Development of a Fuel-Flexible Burner for Process Plants

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Jamal Jamaluddin[1]
Charles Benson[2], Roberto Pellizzari[2]
Seth Marty[3], Thomas Young[3], Rex Isaacs[3]
Joseph Renk[4]

[1]Shell Global Solutions (US), Inc.
[2]etaPartners
[3]Zeeco
[4]US Department of Energy

Abstract

The US Department of Energy and project team members are co-funding the development of a fuel-flexible combustion system for refineries and chemical plants. This technology will enable operation of fired heaters on fuels ranging from conventional gases to bio-gases and syn-gases.

The burner technology was developed by modifying Zeeco's Freejet-style, ultra-low-NO_x burner. Combustion testing of two fuel-flexible versions was undertaken in horizontal and vertical test furnaces at Zeeco's test facilities in Tulsa. Fuel blends corresponding to natural gas and a variety of bio- and waste-gases were utilized in these tests. The lower heating value of the fuels ranged from 910 to 88 Btu/scf, while the Wobbe number varied from 1350 to 125. To accommodate this broad range of fuel characteristics, each burner was equipped with multiple fuel rings.

The fuel-flexible burners were tested over their entire range of fired duties when operating on each fuel. Combustion performance was assessed based on the following criteria:

- Flame length and width
- Flame stability
- Excess air level
- NO_x and CO emissions

A special feature of these burners is their ability to accommodate rapid changes in fuel composition while maintaining stable operation and low emissions. No commercially available burner can respond to such changes as effectively. Consequently, the new "flex-fuel" burner should find wide acceptance by the refining and chemical community once its effectiveness is demonstrated in an operating process heater. Such a demonstration is planned for the latter part of next year.

Introduction

Shell, Zeeco, and etaPartners are developing a fuel-flexible combustion system for refineries and chemical plants. This technology will enable operation of fired heaters on fuels ranging from conventional gases to bio-gases and syn-gases. Deployment of this system could enable the reduction of greenhouse gas emissions associated with plant operations.

The goal of this project is to develop and demonstrate a full-scale combustion system which will allow a broad range of gaseous fuels to be safely, cost-effectively and efficiently utilized while generating minimal emissions of criteria pollutants. The project is being conducted in three phases, as follows.

- The ***Concept Definition*** phase was completed in 2011. A design specification was prepared by the team. Then, the preliminary designs of two preferred burner configurations were completed. Next, a series of Computational Fluid Dynamics (CFD) simulations were conducted to refine the burner designs.

- The ***Technology Development*** phase, discussed in this paper, is nearing completion. Activities focus on testing and optimization of the prototype combustion system. This work is being conducted at Zeeco's test facility in Broken Arrow, OK

- The ***Technology Demonstration*** phase will take place in 2013. A field demonstration of the burner, retrofitted in a Shell fired heater, is planned.

Upon completion of the project, Zeeco will manufacture and market the technology.

Conventional fuels of interest are provided in Table 1. The composition of refinery fuel gas (RFG) varies considerably, depending upon the refinery configuration and operating characteristics. This variability has led to the development of combustion systems for process heaters which can accommodate a moderately wide range of fuel gases. Natural gas (NG) typically has a much narrower range of compositions. Often NG is blended with refinery-generated gases to supply the balance of a plant's energy requirements. NG can also serve as a dedicated fuel for a unit or an entire chemical plant. Flexicoker off-gas is an example of a low-Btu gas which is currently used in certain refineries. Since this gas is significantly different from the range of RFG's and natural gas, it is fired in specially-designed burners.

The Wobbe number (Wo) is a parameter used in evaluating the interchangeability of gaseous fuels in combustion applications. It is defined as the fuel's higher heating value divided by the square root of its specific gravity. For incompressible flow through a fixed fuel orifice with constant fuel supply pressure, the energy flow rate (i.e., firing rate) is proportional to the Wobbe number. Included in this table are the Wobbe numbers for the various fuel gas compositions.

Alternative gaseous fuels of interest include biogas from organic matter digesters, including animal and agricultural wastes, waste water plants, and landfills; as well as syngases from gasification of biomass, municipal solid wastes, construction wastes, or refinery residuals such as tar, pitch and petroleum coke. Table 2 shows the range of compositions of potential alternative fuels from gasification or anaerobic digestion of various feed-stocks.

A key consideration in designing the fuel-flexible burner is the broad range of Wobbe numbers that these fuels span: from 120-150 for syngases, through 500-600 for biogases, to 1300-1400 for natural gases and 1100-1500 for RFG's. A combustion system which could accommodate all these fuels would be working over an order of magnitude variation in Wobbe number.

Desired Features of the Flex-Fuel Burner

The main attributes of the flex-fuel burner will be the ability to burn a wide variety of fuels, from various sources, in a stable flame with acceptable emission levels. An additional requirement, from the end-user perspective, is to be able to sustain the flame if and when the fuel quality changes rapidly, as is occasionally the case in an operating heater where the fuel is a mixture of lighter hydrocarbons from various sources. Rapid change in fuel quality (heating value/Wobbe number) has often caused flame-loss scenarios in refinery heaters, sometimes with serious consequences.

Ease of maintenance also features highly as an acceptance criterion for new hardware. The new burner, therefore, should not be too complicated to maintain, compared to the "conventional" ones. This means that the burners should not have any more fuel manifolds, and additional valves and/or controls, than is absolutely necessary to efficiently burn the range of fuels expected to be constitute the energy source for the subject heater.

	Flexicoker Off-gas*	Refinery Fuel Gas*	Natural Gas*
CH_4	2.0%	43.7%	95.4%
C2	0.5%	14.6%	2.1%
C3		7.7%	0.5%
C4		3.3%	
C5		1.3%	
CO	22.5%		
H_2	12.5%	27.5%	
O_2		0.1%	
CO_2	6.5%	0.4%	1.3%
N_2	56.0%	1.4%	0.8%
HHV (Btu/scf)	142	1148	1018
SG	0.88	0.65	0.58
Wo	**151**	**1426**	**1332**

***Typical, gas compositions vary.**

Table 1 Conventional Fuels

	Bio-gas*	Landfill Gas*	Biomass Syngas*	Wood Syngas*	Charcoal Syngas*
CH_4	56.0%	52.0%		3.0%	1.0%
CO			20.0%	20.0%	28.0%
H_2			18.0%	18.0%	4.0%
H_2O			9.0%		0.0%
CO_2	36.0%	47.0%	8.0%	9.0%	2.0%
N_2	8.0%	1.0%	45.0%	50.0%	65.0%
HHV (Btu/scf)	568	528	128	153	113
SG	0.93	1.01	0.82	0.84	0.94
Wo	**588**	**525**	**141**	**167**	**117**

***Typical, gas compositions vary.**

Table 2 Alternative Fuels

Objective of the Tests

The objective of the tests performed at Zeeco Test facilities were the followings:

- Demonstrate that the burner could burn a wide variety of fuels (an order-of-magnitude variation in fuel heating value). This aspect of the tests is a requirement from the DOE.

- Demonstrate that the burner would maintain a stable flame when the fuel is rapidly switched between the highest and lowest heating value fuels within the range considered for the tests. This was a requirement from the Shell plant that would install these burners for the "practical" part of the demonstration.

Flex-Fuel Burner Design

Zeeco® GLSF Free-Jet burner was adopted as the basis for the flex-fuel burner design. Zeeco's GLSF Free-Jet Burner technology conditions the fuel by mixing the fuel and flue gas together before combustion can occur. This fuel conditioning allows for reduction of the peak flame temperature of the fuel/air mixture and lowers thermal NO_x emissions. As illustrated in Figure 1, the Free Jet theory entrains inert flue gas with fuel gas in order to generate less thermal NO_x. In contrast, traditional raw gas burners must employ additional technology such as EFGR or SCR to achieve low NO_x emissions levels.

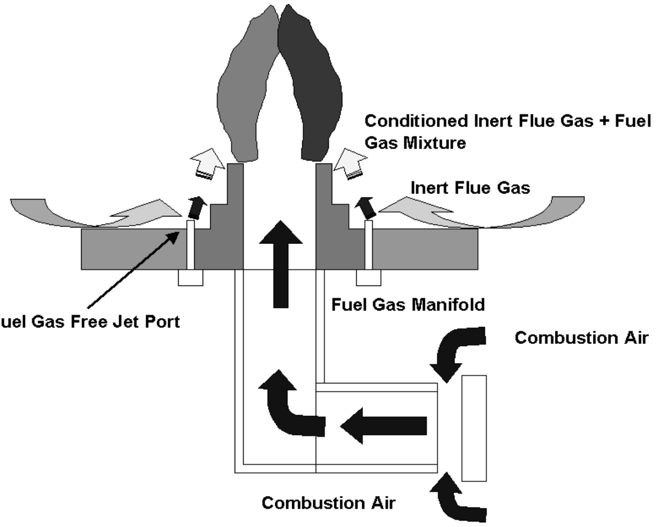

Figure 1 Free Jet Schematic

In the past, the majority of traditional burners were designed to direct a small portion of the fuel gas to a low pressure area where combustion could be initiated and stabilized. This portion of the gas is commonly referred to as ignition gas. The remaining fuel gas was directed toward the combustion air stream. This traditional burner (Figure 2) used a stabilization zone with a sufficient temperature to ignite the remaining fuel gas once it contacted the combustion air stream. Combustion then proceeded at high temperatures, and high levels of thermal NOx were produced.

Typical raw gas burners have one or more ignition and firing ports on each tip. The ignition port directs gas to a low-pressure area where combustion is initiated and stabilized. The firing port is used to shape the flame. This method of fuel gas introduction has been common practice for over fifty years and has proven a very effective means of providing burner stability. In this tradition, the Zeeco® Second Generation Min-Emissions Ultra-Low NO_x burner was designed with both ignition and firing ports. In order to achieve lower NO_x emissions than that of the second-generation designs in the marketplace, it was determined that both the ignition gas and the main fuel gas must be conditioned with inert flue gas by means of Free Jet mixing.

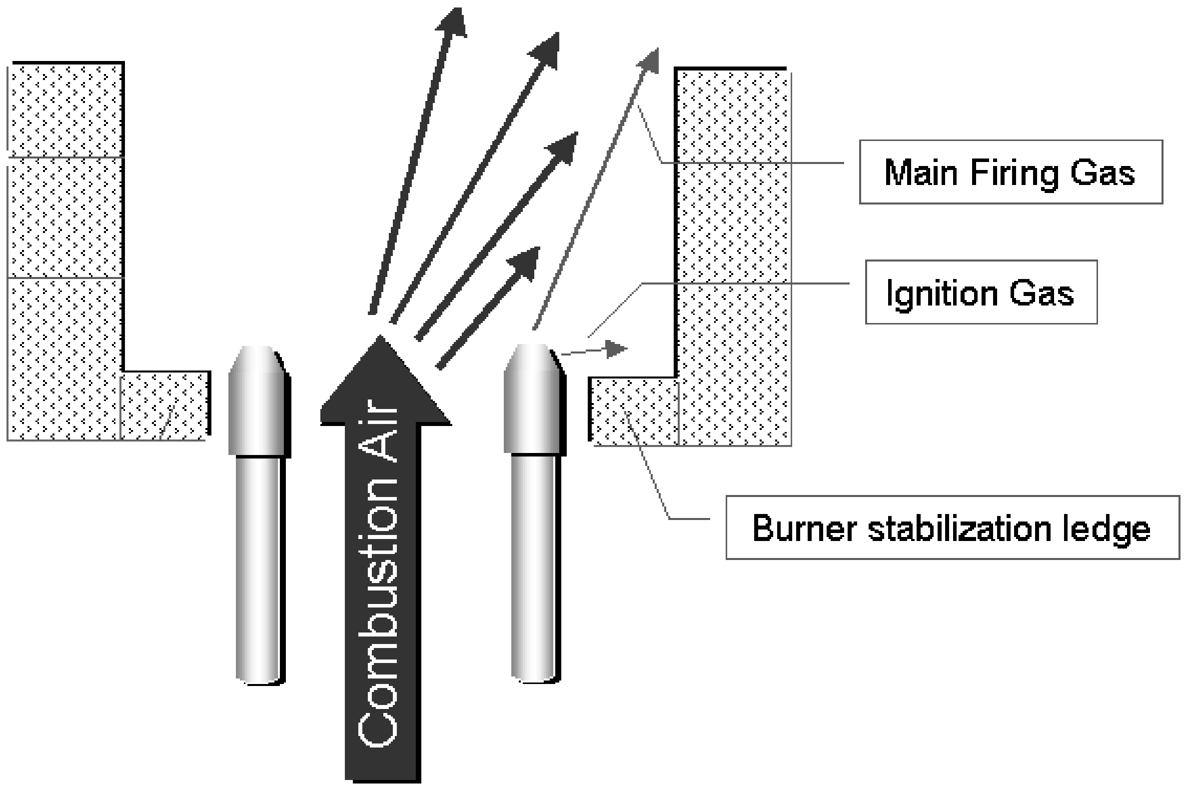

Figure 2. Traditional Burner Stabilization Technique

In order to fully utilize the Free Jet Theory, Zeeco devised a method to stabilize the burner flame with a highly inert fuel gas/flue gas mixture. This type of combustion is achieved when the flame is stabilized in a low-pressure area created on a series of specially designed hot refractory ledges. As combustion occurs, the refractory ledge retains heat and flame stability is enhanced. Thus, to achieve improved stability and extreme thermal NO_x reduction, the Free-Jet Technology:

- Mixes inert flue gas through free-jet methods with all of the fuel gas before combustion occurs, lowering flame temperature.
- Stabilizes the flame on a series of refractory ledges, improving flame characteristics.

Before combustion is initiated, a furnace is typically filled with air, containing 21% oxygen. Once the burner is ignited, the oxygen content inside the furnace decreases until the burner achieves maximum duty. At this point, the oxygen content in the firebox is normally 2% to 3%. To maintain burner stability throughout the transition from start-up with 21% oxygen to maximum duty with 2% to 3% oxygen, Zeeco developed a series of stabilization ledges as shown in Figure 3.

This stabilization technique makes the Zeeco GLSF Free-Jet technology a good fit for a flex fuel application. By utilizing these stabilization ledges, the Zeeco GLSF Free-Jet burner can accommodate fuels with a wide range of Wobbe numbers and still achieve Ultra-Low NOx emissions.

Traditionally, burning fuel gases with high levels of inert components has proved technically challenging. On low Wobbe number fuels, traditional burner technology relies on enhanced fuel and air mixing to ensure stable combustion on these fuels. However, when a higher Wobbe number fuel was introduced, the fuel and air mixture caused excessive NO_x emissions. Another issue that has proved technically challenging is that available fuel pressure for low Wobbe number fuels has often been relatively low, so when the burner is operated on a high Wobbe number fuel, the fuel pressure is very low.

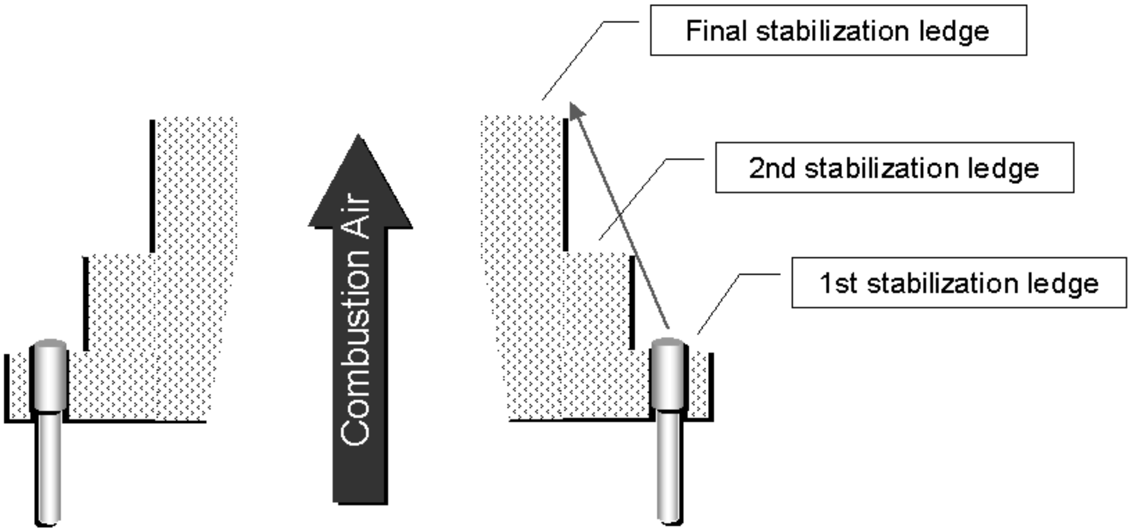

Figure 3. Free Jet Stabilization Technique

In order to overcome these challenges, the Zeeco GLSF Free-Jet Burner design was modified to include multiple staged gas manifolds. Each staged gas manifold was independently controlled and fuel gas flow to each manifold was modulated based on fuel gas characteristics. This design allowed for a wide range of fuels to be operated at similar operating pressures, allowing for lower NOx emissions and improved stability on all fuels. As the Wobbe number of the fuel was decreased, a greater percentage of the fuel gas was present in the staged gas manifolds. This allowed for the proper fuel to air ratio to be maintained in the "primary" combustion zone, improving flame characteristics. As the Wobbe number of the fuel was increased, a greater percentage of the fuel was present in the primary gas manifold, resulting in a higher fuel pressure and maintaining low thermal NOx generation.

Flex-Fuel Burner Tests

The team completed a series of burner tests at Zeeco's facilities in Broken Arrow, OK. The prototype burner, incorporating Zeeco's free-jet technology, was installed in a test furnace and evaluated when operating on a six different fuels, including natural gas and low-BTU gasification products. These fuels had Wobbe numbers ranging from about 125 to 1325. The fuel-flexible burner was tested over its entire range of fired duty when operating on each fuel. Combustion performance was assessed based on the following criteria:

- Flame length and width
- Flame stability
- Excess air level
- NO_x and CO emissions

Test Furnace

The GLSF Free-Jet Burner was installed horizontally in Zeeco Test Furnace # 1 (Figure 4). Test Furnace # 1 is a single pass cabin style furnace that is approximately 37 ft long x 12 ft tall x 7 ft wide (inside of tube to inside of tube). The furnace has two sets of tube banks along the walls of the furnace. The west set (closest to the burner) has 12 horizontal, single pass water-cooling tubes (6 on each side) running from approximately 2 ft from the burner end of the heater to approximately 25 ft from the burner end of the heater. With the east set of tube banks, there are 24 horizontal, single pass water-cooling tubes (12 on each side) running from approximately 26 ft from the burner end of the heater to approximately 36.5 ft from the burner end of the heater. All of the tubes were blanket insulated to minimize heat transfer.

Flue gas samples for emissions and Stack temperature were measured at the base of the furnace stack below the stack damper. Firebox temperature was measured with a velocity thermocouple located 8 ft from the burner at the top of the furnace.

Figure 4. Zeeco Test Furnace #1

Flex-Fuel Tests

The GLSF-12 “Free-Jet” Burner was tested operating on a wide range of fuels (Table 3), from natural gas (Figure 5) to low BTU gasification products (Figure 7). On each fuel, the burner was tested at maximum, design and turndown firing rates. On several fuels, the burner was operated at its CO break-through duty and at its Absolute Minimum duty (lower than a 10:1 turndown).

FUELS	LHV	SP.GR.	FUEL A	FUEL B	FUEL C	FUEL E	FUEL F
NATURAL GAS	914.0	0.5830	56.0	52.0	0.0	0.0	100.0
HYDROGEN	273.8	0.0696	0.0	0.0	38.0	32.0	
NITROGEN	0.0	0.9672	8.0	0.0	45.0	68.0	
CO2	0.0	1.5196	36.0	48.0	8.0	0.0	
STEAM	0.0	0.0000	0.0	0.0	9.0	0.0	
TOTAL			100.0	100.0	100.0	100.0	100.0
LHV (BTU/SCF)			511.8	475.3	104.0	87.6	914.0
SP. GR.			0.951	1.033	0.583	0.680	0.583
MW			27.54	29.91	16.89	19.69	16.89

Table 3 Fuel compositions/characteristics

Test Point	1	2	3	4	5	6	7	8
FUEL GAS								
Natural Gas %	100.0	100.0	52.0	52.0	-	-	-	-
Hydrogen %	-	-	-	-	32.0	32.0	38.0	38.0
Nitrogen %	-	-	-	-	68.0	68.0	45.0	45.0
Carbon Dioxide %	-	-	48.0	48.0	-	-	8.0	8.0
Steam %	-	-	-	-	-	-	9.0	9.0
FUEL GAS DATA								
Heat Release MMBTU/HR.	6.000	0.600	6.000	0.600	6.000	1.200	6.000	0.600
Fuel Gas Temperature F.	96	66	75	86	120	160	159	132
Inside Manifold Pressure PSIG	4.4	0.1	2.9	0.4	12.5	3.4	8.7	2.9
Middle Manifold Pressure PSIG	-	-	2.9	-	12.5	2.1	8.7	-
Outer Manifold Pressure PSIG	-	-	-	-	12.5	-	8.7	-
EMISSIONS DATA								
Oxygen % (Dry Basis)	3.0	18.8	3.1	18.8	3.0	16.6	2.8	19.2
CO PPMV	0.0	5.8	0.0	22.5	0.0	2.4	0.0	13.7
NOx PPMV	20.6	8.5	9.8	2.7	1.7	0.0	4.0	0.0
Firebox Temperature F.	1670	922	1619	927	1389	749	1425	821
Stack Temperature F.	1556	842	1507	867	1347	728	1369	681

Table 4 **Test Data**

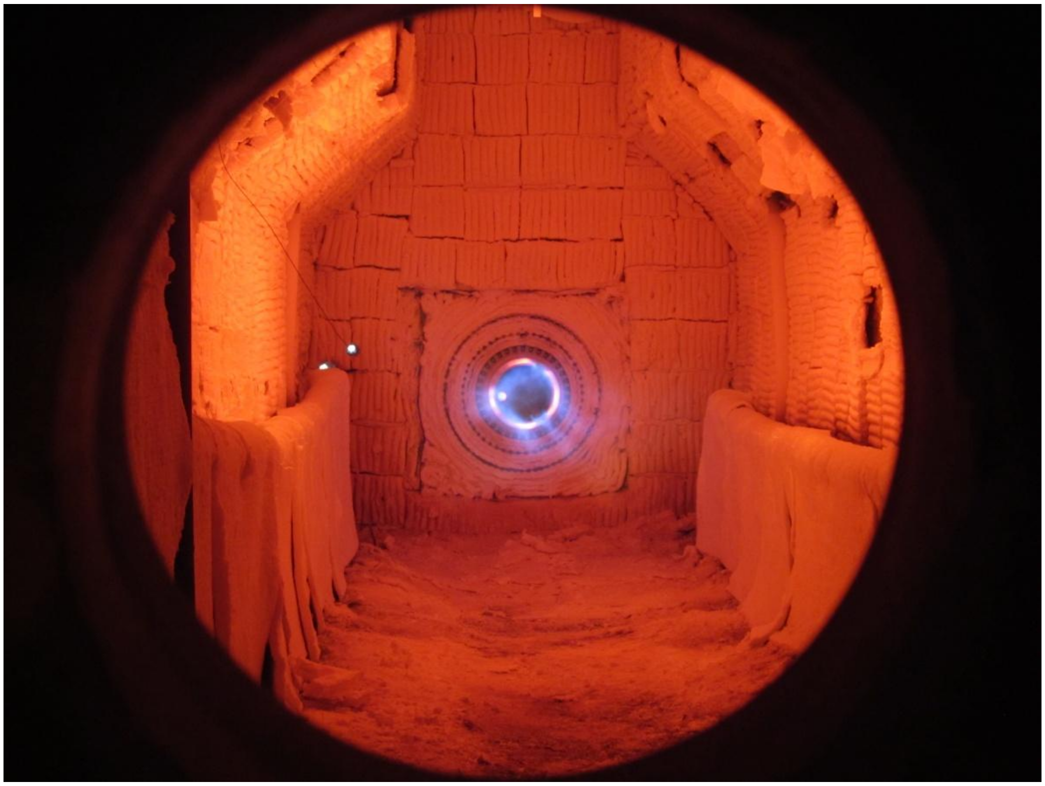

Figure 5. Test Point 1 (Test Fuel F)

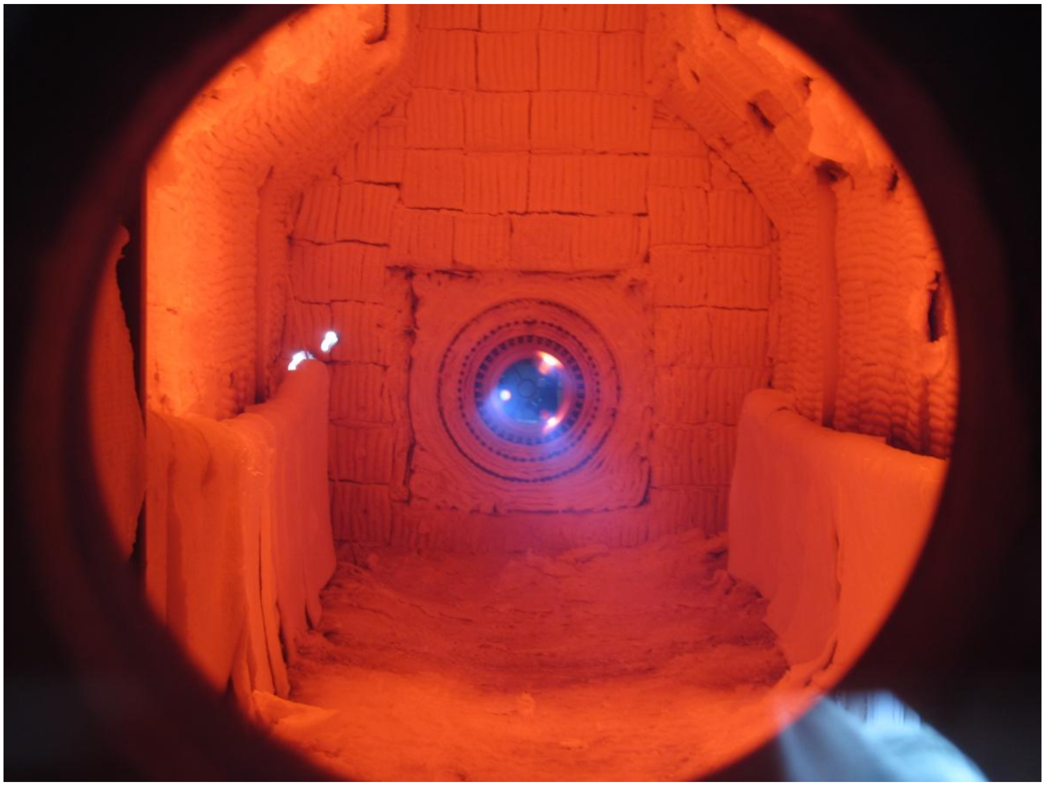

Figure 6. Test Point 3 (Test Fuel B)

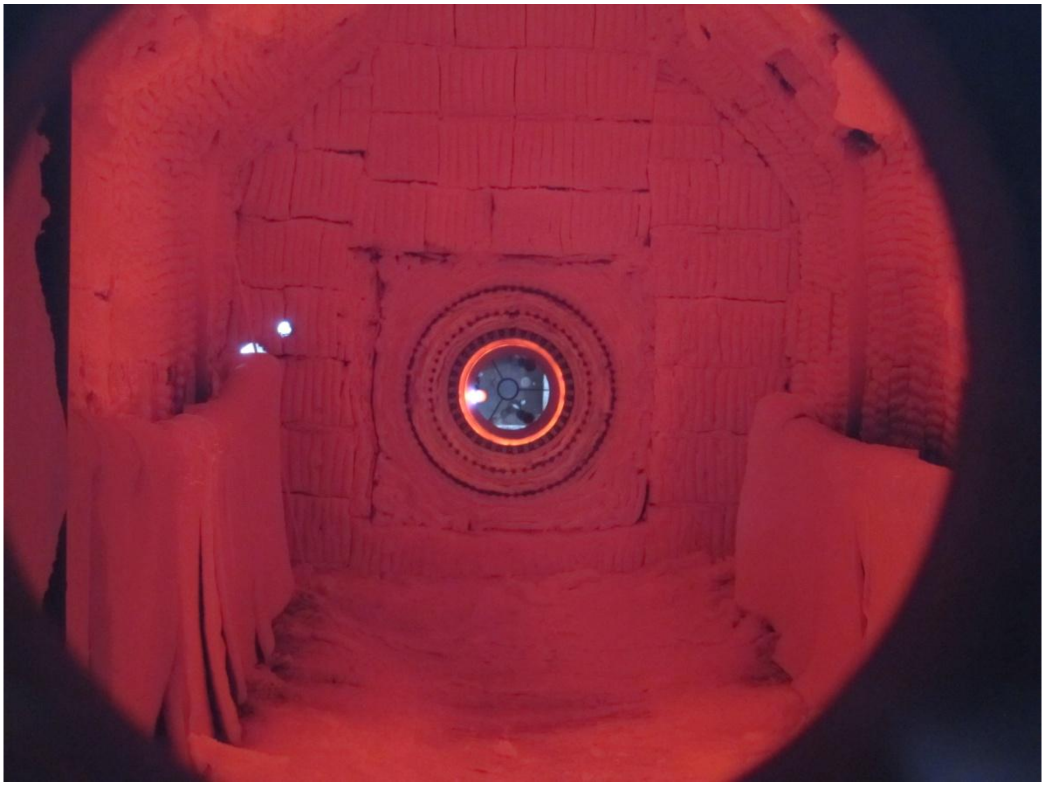

Figure 7. Test Point 5 (Test Fuel E)

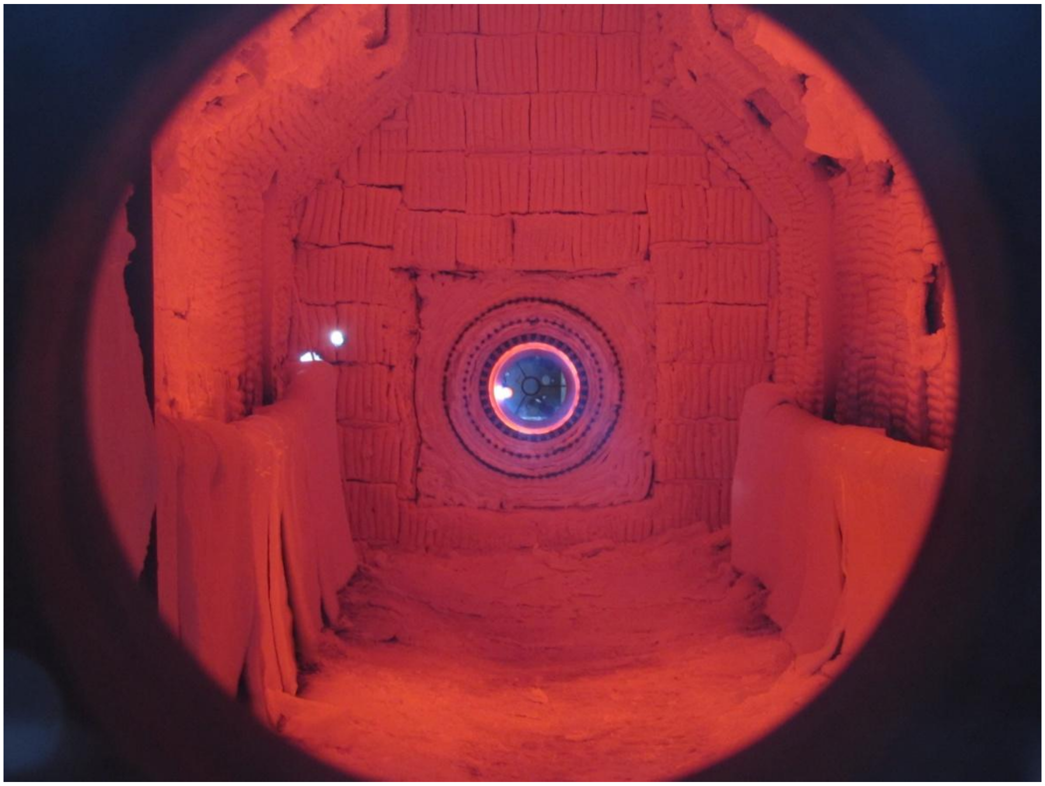

Figure 8. Test Point 7 (Test Fuel C)

Results and Discussion

Figures 5 through 8 show the flames while firing fuels F, B, E and C, respectively. In all of these cases, the flames were stable through the entire range of the test matrix, except for flame-E (LHV of 88 Btu/scf) which appeared to have lost the flame when the firing rate was reduced below 50% of normal firing capacity. It was clear from the demonstration that the burners was able to satisfy the DOE requirement for fuel flexibility.

NOx emissions for the range of fuels is shown in Figure 9. The NOx emission was lower as the adiabatic flame temperature decreased. All the reported NOx data are for normal firing rate with 3% excess O2 in the flue gas.

The ability of the burner to maintain stable flame when the fuel is rapidly switched is the subject of on-going tests at Zeeco. The initial results look very encouraging.

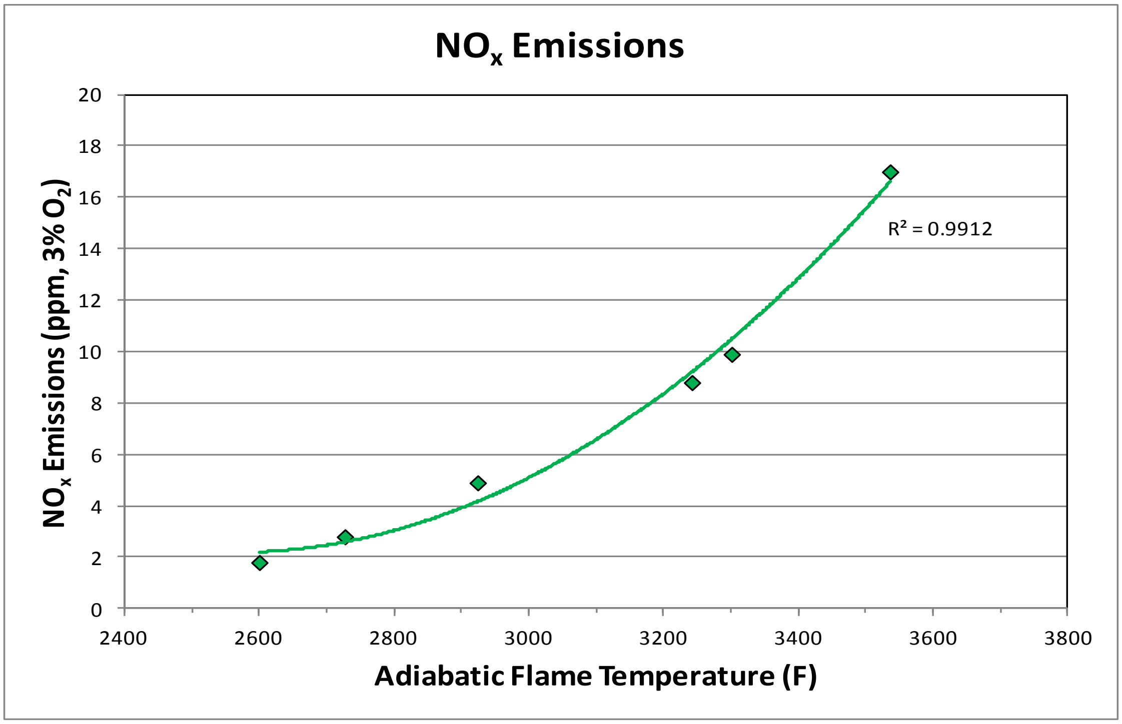

Figure 9 NOx emissions for the range of fuels fired.

The team also initiated testing of an alternative configuration containing an enhanced flame stabilization mechanism. This design had been refined through Computational Fluid Dynamics modeling. Once this second configuration has been optimized, the better-performing of the two burner configurations will be selected for the Phase 3 field demonstration. This final burner configuration will be tested at Zeeco prior to the retrofit.

Conclusions

The CFD simulations, and the tests performed thus far, have demonstrated that with small modifications, the Zeeco® GLSF Free-Jet burner is able to burn fuels with an order-of-magnitude variation in lower heating value with stable flames and with very low emission. On-going tests indicate that a further modified version of the burner will withstand rapid and wide changes in fuel heating value without a mentionable change in flame stability. These simulations and tests are facilitating the development of a new generation of burners that will be suitable for the fuels of the future, with significant benefits expected in the following aspects of heater operation:

- Reduction of carbon emissions
- Reduction in energy costs
- Lower NOx emissions
- Mitigation of vulnerability of the manufacturing industry to natural gas price increases
- Reduction in vulnerability to fuel quality swings

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