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MINIMIZING EMISSIONS FROM MODERN BURNERS WITH EFGR AND HIGH HYDROGEN FUELS

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Abstract

The Oil and Gas Industry continues to explore new ways to reduce air emissions to comply with increasingly stringent regulations. Historically, the focus has been on technologies that reduce nitrogen oxide (NO_x) emissions. Today, it has shifted to reducing carbon dioxide (CO_2) production while also abiding by NO_x requirements. Companies are exploring switching fuels from hydrocarbon-rich to high hydrogen, with the expectation that the hydrogen is produced with a minimal CO_2 footprint. Others are considering replacing air with oxygen to both eliminate NO_x emissions and facilitate the efficient capture of CO_2 for sequestration.

Meeting future emission requirements will likely require combining old and new technologies. This paper evaluates coupling modern ultra-low NO_x burners (ULNBs) with external flue gas recirculation (EFGR) to test the NO_x reduction effectiveness. It also examines the NO_x benefits of adding steam to the fuel. Additionally, it compares the results and provides insights on which technology may be more effective in the field. Lastly, the paper evaluates the differences to the fired equipment's heat transfer and efficiency when using hot or cold EFGR.

Introduction

Flue gas recirculation (FGR) is a proven technology that has been used for decades. FGR is a method of injecting flue gas into the combustion air upstream of the point of combustion. The additional mass flow rate cools the flame temperature, resulting in less thermal NO_x production. Also, because it lowers the oxygen concentration in the combined air-flue gas stream, it slows the combustion process, further reducing thermal NO_x emissions. The two types of FGR used in fired equipment are external and internal flue gas recirculation (IFGR).

EFGR is when a slipstream of cool flue gas is externally removed from its normal flow path and mixed with the combustion air upstream of the burner. EFGR, in earlier burner technologies, has reduced NO_x emissions by up to 75% when 25% of the flue gas is recirculated. Generally, it has been limited to 30% flue gas recirculation to avoid burner instability. EFGR has been used most often in boilers because of its low cost to implement and simplicity as compared to fired heaters or ethylene crackers. Additionally, it has most often been used at temperatures less than 600°F. In contrast, IFGR has been widely used in fired heaters and ethylene cracker burners. Unlike EFGR, which uses a mechanical fan to recirculate the flue gas, IFGR uses either the momentum of fuel gas jets or low-pressure zones created by a burner swirler to drive flue gas from inside the firebox into the airstream. Generally, burner manufacturers can achieve about 10% flue gas recirculation and a resulting 40% NO_x reduction with this process.

EFGR is advantageous over IFGR because it allows for a higher percentage of lower-temperature flue gas to be recirculated, resulting in a higher amount of NO_x reduction. Additionally, the amount of EFGR can be controlled and adjusted to maintain NO_x within the regulated limit, whereas the amount of NO_x reduction of IFGR is simply a function of the design. IFGR is more cost-effective than EFGR because it requires no additional controls or flue gas ducts.

Injecting steam into the burner has been another technology used to suppress NO_x emissions. Steam can be injected directly into either the air or the fuel. Like FGR, it reduces the flame temperature, which reduces thermal NO_x production. Adding steam to the fuel is more effective at reducing NO_x than adding the same quantity of steam to the air. However, it does require larger burner tip orifices and tighter controls to manage the steam-fuel ratio than if the steam was added to the air.

High EFGR Temperature Testing

Ethylene crackers, because of their high firebox temperatures, emit more NO_x than fired heaters or boilers. Therefore, a test was conducted to simulate an ethylene cracker furnace using two 8.0 MMBTU/hr modern ultra-low NO_x burners (ULNBs). The burners used were Zeeco Free Jet® Gen 3™ with lean pre-mix. The combustion test was performed in Zeeco's test furnace 14, which has external dimensions of approximately 8 feet wide, 12 feet long, and 45 feet tall. One of the 12-foot-long sides has fire bricks installed partially up the wall. The two burners were mounted slightly off the fire brick wall. The opposing wall had water-filled tubes, which were partially insulated to closely resemble ethylene cracker furnace temperatures.

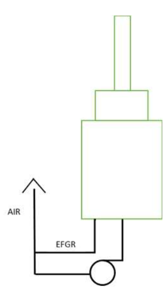

Figure 1: EFGR test apparatus

During the EFGR testing, combustion air and EFGR were supplied to the two burners by a single forced draft blower, as shown in Figure 1. EFGR was induced from the furnace floor and mixed with ambient air in a chamber upstream of the blower's inlet. The air-EFGR mixture traveled in uninsulated ducts through the blower and into the inlets of the two burners. Temperatures were taken along the duct between the floor and the mix box, after the mix box, and at the burner inlets. Oxygen was recorded in the duct after the mix box and at the burner air inlets.

During the portion of the test where steam was used to suppress NO_x formation, steam was injected at a metered rate directly into the main fuel gas connection of each burner.

Emissions were measured by two oxygen analyzers, one NO_x analyzer, and two CO analyzers. Flue gas and combustion air temperatures were measured with thermocouples and digital readouts. Steam and fuel gas temperatures were measured with a dial thermometer. Furnace temperatures were measured with velocity thermocouples located at one foot, fourteen feet, and thirty-four feet above the floor, and at the furnace stack.

EFGR Results

Table 1 shows raw data taken during the high EFGR temperature testing for three fuels, which ranged from 90% Tulsa natural gas (TNG)/10% H_2 to 40% TNG/60% H_2. Testing occurred over a ten-day period

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with variable ambient conditions. Throughout the testing, the peak firebox temperature averaged around 2100°F. Because the EFGR ducts were uninsulated, an appreciable amount of heat was lost in the air-EFGR mixture prior to reaching the burners. Table 1 captures the measured temperature at the burner of the air-EFGR mixture for each test point.

Table 1: Subset of EFGR raw data taken during simulated ethylene cracking operations.

$Q_{total\ fired}$ =16.00 MMBTU/hr	90% TNG/10% H2				65% TNG/35% H2				40% TNG/60% H2			
EFGR %	0%	10%	15%	26%	0%	8%	16%	29%	0%	7%	17%	29%
Peak Firebox T (F)	2099	2094	2090	2060	2122	2123	2091	2105	2119	2122	2088	2090
Floor T (F)	1832	1866	1865	1860	1841	1902	1884	1889	1840	1890	1871	1875
Air-EFGR T at Burner (F)	67	215	290	N/A	60	215	335	365	52	124	280	341
Oxygen % (Dry)	1.8	2.1	2.1	2.0	2.3	2.0	2.2	1.4	2.1	1.9	2.0	1.5
NOx PPMV (corr. 3% & 2253F)	28.4	15.9	13.9	11.0	33.0	23.2	17.1	13.8	37.8	26.7	20.7	15.0

Preliminary burner testing. Data does not imply performance guarantees.

Figure 2 shows the NO_x reduction as EFGR flow is increased for fuels ranging from TNG to high hydrogen. No corrections were made for the mixed air-EFGR temperature. All three fuels demonstrated a 60% NO_x reduction from their respective baseline number. Included in Figure 2 is a horizontal dashed line depicting NO_x production of the 90% TNG/10% H_2 and no EFGR. As can be seen, only a minimal amount of EFGR is required to maintain current NO_x emissions when transitioning to high hydrogen fuels using modern ULNBs. The composite average of NO_x reduction for all three fuels relative to their respective baselines is shown in Figure 3.

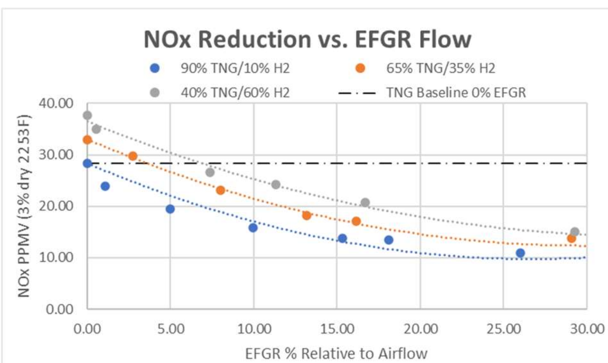

Figure 2: High EFGR temperature test data.

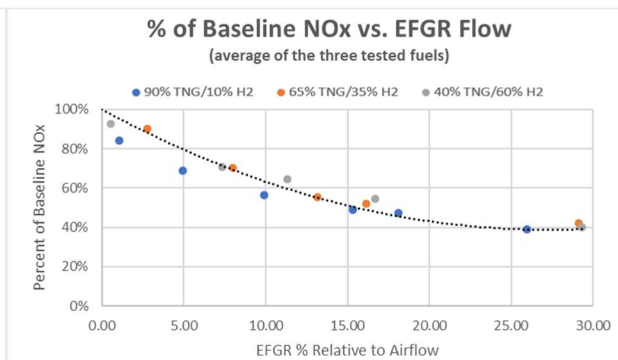

Figure 3: Composite average NO_x percent of baseline.

The electrical energy consumption for a typically sized ethylene cracker using EFGR is shown below in Table 2. An ambient temperature of 60°F, an EFGR temperature of 1700°F, a duct velocity of 50 ft/s at 30% EFGR flowrate, and an electricity cost of $0.085/kWH were used [1]. From Figure 2 above, less than 10% EFGR is required to maintain the same NO_x emissions when transitioning from a 90% TNG/10% H2 fuel to one with 40% TNG/60% hydrogen. Table 3 shows that there is an annual energy increase of about $10K versus 0% EFGR to maintain current NO_x emissions when transitioning to high H_2 fuels, such as the 40% TNG/60% H2. To obtain a 60% NO_x reduction using the current fuel and 30% EFGR is approximately $50K in increased energy costs.

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Table 2: Additional energy consumption and cost for using EFGR NO_x control technology on a typically sized ethylene cracker.

Annual energy consumption assuming 60F air and 1700F EFGR, 180 MMBTU/hr firing rate				
EFGR %	0%	10%	20%	30%
Total EFGR-AIR Flow (lbs/hr)	157,300	173,030	188,760	204,490
Estimated T (°F)	60	209	333	438
EFGR-AIR Flow ACFM x 1000	34.5	48.8	63.2	77.5
Fan dP (in w.c.)	1.1	2.2	3.7	5.6
Power consumed (HP)	9.0	25.4	55.1	101.7
Annual cost at $0.085/KWH, ($)	$ 4,900	$ 14,000	$ 30,300	$ 56,000

Steam Injection Results

The steam injection test was conducted with fuels of 90% TNG/10% H_2 and 65% TNG/35% H_2. The injection rates ranged from zero to 30 wt.% steam to fuel. In practice, this 30 wt.% ratio is commonly used when injecting steam into the fuel. Test results were tabulated in Table 3 below. As shown, NO_x was reduced by 25% for each fuel when the steam rate was 0.3 lb steam/lb fuel.

Table 3: Steam injection data taken during simulated ethylene cracking operations.

$Q_{total\ fired}$ =16.00 MMBTU/hr	**90% TNG/10% H2**				**65% TNG/35% H2**		
Steam Rate (# steam / # fuel)	0	0.2	0.26	0.31	0	0.27	0.31
Peak Firebox Temperature F.	2038	2052	2065	2055	2122	2111	2219
Steam Temperature (F)	NA	285	310	320	NA	310	320
Oxygen % (Dry Basis)	2.2	2.2	2.1	2.4	1.8	2.0	2.0
NOx PPMV Corr. to 3% & 2253F	25.8	21.8	20.4	18.8	30.8	24.3	22.8
% NOx vs. baseline	100%	84%	79%	73%	100%	79%	74%

Preliminary burner testing. Data does not imply performance guarantees.

Figure 4 below shows the NO_x reduction for each fuel with increasing steam injection rates. Like Figure 2, a horizontal line has been drawn to reflect the baseline NO_x of the 90% TNG/10% hydrogen fuel without steam injection. It shows that 0.2 lb of steam injection is required when firing the 35% hydrogen fuel to maintain the same NO_x emissions as the baseline case. Although the 60% hydrogen fuel was not tested, one can extrapolate from the data that the required steam flow rate to maintain NO_x emissions would be more than 0.3 lb steam per lb fuel.

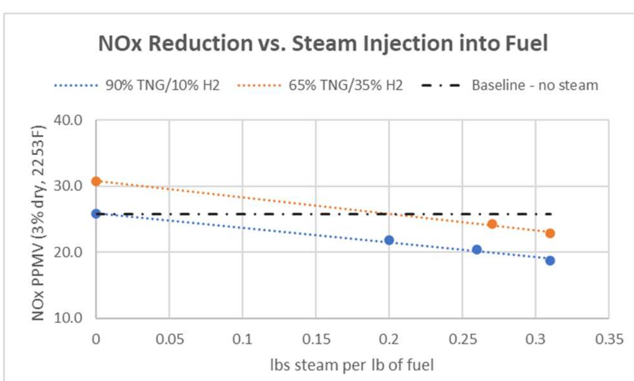

Figure 4: Steam injection test data, high peak firebox temperatures.

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The additional energy consumption for a typical-sized ethylene cracker using steam injection is shown below in Table 4. Steam was priced at 125% of natural gas price, which represents the cost of producing additional steam using the least efficient piece of steam-producing equipment in the plant. This equipment is often run at reduced rates. To arrive at the 125% of natural gas cost, it was assumed that 1.0 MMBTU/hr of heat absorbed is required to make 1.0 klb of steam. Using a fired equipment efficiency of 83%, the heat release is 120% of the heat absorbed. An additional 5% was added to account for the cost of water treatment chemicals. Finally, \$8.45/$MMBTU_{lhv}$ was used for natural gas price [2].

Table 4: Steam consumption and cost for using Steam Injection NO_x control technology on a typically sized ethylene cracker.

Annual energy cost assuming 180 MMBTU/hr firing rate	90% TNG/10% H2				65% TNG/35% H2				40% TNG/60% H2			
Steam Rate (# steam / # fuel)	0	0.1	0.2	0.3	0	0.1	0.2	0.3	0	0.1	0.2	0.3
Fuel BTU/lb	21,935	21,935	21,935	21,935	23,428	23,428	23,428	23,428	26,295	26,295	26,295	26,295
Steam rate tons/hr	0	0.4	0.8	1.2	0	0.4	0.8	1.2	0	0.3	0.7	1.0
Annual steam consumed klbs/yr	0	7,200	14,400	21,600	0	6,700	13,500	20,200	0	6,000	12,000	18,000
Annual Cost @$10.56/klb steam)	0	76,000	152,100	228,100	0	70,800	142,600	213,300	0	63,400	126,700	190,100

EFGR vs. Steam Injection

Both technologies are effective at reducing NO_x production and can be deployed to mitigate higher NO_x emissions associated with a transition to higher hydrogen fuels. Based on the prices used in this analysis and neglecting capital investment costs, EFGR is both more effective at reducing NO_x and more cost-effective. However, it is recognized that prices can vary considerably both internally and regionally, which can lead to different conclusions. Ultimately, designers should evaluate both options to determine which solution works best given their needs, constraints, and costs.

CFD Analysis

Figure 5: Test furnace representation in the CFD simulations.

The Computational Fluid Dynamics (CFD) model was used to simulate the combustion process and flue gas recirculation patterns inside the test furnace. The CFD was chosen for its ability to provide insights into the flow and temperature fields, and for its use to extend the range of conditions under consideration that would otherwise be either time-consuming or not cost-effective to include in the test setup. In addition, once validated, CFD tools can be used to simulate a wide range of conditions, burner designs, furnace designs, and EFGR configurations, just to name a few, in a cost-efficient and safe manner, and can be used to provide insights into the effectiveness of reducing NO_x emissions.

The simulation setup, shown in Figure 5, mimics the test setup except for the EFGR ducting. During the test, a fan was used to induce the EFGR flow from the bottom of the furnace and then mix it with fresh air inside the mixing chamber. In the simulation, the EFGR flow is induced by a negative mass flow boundary condition. The EFGR composition, the temperature, and the flow rate, were mapped at the side inlet on the burner windbox, with the EFGR flow rate being equally split between the two burners. The EFGR stream then mixes with the fresh air in the windbox and the burner throat. For the simulations, the EFGR temperature was assumed to be the measured temperature of the flue gas just

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prior to entering the air-EFGR mixing chamber. It varied between 1400°F and 1600°F, and its flow rate varied between 0 and 4000 lb/hr to achieve the desired EFGR percentage. The air stream flow was fixed to provide 10% excess air for 16 MMBTU/hr burner heat release for a given fuel composition, but the temperature was varied from 55°F to 1000°F to provide increased EFGR and air combined temperature. The combined air-EFGR temperature ranged between 55°F (0% EFGR and 55°F combustion air temperature) and 1150°F (29% EFGR and 1000°F combustion air temperature). With this setup, it is possible to explore the NO_x impacts because of 1) the combustion air preheat system alone, 2) the EFGR system alone when it is mixed with ambient air, or 3) the combined effect when EFGR flow and preheated combustion air are mixed. In total, 25 simulations were run with 5 combustion air preheat temperatures and 5 EFGR flow rates. All simulations used a steady-state formulation of the Reynolds-Averaged Navier Stokes realizable k-epsilon turbulence model coupled with a two-step Eddy Break-Up combustion model. All simulations used the 90% TNG/10% H_2 fuel. The NO_x model was validated against the experimental results, as shown in Figure 6.

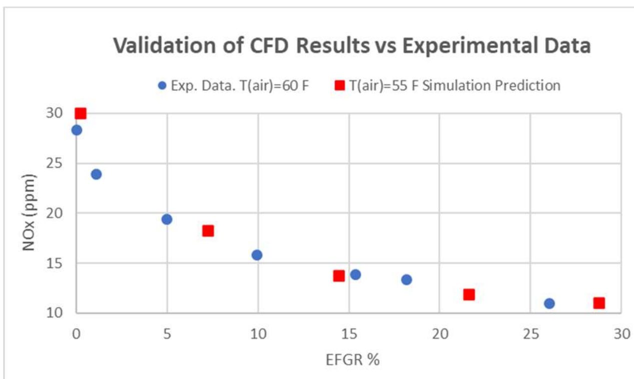

Figure 6: Plot showing a comparison of NO_x values of experimental data against predicted CFD simulation values for similar conditions of EFGR flow, EFGR temperature, and combustion air temperature. Results are for the 90% TNG/10 H_2 fuel mix.

Figure 7 shows the predicted NO_x values as a function of the amount of EFGR flow and the combined EFGR and combustion air temperature. The figure shows the actual predicted values, red markers, and a fitted surface to better illustrate the interconnectivity of the quantities of interest. The highest predicted NO_x, 62 ppm, is for the maximum combustion air temperature considered in the study, 1000°F, with no EFGR flow. As soon as EFGR is introduced, the NO_x decreases dramatically. Even if only 7% EFGR is used, the NO_x decreases by approximately 50%, close to 32 ppm. For lower combined EFGR and combustion air temperatures, the NO_x reduction is still significant. For instance, at approximately 400°F combustion air temperature and no EFGR, the predicted NO_x is approximately 30 ppm. The introduction of 7% EFGR flow reduces the NO_x to approximately 18 ppm, or 40% NO_x reduction. Overall, this figure captures the potential beneficial impact of EFGR on NO_x production across a wide variety of operating conditions. It is especially enlightening when comparing the slopes of increasing air preheat temperature without EFGR against the same increase in temperature with 30% EFGR. It highlights the absolute NO_x reduction value of adding EFGR to fired equipment with air preheaters.

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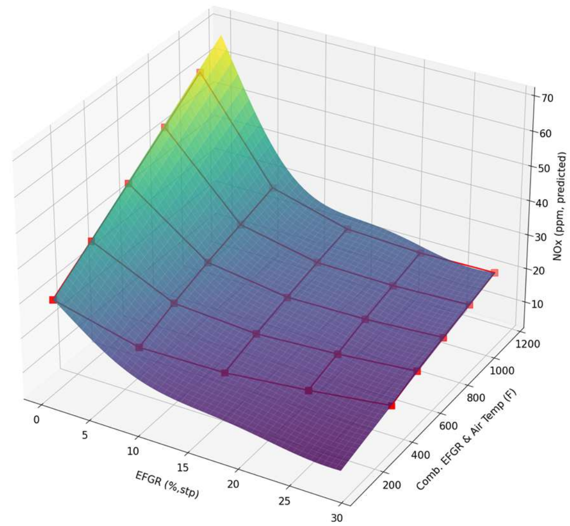

Figure 7: 3D plot of simulated NO_x reduction vs. EFGR flow and combustion air mix temperature for the 90% TNG/10 H_2 fuel mix.

FRNC5 Modeling to Predict Impacts on Fired Equipment

As mentioned previously, EFGR is most often associated with cool flue gases being recirculated into the combustion air. The flue gas is often recycled from the backend of the equipment after being cooled by all or most of the heat transfer surface area. Consequently, when it is returned to the front end of the equipment, this recycled flue gas passes across all heat transfer surface areas for a second time. From a heat transfer perspective, there is an adverse impact to radiant heat transfer because of the lower flame temperature and an increase in convective heat transfer because of the increased velocity of the flue gas. In practice, this results in minimal debits to the overall efficiency of the fired equipment when equipped with both radiant and convection sections. Regarding recirculating hot flue gases from the radiant section like the furnace tested above, the recirculated flue gases are confined to the radiant section only. Also, there is a much smaller debit to the radiant heat transfer because the EFGR temperature is essentially the same as the firebox temperature.

To understand the differences when recirculating both cold and hot flue gases, Fired Heater Simulation Program FRNC5 version 9.6.0 was used. First, a radiant section-only model was created with various EFGR temperatures and flow rates. Figure 8 displays the impact on heat flux, and Figure 9 reflects the additional heat input required to restore the radiant duty. A few important points can be gathered from the figures. The first is that increasing the EFGR flow rate requires an increase in heat input (Q_{Fired}) to restore the heat flux. The second is that using hotter EFGR temperatures minimizes the heat flux impact because of the smaller effect on the radiating gas temperature. This can be beneficial for cases where increasing the firing rate is either limited or not desired. Thirdly, though the modeling excluded a convection section, the results can be applied to heaters that have a convection section with only waste heat coils, such as a continuous catalytic reforming (CCR) heater.

For those heaters such as a CCR, adding EFGR and extracting cooler flue gas from the convection section or at the stack would likely provide additional NO_x benefits than extracting hot flue gas from the radiant section(s). This is based on current experience with cool EFGR and as depicted in Figure 6 CFD plot.

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Additionally, it will increase the absorbed duty in the convection section. Conversely, it will require an additional firing rate, as shown in Figure 9, which may not be available for heaters that are limited by either firing rate or flue gas hydraulics. In those cases, extracting EFGR from the radiant box(es) can still provide significant NO_x reduction without adverse flue gas hydraulic impacts.

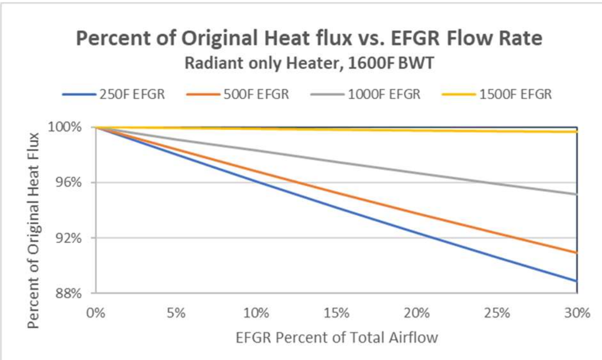

Figure 8: Radiant box heat flux comparison with various EFGR temperatures.

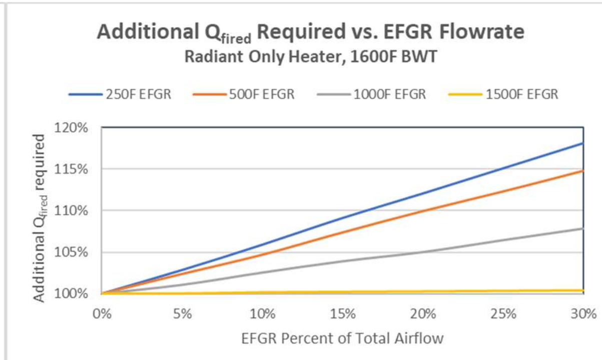

Figure 9: Additional heat input required to restore heat flux at various EFGR temperatures.

A second model was built to simulate a typical fired heater with process coils in the radiant and convection sections. It was modeled absent of waste heat coils. Prior to introducing EFGR, the duty between the radiant and convection sections was split 60% to 40%, and the bridgewall and stack temperatures were roughly 1600°F and 300°F, respectively. For the first case, flue gas was removed from the stack and recirculated to the burner. For the second case, EFGR was extracted from the radiant section. Table 5 shows the results of the simulation. As depicted in the table, the 300°F EFGR has about a 10% drop in radiant section duty relative to no EFGR. This drop is offset by a gain in the convection section. Overall, there is only a minor debit in the fuel efficiency. Regarding the 1600°F EFGR case, though the model reflects a slight increase in radiant duty, there is virtually no change to the fired heater efficiency. Results in the field will vary depending on the configuration of the fired equipment and operating conditions.

Table 5: Simulation comparisons between 300°F EFGR taken from the stack vs. 1600°F EFGR taken from the radiant section.

	0% EFGR	30% EFGR, 300F	30% EFGR 1600F
Qa MMBTU/hr	40.0	40.0	40.0
Qf MMBTU/hr	43.7	44.0	43.6
RS Heat flux BTU/hr/ft^2	10200	9222	10397
RS Duty MMBTU/hr	23.8	21.5	24.3
CS Duty MMBTU/hr	16.2	18.5	15.8
% RS Duty	59.5%	53.8%	60.6%
% CS Duty	40.5%	46.2%	39.4%
Stack T °F	335	354	331
BWT T °F	1593	1522	1601
Radiating Gas T °F	1679	1608	1686
Eff fuel	91.6%	90.9%	91.8%

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Equipment Considerations for EFGR

To add EFGR to either a fired heater or ethylene cracker is analogous to adding an air preheat system. Both will require insulated ducts, one or two fans, additional controls, and inputs to the protective system. The new design may also require a burner retrofit.

An induced-draft EFGR system as depicted in Figure 1 can use standard fan impeller materials in most applications. A forced-draft EFGR system, which uses a separate blower to move flue gas from the furnace to the discharge of the air blower, may require special materials or be limited to applications with cooler flue gas temperatures.

If spacing is available, the velocities in the ducts should be kept relatively low to keep the annual electricity cost to a minimum. In Table 2, the duct velocity was designed for 50 ft/s. Retrofit applications can be particularly challenging if the area is congested underneath and around the fired equipment. This may force smaller and longer ducts to have higher velocity. A fifty percent increase in velocity can double the annual electrical cost.

Considering the hardware cost benefits of a cold vs. hot EFGR system, the cold EFGR will have smaller ducts, fans, motors, and burner throat sizes. In a hot EFGR, the total length of the ducts and the associated structural supports should be less because all ducts are located at grade. The designer will need to compare the capital and operating costs of each to decide the best configuration for their equipment.

Whether using cold or hot EFGR, the controls and safety instrumented system need to address actions to be taken in case of a firebox flooding incident. In both cases, fuel-enriched flue gas will mix with combustion air upstream of the burners. Regarding high EFGR temperature, additional considerations should be given because of the potential of having a flammable flue-fuel gas mixture above autoignition temperature prior to mixing with air.

If an existing piece of fired equipment already has an air preheater, then the cost to add EFGR drops significantly. The ducts are already in place, and the only other duct required is a tie-in from the induced draft to forced draft systems. Additional controls, a protective system, and possibly another fan will be required to complete the configuration.

Conclusions

As the industry transitions towards high hydrogen fuels, EFGR, and steam injection can play important roles in maintaining or reducing NO_x emissions. Testing showed that using high EFGR temperature can be particularly effective. Consequently, it, alongside cold EFGR, should be considered as a valuable tool in reducing NO_x. Additionally, adding EFGR to equipment with a pre-existing air preheat system can be done at a reduced cost because of the minimal amount of ductwork required. When considering EFGR, a complete analysis of the fired equipment will assess the impacts to heat transfer, tubes and extended surfaces, flue gas hydraulics, and other components. Steam injection can be valuable when low-cost steam is readily available.

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Utilizing simulation tools together with experimental tests provides a comprehensive approach to developing effective screening tools, enabling a detailed analysis of the feasibility aspects of using EFGR in furnaces for NO_x reduction across a wide range of operating conditions. These integrated methods ensure that solutions are both technically sound and economically viable, while considering special focus to existing infrastructures. Recognizing variability across sites and furnaces is important, as there is no one-size-fits-all solution. Rather, a tailored approach, informed by real-world tests and simulations, provides the most appropriate and efficient outcome for NO_x reduction strategies.

References

[1] U.S. Energy Information Administration (EIA), 2022 Annual Natural Gas Prices in the U.S.: https://www.eia.gov/energyexplained/electricity/prices-and-factors-affecting-prices.php (*Last accessed September 8, 2023)*

[2] U.S. Energy Information Administration (EIA), 2022 Annual Natural Gas Prices in the U.S.: https://www.eia.gov/dnav/ng/ng_pri_sum_dcu_nus_a.htm (*Last accessed September 8, 2023)*