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EXHAUST GAS RECIRCULATION PERFORMANCE IN DRY LOW EMISSIONS COMBUSTORS

A. M. Elkady, A. R. Brand and C. L. Vandervort
Energy and Propulsion Technologies
GE Global Research Center
Niskayuna, NY, USA

A. T. Evulet
GE Oil and Gas
Florence, Italy

ABSTRACT

In a carbon constrained world there is a need for capturing and sequestering CO_2. Post-combustion carbon capture via Exhaust Gas Recirculation (EGR) is considered a feasible means of reducing emission of CO_2 from power plants. Exhaust Gas Recirculation is an enabling technology for increasing the CO_2 concentration within the gas turbine cycle and allow the decrease of the size of the separation plant, which in turn will enable a significant reduction in CO_2 capture cost. This paper describes the experimental work performed to better understand the risks of utilizing EGR in combustors employing dry low emissions (DLE) technologies. A rig was built for exploring the capability of premixers to operate in low O_2 environment, and a series of experiments in a visually accessible test rig was performed at representative aeroderivative gas turbine pressures and temperatures. Experimental results include the effect of applying EGR on operability, efficiency and emissions performance under conditions of up to 40% EGR. Findings confirm the viability of EGR for enhanced CO_2 capture; In addition, we confirm benefits of NO_x reduction while complying with CO emissions in DLE combustors under low oxygen content oxidizer.

INTRODUCTION

In order to capture and sequester the CO_2 emitted from Natural Gas based power-generation plants, three different concepts can be considered [1, 2]:

• Separation of CO_2 from exhaust gas coming from a standard gas turbine combined cycle (GTCC), using chemical absorption with amine solutions or other separation technologies. It can either be performed using a direct contact between exhaust gas and absorbent (amines), or by use of membranes.

• Integrated reformer combined cycles (IRCC) with natural gas de-carbonization, in which the carbon is removed prior to combustion and the fuel heating content is transferred to hydrogen. This concept can be applied for natural gas by a sequence of reforming, water gas shift reaction and by CO_2 removal process.

• Oxyfuel gas turbine combined cycle at near-stoichiometric combustion conditions with oxygen (> 90%+ purity) from an air separation unit as oxidizing agent, producing CO_2 and H_2O vapor as the combustion products and partially re-circulating the products into the combustor, followed by post-combustion separation.

In all cases the CO_2 separation process needs to be integrated to the combined cycle and usually results in penalties associated with the efficiency of the plant. It is important therefore to minimize the energy (work) consumed for CO_2 capture. Of these three reference configurations, EGR is expected to be most applicable to GTCC.

Today's state-of-the-art amine separation systems rely on gas separation processes with efficiencies highly dependent on the concentration of the CO_2 in the flue gas and its volumetric flow [3]. A great reduction in CO_2 separation work can result from increasing the CO_2 concentration in the flue gas. In addition to increasing the concentration of CO_2 in the cycle, Exhaust Gas Recirculation (EGR) can reduce the capital cost of CO_2 separation units. This could be achieved by decreasing the flow of flue gases while significantly increasing the CO_2 concentration (e.g. by more than 50%.) For this and other reasons to be described below, it is desirable to modify a gas turbine for EGR operation. It is expected that 50% EGR will provide a 35% reduction in the cost of CO_2 capture compared with standard retrofit options due to reduction of the flow rates to the CO_2 capture unit while increasing the CO_2 concentration to up to 10% by volume [4].

The risks associated with combustion when using EGR include effects on operability, emissions (especially CO, UHC) in vitiated air, heat transfer with the altered working fluid, and possibly combustion efficiency penalties associated with incomplete combustion. It is important to note that EGR will present risks and challenges for the power plant system. For example, it will be necessary to ensure that exhaust products do not contribute to corrosion of compressor components and that complete mixing of inlet compressor air and EGR occurs prior to entry. Dependent upon the selected levels of EGR, redesign of the gas turbine may be necessary.

Historically, EGR has been applied as a concept for NO_x reduction especially in diffusion combustion systems. For example, studies performed at GE by Wilkes and Gerhold [5, 6] combining diffusion combustion with EGR without water extraction from the exhaust showed substantial reductions in NO_x concentrations compared to baseline. Without any modification to the combustion system, NO_x reduction by about 50% was achievable at 20% EGR. Gupta et al. [7], studying the effect of oxygen concentration on propane air diffusion flame, concluded that the NO_x emissions are much lower with preheated combustion air at low O_2 concentration than with normal air case. Hazard [8], found that reductions of NO_x of 70-80% could be obtained by recirculating up to 22% of the cooled exhaust gas. Hazard showed that EGR resulted in significant reduction of NO_x emissions with negligible effect upon HC and CO emissions. He also pointed out that NO_x emission levels depend on the oxygen content of the air–and-gas mixture entering the burner.

Arai [9], looked at the EGR effect as the lowering the oxygen concentration before combustion with inert gas that is provided by the engine itself. Arai reported that in EGR combustion, NO_x emissions are reduced by slow reaction of combustible mixture and lower flame temperature. He showed that the ignition delay of fuel is extended by the low oxygen concentration. The low oxygen concentration also reduces the reaction rates and allows for combustion to be spread over a large region, hence suppressing peak flame temperatures zones and lowering pollutant emissions. Rokke and Hustad [10] studied the effect of adding N_2, CO_2 and O_2 in the fuel and air streams at atmospheric pressures. Results show that adding N_2 and CO_2 decrease the NO_x emissions in both diffusion and premixed modes, where as O_2 addition increases NO_x emissions only in diffusion mode. Also in diffusion mode, addition to the fuel stream is proven to affect the NO_x emissions the most. In ethylene diffusion flame experiments by Liu et al. [11], they concluded that the addition of CO_2 to either the fuel side or the oxidizer side chemically reduces the formation of NO_x. They also reported that the addition of CO_2 on the oxidizer side has more significant chemical effects on the flame structure and NO concentration as compared to CO_2 addition to the fuel side.

All these studies have been conducted in diffusion systems or at atmospheric pressures or both.

Numerical analysis has been conducted to help understand the chemical pathways leading to NO_x reduction with the application of EGR. Muley and Lear [12], assumed a perfectly stirred reaction to model the primary zone of a combustor. NO_x formation was modeled based on the thermal mechanism. Model results showed a sensitive dependence of the NO_x formation rate on the flame temperature and the inlet oxygen concentration. The results showed about one order of magnitude reduction in the thermal NO_x formation rate with EGR due, in part, to the lower adiabatic flame temperature and in part to the lower oxygen concentration.

Liu et al. [13] conducted a numerical study of chemical effects of CO_2 addition of a premixed flame. They claimed that the CO_2 added will change the equilibrium of the reaction $CO + OH \rightarrow CO_2 + H$, which competes with the $H + O_2 \rightarrow O + OH$ and thus plays a chemically inhibiting role reducing the rate of combustion for the “H” radicals. Park et al [14] performed a numerical study on H_2-Air counter flow flames in preheated air diluted with CO_2. They reported that the chemical effects of added CO_2, which originated from the reaction $CO_2 + H \rightarrow CO + OH$, reduce the flame strength, due to the competition between the chain initiation reaction and reactions of unburned hydrocarbons and the H atom. They also observed that the chemical effect of added CO_2 reduces NO emission indices, mainly because of the reduction of the thermal NO that is caused by the decrease in the flame temperature. In addition they claimed that the reaction step $N + CO_2 \rightarrow NO + CO$ is a relatively contributor to prompt NO production. Hwang et al [15] performed a numerical study using CH_4-O_2-N_2 diffusion flame diluted with CO_2. They concluded that the reduced production rates of thermal NO and prompt NO due to chemical effects are much more remarkable for fuel side dilution. It is also found that the reaction step $H + NO + M \rightarrow HNO + M$ plays a decisive role in the formation and destruction of prompt NO. On the other hand Rokke and Hustad [10] noted that CO_2 and N_2 injections seem to have quite similar effects on NO_x emissions. They explained this similarity is due to the fact that the specific heats of these components are quite similar, and thus the chemical effect is indicated to be less important for such a flame.

One risk associated with EGR is flame stability and lean blowout; this issue is more challenging in lean premixed systems. Rokke and Hustad [10] cited that a decrease in the O_2 concentration, without modifications to the system might cause blowout of the flame. They also noted that combustion systems operated with diffusion flames are less sensitive to variations in oxidizer composition. Bolland and Saether [16] referred that, in typical gas turbine combustor, the combustion air should normally have a minimum of 16-18 % oxygen concentration to reduce stability risks. Incidentally, this value is considered by all the limitation of O_2 concentration of the combustion air, which limits the CO_2 exhaust concentration to well under 8% by volume. An additional risk when applying EGR is CO emissions.

It is an unquestionable fact that utilizing EGR leads to less O_2 concentrations in the oxidizer that will alter the amount of O atoms produced and thus might affect the formation rate of NO_x. In a review on NO_x formation in lean premixed flames, Correa [20] pointed out that the presence of super equilibrium levels of radical [O] is an important factor in NO_x formation.

He described that the flame temperature does not vary enough with pressure to significantly affect the Arrhenius exponential factor in the thermal mechanism; however the oxygen atom concentrations do vary substantially. He also mentioned that equilibrium oxygen atoms concentration indicates a near square root dependence on the pressure.

It is apparent that there is a need for experiments at representative pressures and temperatures utilizing premixed combustion systems, particularly dry low NO_x (DLN) or dry low emissions (DLE) systems. One can thus elaborate on the effect of EGR on combustion operability. Choosing a premix combustion system stems from the need to eliminate the differences between pre-mixing the exhaust gas with air or with the fuel, as some studies indicated [10]. If you have perfectly premixed combustion, then the mixture fraction at the flame front is essentially what came into the premixer as fuel and what came in as air. The flame front will have no way of knowing if the oxygen content at the flame front was reduced due to nitrogen being mixed in the air stream or the fuel stream.

To eliminate the coupling between EGR and flame temperature, experiments should be performed at a fixed flame temperature rather than fixed fuel mass flow rates.

A recent collaboration with the Carbon Capture Project consortium allowed GRC to perform experimental work and better understand the issues related to GT combustion with EGR. This report describes the experimental work performed at GRC in order to better understand the risks of using EGR in combination with dry low NO_x nozzles at representative conditions of pressure and temperatures. We have performed a series of experiments in which inert gases such as N_2 and N_2/CO_2 were used to vitiate the fresh air to the levels determined by cycle models. Our findings confirm the feasibility of EGR for ease of CO_2 capture, exceeding the expectations of operability and efficiency. In addition, we have found groundbreaking benefits of NOx abatement that suggest EGR (as retrofits or for new systems) combined with DLN/DLE as a prime technology to deliver the lowest NOx emissions among all current technologies, possibly with elimination of SCR needs, and at the same time prepare the ground for CO_2 capture-ready gas turbines.

As mentioned earlier, most of the cited studies have been conducted in diffusion systems or at atmospheric pressures or both. However, in the last few years, much attention has been focused on applying EGR to a premix combustion system. For example, combustion research work at GE-GRC on F-Class premixing type nozzles with EGR [35-38]. In addition, to eliminate the coupling between EGR and flame temperature, experiments should be performed at a fixed flame temperature rather than fixed fuel mass flow rates.

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Mitsubishi Heavy Industries [17] identified EGR as a key element of their 1,700 C "J-Class" gas turbine. Measured NO_x at combustor outlet was below 50 ppm with approximately 10 ppm CO. Alstom [18] and Precision Combustion, Inc. [19] have patented power plant configurations utilizing exhaust or flue gas recirculation.

Experimental Setup

The experimental setup used is shown in figure 1. A double annular counter-rotating swirl (DACRS) premixer is used for the experimental evaluation of combustion with EGR. The research premixer is modified from the version used in the GE5 gas turbine combustor. The nozzle has the capability of operating in fully diffusion, partially premixed (piloted), and fully premixed mode via two independent fuel supply systems. The ability to operate in these modes allows experimental assessment of the operability of this combustor in various conditions of pressure, temperature and oxygen content. Analyzers accuracy used was described elsewhere [35,36,38].

The pressure vessel in which the combustor is mounted is rated for temperatures of up to 750 K and 17 bar. The rig includes two 0.203 m diameter windows on either side of the vessel to allow optical access to the quartz liner and the nozzle. Preheated air and natural gas fuel are supplied to the test cell by facility systems. The exhaust is directed into the facility exhaust tunnel. Sample gases are collected from the end of the metallic liner at a single position and sent to the emissions stand. All critical pressures, temperatures and flows are measured within the test cell. The inlet air conditions for this experiment were $T_{air,in}$ = 700 K, $P_{air,in}$ =10.3 bar. All experiments were performed at full pressure to maximize the experiment running time when using the limited pressure inert feed from the fuel blending station. A fuel blending station (FBS) was utilized for this test to provide a constant flow of a mixture of N_2 and CO_2 to the fresh air supply in order to mimic the EGR oxidizer composition into the combustor. The oxidizer composition to be tested was determined by cycle models as shown in table 1. All tests were performed under the assumption that water is condensed out of the exhaust gas before recirculation. This is a departure from the tests done in 1980s by Wilkes et al. [5, 6].

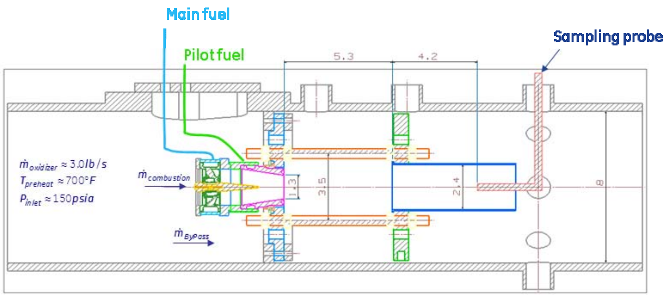

Figure 1. Experimental setup

The quartz tube liner allows for experimental evaluation of flames up to 15 msec residence time and pressures up to 14 bar. The combustor was designed and built specifically for advanced optical diagnostics. A minimal pressure differential between the by-pass air and the reacting flow (combustion gases) is determined such that the quartz tube allows normal operation.

A water-cooled gas-sampling probe was centrally located at the end of the 0.152 m long metal liner. Emissions were measured at a fixed location instead of using a traverse. The sampled exhaust gas is directed to the emissions analyzer where NO_x, O_2, CO_2, CO, UHC and CH_4 measurements are performed after sample is cooled and dried. Based on these measurements and accurate calibration of the analyzers, the stoichiometry of the flame, the CO_2 and O_2 levels and the emissions of NO_x and CO are taken at each point of interest.

Ignition of the combustor is achieved via a H_2 fueled torch placed upstream of the swirler. Once the correct fuel and airflows are established, the torch is ignited for a short period, enough to ignite the downstream primary zone mixture of fuel and air. Typically a pressure drop of about 4% was achieved during operation.

After stabilization of the flame a sweep of fuel-to-air ratios is performed to determine baseline emissions and performance; the FBS is then used to add the required amount of inerts to the combustion air O_2 specifications required (e.g. 15% up to 21% O_2 in N_2/CO_2). Table 1 shows the conditions that were tested in this phase of the project.

Table 1: Inlet oxidizer composition (mole fraction) at different EGR levels

EGR (%)	XO_2	XCO_2	XN_2
50	0.132	0.044	0.823
40	0.159	0.029	0.812
30	0.177	0.019	0.804
20	0.191	0.011	0.798
10	0.202	0.005	0.793

RESULTS AND DISCUSSIONS

For all the emissions data plotted in following sections and in order to clarify the trends, data were curve fit. A transfer function was developed that incorporates flame temperature, O_2 concentration in the inlet air, and pilot percent and returns the NO_x and CO levels, corrected to 15% O_2 levels.

Measurement Details

The flame temperatures reported are based on the O_2 levels measured at the probe location. These values were compared to the thermodynamic equilibrium values estimated using Chemical Equilibrium Analysis Code [21], and excellent agreement was found within 5% as depicted in Figures 2 and 3 (lines). This level of agreement increased the confidence of the measurements and indicates that the sample extracted is representative. In addition, flame temperatures based on the flows of air and natural gas and airflow-splits also show good agreement.

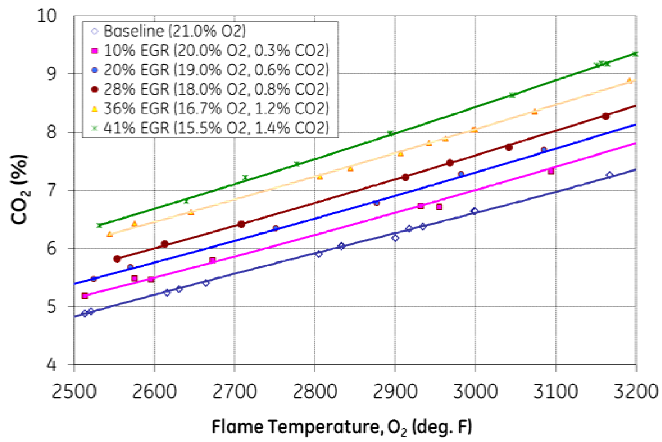

Figure 2: CO_2 levels as function of T_{flame}, (O_2 based), EGR %, Comparison with Equilibrium Calculations

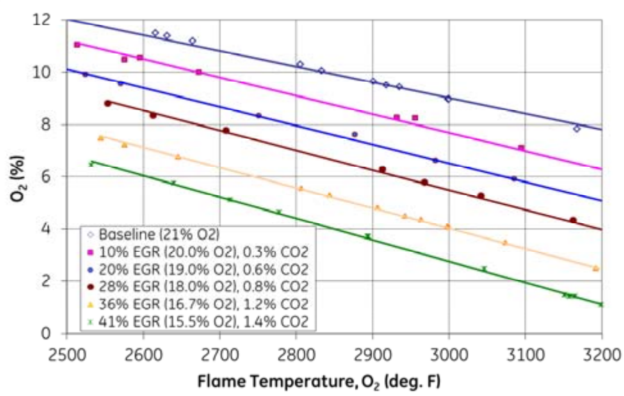

Figure 3: O_2 levels as function of T_{flame}, (O_2 based) and Percent EGR. Comparison with Equilibrium Calculations

Flame stability

The flame was in general very stable when using a pilot, even with the low levels of O_2 tested. The LBO varied with the

percent pilot (diffusion) and it was, as expected, worsening as O_2 levels decreased.
The extreme LBO point observed at 0% pilot and 16% O_2 in the air was around 1783 K. It was determined that operation at 15% pilot is the most appropriate condition to test due to flame stability, and reduced acoustic instabilities. Pilot variation was however explored as one additional parameter. The flame structures were observed by using a remote video camera and still images of the flames at various levels of EGR. No significant changes were observed for partially premixed flames, other than an apparent spreading of the flame, which may be the cause of dynamics reduction as well. Note that dynamics instabilities disappeared with EGR, allowing us to reduce the pilot to zero percent and leading us to believe that EGR may have potential to reduce acoustic instabilities as well. Note that dynamics instabilities reduced with EGR, similar to what was concluded in previous studies [37, 38].

CO_2 emissions

As explained, the main goal of the work was to demonstrate DLE technology operability and efficiency with EGR. At the same time, the high level goal was to demonstrate that high levels of CO_2 may be achieved in the combustor, thus enabling the CO_2 capture plant to operate with minimum losses in a post-combustion CO_2 capture scenario. This, as well as low levels of O_2 resulting from combustion with EGR was demonstrated successfully. The CO_2 emissions results are presented in figure 2. The levels of CO_2 used for doping did not allow us to operate at exactly the CO_2 levels calculated using EGR due to some fuel blending station limitations. Only about half the CO_2 needed to simulate the real EGR was used in the experiments, however they demonstrated that CO_2 levels of more than 10% is achievable at the exit from the combustor. The measured CO_2 levels are shown at different EGR conditions and as function of flame temperature.

O_2 Levels

From figure 3, it can be seen that there is excellent agreement between the O_2 levels measured, compared to the equilibrium calculations. This demonstrates very reliable emissions measurements at the analyzers and also that the measured O_2-based flame temperature calculations are correct. Figure 3, also shows the lower oxygen levels obtained with increasing flame temperature and EGR levels. It can be seen that the lowest oxygen levels, which correspond to more complete oxygen depletion, correspond to higher fuel to oxidizer ratios and therefore high temperatures to below 1% O_2 concentration by volume. It should however be noted that these low levels also result in less consumption of the CO and therefore emissions of CO are higher due to the oxygen starvation of these flames.

NO_x emissions

It was found that the NO_x emissions are strongly reduced via the reduction of oxygen in the combustion air. This is explained by analyzing the thermal NO mechanism formed by the elementary reaction of O and N_2 [20]:

$$O + N_2 \rightarrow NO + N$$

This reaction has very high activation energy due to the strong triple bond in the N_2 molecule and it is sufficiently fast only at high temperatures. Because of its small rate, this reaction is the rate-limiting step of the Zel'dovich mechanism.

As a result of addition of inerts to the incoming air and decreasing O_2 levels, peak temperatures in the flame will be reduced or eliminated. In the case of gas turbines, exhaust gases are considered as inert and their increased heat capacity (due to diplacement of the O_2) determines reduction of the peak temperatures, thus reducing the propensity of NO formation.

Another aspect of the NO_x reduction is the equilibrium calculated [O] atom. This radical, typically measured to be at super-equilibrium in flames, affects the NO_x production as described by the Zel'dovich mechanism. It appears that at lower flame temperatures the reduction of NO_x is less pronounced than at higher flame temperatures due to a smaller combined effect of the flame temperature (i.e. activation energy) and lowering of the [O] radical on the thermal NO_x side, and perhaps an accentuated lowering of prompt NO_x (see [23]).

Figures 4 show the reduction of NO_x for this particular research combustor, and the degree of reduction as a function of EGR level, as raw, and $EINO_x$ plots, respectively. Figure 5 shows the plot of NO_x reduction expected at various flame temperatures, with varying EGR levels. Finally, figure 6 shows the potential of NO_x reduction as a function of EGR for a piloted flame used in this combustor. It should be mentioned that these results do not guarantee exactly the same performance on a production combustor. The potential for emissions reduction is however real and significant.

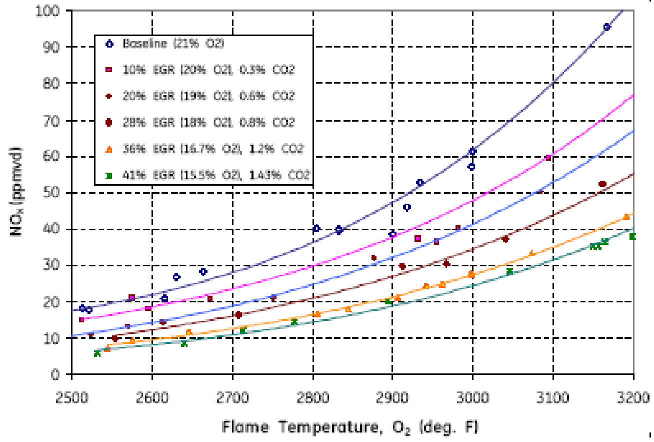

Figure 4a: Measured NO_x (no corrections) levels function of EGR level, at constant T_{flame} and pilot at 15%

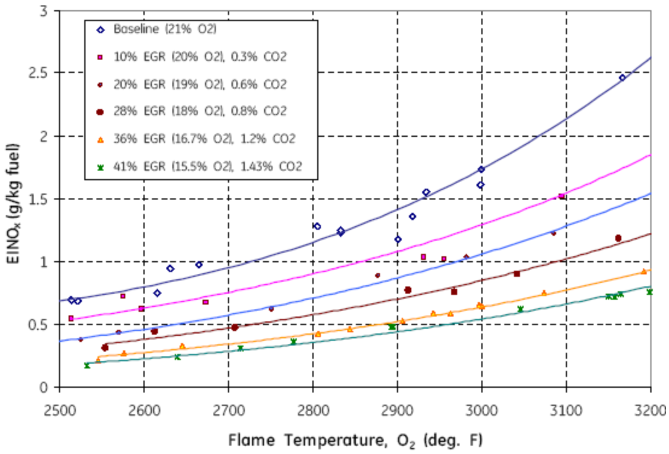

Figure 4b: Measured EINO$_x$ levels function of EGR level, at constant T$_{flame}$ and pilot at 15%

Combustion Efficiency with EGR

The gas turbine combustor needs to operate at high combustion efficiency. The combustion efficiency can be measured based on the levels of unburnt hydrocarbons (e.g. methane) as well as incomplete burnout of CO. Due to oxygen starvation and specific conditions, a gas turbine combustor designed for 21% O_2 air may not guarantee completion of the oxidation reaction to CO_2 in EGR conditions, thus determining inefficiencies. However, for the partially premixed flames and conditions tested with EGR as described in table 1, the efficiencies were very high, similar to the ones in the baseline cases and complying with the CO emissions. This is also reflected by the good oxygen consumption described in the preceding section. Figure 7, shows these levels calculated from measured emissions of CO and UHC.

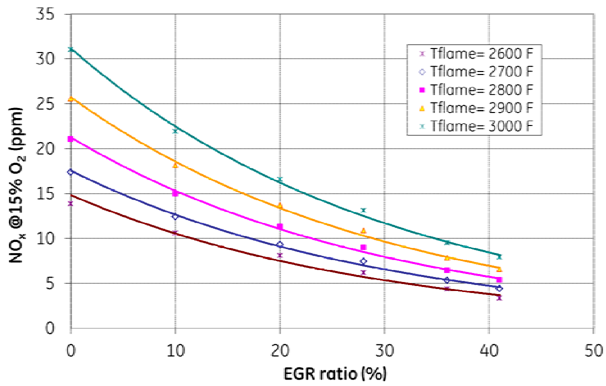

Figure 5: Measured NO$_x$ levels function of EGR ratio, at constant T$_{flame}$ and pilot at 15%

CO emissions

One of the concerns of gas turbine combustor designers is to keep CO concentration to minimum levels. Significant amounts of CO can be produced due to lack of oxygen to complete the oxidation reaction to CO_2 in rich flames, or due to dissociation of CO_2 in stoichiometric or moderate fuel-lean combustion,

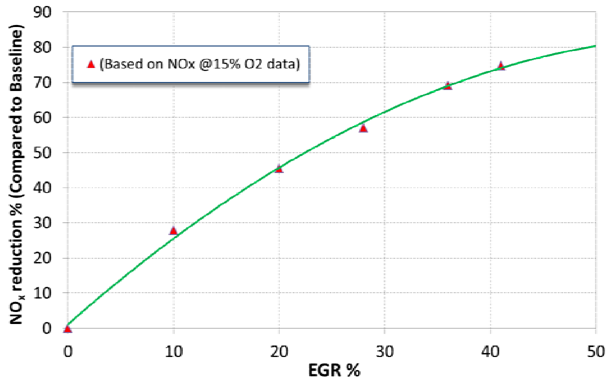

Figure 6: Percentage of NO$_x$ reduction as function of EGR level, at constant Tflame and pilot at 15%

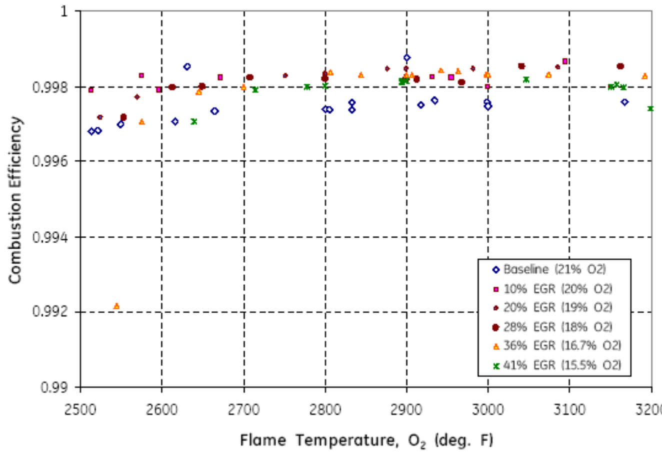

Figure 7: Measured emissions-based combustion efficiency as function of EGR level and pilot at 15%

or due to low combustion temperatures and low burning rates in very lean-fuel reacting flow cases. Correa [26] pointed out that carbon monoxide produced in the flame stabilization zone can survive the flame and must be oxidized in the turbulent post-flame gas, introducing a much greater dependence on aerodynamics than is the case for NO, (in lean premixed flames). Lefebvre [27] acknowledged that, in practice CO emissions are found to be much higher than predicted from equilibrium calculations and to be highest at low-power conditions, where burning rates and peak temperatures are relatively low. These observations suggest that both formation and destruction of CO in combustors is kinetically controlled. In addition, Lefebvre stated that much of CO arises from incomplete combustion of the fuel, caused by one or more of the following:

- Inadequate burning rates in the primary zone, due to very lean fuel-air mixture and/or insufficient residence time
- Inadequate mixing of fuel and air,

- Quenching of the post flame product by entrainment into liner wall-cooling air, especially in the primary zone

At high reacting temperatures, the principle CO oxidation reaction in hydrocarbon flames is:

$$CO + OH \rightarrow CO_2 + H \quad (1)$$

Baulch and Drysdale [28] evaluated the reaction rate of this mechanism and concluded that this reaction path is important in combustion systems where it acts as the principle source of CO_2 and plays a major role in determining the yield of CO. Bowman [29] cited that for temperatures below 1000 K, the reaction rate constant is independent of temperature. However, at higher temperatures in excess of 1500 K, the rate coefficient exhibits significant temperature dependence. Correspondingly, Correa [26] referred that the rate of CO oxidation is reduced by more than two orders of magnitude between flame-like (1800 K) and combustor liner-like (1100-1200 K) temperatures.

Westenberg and deHaas [30] suggested an alternative reaction path that might have significance on CO oxidation at lower temperatures, defined as 1000 to 1500 K.

$$CO + HO_2 \rightarrow CO_2 + OH \quad (2)$$

However, this reaction is usually negligible in comparison to reaction (1) except at very high pressures or in initial stages of hydrocarbon oxidation [31].

Experimental data of CO emissions (corrected to 15% O2) are presented as function of flame temperature and percentage of EGR in Figure 8. In the baseline case (0% EGR) high CO concentrations are found at low flame temperatures and decrease with increasing the flame temperature to a minimum value at about 1730 K due to the oxidation reaction CO + OH → CO_2 + H which becomes significant at temperatures in excess of 1500 K. Beyond a flame temperature of 1800 K the dissociation of CO_2 to CO takes place leading to increase in CO concentrations at combustor exit plane.

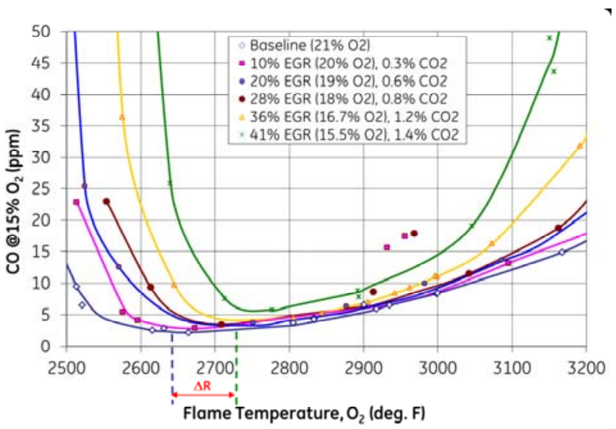

Figure 8: Measured CO levels function of EGR level, at constant T_{flame} and pilot at 15%

Generally when EGR is applied, the trends of CO emissions are similar to that of the baseline case (21% O2). However, CO levels increase with increasing EGR percentage. It is noteworthy that increasing the EGR percentage tends to shift the minimum CO point to higher temperatures. For example, using 40% EGR, minimum CO levels appeared at flame temperatures around 1780 K whereas this minimum was around 1725 K for 0 % EGR. This shift of the locus of minimum is presented by the "ΔR" shown in Figure 8.

Figures 9 show the small impact of the CO_2 addition to the inerts used in our experiments, thus confirming that the CO_2 introduced acts as an inert and not influencing the CO production significantly at these levels of EGR and flame temperatures and pressures. Clearly the 36% EGR levels, simulated by introducing pure nitrogen (blue points) or nitrogen and CO_2 mixture (yellow and red triangles) result in identical CO measured emissions.

Referring to Figure 8, it should be mentioned that if current levels of 25 ppm CO are the standard for CO emissions, the minimum oxygen content in the exhaust with compliance to below 25 ppm CO is presented. Not all EGR levels will comply with this but it can be seen that the minimum O2 levels may be achieved in the flame temperatures of interest for gas turbines. Further modifications in the combustor design may lower the CO even further (e.g. residence time), not to mention the favorable effect of higher pressures on CO reduction.

In summary, the presence of EGR leads to low oxygen concentrations, which play a role in shifting as well as reducing the reaction rates, allowing for combustion to spread over a large region and suppress the flame temperature, which is not in favor of the oxidation of CO to CO_2, however may help with combustion instabilities.

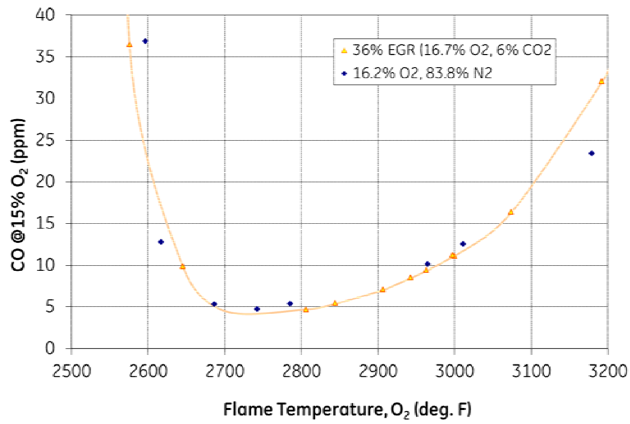

Figure 9: Measured CO levels function of T_{flame} and pilot at 15% doping with N_2 and N_2/CO_2

Fuel mass flow

Introduction of inert gases such as nitrogen and carbon dioxide via EGR change the working fluid composition accordingly. It follows that the thermodynamic properties, such as heat capacity, specific heat ratio, etc. of the working fluid will change accordingly. It follows that heating the working fluid up to the firing temperatures of interest will require more fuel, and this assumption has been verified in our tests.

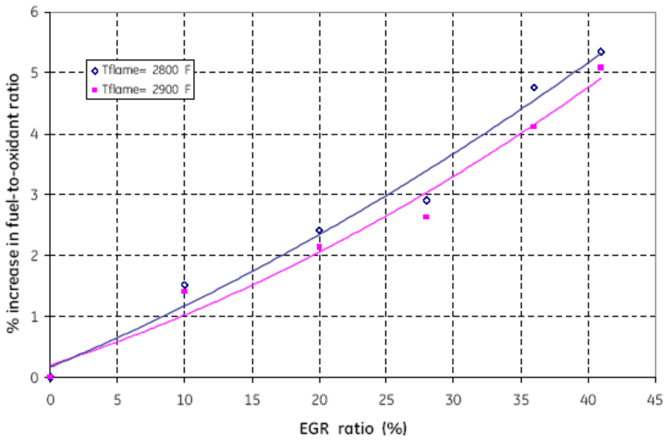

Figure 10: Fuel to oxidant ratio increase as function of EGR level, for two T_{flame} and pilot at 15%

Typically, the variation of fuel-to-oxidizer is linear when plotted against the flame temperature, at various EGR levels. Figure 10 presents the variation of Fuel-to-oxidizer ratio for EGR variation at two flame temperatures of interest.

Optimum EGR

The question to be asked is: from emissions point of view, what is the maximum acceptable EGR level for a gas turbine combustor? For the current lean premixed gas turbine research combustor, the emissions of concern are NO_x, CO, and UHC. It has been demonstrated that NO_x emissions decrease with increasing EGR levels. On the other hand, CO emissions increase with EGR. UHC usually follows the same trends as CO and if we keep CO levels to minimum levels, this in turn will keep the UHC as minimum. Thus it is apparent that the CO emissions are the main concern when EGR is applied.

In order to determine the maximum acceptable EGR level, the combustor will need to meet the CO emission requirements. From the previous analysis, it was concluded that CO emission is a function of flame temperature and oxygen concentration (or %EGR), which can be determined by exhaust O_2 concentration. As presented earlier in figures 3 and 8, CO concentrations at different EGR levels were overlapped with the exhaust O2 concentrations. This overlapping can be used to determine the limits of EGR as shown in Figure 11b. For example, if the maximum acceptable CO concentration is about 25 ppm, we can determine the minimum acceptable exhaust O_2 in the primary zone (as presented by the black dots). A curve fit for these points is shown in Figure 12. Based on this analysis, it is fair to say that in gas turbine operating range, EGR levels which allow about 2% O_2 in the exhaust can be applied, complying with exhaust emissions. In order to determine the corresponding values of EGR levels, the exhaust O_2 concentration was predicted using chemical equilibrium code NASA-CEA [21]. These calculations were performed based on inlet oxidizer compositions, as shown in table 1, at different flame temperatures. As depicted in Figure 13, predicted O_2 concentrations along with results obtained from Figure 12 suggest the maximum EGR level at each flame temperature. This result suggests that an aeroderivative or "F-Class" gas turbine could be suitable for application of EGR since it operates around this range of flame temperatures, allowing the highest possible EGR levels and complying with emissions without the use of a Selective Catalytic Reduction (SCR) system. In addition, other machines such as aero-derivatives may also benefit from EGR and comply with less than 5 ppm NO_x with minor modifications to the nozzles. These experimental results indicate that combustion instabilities can be reduced by EGR and this, combined with a higher degree of premix operation, could be a means for achieving 5 ppm NO_x without use of SCR.

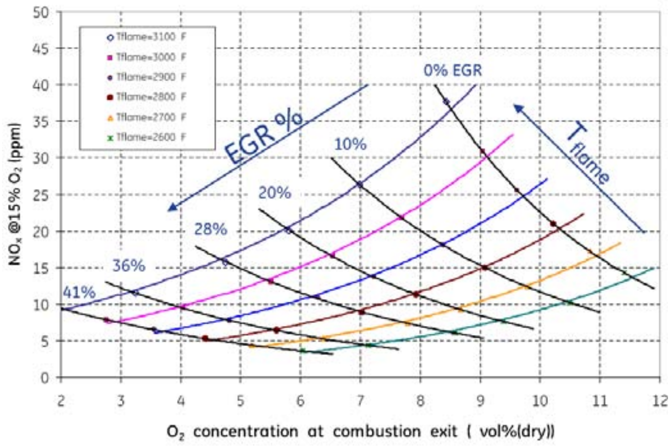

Figure 11a: EGR levels NO_x versus oxygen levels at the end of combustion process

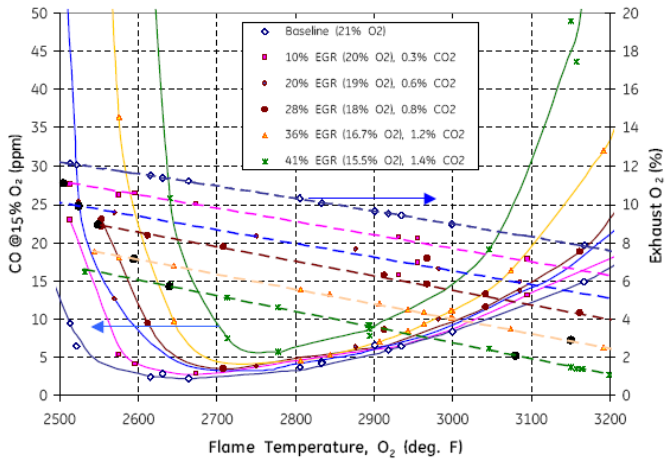

Figure 11b: Overlap of O_2 and CO measured levels versus flame temperature at various EGR levels

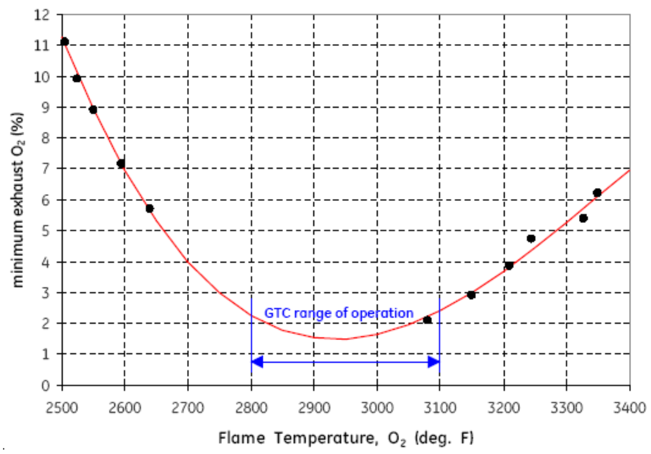

Figure 12: Minimum measured oxygen content at end of combustion process assuming CO levels of 25 ppm

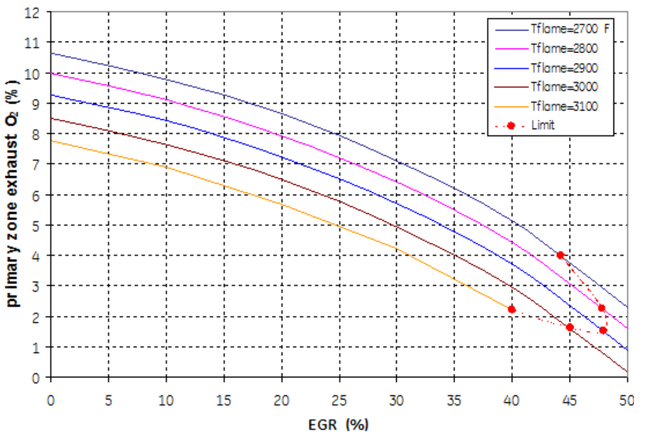

Figure 13: Predicted O_2 exhaust levels as a function of EGR and flame temperature

CONCLUSIONS

Combustion tests in Exhaust Gas Recirculation conditions at representative pressures and temperatures have been completed at General Electric Global Research Center in Niskayuna, NY. They confirm the feasibility of using current combustion technologies in low oxygen conditions determined by EGR. Under carefully chosen conditions and with some design changes, gas turbine combustors can operate with high efficiencies and determine CO_2 levels of more than 10% by volume in the gas products. The consumption of oxygen with EGR can be down to as low as less than 2%, associated with excellent NO_x emissions reduction benefits. CO levels are found to be the limiting factor for EGR. Current models may be updated with our current findings and allow for optimization of the EGR cycles for carbon capture.

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