure. http://www.cleaver-brooks.com/Products-and-Solutions/Exhaust-Solutions/Selective-Catalytic-Reduction-(SCR)/Selective-Catalytic-Reduction-(SCR)/SCR-Brochure.aspx

SCR systems also require significant investments in downstream equipment that substantially increase overall capital costs[3]. Compared to the use of SCR, the costs on an avoided-NO_x basis are estimated to be approximately 70% lower – about \$0.50 per pound (lb) NO_2 for the DSE

[3] R. K. Agrawal and S. C. Wood, "Cost-effective NO_x Reduction," Chemical Engineering, pp. 78-82, 2001.

burner technology developed within this project. Moreover, the capital cost for the DSE burner is anticipated to be no more than an equivalent sized conventional low-NO_x burner.

Beyond the high costs of SCR systems, there are further disadvantages in terms of efficiency. Net fuel and electricity consumption rates are higher for SCR systems, resulting in higher operating costs and GHG emissions for the same steam or hot water output. To achieve air quality improvement targets and regulatory compliance, efficient and cost-effective pollution control technologies need to be deployed to the market. The DSE burner technology has the potential save 2.5 million tons of NO_x annually in California alone, by achieving robust operation with NO_x emissions below 9 vppm as based on information from California Air Resource Board databases. Broader deployment throughout North American markets will have even broader impact on NO_x mitigation, energy savings, and greenhouse gas reductions.

Benefits in Comparison to External Flue Gas Recirculation Technologies

FGR is a well-known NO_x reduction strategy whereby exhaust products from the boiler stack are returned to the inlet of the burner to reduce peak flame temperatures, inhibiting NO_x formation (Figure 26). Very high levels of external flue gas recirculation have been employed in a small number of applications to achieve <9 vppm NO_x. However, this approach struggles with the high levels of recirculated flue gas to maintain a high degree of reliability and operational latitude required for the broader boiler market. There are still many disadvantages of this approach in comparison to the newly developed DSE burner technology in terms of cost, efficiency, and complexity.

Figure 26: Integrated Boiler-Burner System Utilizing External Flue Gas Recirculation

Source: Figure adapted from Hurst boiler product brochure. http://www.hurstboiler.com/

A review of air quality source test results for boilers seeking to achieve <9 vppm NO_x emissions without SCR, reveals that all boilers currently in compliance are employing either external FGR, surface stabilized burners (which rely on high excess air operation), or a combination of these technologies[4]. Thus, for <9 vppm NO_x operation, FGR systems are well proven and commonplace.

The DSE burner developed within this project demonstrated the ability to achieve operation at <9 vppm with high efficiency, and without the need for FGR. This newly developed burner technology avoids the added cost required for the supporting duct work, high temperature exhaust blower, and additional controls associated with FGR systems. Moreover, it avoids the added complexities associated with cold-startup and condensation challenges that arise with FGR systems.

The DSE burner also achieves efficiency gains relative to FGR systems, both in terms of electricity and natural gas consumption. External FGR boiler systems consume up to 50% more electricity than conventional boilers, as a result of the power required to drive the high temperature blower to return exhaust products from the boiler stack to the inlet of the burner.

Regarding fuel consumption, the DSE burner achieves comparable or slightly increased efficiency as well. External FGR systems typically operate at excess air levels in the range of 28% to 32% (5.0% to 5.5% excess oxygen) to achieve <9 vppm NO_x[5]. The newly developed DSE burner has demonstrated <9 vppm NO_x with operation at 24% to 28% excess air (4.5% to 5% excess oxygen), thereby achieving comparable, or improved, efficiency relative to FGR systems, without the added equipment cost and electricity consumption.

The system performance benefits of the DSE burner technology in comparison to conventional low-NO_x FGR systems are summarized in Table 3.

Table 3: Comparison of the DSE Burner to a Conventional FGR Burner, Operation at <9 vppm NO_x

Operating Parameter	Units	Conventional Low-NO_x Burner (with FGR)	DSE Burner (9 vppm NO_x)
Full Fire	MBtu/hr	5,000	5,000
Flue Gas Recirculation	-	Yes	No
Turndown	-	4:1	5:1
Excess Oxygen Level	%	5.5	5.0
Boiler Efficiency	%	83.2	83.4
NO_x (at 3% O_2)	vppm	<9	<9
CO (at 3% O_2)	vppm	<200	<200
Blower Power	HP	5 to 7.5 (estimate)	2.5

Information adapted from product specifications of commercially available burner products.

Source: Gas Technology Institute

[4] W. Barcikowski, K. Orellana and G. Quinn., "Implementation Assessment Report on Ultra-Low NO_x Burners subject to Rules 1146 and 1146.1," South Coast Air Quality Management District, 2010.

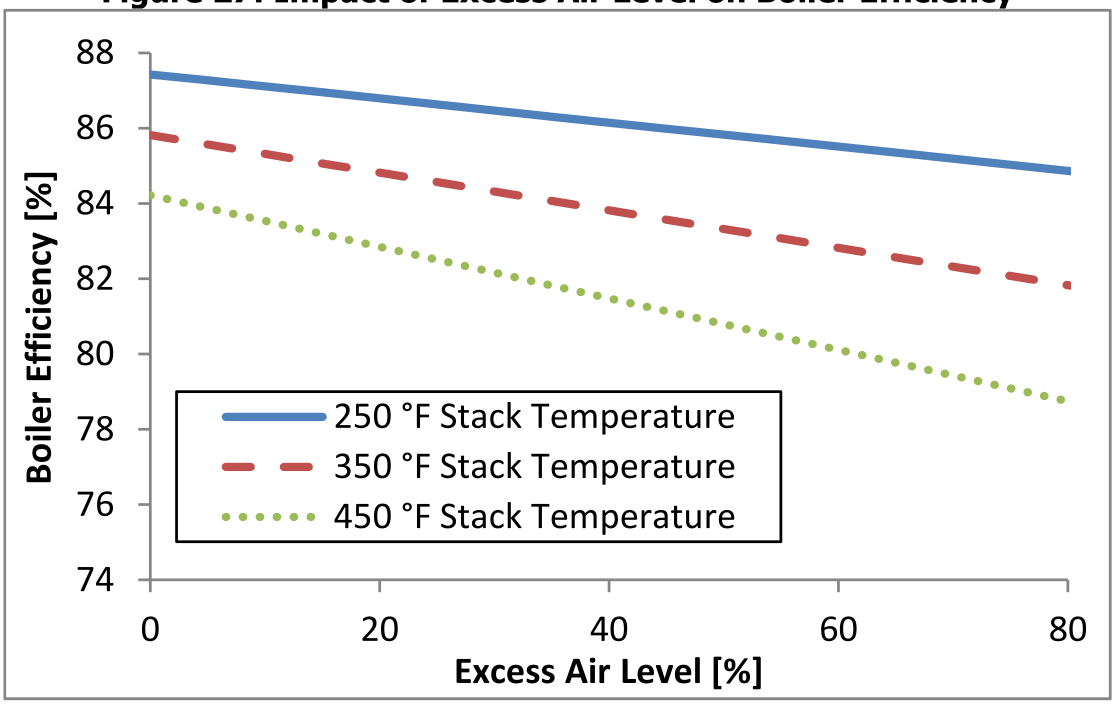
[5] "Suggested Specification for Model NVC2 Through NVC6 Ultra Low NO_x Gas Burners," in Product Specifications, Power Flame Incorporated, 2007.

Benefits in Comparison to High Excess Air Burner Technologies

Given the high costs and complexities of SCR and FGR technologies, many boiler burners employ HEA operation to achieve low NO_x levels, at the expense of operating with greatly reduced efficiency. While this approach has demonstrated reliable and robust operation to achieve <9 vppm NO_x, there are currently no HEA burner technologies which achieve <5 vppm NO_x.

The large majority of burners employing HEA operation are surface stabilized burner designs, in which combustion is stabilized at the surface of a porous material, such as a fiber mesh, perforated plate, or foamed metal. While these burners are sometimes integrated with FGR systems, they are often applied for direct use in a boiler. When operated without FGR, these burners typically operate with excess air levels greater than 65% (8.8% excess oxygen) to achieve NO_x emissions <9 vppm.[6] Operation at these very high excess air levels; however, results in significant reductions in efficiency (Figure 27).

Figure 27: Impact of Excess Air Level on Boiler Efficiency



Source: H. R. Taplin, Combustion Efficiency Tables, Lilburn, GA: Fairmont Press, 1991

At present, HEA burner technologies dominate the market for small to moderate scale commercial and industrial boilers requiring <9 vppm NO_x. For systems rated below 250 BHP (10 MMBtu/hr), there are a total of 117,145 boilers currently installed throughout the United States (23,495 industrial + 93,650 commercial), with an installed capacity of over 400,000 MMBtu/hr.[7] A study of boiler compliance for achieving <9 vppm NO_x emissions performed by

[6] "CSB Burner Product Brochure," Alzeta Corporation, J. D. Sullivan and e. al., "Temperature-Compensated Combustion Control". United States Patent 7048536, May 2006, and W. V. Krill and e. al., "Adiabatic Surface Combustion With Excess Air". United States Patent 5211552, May 1993.

[7] Energy and Environmental Analysis Incorporated, "Characterization of the US Industrial/Commercial Boiler Population," Oak Ridge National Laboratory, 2005.

the South Coast Air Quality Management District (SCAQMD) reveals that 83% of boilers rated below 250 BHP are employing HEA operation; the remaining 17% utilize FGR. The limited use of FGR at this scale is further evidence of the significant additional equipment cost and complexity associated with FGR systems. As a result, customers have turned to low-efficiency HEA burners to achieve compliance.

Relative to the commercially available HEA burners that are in the boiler market, the DSE burner technology offers several performance benefits when operated to achieve <9 vppm NO_x, as outlined in Table 4. To achieve these levels, current HEA burners operate with excess oxygen levels of 8.8% (65% excess air), whereas the DSE burner operates in the range of 5.0% excess oxygen (28% excess air). As a result, the DSE burner realizes an efficiency gain of more than 2 percentage points over conventional HEA burners. Moreover, the total blower pressure and blower power requirements are much lower for the DSE burner, resulting in reduced electricity consumption and equipment cost.

Table 4: Comparison of Dynamic Staged Entrainment Burner to Conventional Low-Oxides of Nitrogen Burner, Operation at <9 vppm NO_x

Operating Parameter	Units	Conventional Low-NO_x Burner (without FGR)[8]	DSE Burner (9 vppm NO_x)
Full Fire	MBtu/hr	5,000	5,000
Flue Gas Recirculation	-	No	No
Turndown	-	4:1	5:1
Excess Oxygen Level	%	8.8	5.0
Boiler Efficiency	%	81.3	83.4
NO_x (at 3% O_2)	vppm	<9	<9
CO (at 3% O_2)	vppm	<200	<200
Total Blower Pressure	In. w.c.	24	15.2
Blower Power	HP	5	2.5

Source: Gas Technology Institute

The performance benefits of the DSE burner directly translate to significantly reduced natural gas and electricity consumption, with quantifiable cost savings and corresponding CO_2 reductions. For a boiler rated at 250 BHP and operating at 35% average load capacity, the 2 percent point efficiency gain achieved for the DSE burner in comparison to an HEA burner equates to a reduction of nearly 740 MMBtu in annual gas consumption at a savings of $5,000 for a commercial customer (Table 5).

By operating with reduced excess air levels in comparison to conventional HEA burners, the combustion air flow required for the DSE burner is reduced by 23%. Additionally, the DSE burner operates with lower air pressure, such that the compounded effect is a 50% decrease in required combustion air blower power. This directly translates to reduced electricity consumption. For a 250 BHP boiler application, this decrease in blower power equates to a

[8] Information adapted from product specifications of commercially available burner products

reduction of nearly $1,500 in electricity costs annually for a commercial customer (Table 5). Further, total annual greenhouse gas and NO_x emissions is reduced by over 48 tons for a boiler operating with a DSE burner rather than a conventional HEA burner.

Extending the performance of a 250 BHP rated DSE boiler/burner system over an anticipated 30-year life expectancy of the equipment yields total reductions of natural gas and electricity consumption of 22,000 MMBtu and 340,000 kWh, respectively. This corresponds to total reductions of CO_2 and NO_x emissions of 1,440 tons and 240 lbs, respectively, and total energy cost savings of nearly $200,000.

Table 5: Energy Cost and Emissions Benefits of Dynamic Staged Entrainment Burner in Comparison to Conventional High Excess Air Burner

Parameter	Unit	Basis	Difference
Boiler Size	BHP	250	
Annual Average Load	%	35	
Stack Temperature	°F	350	
NO_x Emissions	vppm	9	
Natural Gas Cost	$/MMBtu	6.8	
Electricity Costs	$/kWh	0.13	
CO_2 lb/MMBtu Natural Gas Saved	lb/MMBtu	117	
CO_2 lb/kWh Electricity Saved	lb/kWh	0.83	
Boiler Efficiency Increase	%		2.0
Air Blower Horsepower Requirement Decrease	%		25
Annual Gas Consumption Decrease	MMBtu		736
Annual Gas Cost Decrease	$		5,006
Annual Electricity Consumption Decrease	kWh		11,432
Annual Electricity Cost Decrease	$		1,486
Annual CO_2 Emissions Decrease	ton		48
Annual NO_x Emissions Decrease	lb		8

Source: Gas Technology Institute

CHAPTER 6: Commercialization Status

Field Demonstration

The laboratory testing and development efforts performed thus far have proven the technological merits of the DSE burner. To further accelerate the technology towards market deployment, the project team demonstrated the technology under real-world conditions at a customer facility located in Santa Barbara, California. This high-visibility field demonstration project is anticipated to build interest and transfer knowledge throughout commercial and industrial boiler markets.

Commissioning

GTI shipped the complete boiler package as shown in Figure 28 to the host site facility. The boiler with DSE burner was unloaded and installed in the boiler room (Figure 29). A new boiler feed water system was installed as well. All electrical and mechanical connections were completed. A steam bypass was installed for test purposes and hence some assembly modifications were required. Leak testing was performed at the end of the installation to ensure all the piping and assemblies were leak proof. The installation went smoothly and there were no major concerns or issues in terms of assembly of the equipment. No major modifications were required either to the facility or the boiler itself to be compatible with the existing process lines. The complete installation is shown in Figure 30.

Figure 28: Complete Boiler/Burner System Shipped to Host Site

Source: Gas Technology Institute

Figure 29: Installation Sequence at Host Site

Source: Gas Technology Institute

Figure 30: Boiler/Burner System Complete Installation at Host Site

Source: Gas Technology Institute

Operational Readiness

After installation, the next task was to make the system operational and ready for the host facility as a primary source of steam. There were three critical aspects to making the system operational: controls, blower operation and burner operation.

Controls

The Slate Honeywell control system was selected. The platform is a single source configurable safety and programmable logic that can be easily adapted for combustion applications. The boiler/burner system was tuned for the boiler curve, trim, emergency alarms and stops were preprogrammed into the control logic at GTI for smooth and reliable operation. The control hardware is shown in Figure 31. At the host facility, the controls were further tuned and some minor modifications to the boiler curve and the trim control were made to ensure that the burner follows the load and has smooth ignition, start-up and shutdown. Connections to the controls and terminals in the panel and the wiring diagrams were reviewed. Other parameters such as steam pressure, pressure switch controls, time for the pilot ignition etc. that were determined at GTI were reviewed and tested at the host facility. The data recording and the remote access features were activated in the controls package. The various sensors were wired, that is, air humidity/temperature sensor, steam flow meter, feed water flow meter and gas pressure sensor.

Figure 31: Honeywell Slate Controls with various Modules at the Bottom

Source: Gas Technology Institute

Blower Operation

Following commissioning of the controls, cold flow testing of the blower was performed. When the system was at GTI, taps were installed at multiple locations to record pressure drop within the windbox and the blower exit (Figure 32). These measurements were verified at the host site to ensure consistent operation. Also, an extension was put on the blower to ensure that there is no lint entering the blower.

Figure 32: Measurement Locations to ensure Consistent Operation

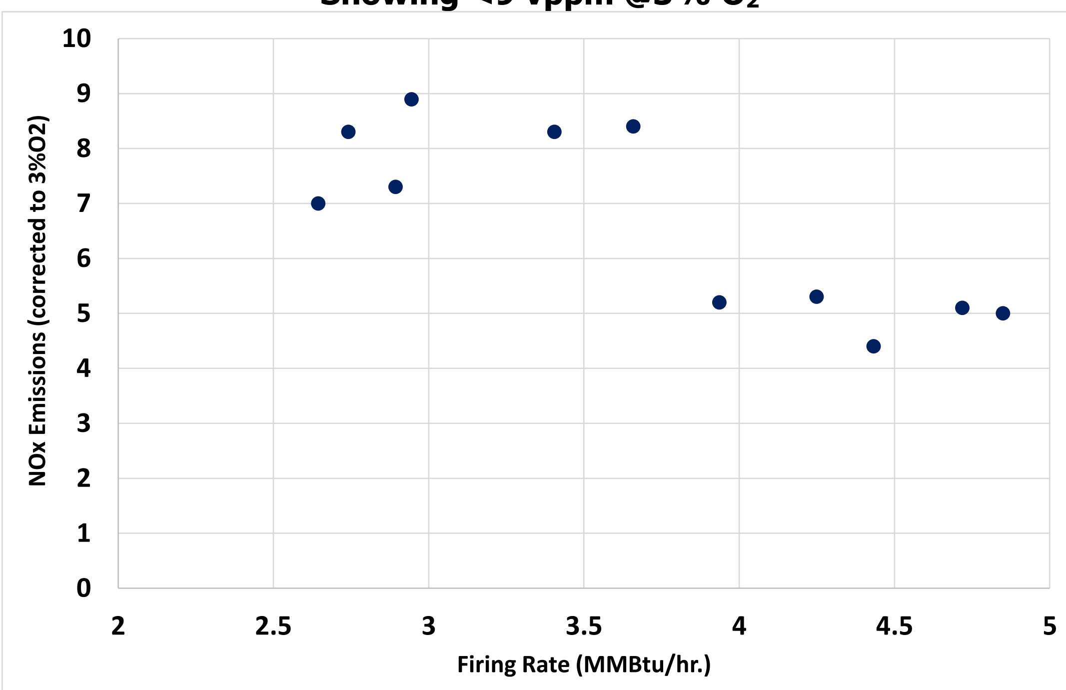
Source: Gas Technology Institute

Burner Operation

After the controls and blower setup and all necessary modifications were made, GTI began testing the burner for the operational parameters. After pilot ignition, it was critical to ensure that the main burner followed the boiler curve/load properly and consistently. Testing was performed with steam load and at a pressure of 110 pounds per square inch – gage (psig) where the mains would shut down when the pressure was achieved. The boiler control curve was tuned slightly to ensure smooth operation across the range. The burner's start-up, operation and shut down were smooth and there were no concerns observed. This testing was repeated multiple times to ensure that the burner operation was consistent. During operation, there was a blower air limit error that was occurring at the lower end of operation. The air switch was replaced and resolved the issue.

In addition to operational testing, GTI also performed emissions testing of the boiler/burner. Figure 33 shows the NO_x emissions for the variable firing rate of the system. The data indicates that the system could achieve the NO_x targets. CO emissions across this entire range were <10 vppm.

Figure 33: Oxides of Nitrogen Emissions as a Function of Firing Rate Showing <9 vppm @3% O_2



Source: Gas Technology Institute

Source Testing

Source testing was carried out by an independent third party, Almega Environmental for process parameters, stack gas parameters and NO_x, CO and VOC emissions. Table 6 shows the results that were obtained from the testing.

Table 6:. Source Test Results

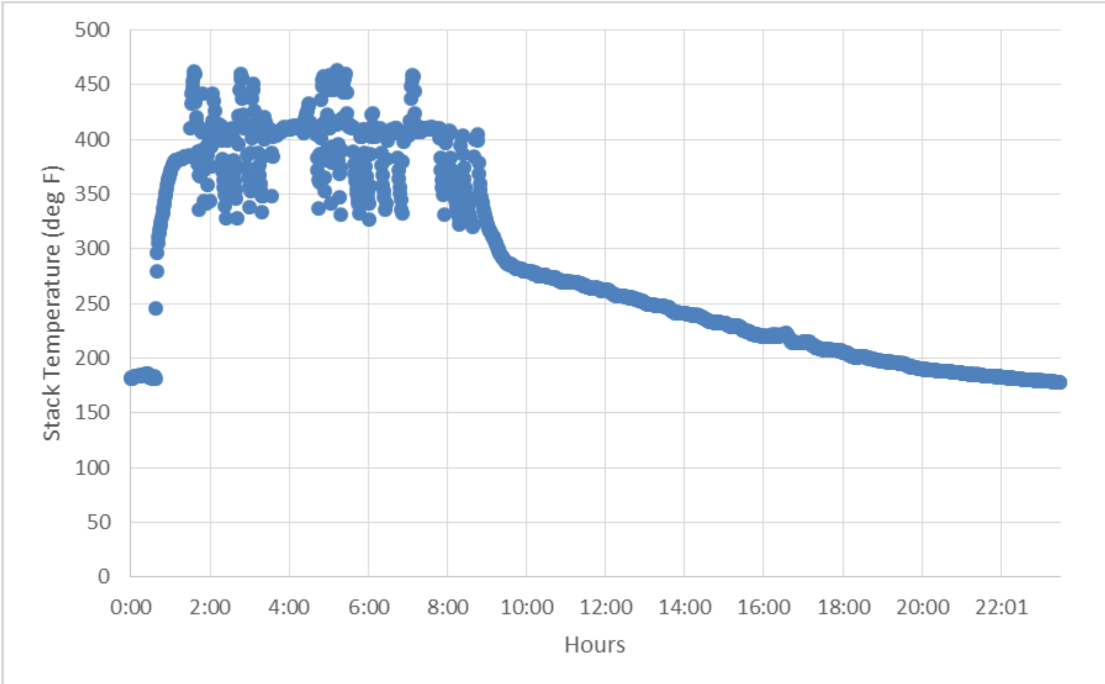
Measurement	Unit	Value
Firing Rate	MMBtu/hr	4.87
Percent Rated Capacity	%	92.7
Stack Gas Temperature	°F	413
O_2	%	5.1
CO_2	%	9.2
NO_x	ppmv	8.6
CO	ppmv	<10
VOC	ppmv	< 0.1

Source: Gas Technology Institute

Continuous Operation

After installation and operational readiness of the boiler/burner, the system was brought on-line to provide steam for process operations. Unfortunately, GTI was not able to achieve continuous remote access to the data system and hence live monitoring of the system was not possible. However, the team was able to acquire real time data from the fuel flow meter and the control systems. Figure 34 shows one day operation of the boiler with variation in the stack temperature indicating load following ability of the DSE burner. At the host facility, the boiler is usually started at around 4:00 AM (showing 0:00 in the figure). The burner cycles multiple times during the day, but can reliably start-up, follow the load and then shutdown as expected. This is critical for the operations with any facility and the burner technology has proven to work successfully. **Error! Reference source not found.** shows the operation of the burner for nearly 10,000 hours of operation. The burner was cycling and following the load in addition to achieving reliable start-up and shutdown. This demonstrates that the DSE burner is a long-term low-emissions, high efficiency solution for commercial building applications. There are regions operating at lower load conditions as a result of the operator selecting manual operation over automatic operation. The burner was still functional and reliable; however, it was not cycling as much. Even at these low firing conditions, the host facility maintained adequate steam. Table 7 shows the comparison of energy consumed by the baseline boiler to that of the new boiler/burner system. As shown, there is 9% savings in the fuel usage as compared to the baseline boiler. This highlights the benefits of applying a newer and reliable boiler/burner technology, which can provide significant energy and cost savings to commercial buildings.

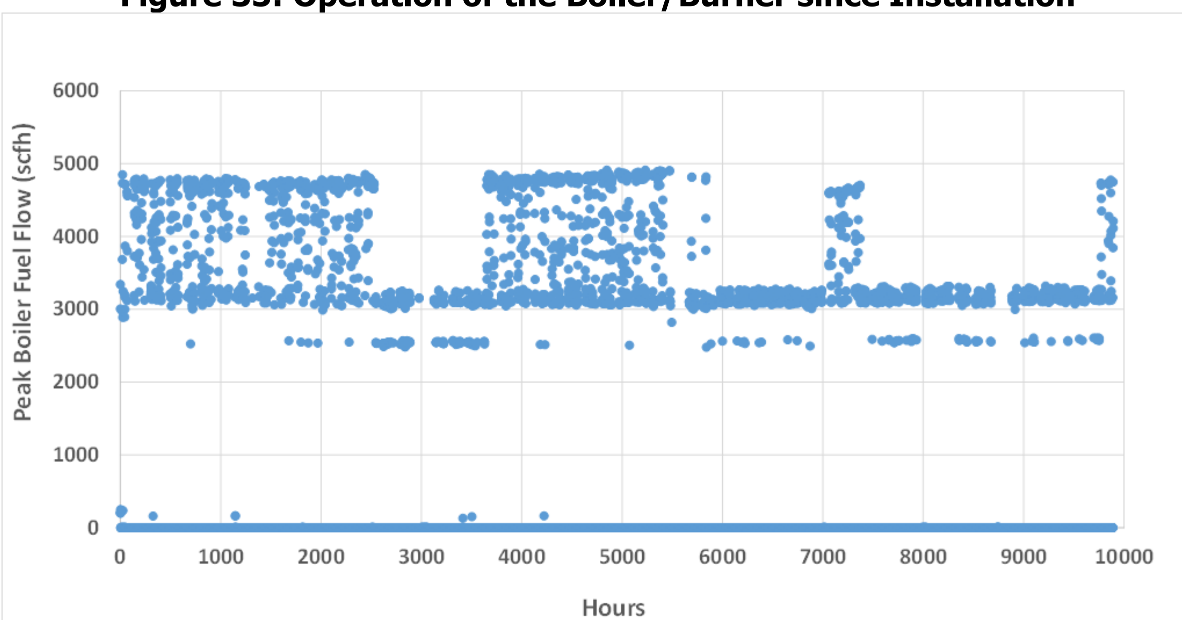
Figure 34: Data Showing One Day Operation of the Boiler/Burner with Cycling and Load Following



0:00 Indicates around 4:00 in the Morning When the Site Starts Operation.

Source: Gas Technology Institute

Figure 35: Operation of the Boiler/Burner since Installation



Source: Gas Technology Institute

Table 7: Comparison of Natural Gas (Therms) Consumed for Baseline Boiler and Gas Technology Institute Boiler/Burner System

Baseline Boiler		GTI Boiler/Burner	
Month	**Therms**	**Month**	**Therms**
14-Sep	6,284	16-Sep	5,477
14-Oct	7,017	16-Oct	5,388
14-Nov	5,509	16-Nov	5,542
14-Dec	6,083	16-Dec	5,029
15-Jan	5,808	17-Jan	5,176
15-Feb	5,275	17-Feb	4,722
15-Mar	5,675	17-Mar	5,842
15-Apr	5,607	17-Apr	5,238
15-May	5,171	17-May	5,867
15-Jun	5,992	17-Jun	5,313
15-Jul	5,738	17-Jul	4,445
15-Aug	5,272	17-Aug	5,172
Total	**69,431**	**Total**	**63,211**
Therm Savings = 8.96%			

Source: Gas Technology Institute

In addition to successful continuous year-long operation and energy savings, the following feedback was received from the site's operations manager highlighting the key benefits of the technology and installation at the host facility:

- Control panel display provides the operator with a clear concise readout of the operating parameters.
- Operating conditions are stable and stay consistent with set points.
- Data logging system provides operator knowledge for troubleshooting issues that may arise.
- Operating emissions are much below regulatory threshold with significant fuel savings when compared to the previous installation.

Manufacturing Partner

The project team has developed a robust relationship with Power Flame, Inc., a leading manufacturer in the United States of commercial and industrial burners. Power Flame assisted with the design and fabrication of the initial DSE burner evaluated and has remained engaged in development activities, providing key insights for performance metrics, market needs, and manufacturing constraints. Further, Power Flame led the design and development of the control system for the integrated boiler/burner system, as well as the air blower and burner pilot components.

Power Flame has a major presence in the packaged boiler market, especially for low-NO_x applications. Throughout California alone, Power Flame captures an estimated 30-50% of burner sales for commercial and industrial boiler applications[9]. Power Flame has a wide network of sales and service distribution partners throughout the U.S., deploying its products for both new and retrofit applications.

Many of Power Flame's current low-NO_x product offerings utilize either FGR systems or surface stabilized combustion technologies which rely on HEA operation. Given the benefits of the DSE burner in comparison to FGR and HEA systems, Power Flame is very optimistic about the market potential for the technology. Further, Power Flame has expressed enthusiasm for the simplicity of the burner design, which avoids the need for porous/fibrous materials that can be costly and have potential for clogging. The anticipated manufacturing cost of the DSE burner will be low in comparison to existing low-NO_x burner products. Thus, once commercialized, it is anticipated that the DSE burner will enter the market at a very competitive price in comparison to competing systems, providing a cost-effective and higher efficiency path to regulatory compliance for boiler operators.

[9] As based on discussions with Power Flame Incorporated.

CHAPTER 7: Conclusions

The demonstration of the DSE technology will benefit California, by helping to bring to market a high efficiency, cost-competitive low NO_x burner technology for commercial boiler applications that is specifically suited to meet the regulatory requirements in California, with NO_x emissions below 9 vppm. The results of this demonstration will help promote interest and market acceptance of the DSE technology, which will increase commercialization and deployment of the technology in the state's commercial building segment, ultimately helping end-users to achieve compliance without sacrificing efficiency.

The demonstration effort strongly supports the 5-year strategic objectives of the PIER Natural Gas program. Specifically, this project was positioned to demonstrate energy efficient technologies for unique California conditions. Demonstration of the DSE technology will reduce the demand for natural gas at commercial sites, and consequently the overall natural gas demand in California. Natural gas rate payers will benefit from increased efficiency of natural gas-fired equipment, more efficient use of gas, and reduced gas use for heating and hot water. Commercial facilities will benefit from energy efficiency and environmental stewardship, sustainable energy use, good citizenship and lower natural gas costs, and increased profits. Widespread deployment of the DSE boiler-burner technology will provide a number of environmental, performance and life cycle cost benefits to California rate payers including:

- Reduced operating costs through reduced gas and electricity consumption resulting from higher system efficiency in comparison to currently deployed technologies.
- Reduced CO_2 and NO_x emissions resulting from reduced energy consumption.
- Reduced equipment cost for commercial-scale NO_x mitigation – the costs for the DSE technology are anticipated to be less than competing SCR and external FGR and comparable or less than competing HEA systems.
- Cost-effective path for air quality compliance in commercial boiler applications – the capital and operating costs associated with currently available NO_x mitigation strategies represent a significant economic burden to California boiler operators, especially for smaller commercial scale operations. The DSE technology provides a cost-effective solution for NO_x reduction, especially for the commercial building sector.
- Reliable operation and equipment longevity – the DSE technology applies fundamental NO_x reduction strategies in a simple and robust design without the complicating elements of SCR or FGR; thus, system reliability and longevity are expected to be high, with an anticipated equipment lifetime of more than 30 years.

The DSE burner technology developed within this project has satisfied all of the performance targets set forth, demonstrating the ability to achieve <9 vppm NO_x emissions without the need for SCR, while maintaining robust turndown (4:1) and operational characteristics. Beyond this, the technology has demonstrated a wide range of operational latitude, with the ability to achieve NO_x emissions from <20 vppm to less than <9 vppm, allowing the burner to adapt to a broad set of markets with varying regulatory requirements (Table 8). This operational flexibility is achieved without need for modification to the burner equipment, allowing the burner to be tuned for different applications with simple operating adjustments made during commissioning.

Table 8: DSE Burner Performance Characteristics for Varying NO_x Emissions Targets

Parameter	Units	DSE Burner (9 vppm NO_x)	DSE Burner (12 vppm NO_x)	DSE Burner (20 vppm NO_x)
Full Fire	MBtu/hr	5,000	5,000	5,000
Flue Gas Recirculation	-	No	No	No
Turndown	-	5:1	5:1	5:1
Excess Oxygen Level	%	5.0	4.3	3.0
Boiler Efficiency	%	83.4	83.7	84.1
NOx (at 3% O_2)	vppm	<9	<12	<20
CO (at 3% O_2)	vppm	<200	<200	<200
Total Blower Pressure	in. w.c.	15.2	14.2	12.4
Blower Power	HP	2.5	2.2	1.8

Source: Gas Technology Institute

For smaller industrial and commercial boilers, current regulations require less than 9 vppm NO_x. To satisfy these requirements, current commercially available technologies employ either HEA operation or FGR. In comparison to HEA burners, the DSE burner is 2% more efficient and requires significantly less electric power to drive the combustion air blower (Table 7). In comparison to FGR systems, the DSE burner achieves similar or improved efficiency, with even further reductions in air blower power (Table 9). Additionally, the DSE burner offers a simple, low-cost design relative to FGR systems, which require significant additional equipment and operational provisions for cold startup procedures and gradual introduction of the exhaust gas stream to the burner inlet.

Table 9: Dynamic Staged Entrainment Burner Performance in Comparison to Conventional Technologies at <9 vppm Oxides of Nitrogen

Parameter	Unit	DSE Burner (9 vppm NO_x)	Conventional Low-NO_x Burner (without FGR)	Conventional Low-NO_x Burner (with FGR)
Full Fire	MBtu/hr	5,000	5,000	5,000
Flue Gas Recirculation	-	No	No	Yes
Turndown	-	5:1	4:1	4:1
Excess Oxygen Level	%	5.0	8.8	5.5
Boiler Efficiency	%	83.4	81.3	83.2
NO_x (at 3% O_2)	vppm	<9	<9	<9
CO (at 3% O_2)	vppm	<200	<200	<200
Total Blower Pressure	in. w.c.	15.2	24	24
Blower Power	HP	2.5	5	5 to 7.5 (estimate)

Source: Gas Technology Institute

To bring the technology to market, GTI has partnered with Power Flame Inc., a leading manufacturer in the United States of burners for commercial and industrial applications. Power Flame has been actively engaged in the burner development efforts to date and continues to express great enthusiasm for the technology. Given the high performance of the technology and the straightforward, low-cost design, the team is optimistic they will be able to offer the product to market with competitive pricing, ultimately enabling broad deployment.

LIST OF ACRONYMS

Term	Definition
BHP	Boiler Horsepower
CO_2	Carbon Dioxide
CO	Carbon Monoxide
CFD	Computational Fluid Dynamics
DSE	Dynamic Staged Entrainment
ED	Eddy Dissipation model
FR	Finite Rate model
FGR	Flue Gas Recirculation
GHG	Greenhouse gas
GTI	Gas Technology Institute
H_2	Hydrogen gas
HEA	High Excess Air
HP	Horsepower (electrical)
in.	Inches
in. w.c.	Inches water column
kWh	Kilowatt-hours
lb	Pounds
m/s	Meters per second
MBtuh	Thousands of British thermal units per hour
MMBtu/hr	Millions of British thermal units per hour
NO_x	Nitrogen Oxides
PIER	Public Interest Energy Research
psig	Pounds per square inch gage
O_2	Oxygen
SCAQMD	South Coast Air Quality Management District
SCR	Selective Catalytic Reduction
THC	Total Unburned Hydrocarbons
vVppm	Volumetric Parts Per Million

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