Advancement in Ultra-Low-NO_x-Burner Technology – Next Generation Burner for Hydrogen Firing

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ABSTRACT

Worldwide Net Zero commitments will require significant efforts to decarbonize the Oil and Gas Industry. Use of hydrogen fuel at concentrations close to 100% by volume instead of hydrocarbon-based fuels is one key avenue to address decarbonization efforts. However, the current generation of Ultra-Low NO_x Burners (ULNBs) and recent advances in process burner designs have limited capabilities in handling higher concentrations of hydrogen (potential flashback) and in managing NO_x emissions (higher flame temperature in hydrogen combustion producing higher NO_x). Newer designs currently being tested or offered require complicated additional hardware and sophisticated control/protective systems. In the near future, the industry will have a considerable demand for the next-generation ULNBs suitable for 100% hydrogen firing that produces much lower NO_x emissions and are easy to retrofit on existing fired heaters.

FREE JET Gen 3, the next generation ULNB design developed and presented here, can fire 100% hydrogen in addition to a wide range of fuel gas compositions and produces significantly lower NO_x emissions. Burner tile size is comparable to existing burners of similar heat release, thus allowing easy retrofits. Single fuel gas connection to burner keeps the fuel gas piping modifications to a minimum and, most importantly, does not need additional fuel or air controls or protective systems. No external flue gas recirculation is required, no lean-pre-mix technology is used, and the burner is suitable for both natural and forced draft systems with ambient or preheated combustion air.

Zeeco and ExxonMobil jointly conducted burner testing for both single and multi-burner set-ups for a wide range of process conditions. Results showed exceptional flame stability, performance, emissions reduction, and flame dimensions similar to current design ULNBs. ExxonMobil installed these first-of-a-kind next-generation ULNBs in a process fired heater at the Baytown facility. Early operational results have proven to be consistent with burner shop testing results, and the burner is delivering expected emissions reduction and operational flexibility.

Considering the complexities of current emerging technologies, or potential use of Selective Catalytic Reduction (SCR) systems, this design offers an excellent cost-effective alternative for easy retrofits without complicated controls, additional protective systems or operational requirements and yet achieves considerable emission reduction. This FREE JET Gen3 new burner technology, paired with ExxonMobil's low-carbon hydrogen offering, allows end-to-end solution enabling creation of low emissions pathways to net zero. This has been one key ingredient to ExxonMobil and Zeeco entering into a strategic alliance and will help with wide adoption and support for decarbonization across sectors.

INTRODUCTION

Worldwide Net Zero commitments will require a significant effort to decarbonize the oil and gas industry and move towards net-zero emissions. One key avenue to achieve carbon footprint reductions in fired equipment is through high hydrogen fuel instead of hydrocarbon-based fuel. Because burning hydrocarbon-based fuel containing as much as 80% hydrogen cuts CO_2 emissions only in half, a higher concentration of hydrogen, likely close to 95%, is needed to achieve net-zero emissions targets. Thus, to meet industry goals for decarbonization, a process burner design must be made available that can safely, reliably, and cost-effectively combust close to 100% hydrogen.

Most fired heaters and process furnaces that exist today were designed for firing natural gas or refinery fuel gases that contain a high proportion of hydrocarbons plus hydrogen, inert gases, and traces of other compounds. Hydrogen content for typical refinery fuel gas may vary between 20% and 40%. When converting burners to fire high hydrogen, H_2 concentrations of 90% to 100% are probable. This concentration of hydrogen changes the operating parameters of the burner, requiring adaptations to the burner design to ensure burner and heater operation are not detrimentally affected.

The flame speed of hydrogen is significantly higher than that of hydrocarbon fuels, resulting in faster combustion and increased heat release per unit volume. The flame speed of hydrogen combustion is approximately 1.7 m/s (5.6 ft/s), while the flame speed of natural gas (and most other hydrocarbons) is significantly slower at only 0.4 m/s (1.3 ft/s)[1]. Additionally, the stoichiometric adiabatic flame temperature of hydrogen (2182°C or 3960°F) is higher than natural gas (1937°C or 3520°F). Hydrogen's high flame speed causes the combustion to occur more rapidly than natural gas. This rapid combustion process releases the combustion energy in a smaller volume, leading to localized elevated near-flame region temperatures, which compound the effect of the inherently high adiabatic flame temperatures on NO_x emission rates. Any region with elevated temperatures above 760°C (1370°F) is conducive to creating small amounts of NO_x formation and at temperatures above 1100°C (2000°F), NO_x increases exponentially[2].

Current ULNBs can produce 50% more NO_x emission when switching fuels from low to high hydrogen. Local regulatory requirements for NO_x emission limits are not expected to be relaxed to accommodate hydrogen firing. Instead, NO_x emissions limits are getting more stringent around the globe over time. Thus, the next-generation ULNB designs that are suitable for firing 100% hydrogen also need to reduce NO_x emission further than the current generation of ULNBs.

In the coming years, the industry will have a considerable collective demand for next-generation ULNBs fit for 100% hydrogen firing that are easy to retrofit into existing fired heaters, easy to install on new fired heaters, and have minimal hardware/controls requirements. Without such a new technology, the industry will continue to rely on alternate methods of firing high hydrogen while keeping NO_x emission within current or future limits such as installing Selective Catalytic Reduction (SCR) units or using complicated ULNBs which require significant hardware and control/protective systems upgrades and are therefore not likely to be practical, cost-effective alternatives for large-scale fuel switching to high hydrogen fuels.

CURRENT ULNB TECHNOLOGIES

Process burner designs have significantly improved over the decades, and various technologies have been deployed to lower NO_x emissions. The primary objective of these technologies has been to manipulate localized areas of the air/fuel mixture, creating either fuel-rich or fuel-lean combustion zones to lower the peak flame temperature, therefore reducing NO_x formation. Air staging, fuel staging, Internal Flue Gas Recirculation (IFGR), and lean pre-mix have been the primary techniques used to reduce NO_x with currently available ULNBs. However, current-generation ULNBs struggle to meet the demands of high hydrogen firing while keeping NO_x emissions within limits.

Emerging technologies have attempted to use combinations of these methods, and concepts such as 'flameless combustion' have had some notable successes in lowering NO_x emission. However, these burner designs require complicated hardware and demand sophisticated controls and protective systems to be added to the existing equipment. Additionally, these burners are typically limited to forced draft installations, making them unsuitable for most retrofits without significant investments because most fired heaters are natural draft. Some of these designs use lean-pre-mix technologies, which can have potential flashback limitations when firing high hydrogen fuels, especially at the lower end of the burner heat release (i.e., at higher burner turndowns).

Installation of an SCR unit is an alternative means of addressing higher NO_x emissions due to high hydrogen firing. An SCR is a post-combustion system that is installed in the flue gas duct downstream of the convection section. It consists of catalyst bed and an ammonia/urea injection system. As the flue gas passes through the catalyst bed, the NO_x reacts with the ammonia/urea to create nitrogen and water. SCRs can reduce NO_x emission by up to 95%, but installation of such system has high financial impact and operational challenges. Installation of an SCR on new or existing fired equipment is significantly more expensive than installing new ULNBs, both in terms of capital costs and operational expenses. Furthermore, the additional space requirement of an SCR can be challenging, especially when retrofitting existing equipment. Lastly, SCRs must be operated within the specified flue gas temperature and ammonia/urea injection rates to avoid deterioration of the catalyst bed and/or ammonia slippage to the atmosphere.

ADVANCED ULNB TECHNOLOGY

Accordingly, what is needed is a simple-to-install, easy-to-operate advanced ULNB design that inherently addresses the challenges of firing 100% hydrogen fuel, meets ever-tightening NO_x emission requirements and can be easily retrofitted in most types of fired heaters. This idea led ExxonMobil to work with Zeeco to improve upon the current generation of ULNBs with the goal of a new burner design capable of meeting the above requirements with the ability to seamlessly transition from a variety of fuel blends to 100% hydrogen and vice versa. The outcome of this collaboration is a patent-pending next-generation ULNB design that incorporates an innovative new square burner tile configuration and an adaptation of proven ULNB technology to achieve unprecedented reductions in NO_x emissions. The two companies worked together to design, shop test, and field test the design to verify it would safely, reliably, and cost-effectively achieve all performance and emission objectives.

Previous generations of the ZEECO ULNBs used FREE JET burner technology with individual burner staged fuel tips with a single fuel port. This optimized the benefit of IFGR to lean the fuel mixture, and when combined with the round tile shape, produced a nearly universal lean fuel mixture composition along the burner firing ledge. Primary firing tips located along the throat inner diameter ensured burner stability, and the uniform flame temperature resulting from the fuel mixture generated industry-leading NO_x performance for more than two decades.

The new square-tile next-generation ULNB burner builds upon the well-established FREE JET IFGR concept but includes an innovative way of staging fuel and air to reduce thermal NO_x generation further. This new burner design, named the ZEECO FREE JET Gen 3, significantly reduces the number of staged fuel tips but adds multiple ports to each tip that deliver fuel mixture along the tile surface. Fewer points of fuel introduction and the new square tile shape create non-uniform areas of rich and lean fuel mixtures. These areas of non-uniformity mean the primary tips that generate higher levels of thermal NO_x can be located in a lean fuel region to lower the combined flame temperature produced by the primary and staged fuel. The zone located between the primary tips has a more fuel-rich mixture that remains stable without the assistance of the primary tip.

Combining the IFGR FREE JET technology with this new square tile design results in single-digit NO_x performance when firing typical refinery fuels and lower NO_x emissions than typical ULNBs produce today even while firing 100% hydrogen. Stable, reliable, and practical performance across a wide variety of fuels means operators have the capability to fire 100% hydrogen, a wide variety of refinery/petrochemical fuel gas compositions, 100% natural gas, and large volumes of Low BTU Gas (LBG), and to switch back and forth among various fuels more easily. The burner is capable of a 5:1 turndown in heat release. Burner tile sizes are comparable to existing burners of similar heat release, and its inherent simplicity of configuration allows for easy retrofits. A single main fuel gas connection to the burner keeps the fuel gas piping modifications to a minimum and, most importantly, does not require additional fuel or air controls or protective systems. Ease of operation and lower long-term maintenance costs were key drivers during the development of this burner design. Figure 1 shows the new burner design installed in an operating unit that has been in successful operation for several months now.

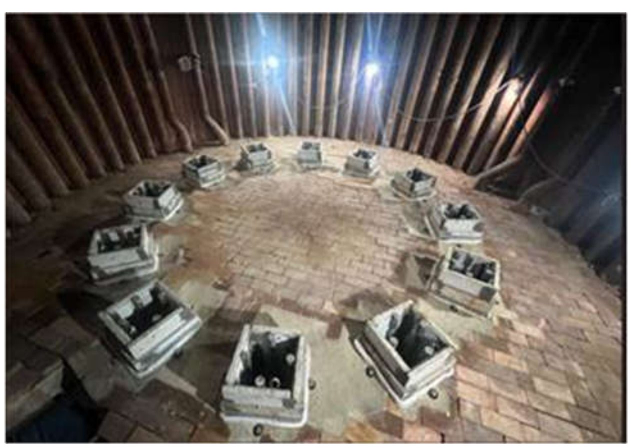

Figure 1: FREE JET Gen 3 burners installed in an operating unit.

Traditional lean-pre-mix methodology is not used in this design, eliminating burner flashback concerns. No external flue gas recirculation is required. Additionally, the burner can operate in either forced or natural draft modes, and with ambient or preheated combustion air.

In terms of NO_x emission performance, this new burner design provides about 50% reduction in NO_x emission compared to current generation of ULNBs while delivering the capability to fire up to 100% hydrogen without sacrificing flame stability. Figure 2 illustrates the NO_x emission performance of this next-generation ULNB FREE JET GEN 3 design versus current generation ULNBs.

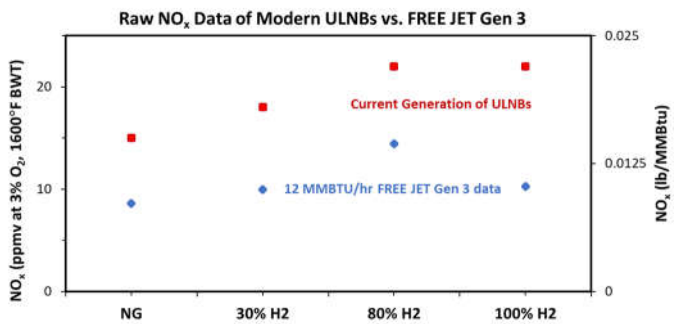

Figure 2: Burner test results of Zeeco FREE JET GEN 3 NO_x performance across a range of hydrogen fuel blends versus measured NO_x of various current generation of ULNBs.

PERFORMANCE TEST RESULTS

The FREE JET Gen 3 burner design was rigorously tested in various operating conditions to verify its performance and evolve its design. Zeeco and ExxonMobil's extensive development program included single burner testing, multi-burner testing, ambient and preheated air, forced draft and natural draft applications; and firing of natural gas, typical blends of refinery/petrochemical fuel gas, 100% hydrogen, and LBG waste gases. Testing of the final design at Zeeco's Global Technology Center showed exceptional performance and flame stability over wide fuel gas compositions. Table 1 summarizes the burner test results for various conditions (single burner / multiple burners, ambient air / pre-heated air, natural draft / forced draft).

Table 1: Performance test data of the FREE JET Gen 3 burner at Zeeco's Global Technology Center.

Natural Draft, Single Burner, Ambient Air

HR (MBTUs/hr)	HR Rate	Fuel	CAT (°F)	O_2 %	NO_x (ppmvd)	NO_x Corr*	CO (ppmvd)	BWT (°F)	Floor T (°F)
12	100%	100% TNG	86	2.0	8.3	8.6	0	1500	1270
12	100%	100% H_2	84	1.9	10	10.3	0	1501	1351
12	100%	Fuel C	82	1.8	14.1	17.9	0	1285	1309
2.4	20%	100% TNG	85	10.4	11.6		200-300	525	780
2.4	20%	100% TNG	86	16.7	10.6		50-100	500	800
2.4	20%	100% H_2	86	11.0	14.6		0	510	810
2.4	20%	Fuel C	86	11.2	13.1		0-5	520	802

Natural Draft, Multiple Burner, Ambient Air

HR (MBTUs/hr)	HR Rate	Fuel	CAT (°F)	O_2 %	NO_x (ppmvd)	NO_x Corr*	CO (ppmvd)	BWT (°F)	Floor T (°F)
26.5	74%	100% TNG	88	3	5.2	6.4	0	1380	1055
36	100%	100% H_2	90	2.0	8.0	7.7	0	1580	1265
30	83%	Fuel C	90	2	13.1	13.5	0	1503	1165
9	25%	100% TNG	89	13.8	10.0		70-80	842	725
9	25%	100% TNG	89	8.6	9.0		400-450	944	760
9	25%	100% H_2	89	5.9	8.7		0	1048	843
9	25%	Fuel C	89	2.1	9.0		150-200	1086	853

Forced Draft, Single Burner, Ambient Air

HR (MBTUs/hr)	HR Rate	Fuel	CAT (°F)	O_2 %	NO_x (ppmvd)	NO_x Corr*	CO (ppmvd)	BWT (°F)	Floor T (°F)
30	100%	100% TNG	93	2	5.1	5.3	0	1501	1053
24	80%	100% H_2	107	2.3	7.7	8.6	0	1436	1105
30	100%	Fuel C	100	2.2	11.1	11.3	0	1524	1154
6	20%	100% TNG	94	16.7	7.3		100-250	773	665
6	20%	100% H_2	108	16.2	13.7		0	852	725
6	20%	Fuel C	103	16.3	12.2		0-5	855	727

Forced Draft, Single Burner, 400°F Preheated Air

HR (MBTUs/hr)	HR Rate	Fuel	CAT (°F)	O_2 %	NO_x (ppmvd)	NO_x Corr*	CO (ppmvd)	BWT (°F)	Floor T (°F)
30	100%	100% TNG	380	2.1	9.3	9.5	0	1519	1037
24	80%	100% H_2	572	2.1	14.2	13.2	0	1487	1088
30	100%	Fuel C	430	2	15.7	15.0	0	1551	1092
6	20%	100% TNG	389	17.3	11.2		80-100	827	665
15	50%	100% H_2	587	2.6	14.6	16.6	0	1306	931
6	20%	Fuel C	617	11.8	16.2		0	1015	763

Abbreviations: HR= Heat Release, TNG = Tulsa Natural Gas, BWT = Bridgewall Temperature

(*) corrected to 3% dry, 1600F BWT

Fuel C: 15% TNG, 80% H_2, 5% Propane

Figure 3 shows single burner testing at Zeeco's Global Technology Center across a range of hydrogen concentrations in the fuel blends. As can be seen from the images, the burner tested included a nozzle for LGB fuel firing, which is depicted from the large circular nozzle in the center of the burner. LBG was not in service when the photographs were taken.

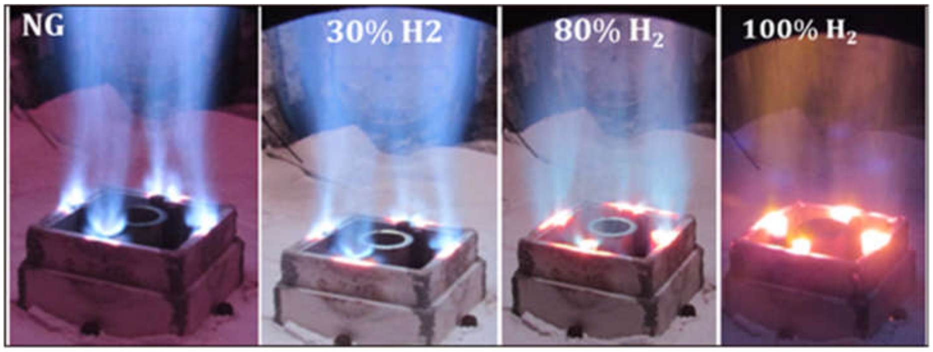

Figure 3: Single burner testing at Zeeco's Global Technology Center showing various levels of hydrogen in natural gas.

Test results show that the burner is fully capable of firing 100% hydrogen and will provide about a 50% reduction in NO_x emission versus current generation UNLBs – with single-digit NO_x emission performance on natural gas firing. Even at 100% hydrogen firing, NO_x emission was close to single digit at approximately 10 ppm(v) in natural draft application and 9 ppm(v) in forced draft application, values corrected to 3% O_2 dry. It was observed that NO_x emission increases as hydrogen content goes up in fuel gas, but peaks at about 80% hydrogen and then drops beyond that until 100% hydrogen firing, as evident in the Fuel C data above. CO probing and O_2 profiling verified that the flame length and width are comparable to current generation ULNBs. CO breakthrough tests verified stability of the burners irrespective of fuel composition.

Multi-burner tests were performed to examine potential adverse effects of any flame-to-flame interactions on NO_x emission and the impacts were found to be negligible. Since many older existing fired heaters have burners spaced tighter than API 560 recommendations, additional burner tests were conducted at burner spacing tighter than API 560 recommendations. NO_x emission increase was less than 20% when burner spacing was reduced to 75% of the API 560 recommended spacing over a wide range of fuel firing, including 100% hydrogen.

Figure 4: Multi-burner testing of FREE JET Gen 3 burners at Zeeco's Global Technology Center.

The FREE JET Gen 3 results verified exceptional performance regarding flame stability, flame dimensions, and emissions. Based on the results the FREE JET Gen 3 burner was considered technologically ready for field installation. Field installation was completed at ExxonMobil's Baytown facility, and the burners were commissioned in early 2024. The current fuel source for the Baytown facility, representing a typical refinery fuel gas blend with as high as 70% hydrogen, is expected to transition to low-carbon hydrogen produced through ExxonMobil's Low Carbon Solutions (LCS) team. Combining a low-carbon footprint fuel and low/no-carbon combustion will reduce the Baytown facility's overall carbon footprint.

FIELD TEST RESULTS

ExxonMobil installed twelve of Zeeco's FREE JET Gen 3 burners in one of their vertical cylindrical heaters at their Baytown facility for field application. The burners are forced draft, preheated air, suitable for natural draft ambient air operation as well, and have a design heat release of 9.8 MMBTU/hr (LHV basis) each. The CO emission remained compliant even during commissioning without the need to adopt additional mitigation measures. Performance was noted as a significant improvement over the previous burners. The CO emission stayed below 50-ppm hourly rolling average even during startup operations. Field reports confirmed that all burners remained stable even at low firing rates and with excess oxygen as high as 10 vol% (wet). Preliminary emission testing was done with the burners firing between 60-75% of designed heat release, with an hydrogen concentration in the fuel gas ranging between 45% to 60%, and with combustion air temperature between 135°F and 230°F. Measured NO_x emissions when corrected to 3% O_2 (dry) and 1600°F Bridgewall temperature remained at or below 12 ppm. This matched exceptionally well with the shop testing results.

CONCLUSION

Net Zero commitments worldwide call for significant efforts to decarbonize the oil and gas industry and rely on using high hydrogen fuel instead of hydrocarbon-based fuel as one primary method. In the coming years there will be demand for next generation ULNBs fit for 100% hydrogen firing yet with much lower NO_x emission. These next-generation burners need to be easy to retrofit into existing fired heaters, easy to install on new fired heaters, and have minimal hardware/control requirements. Current emerging ULNBs are unable to address the above requirements. The alternative is to install SCR systems for fired equipment, which makes the transition significantly more expensive. Thus, emerging complicated burner designs or SCR installation will not be practical answers for large-scale fuel switching to high hydrogen fuels.

This newly developed next-generation ULNB, the FREE JET Gen 3, meets all the above requirements. It has a simple design, is easy to retrofit, is extremely versatile, and creates significantly lower NO_x. The burner is suitable for both natural draft and forced draft applications, for both ambient air and preheated air, and can handle a wide range of fuel gas compositions including 100% hydrogen – and has been proven in field installation. The burner maintains the performance and flame dimensions of current generation ULNBs while significantly reducing NO_x emission. FREE JET Gen 3 ULNB thus offers a robust, reliable and cost-effective alternative for easy retrofits and for new installations without complicated controls or operational requirements to help achieve de-carbonization goals.

<u>Notes and References:</u>

(*) All references to % hydrogen content is in volume%.

[1] Glassman, Irvin. Combustion – Second Edition (1987).

[2] U.S. Environmental Protection Agency (November 1999), EPA 456/F-99-006R Technical Bulletin: Nitrogen Oxides (NO_x), why and how they are controlled. https://www3.epa.gov/ttn/catc/dir1/fnoxdoc.pdf.