PARAMETRIC EVALUATION OF CLEARSIGN'S ULTRA-LOW EMISSIONS DUPLEX^{TM} TECHNOLOGY

Douglas Karkow[1], James Dansie[1], Venkatesh Iyer*[1], Jesse Dumas[1], Donald Kendrick[1], Jon Tonouchi[2], John Hinkey[2]

[1]ClearSign Combustion Corp., 12870 Interurban Ave S, Seattle, WA 98168

[2]Geminus Technology Development, LLC, 4047 39th Avenue SW, Seattle, WA 98116

Abstract: ClearSign's Duplex^{TM} technology is a revolutionary gaseous fuel combustion technology that reduces NOx emissions to sub-6 ppm levels over a wide range of refinery process conditions. Duplex utilizes premixed combustion within porous ceramic tiles to provide ultra-low emissions, high power densities, wide operating envelopes, and reduced flame lengths. The work described here is part of a larger effort to fully characterize, refine, and commercialize the Duplex technology. The paper reviews experimental testing and analytical modeling efforts to quantify the key performance parameters for Duplex. The parametric study involved examining the effects of a subset of Duplex design parameters – Duplex height, burner geometry, fuel injection scheme, and tile characteristics – on performance, operability ranges, and stability at varying operating conditions of fuel composition, firing rate, and excess air. Furnace temperature measurements allowed evaluation of temperature profiles in the furnace during Duplex operation. In addition, a chemical reactor network model to simulate combustion and heat transfer in ClearSign's test furnace was developed and validated. The model predicted trends in CO and NOx emissions and showed good agreement with test data for the parametric variations of interest.

---

1. Introduction:

ClearSign's Duplex platform is a revolutionary combustion technology that has proven its capability to achieve ultra-low levels of nitrogen oxides (NOx) emissions (below 6 ppm, corrected to 3% O_2), while also eliminating flame impingement on process tubes and enhancing radiant heat transfer. Duplex does not require external flue gas recirculation, steam injection, high excess air conditions and/or catalysts/reagents to achieve its superior performance. The technology has been successfully demonstrated in Once-Through-Steam-Generators (OTSGs), refinery process heaters, boilers, and enclosed ground flares. Duplex incorporates a high-temperature porous ceramic tile surface (i.e. Duplex surface) positioned a few feet away from the fuel/air injection plane. Fuel and air are mixed before reaching the Duplex surface and entrain internal flue gases which dilute the mixture prior to combustion. The mixture is then ignited by the hot, glowing Duplex surface which provides an effective

---

*corresponding author, venkatesh.iyer@clearsign.com

means for combustion stabilization, flame confinement, and radiation heat transfer. The modes of operation of the Duplex have been discussed in Ruiz and Kendrick [1] [2] along with the various strategies for NOx reduction that the technology integrates. Recently, Duplex has evolved into a Plug & Play^{TM} design that integrates the burner and the Duplex surface into a modular, pre-engineered package. This paper discusses the previous generation "monolithic" form of the Duplex technology.

2. Experimental

The evaluation studies were performed in a pilot-scale up-fired refinery process heater simulator. The heavily instrumented test furnace was capable of accommodating firing capacities up to 2 MMBtu/hr under natural draft conditions with ternary blends of natural gas, propane and hydrogen fuels. The water cooling system was designed to provide representative bridgewall temperatures and simulate typical radiant section efficiencies as found in standard refinery process heaters (~60%).

The test burner incorporated a swirl-stabilized premixed pilot encircled by a fuel manifold used in Duplex mode operation. The central pilot had an independent fuel supply and capacity up to 0.25 MMBtu/hr. The fuel manifold fed four sets of risers and orifices (see Fig. 1) with each riser individually controlled with ball valves. The pilot was used during furnace/Duplex warm up and was turned off for transition to Duplex mode [1] [2]. The burner incorporated a barrel-style air register. Installation or modification of the Duplex structure was performed by entering through a large furnace door on the side of the heater. The Duplex tiles rested on a lattice of ceramic rods which were supported by a peripheral metallic frame. The metallic support structure was connected to a winch and cable system permitting real time elevation adjustments for optimization and evaluation purposes (Fig. 1). Emissions measurements were acquired using a portable Testo 350 analyzer with the sampling port located immediately downstream of the bridgewall.

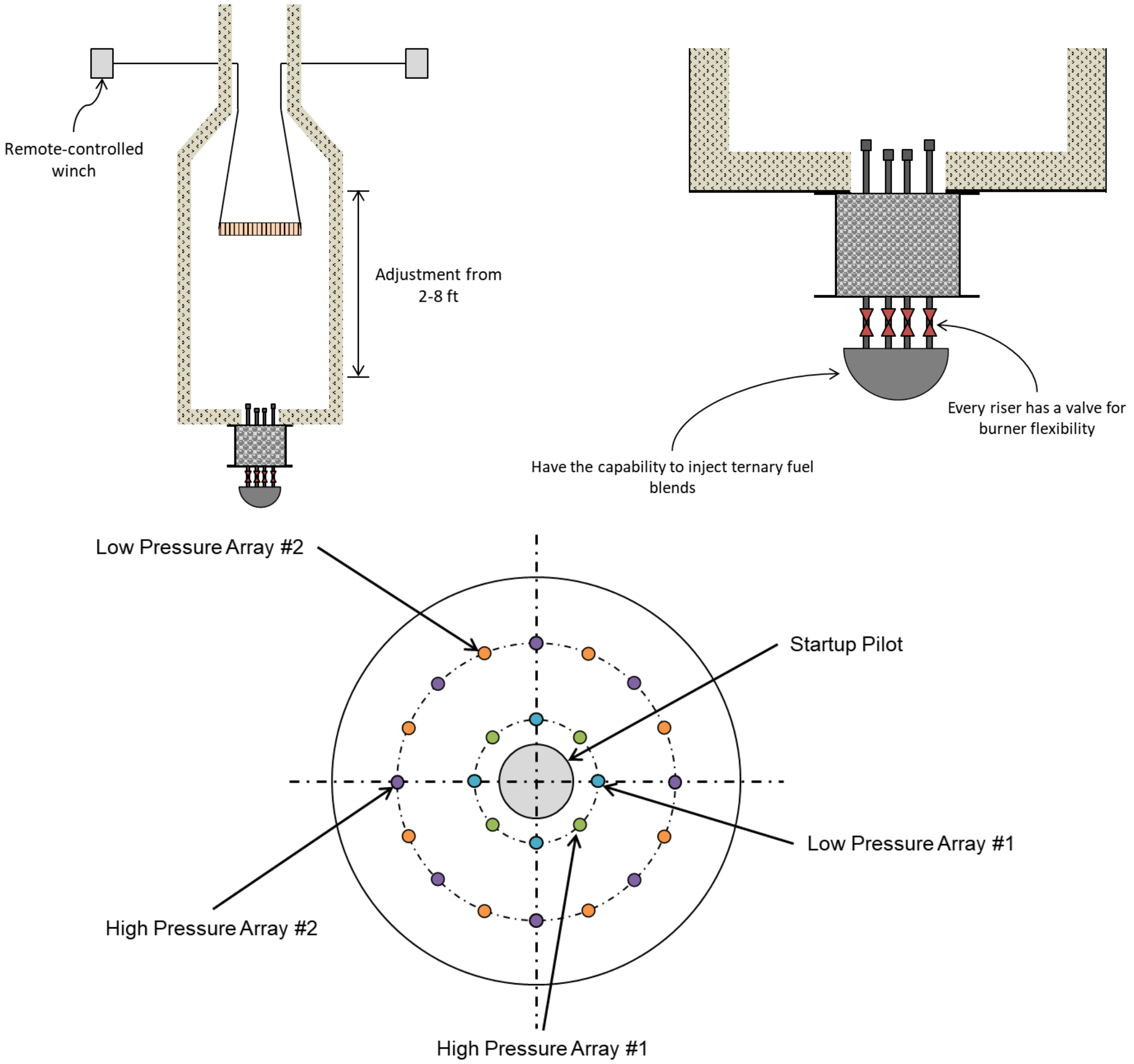

Fig. 1 – Schematic of the test furnace (top left), test burner (top right), and nozzle array geometry (bottom).

The fuel delivery system was capable of blending natural gas, propane and hydrogen as needed. Each fuel was controlled with automated control valves and equipped with a Fox Thermal FT2A mass flowmeter. Details on the fuels used in the testing are denoted in Table 1.

The furnace was instrumented to accurately measure fuel flow rates as well as bridgewall, floor and furnace wall temperatures. Further, a Dwyer Mark II manometer measured the furnace draft. The furnace had view ports at various locations to allow real-time viewing and video recording of furnace conditions. All data were recorded during Duplex operation and after the bridgewall temperature had stabilized (i.e. steady state conditions). At every set point, data was collected for a minimum of 5 minutes at a sampling rate of 0.2 Hz.

Table 1 – Gases used for testing.

Gas	LHV	Supply	Notes
Natural Gas	922	PSE	91% CH4, 6.2% C2H6, 1.5% C3H8
Propane	2385	250 USG Tank	
Hydrogen	275	K-Type Bottles	5.0 Ultra High Purity (99.9999%)

3. Computational Model Set-up

Using computational fluid dynamics (CFD) to calculate emissions is computationally expensive because of the detailed chemical kinetic mechanisms required to model NOx and CO formation. Instead of using CFD, a global network model was developed to calculate emissions using chemical reactor modelling (CRM). Detailed chemistry can be used with CRM because its runtimes are a fraction of CFD simulation times.

The CRM consists of a network of perfectly-stirred reactors (PSRs) and plug flow reactors (PFRs). A PSR is a continuous flow reactor that assumes all the gases in the reactor are perfectly mixed. A PFR is also a continuous flow reactor that consists of a series of thin-sliced PSRs. The CRM was coded using the Cantera chemical kinetics package [3] with Python as a wrapper code. The chemical kinetics mechanism used was GRI Mech 3.0 [4].

The reactor arrangement and sizing were based on an initial reacting CFD simulation of the flow-field in the furnace and is shown in Fig. 2. Streamlines of the CFD solution show different zones within the reactor, including a mixing zone, Duplex flow, post-combustion zone, flow through stack, and upper and lower recirculation zones. Mass flow to the Duplex and mass exchange between the mixing zone and lower recirculation zone was determined from free jet calculations. Estimates from CFD were used to determine the amount of flow bypassing the Duplex and mass exchange between the post-combustion and upper recirculation zones. The model also included wall heat transfer to the Duplex and furnace walls. A layout of the model is shown in Fig. 3.

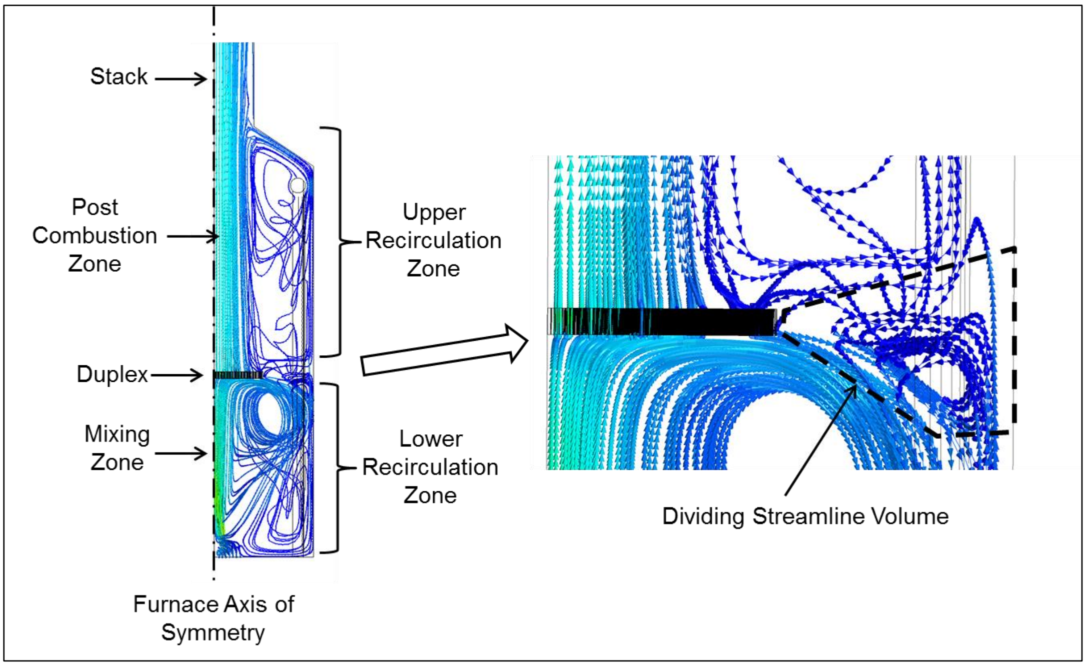

Fig. 2 – Reacting CFD Simulation showing the different flow zones in the furnace.

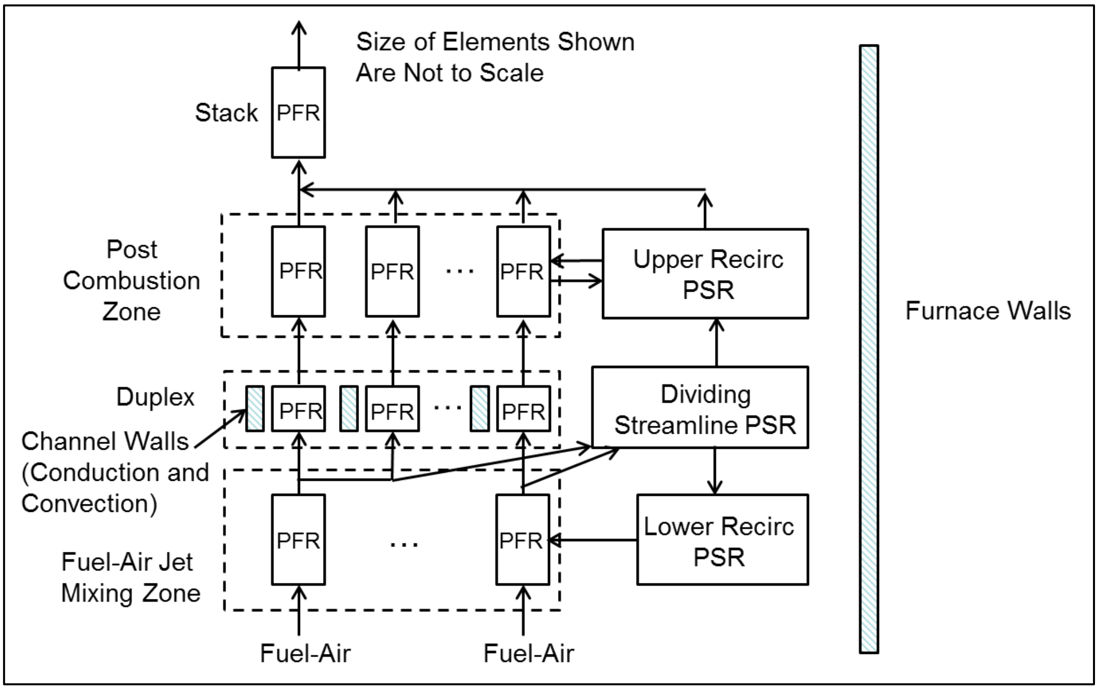

Fig. 3 – Layout of the Network Model for the furnace.

4. Results and Discussion

Four different tile configurations, of varying material, cell size, and thickness, were used for the testing. Details on the tile materials and specifications are proprietary to ClearSign and hence cannot be disclosed in this paper. The tile configurations will hence be referred to as Tile A, B, C, and D. The pressure drop across each tile configuration measured in an inhouse flow rig is summarized in the table below. The total pressure drop through the tile is a quadratic function of the superficial velocity, v, which is defined as the cross-sectional area mean velocity assuming no obstruction [5]:

$$\frac{\Delta P}{L} = Av + Bv^2 \qquad \text{Eq. (1)}$$

L (m) is the length of the tile in the direction of the flow, v (m/s) is the superficial velocity, and A (Pa-s/m^2), B (Pa-s^2/m^3) are the viscous and inertial resistances, respectively. Regression analysis on the pressure drop and flow rate measurements for each tile yielded the inertial and viscous resistances, A and B in Eq. (1). The resistances, normalized to those of Tile A, are summarized in Table 2, and can be used to estimate pressure drop per unit length at a given flow rate (or superficial velocity).

Table 2 – Pressure drop coefficients for the test tile configurations.

Tile Configuration	**Inertial Resistance {Normalized to Tile A}**	**Viscous Resistance {Normalized to Tile A}**
Tile A	1	1
Tile B	1.34	1.06
Tile C	3.88	3.50
Tile D	5.29	4.95

The following sections discuss the design parameters varied in this study and their effects on Duplex operability and emissions. NOx dependence on Excess O_2 is plotted in Fig. 4 for Natural Gas at a firing rate of 1.5 MMBtu/hr. The plot demonstrates the excellent NOx performance of the Duplex technology. Note that all emissions are corrected to 3% O_2 (dry). For typical diffusion flames, NOx decreases as excess air is reduced. The NOx behavior of the Duplex flame is consistent with that of a premixed flame. As the excess air increases, NOx reduces because of lower flame temperatures and dilution with recirculating flue gases. Typically, this trend continues until there is a spike in CO emissions indicating the onset of lean blowout resulting in flame quenching. For these tests, CO breakthrough occurred around 12% excess O_2. Tiles A and B had similar NOx emissions and trends within the measurement uncertainty.

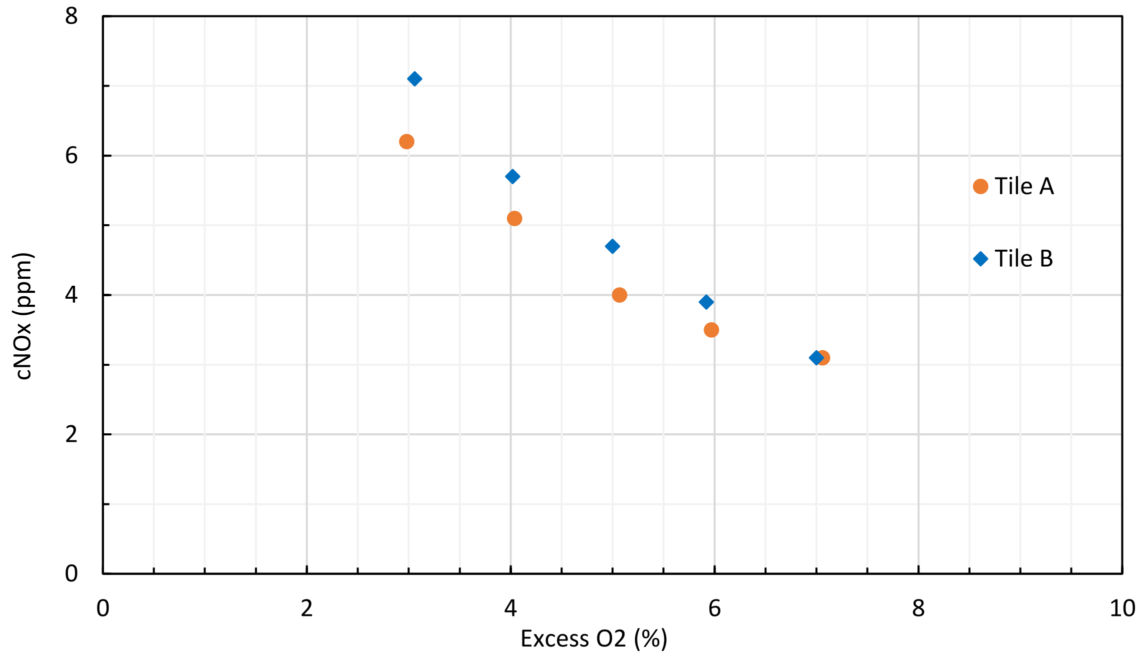

Fig. 4 – Effect of excess O_2 on NOx emissions.

Figure 5 shows NOx measurements at 3% excess O_2 as a function of Nozzle Diameters $\left(\frac{Duplex\ Distance}{nozzle\ size}\right)$ for the four tile configurations. The Nozzle Diameters were altered by varying the nozzle sizes and/or the Duplex distance (as measured from the injection plane to the upstream face of the tile). The firing rate was 1.5 MMBtu/hr with Natural Gas. The trends showed that NOx was a strong function of mixing and a weak function of tile blockage until employing the very high Duplex pressure drop of Tile D. Larger Duplex distances allow for better mixing of fuel and air prior to reaching the ceramic surface as well as more entrainment of internal flue gas to dilute the mixture thus lowering resultant peak flame temperatures. At small Duplex distances (Nozzle Diameters < 300), the high NOx was likely a result of incomplete mixing and lower flue gas entrainment and dilution generating hot spots (fuel rich zones). In the case of Tile D, the high pressure drop combined with low Duplex distances caused the flame-front to stabilize at a location between the tile structure and the furnace inlet. Consequently, its emissions behavior was more akin to that of a diffusion flame.

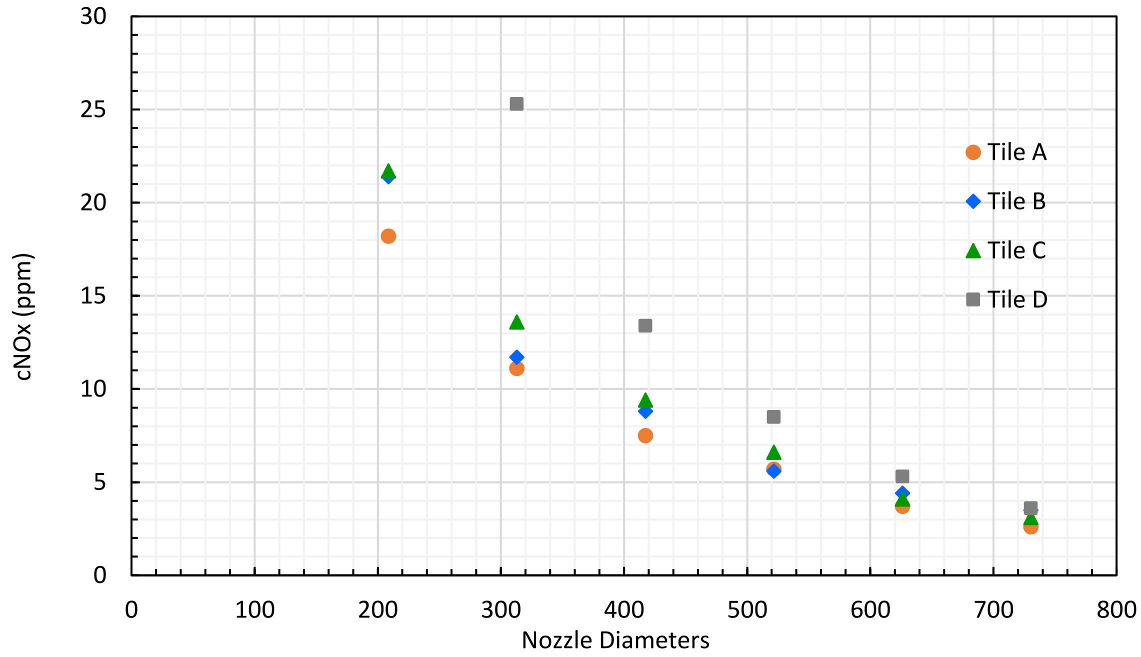

Fig. 5 – Effect of Duplex height on NOx emissions.

Refractory wall temperatures obtained for tile configurations A through D for three different Duplex distances are shown in Fig. 6. The measurements were for Natural Gas at a firing rate of 1.5 MMBtu/hr and 3% excess O_2. During Duplex operation, peak temperatures were observed near the ceramic surface. Tiles A and B demonstrated similar temperature profiles, Tile C showed slightly higher temperatures while Tile D had considerably higher temperatures. It is likely that an increase in tile pressure drop caused a proportional increase in flow bypassing the Duplex tiles and consequently increased the convective heat transfer to the furnace walls.

Figure 7 shows a comparison of NOx emissions for the four test tiles at different firing rates with Natural Gas. The Duplex distance was fixed at 470 Nozzle Diameters and the measurements were obtained at 3% excess O_2. Under these conditions, the NOx emissions were quite similar for the test tiles. As the cooling load was held fixed across the firing rates, any increase in firing rate resulted in an increase in chamber temperature likely causing the gradual increase in NOx emissions.

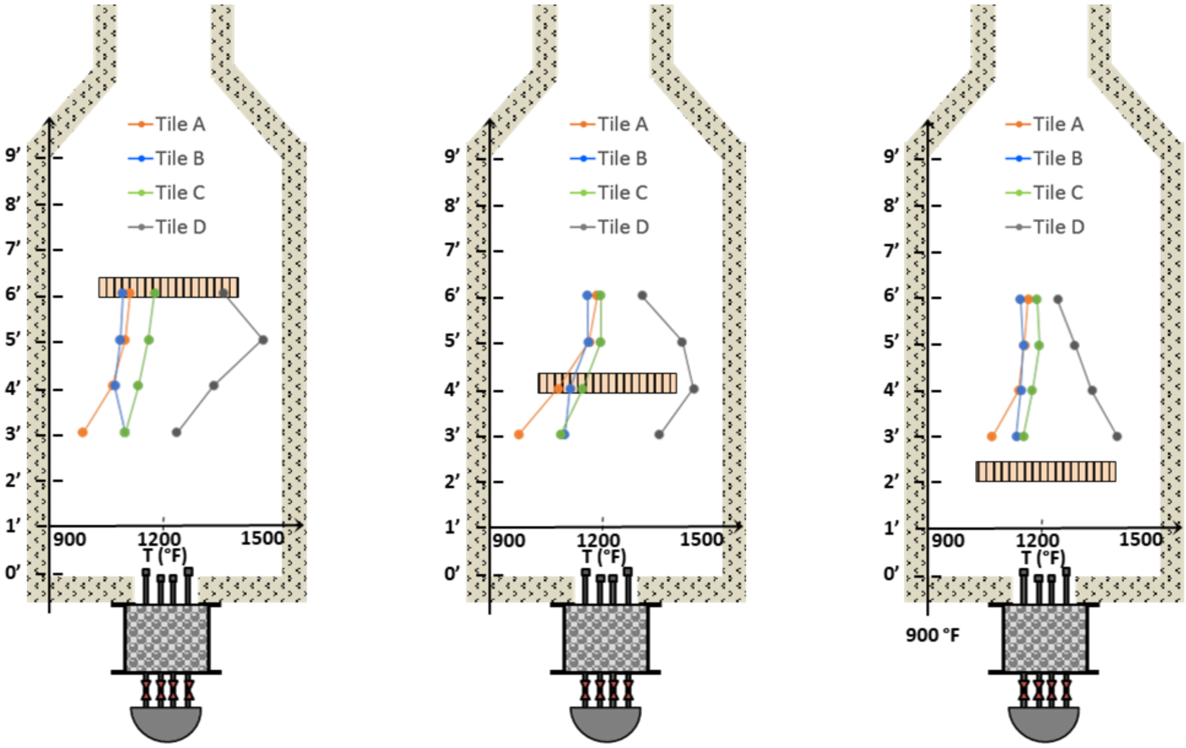

Fig. 6 – Furnace wall temperatures profiles for the test tiles.

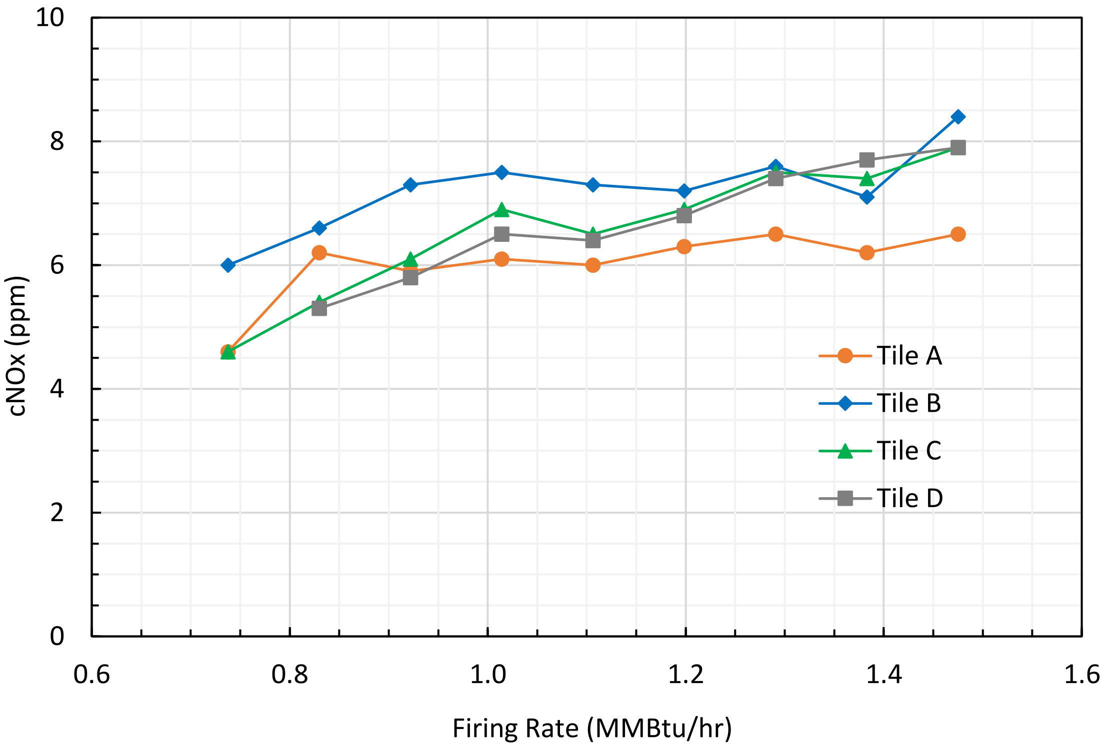

Fig. 7 – NOx emissions as a function of the Firing Rate.

Hydrogen operability limits for the Duplex and the corresponding "critical excess O_2 levels" are plotted in Fig. 8 for three different Duplex distances. The operability limits were defined by flame blow-off under lean/high excess O_2 conditions and flame retransition to the burner for high hydrogen concentrations (i.e. "critical excess O_2 level"). Excess O_2 was varied from 3% up to 15% or when blow-off occurred. Similarly, hydrogen was added to Natural Gas until the flame propagated substantially upstream ("retransitioned") back to the burner. The firing rate was maintained at 1.4 MMBtu/hr and the data were obtained for Tile D. Duplex Heights 1, 2, and 3 corresponded to Nozzle Diameters of 240, 290, and 340, respectively. Increasing the Duplex height allowed operation at higher hydrogen concentrations before retransition. Furthermore, for a given hydrogen concentration it allowed Duplex stabilization at a lower excess O_2. Although the fuel and air are better mixed and the jet velocity is lower at the higher heights, the decrease in propensity to retransition is likely a combination of increased flue gas entrainment and dilution as well as the Duplex being farther away from any flameholders near the burner. Also shown alongside the Duplex operability curves in Fig. 8 are the lean-blow-off (LBO) limits for Natural Gas-Hydrogen mixtures [6] [7].

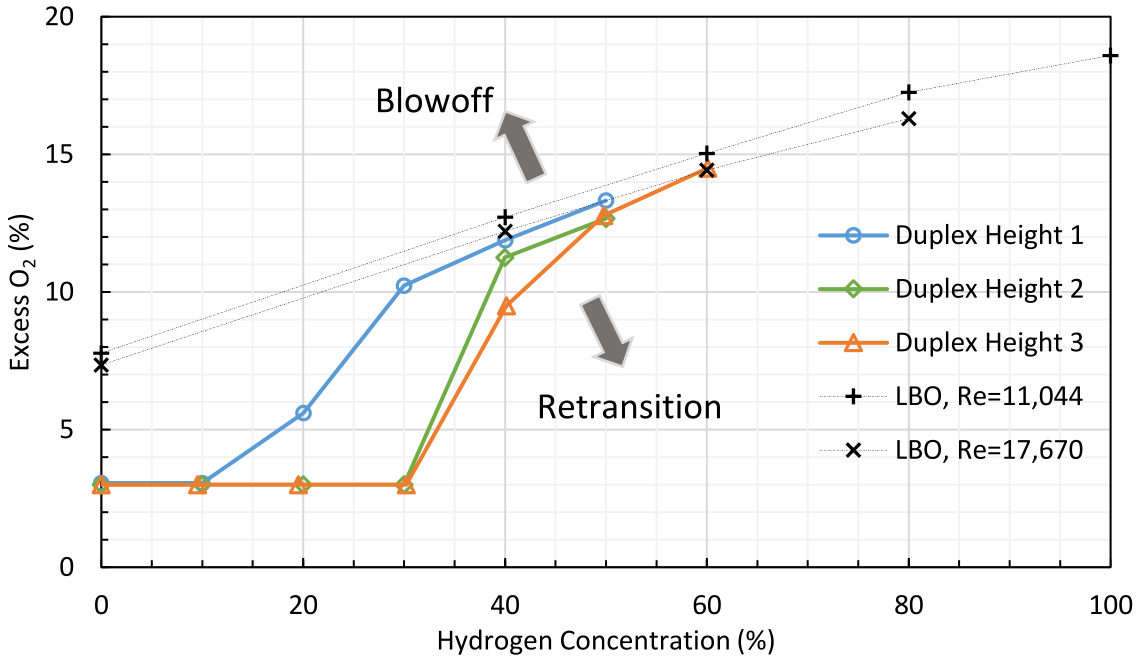

Fig. 8 – Operability Limits of Duplex – Critical excess O_2 and Hydrogen concentration effects. LBO limits from Ref. [6] [7].

The lower heating value (LHV) of the fuel was changed using blends of Natural Gas and Propane. As seen from Fig. 9, NOx emissions rose with increasing LHV of the fuel blend as a result of an increase in residence time and reduced mixing caused by the decreasing jet velocity. The flame front moved upstream, eventually even beyond the upstream face of the tiles. The firing rate was maintained at 1.5 MMBtu/hr and the excess O_2 at 3%. The data obtained was for Tile D positioned at a distance of 470 Nozzle Diameters.

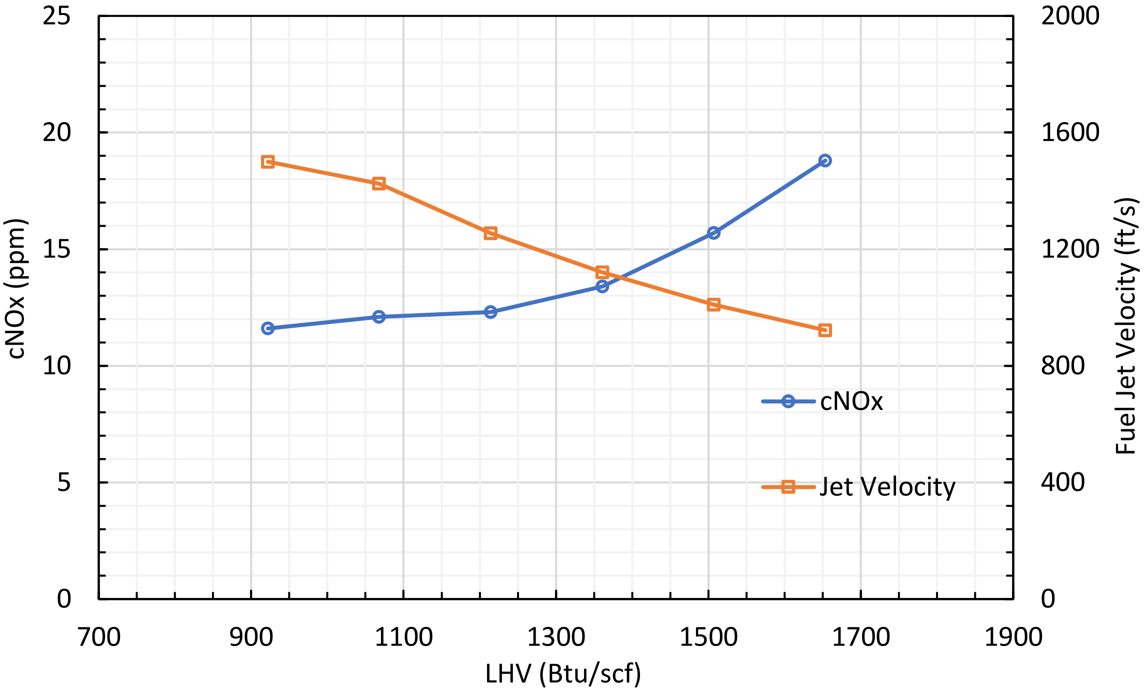

Fig. 9 – Effect of fuel heating value on NOx emissions.

Figures 10 and 11 summarize exemplar emission estimates obtained for the test furnace using the network model. The plots compare model predictions for CO and NOx emissions with experimental measurements. The data correspond to Duplex operation with Tile B at 1.4 MMBtu/hr with Natural Gas. The model showed a nearly linear trend for NOx as a function of Duplex distance and it correctly predicted a rapid increase in CO above Duplex distances of 600 Nozzle Diameters.

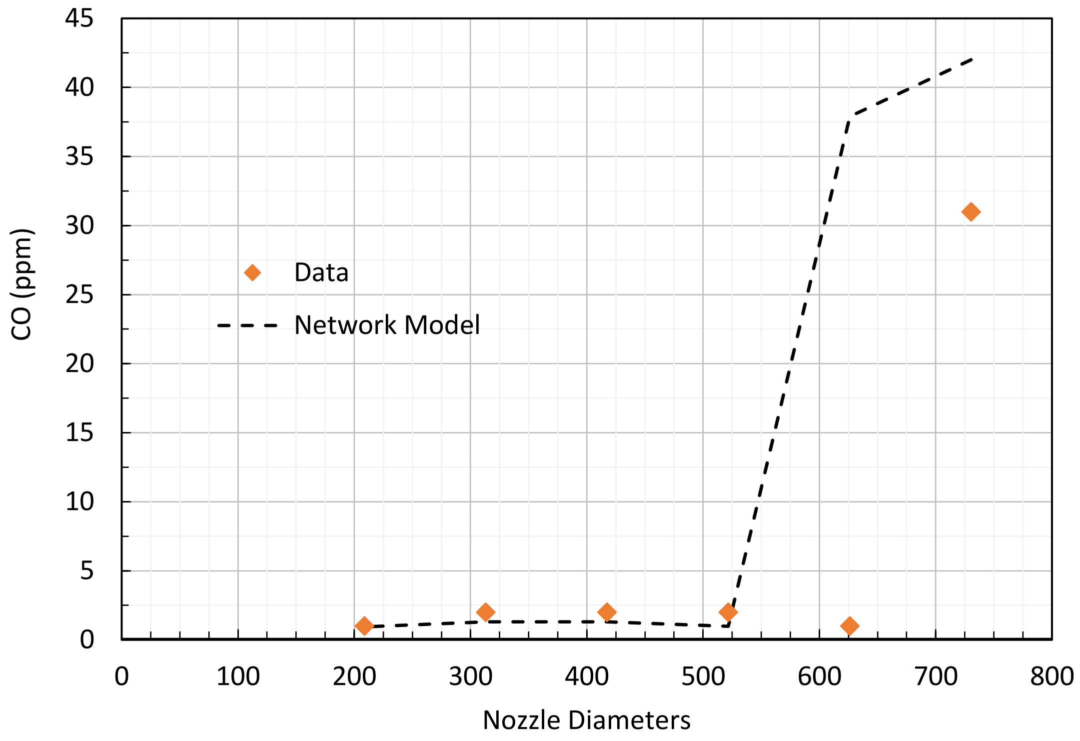

Fig. 10 – CO estimates from the Network Model.

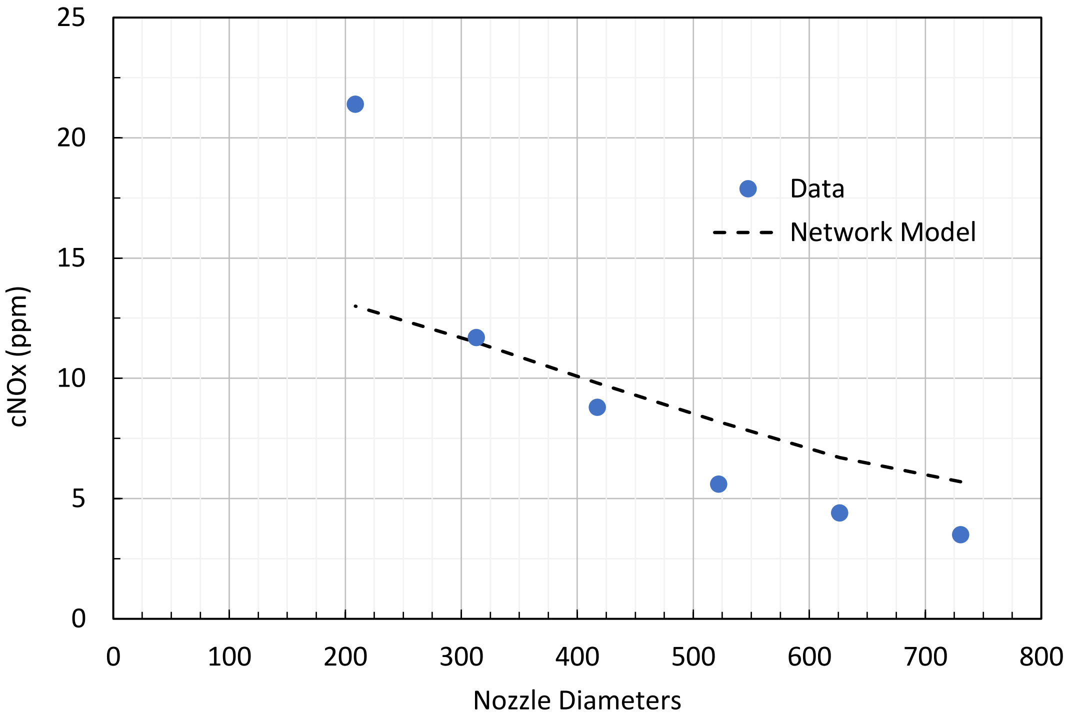

Fig. 11 – NOx estimates from the Network Model.

5. Conclusions

ClearSign's Duplex technology successfully demonstrates ultra-low NOx emissions over a wide range of conditions including variations in thermal output, fuel heating values, fuel hydrogen content, and excess air conditions. The extensive sensitivity studies for key design parameters like Duplex tile characteristics, Duplex height, burner geometry and their effects on Duplex performance and operation helped create a strong knowledge base for the technology, which has greatly assisted in scale-up efforts for commercial applications. The "monolithic" Duplex platform has been successfully retrofitted in furnaces with firing capacities ranging from 5 to 60 MMBtu/hr. Further development has evolved the technology into a second platform, dubbed "Duplex Plug & Play", which expands on the capabilities outlined in this paper and can be easily retrofitted to replace existing conventional or low NOx burners. This architecture has been successfully installed at a customer site with hydrogen fuel fractions approaching 70% by volume while still delivering sub-6 ppm NOx emissions.

References

[1] R. Ruiz and D. Kendrick, "DuplexTM - A Creative Innovation in Industrial Combustion Technology," *American Flame Research Committee's Industrial Combustion Symposium*, Kauai, HI, 2016.

[2] R. Ruiz and D. Kendrick, "New Technology Slashes NOx Emissions at California Refinery," *Oil & Gas Journal,* pp. 56-62, 2017.

[3] D. G. Goodwin, H. K. Moffat and R. L. Speth, Cantera: An Object-oriented Software Toolkit for Chemical Kinetics, Thermodynamics, and Trasport Processes, 2017.

[4] G. P. Smith, D. M. Golden, M. Frenklach, N. W. Moriarty, B. Eiteneer, M. Goldenberg, C. T. Bowman, R. K. Hanson, S. Song, W. C. G. Jr., V. V. Lissianski and Z. Qin, *Gri-Mech,* Berkeley, CA.

[5] J. Howell, M. Hall and J. Ellzey, "Combustion of Hydrocarbon Fuels Within Porous Inert Media," *Progress in Energy and Combustion Science,* vol. 22, pp. 121-145, 1996.

[6] S. Zhu and S. Acharya, "An Experimental Study of Lean Blowout with Hydrogen-enriched Fuels," *Journal of Engineering for Gas Turbines and Power,* vol. 134, pp. 1-10, 2012.

[7] S. Zhu, "Experimental Study of Lean Blowout with Hydrogen Addition in a Swirl-stabilized Premixed Combustor," Ph.D. Dissertation, Louisiana State University and Agricultural and Mechanical College, 2012.