Results of a Hydrogen Fueled Sub-5 ppm NO_x Burner Test Program

Matthew Martin <matt.martin@clearsign.com>; Jeff Lewallen <jeff.lewallen@clearsign.com>; Kirk Meinershagen <Kirk.Meinershagen@clearsign.com>;
Carley Hockett <Carley.Hockett@clearsign.com>

Using hydrogen as a fuel source is one method to reduce carbon emissions from fired equipment. Many nozzle-mix burners used in refineries and petrochemical plants can fire hydrogen with little or no modification. However, when firing hydrogen, NO_x emissions may increase beyond permitted limits, the heat flux profile may change, and modifications required to extend burner component life may adversely affect flame shape.

ClearSign Technologies Corporation builds on its prior experience in single-digit NO_x producing burners for refinery fuel gas fired heaters with a new test program for a burner supporting fuel gas ranging from 100% methane to 100% hydrogen firing. An already completed prototype test program yielded promising results leading to a commercialization program with full scale testing and currently commercial burners in production.

The resulting burner design is presented highlighting the features that enable 100% hydrogen operation. Results of computational fluid dynamics (CFD) simulations show critical dimensions of the burner in relation to NO_x production and hydrogen operation. Resulting performance including NO_x and flame dimensions are discussed as well as the interplay between NO_x and key operating parameters such as excess air and firebox temperature.

This material is based upon work supported by the U.S. Department of Energy, Office of Science, under Award Number DE-SC0022909.

Hydrogen Combustion

Many companies are turning to hydrogen to reduce CO_2 in hard-to-abate industries. Although it is common for fuel in fired heaters to contain hydrogen, even as high as 80% by volume, it is rare to find 100% hydrogen fired burners. Some burners currently installed are capable of firing 100% hydrogen fuel without flashing back or experiencing damage from higher flame temperature. Many burners will require some modification or will need to be replaced. Almost all burners will experience a NO_x increase when firing higher hydrogen fuels and in many cases this higher NO_x will exceed regulated limits.

ClearSign has embarked on a 100% hydrogen capable burner development program. The goal of this program is to deploy a commercialized burner that is capable of firing any refinery fuel gas blend ranging from 100% methane to 100% hydrogen and including mixtures of heavier hydrocarbons. The burner is also designed to produce NO_x from a combustion only solution that is competitive with the NO_x reduction available from selective catalytic reduction units.

The program is still ongoing but has already resulted in a commercially viable burner that can fire 100% hydrogen as a fuel while producing less than 5 ppm NO_x corrected to 3% excess oxygen with bridgewall temperatures consistent with typical refinery heaters. This burner is natural draft and does not require any fans, external flue gas recirculation, or the addition of steam.

ClearSign's Process Heater Burner Evolution

Duplex

The ClearSign Duplex™ resulted from the realization that increased mass and premixing of inert and reactants beyond that available in an Ultra Low NO_x Burner (ULNB) would further reduce NO_x [1]. Critically, this can be done without additional momentum beyond that available in a natural draft fired heater with typical fuel pressure.

Figure 1 shows a diagram of the Duplex installed in a partial view of a fired heater radiant section. A ceramic structure – or distal combustion surface - sits several feet above existing burners. Once the burners bring the firebox to a safe operating temperature, fuel is removed from the burner nozzles and added to a second set of fuel nozzles, or the burner is otherwise adjusted, such that flame will not stabilize before the ceramic structure [2].

The additional jet entrainment length and mixing afforded before the flame is stabilized on the ceramic tile reduces the flame temperature and the resulting NO_x. There is an additional benefit in that the combustion system now responds to excess air as a premixed burner instead of a nozzle mix burner; increasing excess air reduces NO_x instead of increasing it. In practice this technology achieved NOx emissions of 1.5-6.0 ppm [2].

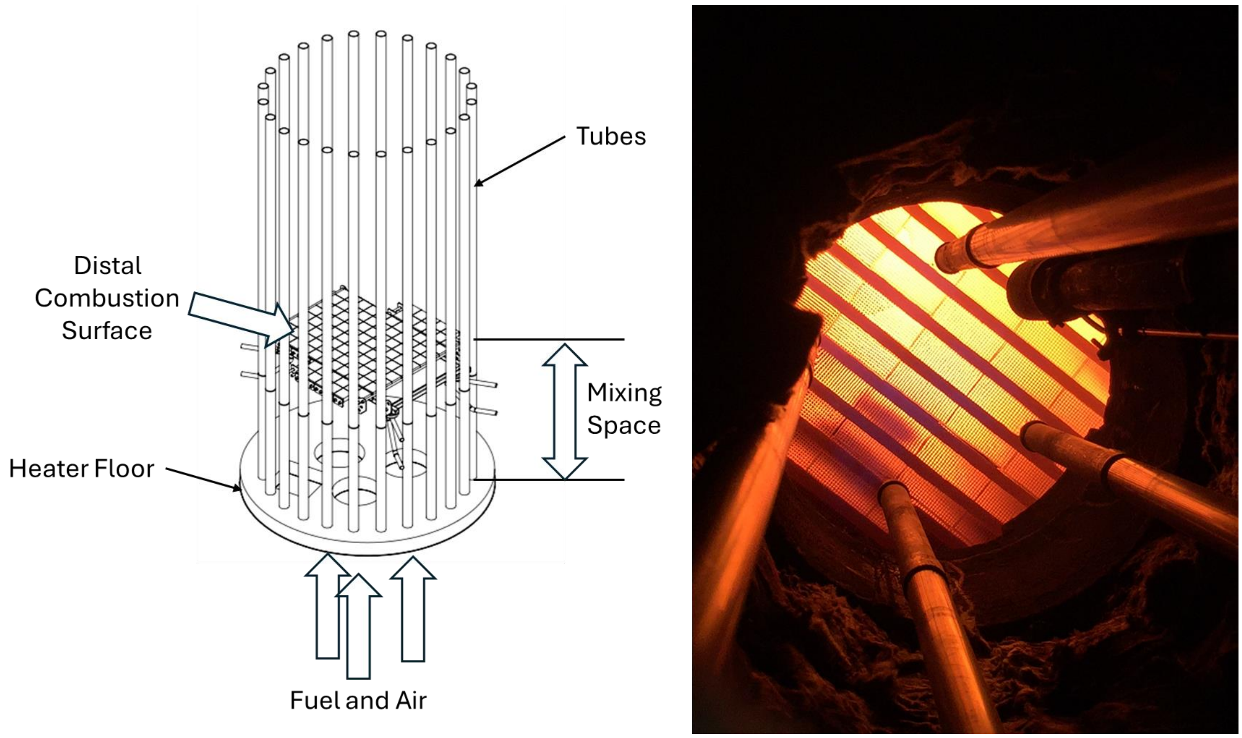

Figure 1 - The ClearSign Duplex. (Left) A diagram showing the system installed in partial view of a fired heater. (Right) Duplex in operation, looking from the bottom of the heater.

ClearSign Core™

The concepts behind the Duplex system were modularized into the base components required to achieve the premixing, entrainment and distal flame stabilization. This modularization is known as ClearSign Core technology. These components were packaged into the Duplex Plug & Play™ Burner in response to industry demands. The new design eases flame safeguarding, light-off procedures, and project execution by using the same technology and work processes as any other burner.

Further refinement to this technology resulted in the current ClearSign Core Process Burner shown in Figure 2. The burner is fully premixed both to minimize NO_x production and to allow for further reduced NO_x with increased excess air. One downside to this approach is that the volume of hydrogen in the fuel is limited to approximately 70% before flashback. Another downside is that with uncontrolled excess air turndown is limited to approximately 2:1. This turndown ratio is a function of the flammability limits of most fuels when fully premixed and is not unique to this burner.

The upper limit of hydrogen content and turndown capability can be increased by turning fuel injection nozzles off when the fuel flow is reduced to maintain exit velocity and alter the mixing. A higher fuel injection velocity locally guards against flash back by keeping the flow above the flame speed. Localizing the fuel injection within the air stream limits premixing before the flame zone thereby reducing the dilution of the fuel to maintain flammability.

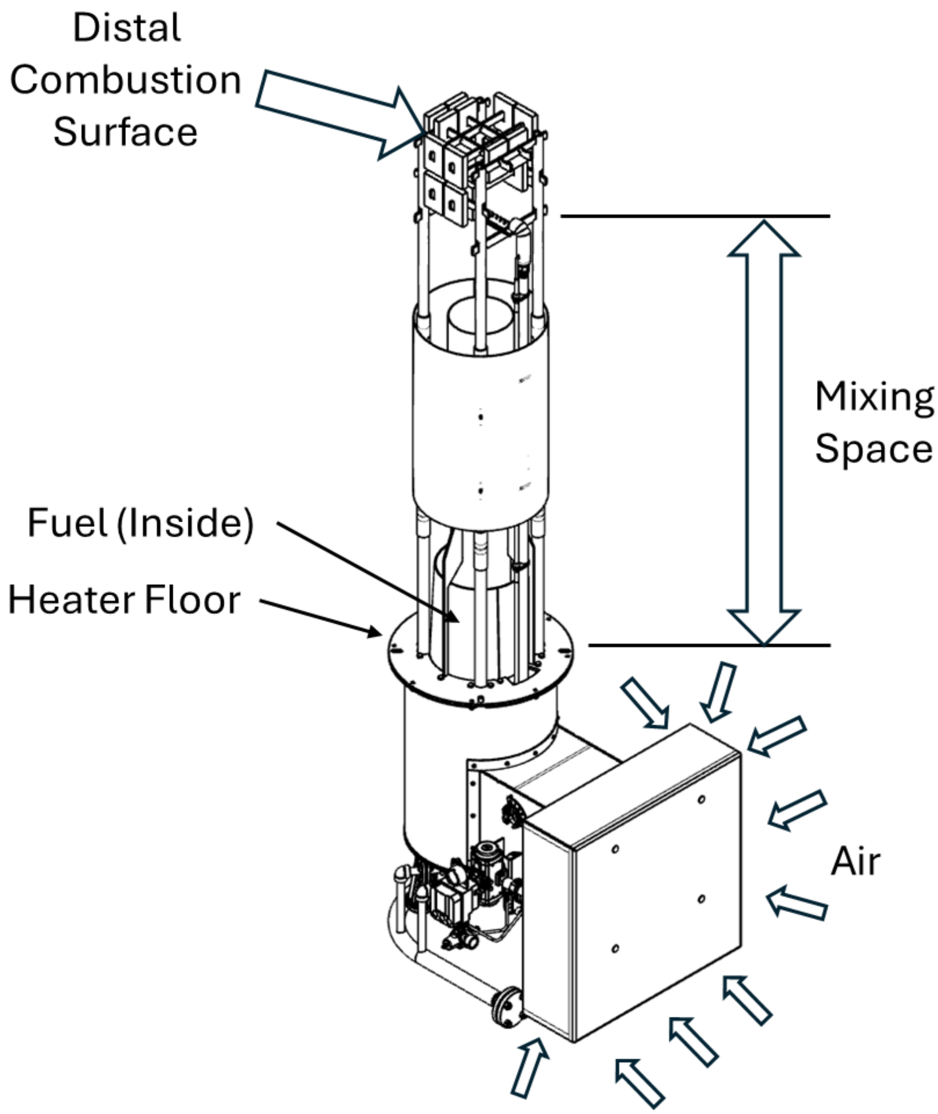

Figure 2 – The fully premixed ClearSign Core Process Burner.

Figure 3 shows another variation on the technology. In this case there are defined flow paths where fuel and air are premixed in a central tube, additional fuel and flue gas are mixed in peripheral tubes, and there is an air/flue gas mixing pathway. This segmented approach has the effect of partially premixing the flow before the final mixing space leading to the distal flame holder without the use of valves to actuate the fuel flow to different parts of the burner.

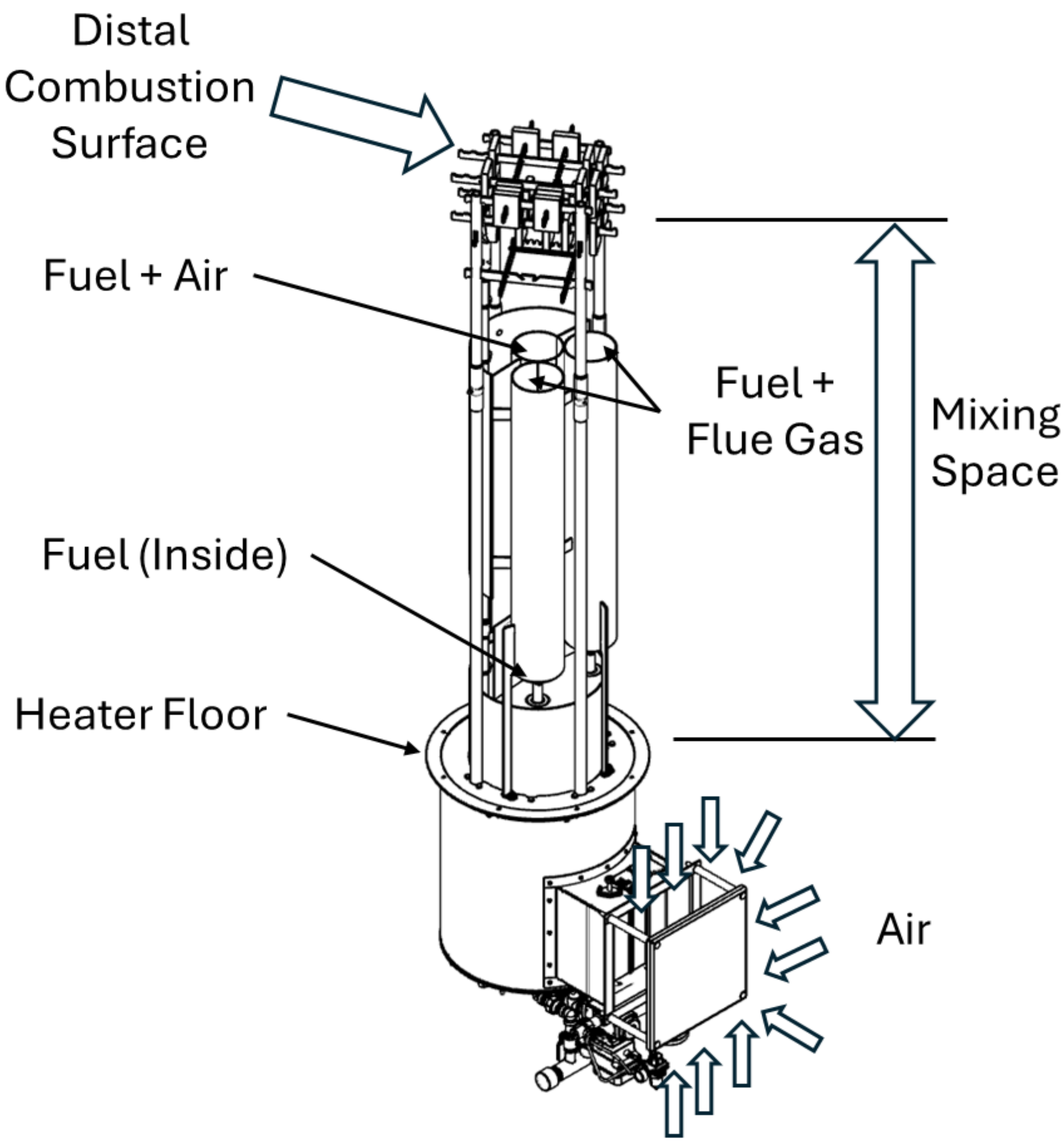

Figure 3 - A variation on the technology used to support greater fuel gas variability.

100% Hydrogen Fuel Burner Testing

Phase I Burner Design

ClearSign developed a small scale 100% hydrogen capable burner during the initial phase of a DOE sponsored projection. Figure 4 shows the prototype burner. The fuel's motive force pulls flue gas through the horizontal pipes. The mixture is ejected through the central vertical pipe toward the distal flameholder. This configuration reduces the flame temperature by first premixing the fuel with vitiated flue gas and then allowing the flame temperature to be further reduced by premixing this fuel/flue gas mixture with air before the distal flame holder. The air at the periphery of the burner is allowed to mix with flue gas before the same distal flame holder, further reducing the ultimate flame temperature and the resulting NO_x. An important feature of this design is that it maintains premixed flame characteristics while using hydrogen as a fuel. This configuration was successfully tested with 100% hydrogen fuel.

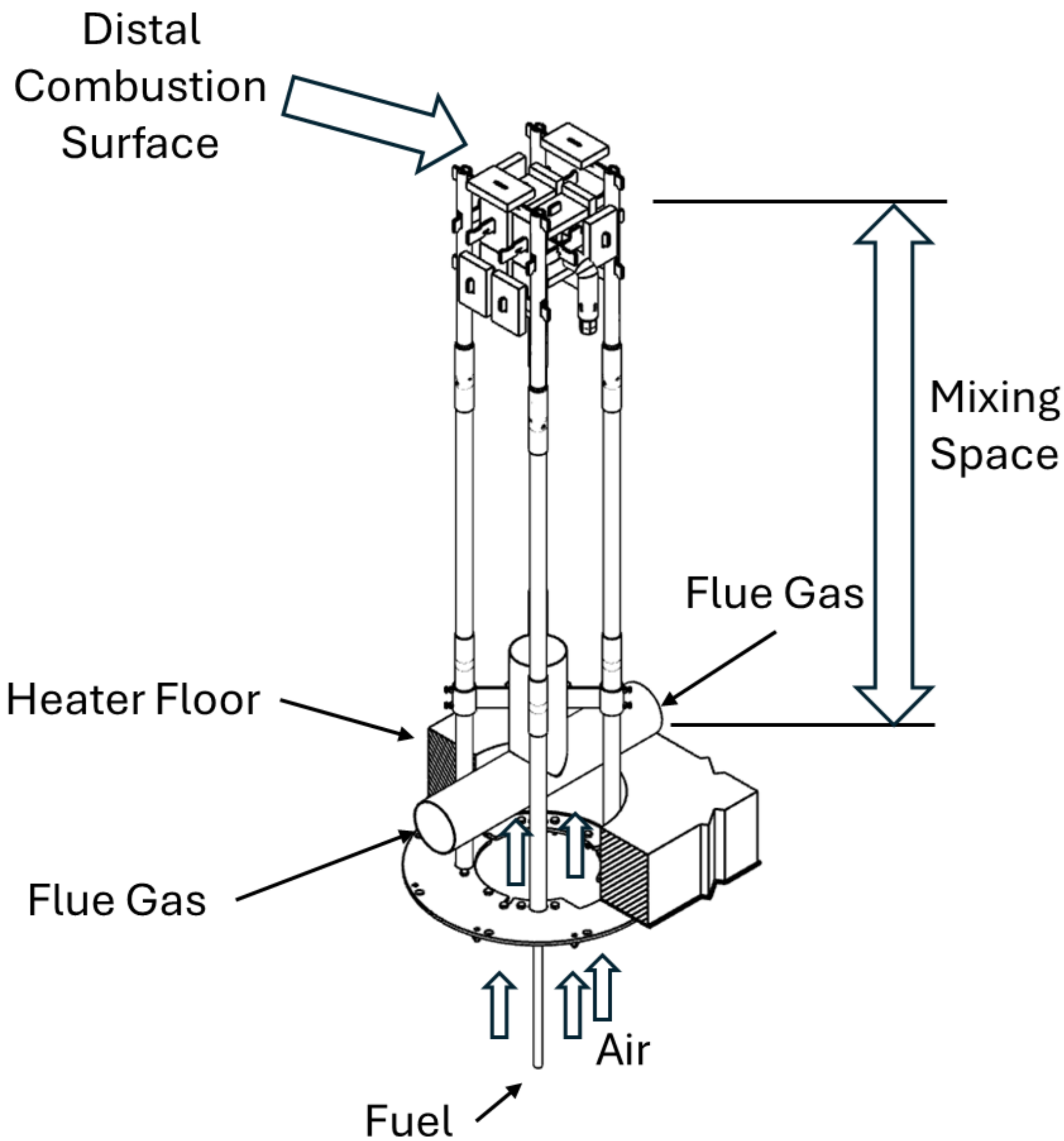

Figure 4 – The prototype ClearSign 100% hydrogen burner.

Phase II Burner Design

In the next phase of development, the burner was scaled up to 4 MMBtu/h (1.17 MW). This burner design incorporates design elements from the partially premixed burner of Figure 3 to support better turndown and improve performance in multi-burner installations. Here again the fuel gas is used as the motive force to mix fuel and flue gas prior to the distal flame holder. The air is mixed with flue gas prior to the distal flame holder as well. The functional characteristics of the Phase I burner of Figure 4 are replicated in a different form factor. Although ongoing, the initial testing was very successful. The burner produces 3.62 ppm NO_x corrected to 3% O_2 at a 1435 °F firebox temperature operating at 2.6% excess oxygen.

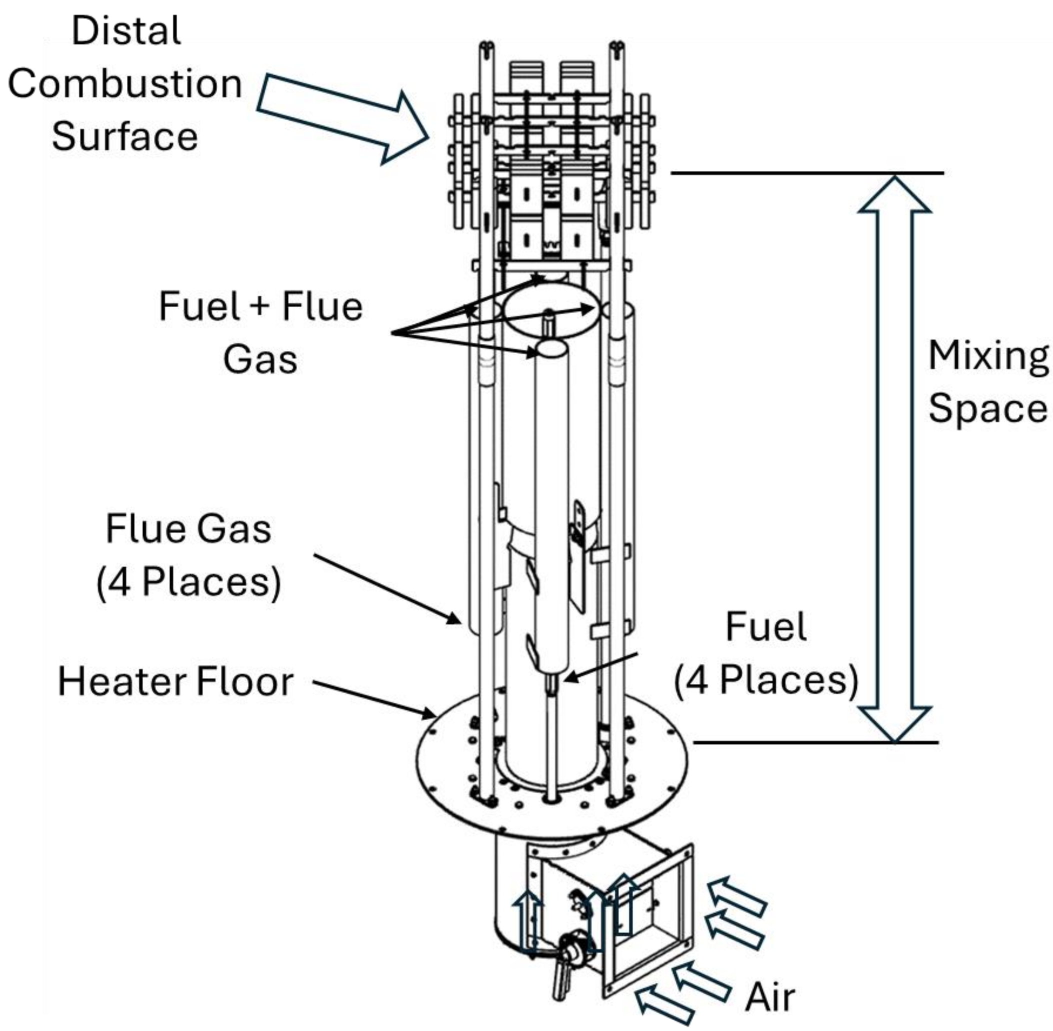

Figure 5 - Higher heat release 100% hydrogen burner.

Test Program Results

NO_x Production versus Excess Oxygen

Figure 6 shows dilution corrected NO_x produced by the burner versus excess oxygen for roughly equivalent conditions. The regression line through the data shows that the NO_x does increase as the excess air (oxygen) increases indicating that the burner is functioning as a nozzle mix burner and not as a premix burner. Given that the bulk of the fuel is injected through the mixing tubes at the periphery of the burner as shown in Figure 5 and since the distal flame holder is significantly closer to the air and fuel outlets this outcome would be expected.

It is noteworthy that over a range of excess oxygen from 1.4 to 5% that the NO_x only varies by 2.82 ppm and that this variation also includes variability from other sources such as fuel composition and operating temperature. It is usually possible to control the excess air to within less than a 4% oxygen band, restricting the NO_x variability to less than 3 ppm.

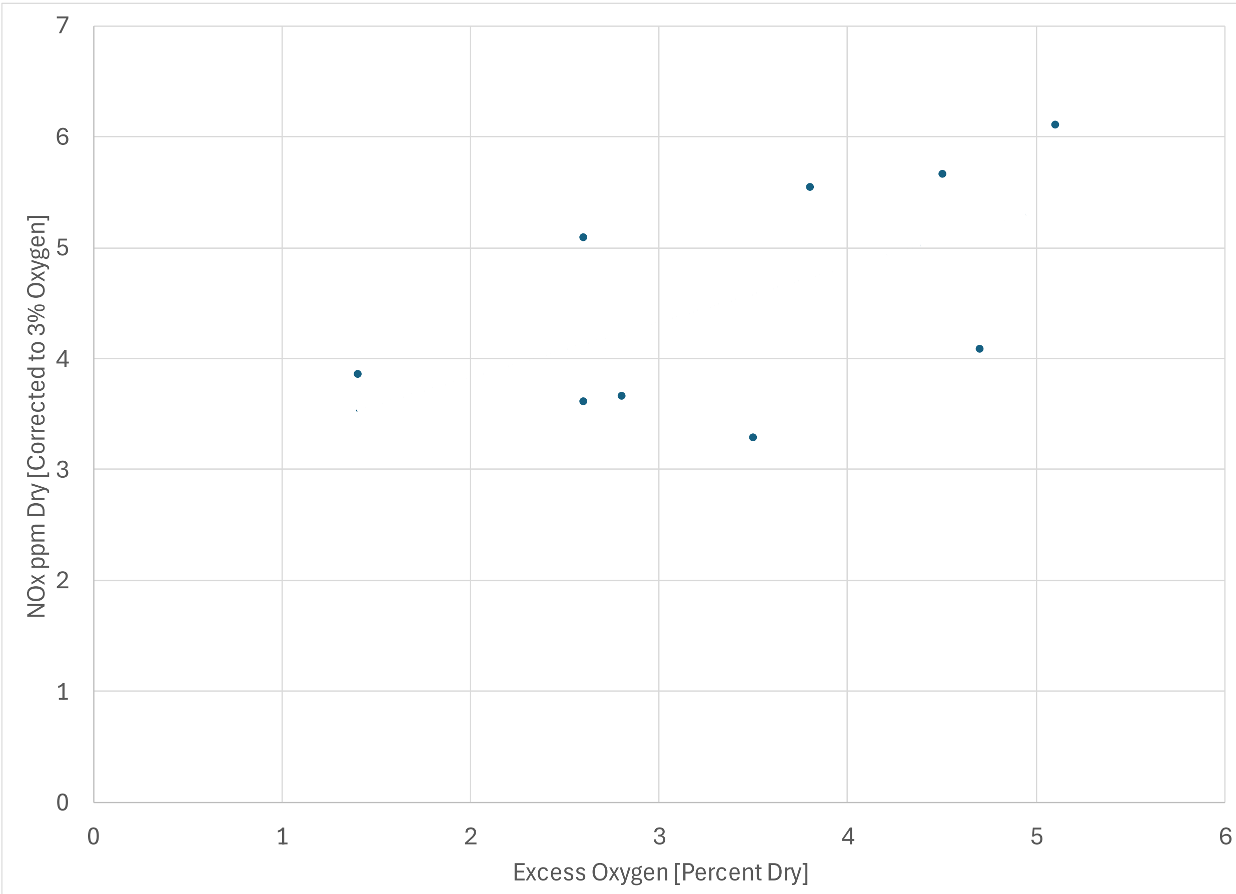

Figure 6 - NOx versus Excess Oxygen.

NO_x Production versus Bridgewall Temperature

Figure 7 shows NO_x production versus the bridgewall temperature. The results show that the NO_x decreases slightly as the bridgewall temperature increases. This behavior is counter to expectation, NO_x chemistry, and that of other burners. The most likely explanation is that the aerodynamic behavior of the burner changes with increased fuel pressure. As the firing rate of the burner increases against the essentially fixed heat transfer of the test furnace, the bridgewall temperature increases. However, the increase in entrained flue gas resulting from increased fuel flow also increases the flue gas mass in the combustion zone. The flame temperature and NO_x are reduced in turn.

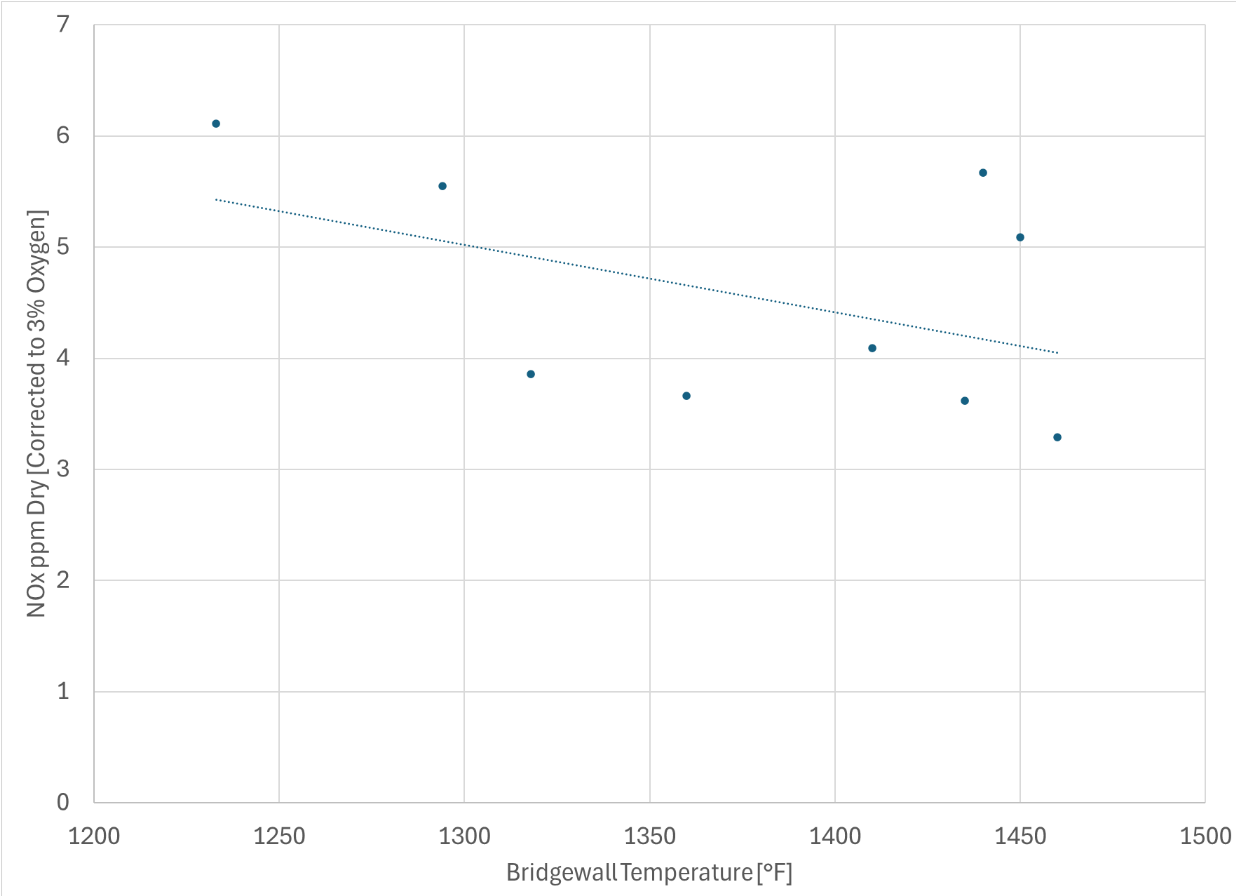

Figure 7 - NOx versus Bridgewall Temperature.

The change in NO_x versus bridgewall temperature is very small compared to the behavior of conventional burners. This suggests that the NO_x performance, in practical terms, is largely independent of the radiant section temperature. Although the burner has a well-defined flame, this behavior is similar to MILD or flameless combustion, indicating a Damköhler number approaching 1.

NO_x Production versus Fuel Pressure

Figure 8 appears to confirm the conjecture that increased fuel pressure reduces NO_x for this burner. As the fuel pressure increases, either due to increased firing rate or increased hydrogen volume in the fuel, the NO_x is reduced.

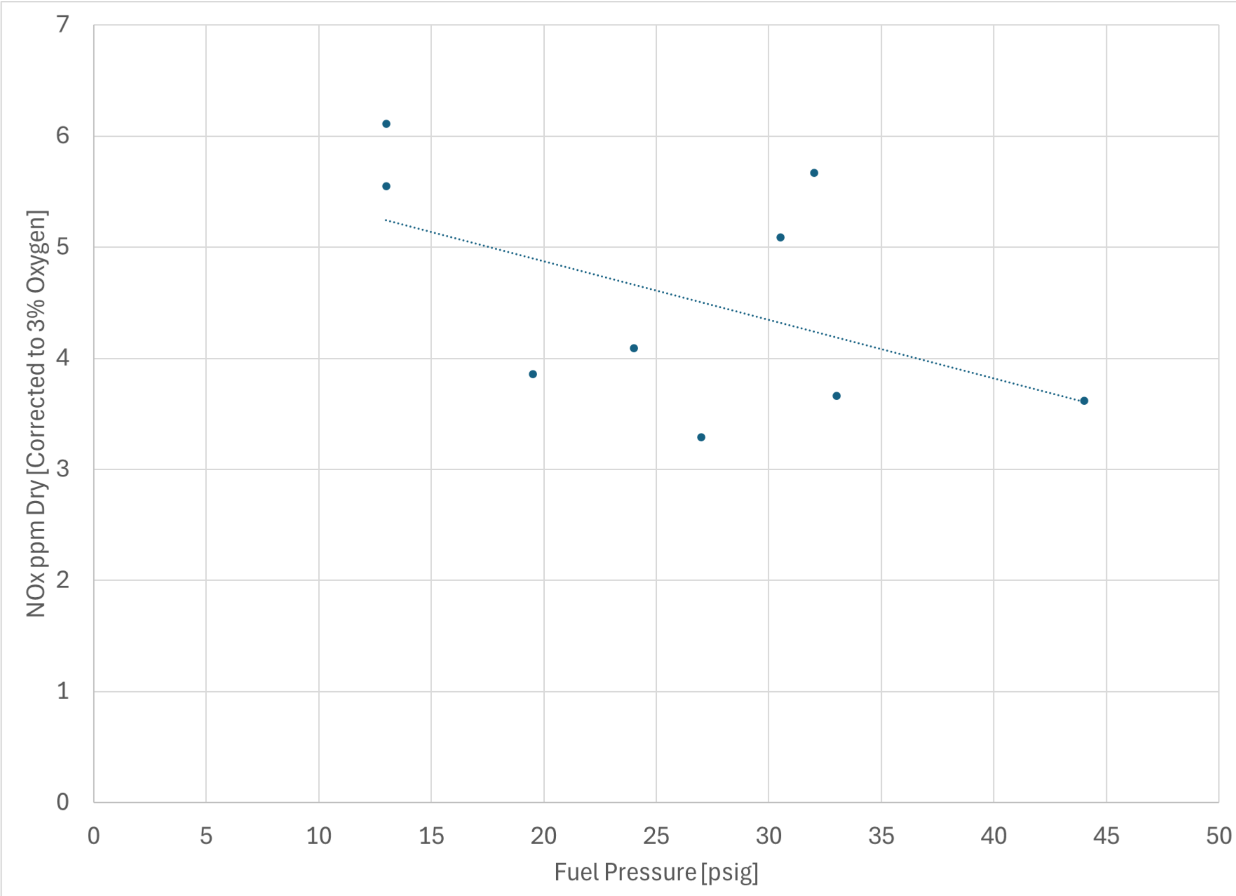

Figure 8 - NOx versus Fuel Pressure.

NO_x Production versus Hydrogen Content in the Fuel

Figure 9 shows NO_x production versus the mole percent hydrogen in the fuel gas. This graph shows one of the more interesting output responses for the burner. It appears that as the hydrogen concentration of the fuel initially increases the NO_x is increased due to elevated flame temperature but is then reduced from the elimination of prompt NO_x as the hydrogen approaches 100%. It can be confirmed that this effect is not a function of the fuel pressure; the resulting pressure for a 50% CH_4/50% H_2 volume mixture is essentially identical to that of a 100% H_2 fuel at the same heat release and yet the NO_x is higher.

Pilot Burners and NO_x

For all test points the pilot remained in operation using natural gas as a fuel source. Although not represented in this data set, experience has shown that there is a 1 to 2 ppm NO_x contribution to the total from the pilot burner. For this data set it implies that on average another 21 to 42% reduction in NO_x can be obtained by turning the pilot burner off.

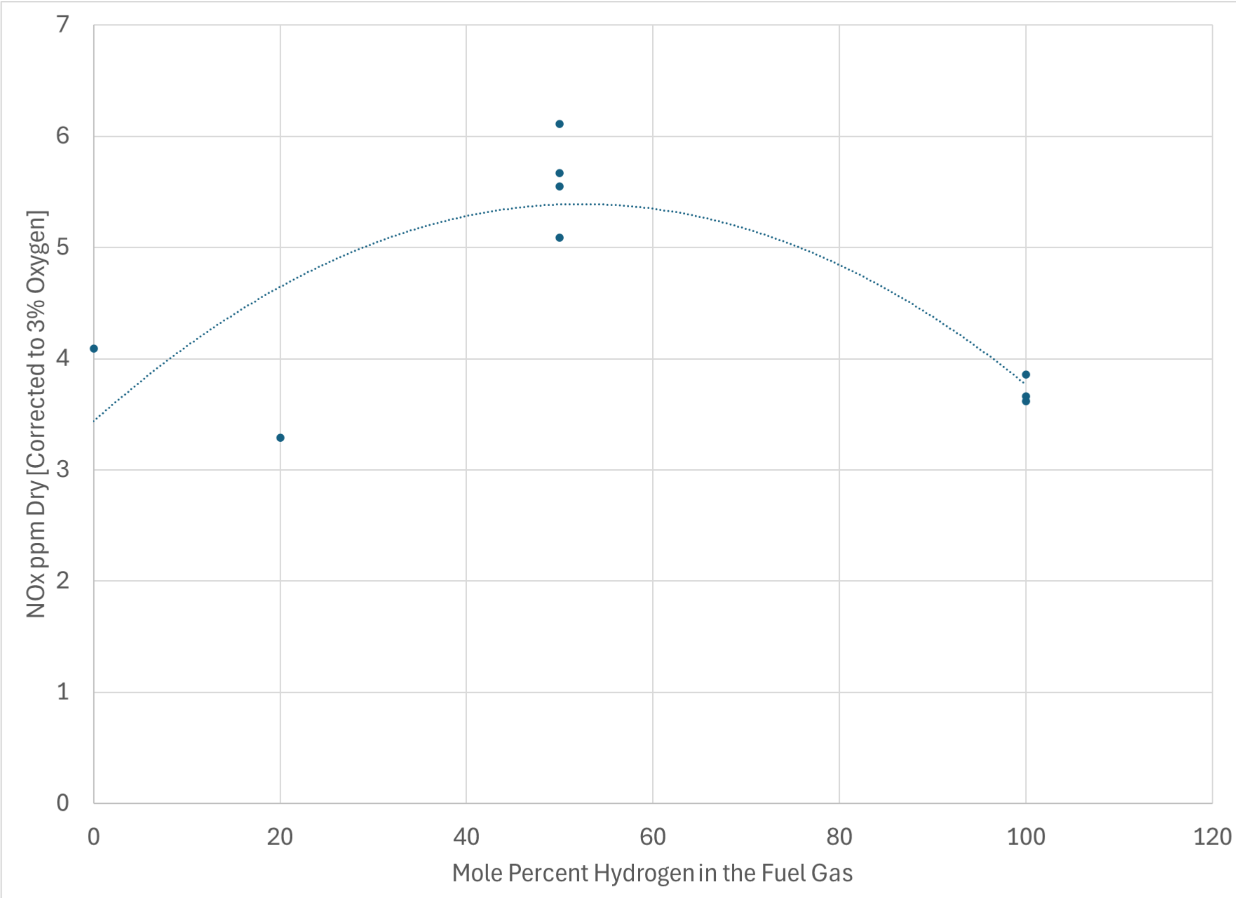

Figure 9 - NOx versus Mole Percent Hydrogen.

CFD Burner Simulations and Data Comparison

Quantitative Validation

Table 1 shows a comparison of test data to a CFD simulation of the same. There is a notable discrepancy between the actual and simulated temperature measurements. There remains some uncertainty in the precise position of velocity thermocouple sample point inside the test furnace. Perhaps more importantly the tubes of the test furnace were insulated. This insulation is not in perfect contact with the tube surfaces introducing uncertainty in the composite thermal conductivity of the main source of heat transfer from the flue gas. Given more adjustment to the model the temperature could be more closely matched.

The predicted NO_x from the CFD simulation is 3.36 ppm dry corrected to 3% excess oxygen compared to 3.62 ppm measured. This predicted NO_x includes approximately 1 to 1.5 ppm in NO_x from the natural gas fueled pilot burner as well as 0.5 ppm in uncertainty from the iterations of the CFD solver. These NO_x predictions are made by including complex chemistry in the CFD simulation as opposed to the one or two-step mechanisms commonly used in industrial CFD.

Table 1 - Comparison of physical test data to CFD simulation.

Measure	Test	CFD
Bridgewall Temperature [°F]	1435	1526
Floor Temperature [°F]	990	1135
NO_x [ppm @ 3% excess O_2 dry]	3.62	3.36
Excess Oxygen [% dry]	2.6	2.6

Visual Comparison

Figure 10 shows a comparison of the predicted appearance of the burner and the actual when in operation. The predicted temperature from CFD was used to color the left image from the simulation with the scale being set to match the observed color at right. In the area of the image marked (1), one can see the CFD simulation correctly predicts that the tiles at the interior of the distal flame holder operate at a higher temperature than the adjacent tiles that are farther from the burner axis. The area denoted as (2) shows that the simulation is predicting much higher temperatures at certain locations on the interior of the distal flame holder; a similar hot streak can be seen in both images. The support posts in the areas (3) to (4) show the hot-to-cold gradient from top to bottom. Finally, the 100% hydrogen fueled flame is shown in the area marked (5). The flame is represented by a hydroxyl iso-surface in the CFD simulation.

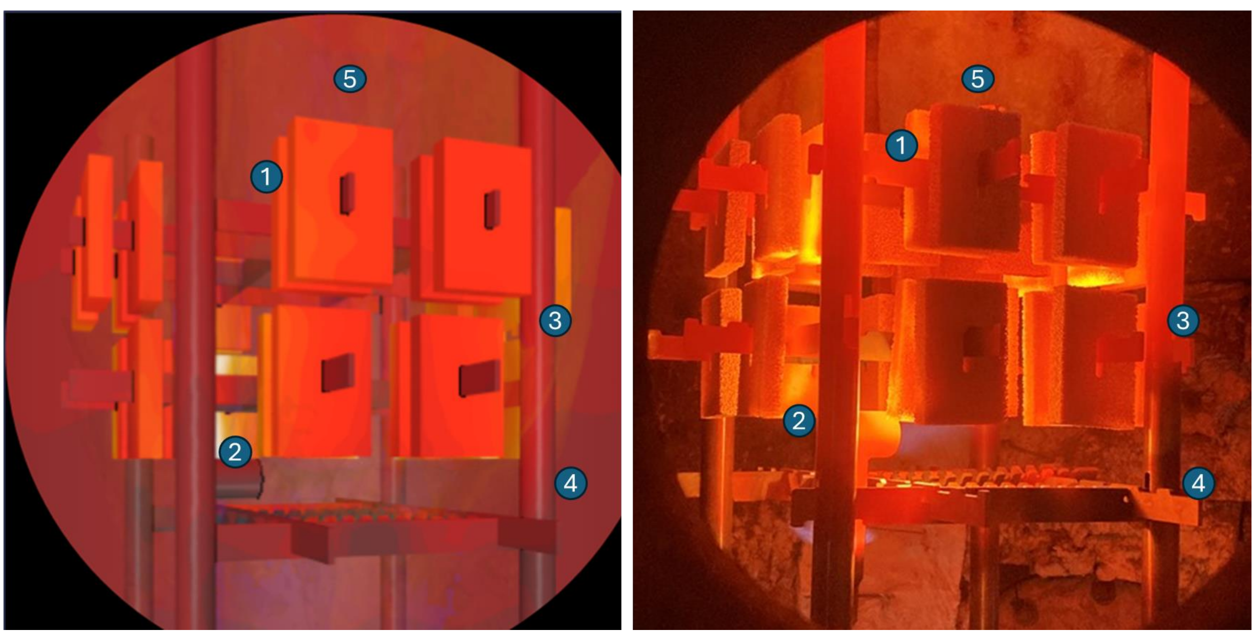

Figure 10 - Comparison of the CFD simulation (left) and the test burner (right).

Comparison of Mixing and Reaction Progress

Figure 11 shows a comparison of peak hydrogen and temperature between the development (ClearSign) and a generic nozzle mix ultra-low NO_x burner (ULNB). The x-axis is the distance from the burner throat normalized by the burner throat diameter. At axial distances $D/D_0=0$ and $D/D_0=1$, the ClearSign burner achieves a lower concentration of hydrogen due to the premixing with flue products prior to the flame. This behavior persists at $D/D_0=2$ where the flow from the ClearSign burner still has a peak mole fraction of hydrogen of 0.231 versus 0.239 for the nozzle mix ULNB. At axial distance $D/D_0=3$ and greater the ULNB exhibits lower peak concentrations of hydrogen. This is due to the relatively high peak flame temperature of the ULNB at $D/D_0=1$ of 3718 °F. In contrast, the ClearSign flame is temperature is predicted to peak at 2892 °F at $D/D_0=1$ and reduce to 2578 °F by $D/D_O=5$.

The moderating effect of mixing in the ClearSign burner on the flame temperature is key to the reduced NO_x production. Less evident from this graph is that not only is the peak flame temperature lower but also the volume of the flame at the high temperature is also reduced. This principle reduces the NO_x by an order of magnitude compared to earlier generations of ULNB.

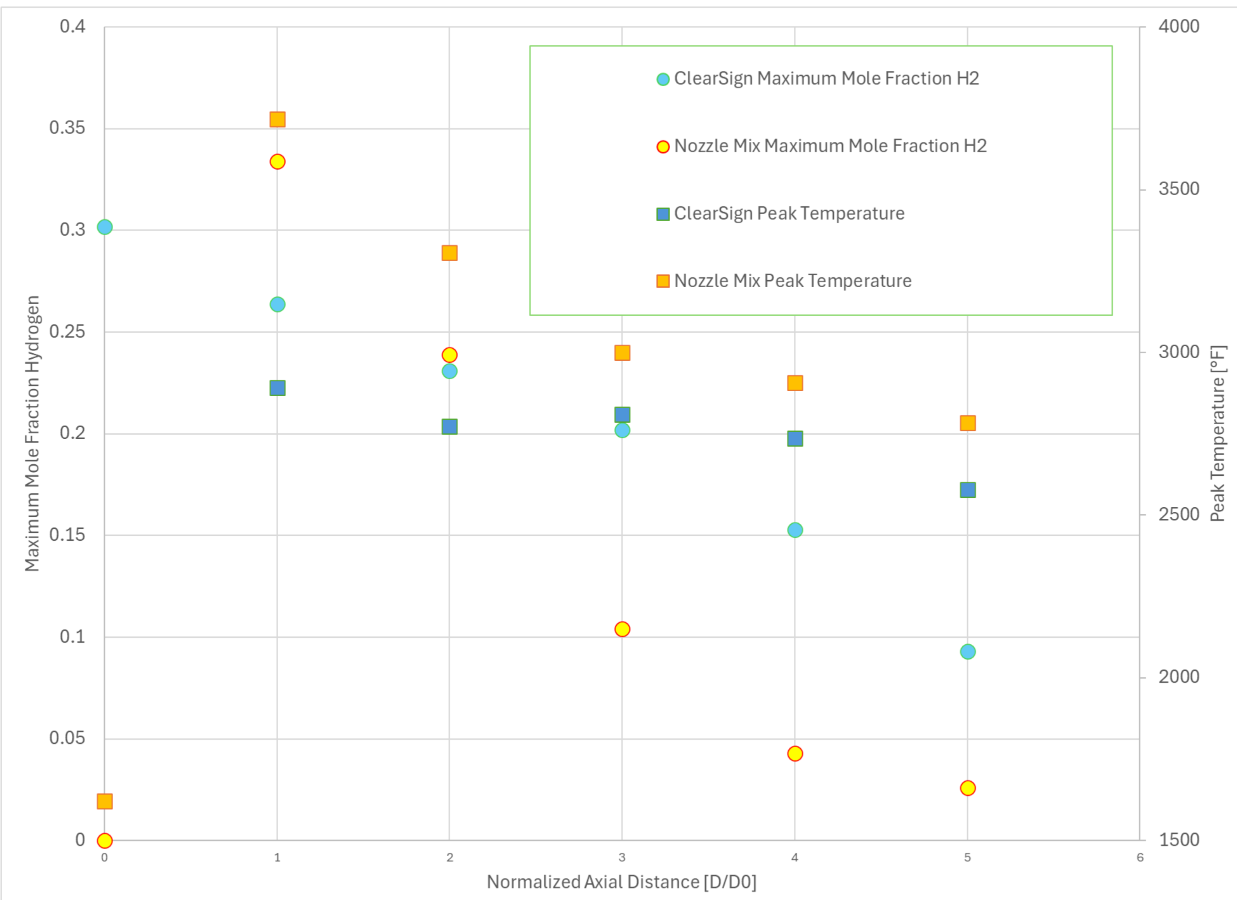

Figure 11 - A comparison of peak hydrogen concentrations and temperatures at normalized downstream locations.

Summary and Conclusions

ClearSign Technologies Corporation has developed a novel burner capable of firing 100% hydrogen. This technology can produce less than 4 ppm NO_x dilution corrected to 3% excess oxygen at a bridgewall temperature consistent with typical refinery heaters. At least 1 ppm of the recorded NO_x is emitted by a natural gas pilot, which may be turned off during normal operation. This is achieved without steam, external flue gas recirculation, or forced draft operation.

The burner's NO_x performance is relatively insensitive to changes in bridgewall temperature and excess oxygen. Increasing the available fuel pressure at the burner will further reduce NO_x. The NO_x performance is dependent on the fuel mixture, with the most NO_x being produced when the fuel is a 50%/50% blend, by volume, of hydrogen and natural gas.

The performance of the burner can be replicated in CFD simulations. Comparison of the mixing between the new ClearSign burner and an ultra-low NO_x nozzle mix burner of conventional design shows that lower flame temperatures drive NO_x production that is an order of magnitude lower than previous generation burners.

Firing pure hydrogen eliminates CO_2 emissions from flames. For most refineries and petrochemical plants any increase in NO_x is unacceptable. This new burner design is based on providing inert mass in the combustion zone, fuel/air premixing, and a distal flame holder. These features provide a method to not only fire hydrogen as fuel in concentrations up to 100%, but also to reduce NO_x to single digit performance.

References

[1] D. Karkow, "DUPLEX Technology Demonstrates Sub-5 PPM NOx and CO Simultaneously Without SCR, FGR, or High Excess Air," Salt Lake City, 2015.

[2] R. Ruiz, "Duplex™ – A Creative Innovation in Industrial Combustion Technology," in *Proceedings of the American Flame Research Committee*, Popui, 2016.