LSR Investigation on a Demonstration-Scale Lab Furnace

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Abstract
This is the fourth in a series of recent American Flame Research Committee (AFRC) papers related to the motivation, simulation technology, simulation results, and lab testing of the LSR (Large Scale Recirculation) concept for application to oilfield steam generators and boilers.

At the 2013 Kauai AFRC meeting, the first paper was given on the regulatory and combustion system progression that led to the need and ability for single digit-capable, Ultra Low NOx combustion. A second paper was given on the computational framework for analyzing such a system – the High Performance Computing ARCHES Large Eddy Simulation (HPC LES) tools developed between the Department of Energy and the University of Utah (UU), including a validation against field data collected on a full-scale, 62.5 MMBtu/h steam generator equipped with a Fives North American Combustion MagnaFlame™ GLE (FNAC GLE).

The third paper, given at the 2014 Houston AFRC meeting, introduced the LSR arrangement: a lean premix primary combustion zone with a secondary, flameless combustion zone created by secondary fuel diluted by externally-provided Flue Gas Recirculation (FGR); it also presented simulation results for LSR on a 62.5 MMBtu/h steam generator to be less than 5 ppm NOx.

This fourth paper, for the 2016 Kauai AFRC meeting, describes demonstration-scale testing of multiple configurations of a 13.3 MMBtu/h, LSR-based system on a water-cooled test furnace at FNAC. Parameters of interest to the LSR investigation include the FGR flow rate within the LSR, LSR injector quantity (and implicitly velocity), and LSR premixedness.

Results from this demonstration-scale testing indicate that LSR may be a viable approach for industrial-scale steam generator and boiler applications.

Introduction
As described in Nowakowski et al., air quality in the San Joaquin Valley (SJV) of California has failed to meet federal and state requirements for decades which has led to increasingly strict emissions standards and has in turn necessitated combustion innovation. The authors note that this cycle of innovation driving progress to the application of Once-Through Steam Generators (OTSG) utilized in thermally enhanced oil recovery (TEOR) has yielded a 98% reduction in nitrogen oxides (NOx) emissions from the late 1980’s to present.

Spinti et al. utilized and developed HPC LES tools for numerical simulation of a TEOR steam generator and performed a skeletal Validation/Uncertainty Quantification (V/UQ) study using NOx emissions as the quantity of interest. Simulation results showed agreement with field data collected from a GLE combustion system-equipped OTSG for flow dynamics at large and small scales, temperature, and NOx, thus warranting further usage of the HPC LES tools.

Thornock et al. advanced and utilized these HPC LES tools to compare a baseline GLE OTSG to an alternate combustion system arrangement called Large Scale Recirculation. Both the GLE and LSR configurations are discussed in further detail below; however, the LSR arrangement can be summarized as modifying the secondary fuel injectors of the primary lean premix-based GLE to include the addition of FGR. A key conclusion from this work regarding the success of LSR approach was that “[t]he well-mixed stream of natural gas and FGR that is fed through the injectors at high velocity creates a flameless-like combustion zone where heat release is distributed, resulting in temperatures that are too low for thermal NOx formation.” The simulation indicates a NOx reduction from ~10.5 ppm for the GLE down to 4.5 ppm for the LSR case, thus warranting further consideration of the LSR arrangement.
GLE and LSR Overviews

As shown in Figure 1, the GLE premixes all of its combustion air with a primary portion of the total fuel to create lean premix within integral mixing elements (“mixers,” “primaries,” or “1ry”) which is ignited and stabilized in a primary combustion zone within a reaction chamber. The resulting adiabatic flame temperature from this premix is typically around 2500 °F, resulting in Ultra Low thermal NOx (~2 ppm-dv, corrected to 3% dry O₂; this is the same basis for all results unless noted otherwise). The majority of the balance of the fuel is delivered through secondary fuel injectors (“secondaries” or “2ry”), which gets diluted by products of combustion (POC) of the primary combustion before igniting within a secondary combustion zone, yielding a combined NOx from the primary and secondary combustion of generally 9-12 ppm-dv without any FGR. 0-5% of the fuel may also be included along the central axis in either a center fuel nozzle or an integral radial burner.

NOx from a GLE-equipped OTSG can be reduced to <5.0 ppm with the addition of FGR to the combustion air stream; however, because this would depress the adiabatic flame temperature of the lean premix, fuel must be shifted to the primaries from the secondaries to maintain the adiabatic flame temperature and stability. This allows for additional fuel to be combusted within the Ultra Low NOx primary combustion zone and less fuel combusted within the higher NOx secondary combustion zone.

![Figure 1 – GLE Burner](image)

LSR Overview and Advantages over Conventional FGR Delivery

As mentioned above and further illustrated in Figure 2, an LSR system modifies the secondary fuel injectors of a GLE to include the addition of FGR (i.e. LSR = 2ry fuel + FGR); this inclusion of FGR additionally dilutes the secondary fuel before it is injected into the OTSG. This was shown in Thornock et al. to allow the secondary fuel to combust at a significantly lower temperature and thermal NOx productions rates as compared to the baseline GLE.

The conventional introduction of FGR in the combustion air stream adds several complications to a combustion system. First, the combustion air blower – which is already handling a significant flow rate and must overcome the total system airside pressure drop – is an operationally expensive means to add the additional FGR flow. LSR addresses this by allowing for a blower which only needs to be sized to accommodate the FGR flow rate (and not the combustion air flow + the FGR flow), and must only overcome the pressure drop through furnace chamber itself (and not through the burner + through the furnace).
Further, the reduced oxygen content of the vitiated air / FGR mixture (and the ensuing increased velocity due to the additional mass flow) reduces the stability of the burner. By mixing the FGR with the secondary fuel, the LSR system can leave the entire lean premix primary portion untouched in design and operation, thus allowing for stability comparable to FGR-less operation.

Figure 2 - LSR System

Additionally, if the fuel contains sulfur (as is common for recovered oilfield gases), then system costs can increase appreciably since the FGR-wetted components will need to be made of corrosion-resistant stainless steel; in the case of conventional FGR delivery this would include the entire burner, while LSR would only require the secondaries to have the specialized construction.

Finally, for systems with high FGR temperature the inclusion of hot FGR in the primary combustion zone may not yield significant NOx reduction due to the shift of primary adiabatic flame temperature. Because it does not affect the primaries, LSR systems can utilize hot FGR for NOx reduction where conventional systems cannot.

Test Facility Overview

With the HPC LES simulation predicting significant NOx reduction along with the numerous design and operational advantages considered above, a test program was designed and implemented at FNAC’s combustion laboratory in Cleveland, Ohio. The two most fundamental requirements for the test system were that the burner had to share the GLE’s lean premix / secondary fuel injection technology platform and that the furnace walls had to present a reasonable boundary condition approximation of those used for the field OTSG and the HPC LES.

Fives North American’s D-1 furnace had been a multi-fuel, 400 boiler hp (13.3 MMBtu/h), three-pass, firetube boiler, but has since been repurposed as an open system, natural gas-fired, water-cooled test furnace. A number of custom modifications, including the fuel train as shown in Figure 3 and Figure 4, the oxidant system as shown in Figure 5 and Figure 6, the control panel in Figure 7, and the burner mounting in Figure 8 were made to the original furnace construction to allow flexibility to assess a variety of burner and system parameters.
Figure 3 - Updated Fuel Train Schematic

Figure 4 - Updated Fuel Train
Figure 5 - Updated Oxidant System Schematic

Figure 6 - Updated Oxidant System and Front End
Figure 7 - Updated Control Panel

Figure 8 - Updated Burner Mounting
As shown in Figure 9, the specific test burner utilized was a GLE variant which happened to have split plenums for the primaries: the top four mixers had a separate air and fuel supply from the bottom two primaries, though for LSR testing the flows were adjusted to have the per-mixer flows and air/fuel ratios mimicked from top to bottom.

![Figure 9 - Test Burner Primaries](image)

**Testing Summary and Results**

The general procedure for most of the testing presented herein is shown in Table 1 and was conducted at 8 MMBtu/h for the LE Mode. “Max” FGR was a heuristic determination based primarily on system stability and CO production rate. The primary parameters studied in Figure 10 and Figure 11 were A) for a given 2ry fuel flow rate, variation of the FGR flow rate within the LSR mixture (0% - 40%), and B) variation of the number of LSR injectors (and implicitly velocity) (1-4); for these two figures, all 2ry fuel and FGR is fully premixed in the LSR.

<table>
<thead>
<tr>
<th>Step</th>
<th>Summary</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
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<tr>
<td>Summary</td>
<td>Establish LEx Mode Baseline</td>
<td>Add 2ry Fuel</td>
<td>Establish LE Mode Baseline</td>
<td>Add FGR to LSR Mix</td>
<td>Reach Final FGR Flow Rate in LSR</td>
<td></td>
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<tr>
<td>1ry Fuel</td>
<td>Top and Bottom at 70% XSA</td>
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<td>(unchanged)</td>
<td>(unchanged)</td>
<td>(unchanged)</td>
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</tr>
<tr>
<td>2ry Fuel</td>
<td>Off</td>
<td>Increase</td>
<td>~2x the 1ry fuel</td>
<td>(unchanged)</td>
<td>(unchanged)</td>
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<tr>
<td>FGR</td>
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<td>Off</td>
<td>Off</td>
<td>Increase</td>
<td>Max</td>
<td></td>
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<td>Stack O2</td>
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<td>(decreases)</td>
<td>3.0%</td>
<td>(unchanged)</td>
<td>(unchanged)</td>
<td></td>
</tr>
</tbody>
</table>
Figure 10 - LSR General Results – Stack O2 Slice

Figure 11 - LSR General Results - FGR Slice
Note that the definition of FGR here is considered as:

\[
FGR\% = \frac{\text{Standard Volumetric Flow of FGR (scfh)}}{\text{Standard Volumetric Flow of Ambient Air (scfh)}} \times 100\%
\]

Additionally, in order to evaluate the effect of the premixedness of the 2ry fuel and the FGR in the LSR, several nozzle-mixed tests were performed (with 3xLSR injectors) where the 2ry fuel injectors were located at various mixing distances upstream of the discharge into the furnace within an FGR annulus. Positive values for the recess indicate that the 2ry fuel injector was upstream of the furnace hot face, while negative values for the recess indicate that the 2ry fuel injector stood proud of the hot face within the furnace. All nozzle mixed data in Figure 12 is at 24.7-25.3% FGR and 3.1% dry stack O2 while the premixed nozzle data is at 23.9% FGR (6.7 ppm) and 27.0% FGR (5.7 ppm).

![Figure 12 - Premixedness Effect](image)

**Data Interpretations**

Every LSR configuration was demonstrated to be capable of 6 ppm NOx emissions with the exception of the single, premixed LSR nozzle - which was unable to utilize more than ~10% FGR before experiencing stability issues; further, it is noteworthy that for this system, this low NOx level for each configuration occurred at the respective maximum FGR flow rates. However, it is likewise notable that if the 2/3 of the total fuel which was added in the primaries and radial generated only ~4 ppm NOx, then the remaining 1/3 of the total fuel added via the 2ry in the LSR generated only 2 ppm NOx. Stated differently, the NOx generation rate per mass of fuel was the same between the 1ry and the 2ry for maximum FGR in LSR configurations.

As fewer premixed LSR injectors were used, less FGR was required before reaching the 6 ppm NOx performance level; however, coupled with stability observations above, it is also concluded that decreasing the number of LSR injectors also reduced the maximum tolerable FGR rate.

The NOx performance of nozzle-mixed LSR was comparable to that of fully premixed LSR – in the same 6 ppm range. Further, the NOx reduction observed as the 2ry fuel injector recess was decreased suggests that the ideal 2ry fuel nozzle location for
nozzle-mixed FGR is not upstream of the hot face discharge and thus that phenomena other than premixedness are contributory for the shape of the nozzle-mixed NOx curve in Figure 12.

The system exhibits a noticeable NOx sensitivity to the amount of radial fuel used - see for example the differences between the premixed 4xLSR injectors at 350 and 275 scfh of radial fuel: an offset of about 1.5 ppm for a mere 75 scfh of radial fuel. This effect was investigated a little further as shown below in Figure 13, and is partially responsible for the baseline LEx NOx being above a typically expected value of 2-3 ppm to the 3.7 ppm observed in this testing.

![Figure 13 - Radial Fuel NOx Effect](image)

Finally, an additional configuration – Internal Large Scale Recirculation (ILSR) – was also tested, wherein the LSR mixture of 2ry fuel + FGR was introduced in the bottom two primary mixers instead of lean premix of air and fuel. Though full results will not be presented here, similar, promising NOx results were achieved (in the 5-7 ppm NOx range when using 25% FGR at 3% stack O2).

**Additional Observations**

Undertaking the LSR demonstration on the D-Lab water-cooled test furnace, though necessary to match boundary conditions of field OTSG and boiler applications, represented a significant technical risk to manage throughout the project. Previous investigations of flameless combustion have been performed in furnaces which were well above autoignition temperature, whereas the water-backed firetube is significantly below autoignition temperature. This has created challenges for traditional industrial combustion systems which are injecting fuel in this location; however, with the addition of FGR to the 2ry fuel to create the LSR, this demonstration intentionally demonstrated highly diluted fuel (vitiated with CO2 and H2O containing FGR) being introduced into the coldest area of a furnace, below the autoignition temperature, without preheat is believed to be the first work of its kind to be attempted.
Further, the inclusion of LSR as flameless complement to the stabilized lean premix primaries appears to be the first time that this complementary mode combustion between a stabilized and an unstabilized flame has been established for Ultra Low NOx.

Similar to other cases of flameless combustion, the flameless reaction zone is difficult to visually detect; however, since in this instance the furnace is much colder that those above autoignition temperature, the radiation from the furnace walls is lessened enough to allow some perception of it with the naked eye such as the blue wisp at the 10 o’clock position in Figure 14. Variation of camera settings allow for enhanced visualization as well.

Operation of the demonstration rig was significantly complicated – multiple fuel streams and flows to control (top 1ry, bottom 1ry, radial, 2ry, pilot), multiple air streams and flows to control (top 1ry, bottom 1ry, radial, pilot), multiple FGR streams and flows to control (top 1ry, bottom 1ry, 2ry (LSR)), and multiple air/fuel ratios to control (top 1ry, bottom 1ry, radial, overall) all meant that managing the risk discussed above while discovering system operational limits required significant care.

A number of operational limits were systemic in nature, and many were presented via the coupling of the FGR. When CO was produced at levels greater than ~20 ppm-dv, the recirculation of the CO back into the system via the FGR in the LSR had the potential to lead to runaway CO production and the test had to be terminated. For the premix LSR tests, a minimum of 5% FGR was included in the LSR stream to avoid having 2ry fuel fill the LSR header.

Future Work
Additional data analysis is warranted, including a sensitivity analysis to attempt to quantify the effects of radial fuel flow, radial air flow, primary air/fuel ratio, etc.; this would allow for an increasingly meaningful apples-to-apples comparison between data sets. A theoretical analysis of the jet entrainment variation between undiluted 2ry fuel and LSR could yield insights which allow scaling the demonstration rig to industrial applications.
Experimentally, since NOx was found to be so sensitive to the radial fuel flow, NOx reduction techniques on the radial burner itself (i.e. FGR) may prove fruitful. A temperature/species traverse performed within the Morrison tube could be compared against the results predicted by the HPC LES tools of Thornock, et al.

Conclusions

A 13.3 MMBtu/h, demonstration-scale lab furnace has been successfully configured with FNAC GLE platform and LSR technology. The setup was operated, carefully, with various quantities and configurations of LSR injectors and operated across a range of FGR flows until the system limits were reached. Nearly all arrangements tested were shown to achieve 6.0 ppm-dv NOx at 3% dry stack O2, with the lean premix primaries and the LSR generating NOx at the same rate per mass of fuel input at maximum FGR in LSR conditions. Nozzle-mixed LSR performed comparably to fully premixed LSR, and the total system NOx was highly sensitive to the radial fuel flow.

Overall, this testing indicates agreement with Ultra Low NOx results predicted by Thornock et al., and shows that LSR holds promise for industrial-scale steam generator and boiler applications.

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References

1 John Nowakowski, Tom Robertson, Beverly K. Coleman, Stein Storslett, and Nicholas Brancaccio. The Road to Single Digit NOx for Oilfield Once-Through Steam Generators. AFRC conference, Koloa, Hawaii, September, 2013.

