Available online at www.sciencedirect.com
ScienceDirect
Physics Procedia 00 (2008) 000–000
Physics Procedia
www.elsevier.com/locate/XXX

GHGT-9

On the Performance and Operability of GE's Dry Low NO_x Combustors utilizing Exhaust Gas Recirculation for Post-Combustion Carbon Capture

Andrei T. Evulet[a,]*, Ahmed M. ELKady[a], Anthony R. Brand[a], and Daniel Chinn[b]

[a]*General Electric, Global Research Center, Niskayuna, NY 12309, New York, USA*
[b]*Chevron Energy Technology Company, 100 Chevron Way, Richmond, CA 94802, USA*

Elsevier use only: Received date here; revised date here; accepted date here

Abstract

The capture and sequestration of CO_2 will be necessary to mitigate CO_2 emissions from fossil fuel (coal, oil, natural gas or biomass) power generation facilities in a carbon constrained world. Post combustion carbon capture is a viable technology alternative to reduce CO_2 emissions from power plants in the short term. The CO_2 concentration in the exhaust gases of natural fired power plants can be increased through exhaust gas recirculation (EGR). A joint CO_2 Capture Project (CCP) and GE study of the Best Integrated Technology (BIT) shows that EGR enables reduced exhaust gas flow to the post combustion capture plant and cost of the CO_2 capture. This paper describes the experimental work performed at General Electric Global Research Center in order to better understand the risks of utilizing EGR in combination with dry low NO_x (DLN) combustors. A research combustor was developed for exploring the dry low emissions capability of nozzles to operate in low O_2 environment. A series of experiments have been conducted at representative gas turbine pressures and temperatures, in an EGR test rig. Exhaust gas generated in a first stage, at pressure, is used to vitiate the fresh air to levels determined by cycle models. Experimental results include the effect of applying EGR on operability, efficiency and emissions performance under conditions of up to 30% EGR (low oxygen). Our findings confirm the feasibility of EGR for enhanced CO_2 capture, exceeding the expectations of operability and combustion efficiency predicted by models. In addition, we confirm benefits of NO_x reduction while complying with CO emissions in Dry Low NO_x Emissions combustors under low oxygen content oxidizer.

Exhaust Gas Recirculation (EGR); Dry Low NO_x(DLN); CO_2; gas turbine; combustion; Best Integrated Technology (BIT); CO_2 Capture Project

1. Introduction

Capture and sequestration of the CO_2 emitted from natural nas based power-generation plants can be achieved in three different ways [1]:

- Post combustion capture: separation of CO_2 from exhaust gas coming from a standard gas turbine combined cycle (CC), using a direct contact between exhaust gas and absorbent (amines), or by using of membranes.
- Pre-combustion capture: Integrated reformer combined cycles (IRCC) with Natural Gas de-carbonization, in which the carbon is removed prior to combustion and the fuel heating value 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 Combustion: The fuel is combusted at near stoichiometric conditions in the presence of high purity oxygen (95-99.5% mol O2) instead of air. Very high temperatures are reached in t combustor when pure O2 is used; therefore, part of the flue gas is recycled to the burner to moderate the flame temperature. The flue gas primarily contains CO2 and H2O. The water vapor can easily be condensed resulting in near 100% CO2 capture.

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 (heat and work) consumed by CO_2 capture. The efficiency and cost of any gas separation process strongly depend on the concentration of the gas of interest in the gas mixture and its volumetric flow. Increasing the CO_2 concentration in thee flue gas reduces the volume of the gas sent to the capture plant and results in a smaller capture plant i.e. a lower capture plant cost.

Exhaust gas recirculation is viewed as an enabling technology to increase the CO2 concentration of the flue gas stream of gas fuelled power plants. While models predict advantages of using EGR, assumptions such as combustion under EGR conditions, need to be verified experimentally. The experimental verification of combustion under EGR conditions is the focus of this paper.

This experimental work was performed in two phases, phase 1 with a small research DLE nozzle using doped air with major species only at representative pressures and temperatures, and phase 2 which required a better understanding of minor species and a DLN nozzle at similar pressures and temperatures. From the previous work of CCP2, it was determined that 9FB turbomachinery is aerodynamically suited to EGR operation. Hence, it was selected for Best Integrated Technology concept evaluation. On the other hand, state-of-the art DLN combustors currently employed in the GE-109FB (9FB) frame product, are optimized for high performance with fresh air. Current levels of NO_x without the use of diluents (Dry Low NO_x) ensure a good operability, turndown, emissions levels and efficiency of combustion. In case of introducing EGR to the gas turbine, the combustor will need to produce acceptable performance while operating with low levels of oxygen in the oxidizer. Flame stability of lean premixed flames, operability, dynamics and emissions characteristics change accordingly.

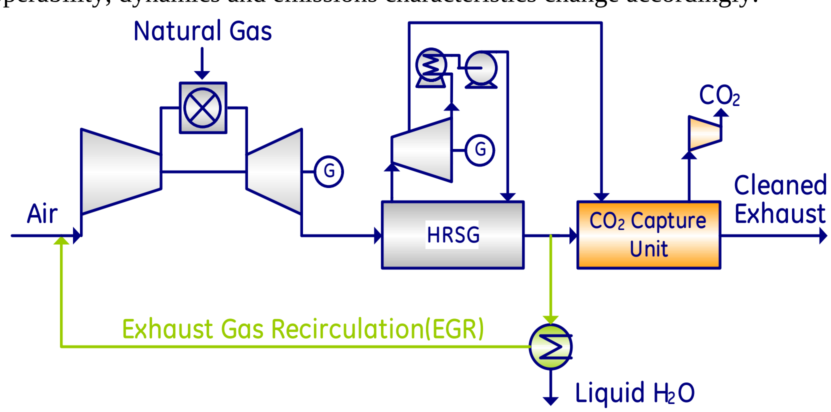

Figure 1 – Combined Cycle with Exhaust Gas Recirculation

This work builds on the understanding of EGR combustion component capabilities at conditions similar to real gas turbine conditions but with simulated EGR major compositions. Previous work done under the second phase of the CCP determined that at elevated pressures and temperatures typical of GE combustors, high levels of exhaust gas recirculation may facilitate post-combustion capture of CO_2. We have successfully demonstrated combustion in EGR-mimicked conditions of up to 40% recirculation on a research combustor at gas turbine conditions using air vitiation with inert gases such as nitrogen and carbon dioxide. We have demonstrated that the operability of a research combustion nozzle with oxygen levels equivalent to 40% EGR is promising and that emissions are within limits denoting high combustion efficiencies. We have also shown that many assumptions used today with respect to EGR combustion are erroneous (i.e. kinetic models predictions, minimum oxygen content, emission efficiencies, allowable EGR levels). The research combustion nozzle on which we performed the experimental work under CCP2 has shown sufficient potential to justify further investigation of nozzles more typical of gas turbines both for heavy duty and aero-derivative applications. Previous work was performed with doped air and major species only, utilizing a small flow research nozzle based on dry low emissions (DLE) concept, at appropriate pressures.

As the combustor inlet conditions for these applications vary significantly, the second phase program focused on research of the compatibility of current combustion nozzles for a heavy-duty gas turbine DLN combustor in varying EGR percentage conditions. We built a platform to research in greater detail performance of combustor nozzles in real EGR conditions by developing and implementing a two-staged combustion rig. A first stage, generic combustor, was used to generate the required exhaust gas composition and conditions without the previous limitations imposed by using pressurized inert gases from gas tanks. The setup, described in great detail below, consists of a water injection system used for quenching of the primary hot gases, followed by a heat exchanger to cool and condense the water out from this exhaust. The cooled and dry CO_2-rich gases are then directed towards a secondary combustor rig after mixing with secondary fresh, hot, pressurized air. This secondary combustor rig allows any GE combustor nozzle to be tested in real EGR conditions. Changes in the primary combustor parameters (such as preheat temperatures, pressures, fuel to air ratios and air flows, etc.) allow the continuous production of the required exhaust gas. Continuous monitoring of such gases was also done thus allowing important data collection for the validation of the assumptions made with respect to EGR auxiliaries (flue gas compositions, water condensation, etc.) For instance, we determined in this phase whether CO and NO_x re-circulated in the exhaust gas will accumulate or be consumed in the combustion process.

2. Experimental Setup

The objectives of the present work were to build a platform to perform detailed research at conditions closer to exhaust gas recirculation (EGR) by developing and implementing a staged combustion rig; the validation of the 2006 previous work under the CCP2 collaboration results done with mimicked EGR; and the risk reduction as a tollgate for full can testing in the future. In addition, this experiment allows the evaluation of commercial combustion nozzles in a real EGR environment, including recirculation of minor species such as NO_x and CO.

The experiment setup includes two combustors in series. The first combustor is used as an exhaust gases generator; the exhaust gas is quenched, then cooled and dried. The cold exhaust gas is then mixed with preheated air to achieve the expected vitiated air entering the secondary combustor. The latter is the nozzle of interest currently under investigation, namely the combustion premixer nozzle employed in the 9FB platform in the BIT design. The test assembly is shown in figures 2 and 3. The experiment involved operation of a DLE gas generator first stage, which is a microturbine combustor, followed by DI-Water injection system to quench the exhaust gases from the 1st stage combustor exit to the designed heat exchangers inlet temperature. The heat exchangers cool down the exhaust gases to allow condensation of the DI-water and the water product from the 1st stage combustor. Virtually all the water (99%+) is eliminated by using water moisture separators/drainers installed downstream of the heat exchangers. Finally the conditioned exhaust gas is mixed with the preheated air in the chamber of the second combustor to mimic EGR oxidizer, including the major and minor species involved in re-circulation. The second stage can utilize any GE DLN or diffusion single nozzle premixer, for any class of GE gas turbine.

Below is a description of the different sections of the experimental setup:

First Stage: The Microturbine combustor rig was upgraded to operate at high pressures and is a gas generator to provide the second combustor test bed with the correct amount of vitiated air and it operates with low-emissions combustion system at pressure with and without air preheat. The combustor allows for flexible operation from fully diffusion to fully premixed mode. The equipment is designed for high-pressure, high-temperature combustion experiments using natural gas fuel. The four-nozzle combustor is mounted within a pressure vessel as shown in figure 2.

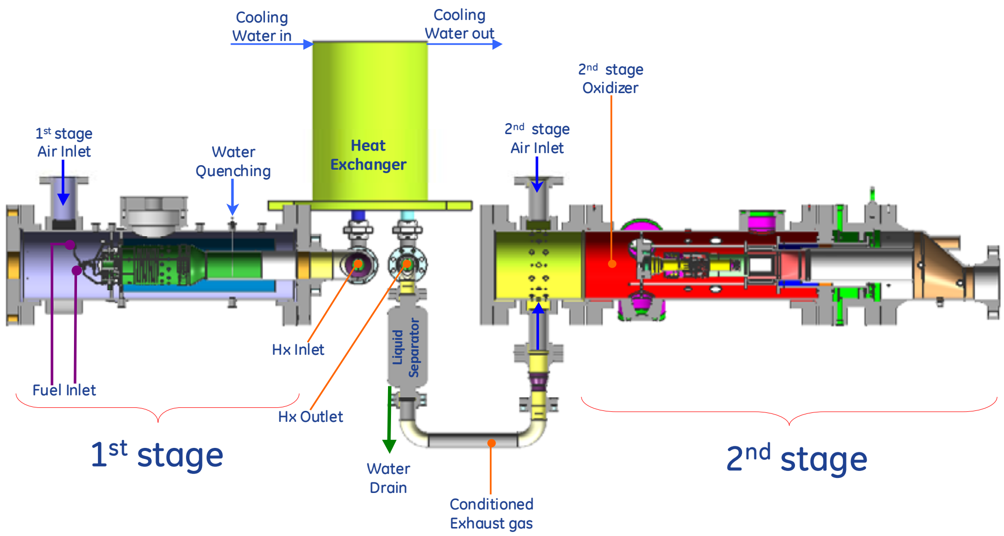

Figure 2 – Schematic of experiment setup

Air and fuel are supplied to the test cell by facility systems. The compressed air supplied to this stage is not preheated, and the stage is operated at pressures up to 600 psi. Burned gas is sampled and sent to a set of continuous gas analyzers for measurements of UHC, CH_4, CO, CO_2, NO_x, and O_2. All critical pressures, temperatures and flows are measured within the first stage. For safe operation the first stage is also instrumented with a set of vessel skin, combustor, and liner thermocouples, which are monitored in the control room. Maximum inlet flow conditions for the reported tests are P = 200 Psia and T_{inlet} = 200 °F.

Heat Exchangers: Two heat exchangers are installed in parallel and designed to cool down the exhaust gases from 1500 °F to <100 °F. Cooling water is provided through the water-cooling tower system with a required flow to cool the gases to the targeted temperature. For safety reasons, the heat exchangers are monitored via thermocouples installed in the shell and tube sides. A pressure transducer is also mounted to the shell side.

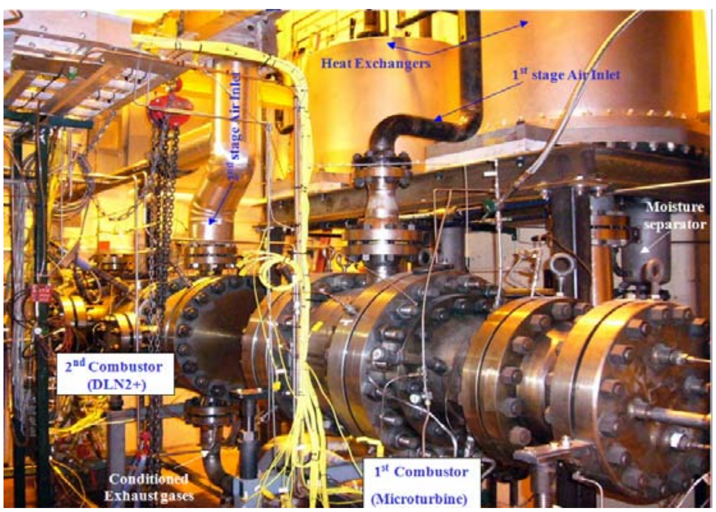

Figure 3 – Test rig as assembled at GE GRC-Niskayuna

Moisture separators /Drainers: Dry-Flo L1 moisture separators are installed at each heat exchanger outlet with a separation efficiency of 99%. Drained water flow through Armstrong 33-LD free floating lever drain traps, which are rated at MAWP of 1000 psi at 100 °F. The trapped gases are vented to the moisture separator.

Second Stage: The second stage is designed for high pressure and high temperature combustion burning preheated natural gas. The rig is designed to investigate the use of low oxygen content oxidizer and its effect on operability and emissions.

The conditioned (dried and cooled) exhaust gases in each line of the heat exchangers are combined and flow through a Micromotion Coriolis flowmeter to meter the final gases mass flow and estimate the amount of water that is still in the exhaust gases. The conditioned gases pipe is instrumented with a pressure transducer and a thermocouple. The gases flow through the plenum of the second stage where it mixes with preheated air to reach the final mix temperature. The assembly of the second stage is shown in fig. 4. The fresh air supplied to the second stage is overheated to about 1100 °F so that after mixing with the cold, vitiated air, the final oxidizer mixture will be at temperatures typical of the compressor discharge of an F class gas turbine. The fresh air supply pressure will be adjusted to match the pressure of the conditioned exhaust gases. A gas sampling probe is located just upstream of the fuel nozzle to determine the final mixture (oxidizer) composition. This sampling probe is mounted on a traverse system to check for the uniformity of the mixture before combustion.

The fuel nozzle and combustion chamber are mounted inside the pressure vessel, which has visual access though quartz windows.

Burned gas is sampled and sent to a set of continuous gas analyzers for measurements of UHC, CH_4, CO, CO_2, NO_x, and O_2. All critical pressures, temperatures and flows are measured within the test cell. Maximum inlet flow conditions for these tests were P = 200 Psia and T = 1100 °F before combustion, although the rig can operate at any pressure and temperature representative of current GE gas turbines (frames and aero-derivatives.)

3. Results

All the data reported in this paper were obtained at the following conditions: Combustor Pressure: 130-150 psia; T_3 (Inlet Temperature): 550-750 °F; For all the emissions data plotted in following sections and in order to clarify the trends, data were curve fit.

3.1. Measurement Details

The flame temperatures reported are based on the O_2 levels measured at the probe location at the time and location of measurement (first or second stage.) These values were compared to the thermodynamic equilibrium values and excellent agreement was found. In addition, flame temperatures based on the flows of air and natural gas (equivalence ratios) and airflow-splits (combustion versus bypass/cooling) also show good agreement. Temperatures at the inlet of the secondary combustor were obtained by mixing cold exhaust gas from the first stage with hot fresh air, overheated, as a countermeasure for determining the correct temperatures at the inlet of the premixer. The emissions of minor species (NO_x, CO and UHC) in the first stage were monitored to determine their evolution before and after the combustion in the second stage. It was found that in general NO_x and CO burn in the secondary combustor, resulting in acceptable levels of emissions. UHC are negligible, showing good efficiency of the combustion process. At this time there was no measurement of the condensed water to determine NO, CO or sulfur levels in the condensate.

3.2. Flame stability

In general, the flame was very stable without using a pilot, even with the low levels of O_2 tested (as low as 17.8% O_2 in the oxidizer). No important acoustic instabilities were observed. Audible dynamics was detected within the window of some lower flame temperatures with decreased pilot (less than 10% pilot). It was determined that operation at full speed full load with EGR is an acceptable condition up to 30% EGR, in absence of acoustic instabilities and with good efficiency of combustion. Based on this initial finding, all our experiments were performed in fully premixed condition. Pilot variation was not explored, although it could be a beneficial addition for extending the operability of the combustor without NO_x degradation.

O_2-based flame temperature calculations are correct. Figure 5 also shows the lower oxygen levels obtained with increasing flame temperature and EGR levels at 25% EGR in this case. The low levels of oxygen also result in less consumption of the CO and therefore emissions of CO may be higher due to the oxygen starvation of these flames.

3.5. NO_x emissions

It was found that the NO_x emissions are reduced via the reduction of oxygen in the combustion air. Even if NO_x is introduced at ppm levels in the vitiated air before combustion in the secondary stage. The NO_x reduction levels were considerable (see figure 6.) NO_x recirculation (as supplied in the oxidizer from the first stage) does not appear to be an issue with EGR. At a minimum, NO_x levels will be preserved when compared to current performance with DLN. If full can tests confirm the operability, it is possible to reduce the NO_x by more than 50% depending on the EGR levels and NO_x recirculation.

3.6. Combustion Efficiency with EGR

EGR may induce loss of efficiency in completely combusting the fuel. The combustion efficiency can be measured based on the levels of unburnt hydrocarbons (e.g. methane) as well as incomplete burnout of radicals like CO, etc. Due to oxygen starvation and specific conditions, a gas turbine combustor designed for 21% O_2 air may not guarantee complete the oxidation reaction to CO_2 in EGR conditions, thus determining inefficiencies. However, for the lean premixed flames and conditions tested with EGR as described in table 1, the efficiencies remain 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.

Table 1 Inlet oxidizer composition at different EGR levels

EGR (%)	YO_2	YCO_2	YN_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
0	0.210	0.000	0.789

3.7. CO emissions

CO concentrations need to be kept to minimum levels. CO will be produced due to lack of oxygen or limited residence time or low pressures and temperatures required to complete the oxidation reaction to CO_2.
Experimental data of CO emissions (raw numbers) are presented as function of flame temperature and compared at 25% of EGR in figure 6. In the baseline case (0% EGR) CO concentrations rapidly climb at low flame temperatures and decrease with increasing the flame temperature to a minimum value at about 2900 °F due to the oxidation reaction $CO + OH \rightarrow CO_2 + H$ which becomes significant at temperatures in excess of 2300 °F. Beyond a flame temperature of 2750 °F the dissociation of CO_2 to CO takes place leading to increase in CO concentrations at combustor exit plane. An interesting behaviour was observed in the presence of modest original CO levels (before combustion) i.e. that the CO levels were in fact lower with CO doped before combustion. This demonstrates that CO burnout is real and that kinetics of CO oxidation is improved. CO emissions measured were not an issue at the EGR levels tested (up to 35%). The authors believe that CO could be kept in check up to 35% EGR, after which a change in emissions can be expected and mitigation methods are needed.

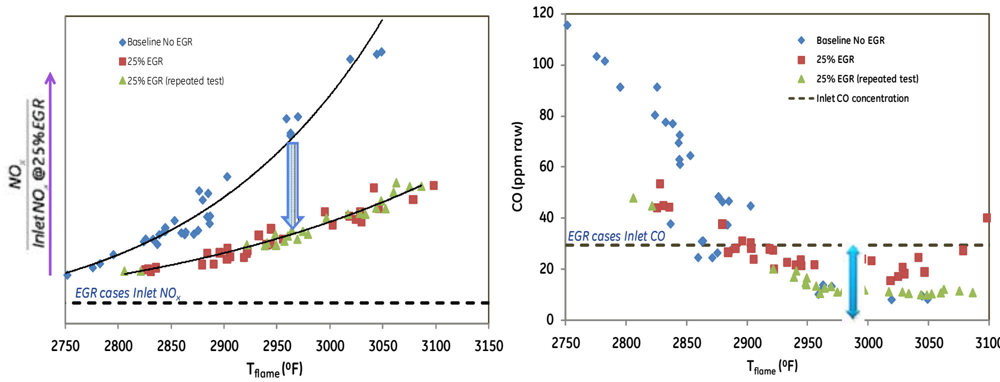

Figure 6 – NO_x and CO compared to recirculation (dotted line) and baseline (fresh air) conditions at 25% EGR conditions

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 favour of the oxidation of CO to CO_2. In these tests however, no special CO issues were observed for up to 35% EGR conditions.

4. Conclusions

A unique rig that allows measurement of real EGR, including minor species recirculation, has been built and successfully operated at the GE GRC facilities in Niskayuna, NY. Combustion tests in Exhaust Gas Recirculation conditions at representative pressures and temperatures have been completed using a commercial 9FB DLN nozzle. They confirm the feasibility of using current DLN combustors in low oxygen conditions determined by EGR of up to 30%, potentially feasible to up to 35%. Under carefully chosen conditions and with some design changes, this GE DLN gas turbine combustor nozzle can operate with high efficiencies and determine CO_2 levels of more than 8% by volume in the gas products. Our prediction is that with minor modifications in the combustor design and its operation, the EGR levels could be augmented to beyond 40%. Hence we validated the results reported in [11] and with mimicked EGR (no minor species such as NO_x and CO in the oxidizer.) Good CO and NO_x emissions burnout is obtained. The CO levels are found to be the limiting factor for EGR but not before reaching 30% EGR conditions.

References:

[1] Bolland, O. and Mathieu, P., Comparison of two CO2 removal options in combined cycle power plants, *Energy Convers. Mgmt* Vol. 39, No. 16-18, pp. 1653-1663, 1998

[2] Rokke, P.E., Hustad, J.E. EGR in Gas Turbines for reduction of CO2 Emissions; Combustion Testing with Focus on Stability and Emissions, *Intl. J. of Thermodynamics*, Vol. 8, (4), Sept. 2005.

[3] Warnatz, J., Maas, U., Dibble, R.W. Combustion, 2nd edition, Springer Verlag, 1999

[4] Miller, J.A. and Bowman, C.T. Mechanism and Modeling of Nitrogen Chemistry in Combustion, *Prog. Energy Combust. Sci.*, 15, pp287-338, 1989.

[5] Correa, S. M., "Carbon Monoxide Emissions in Lean Premixed Combustion," *Journal of Propulsion and Power.* Vol.8, No. 6, 1992, pp. 1144-1151.

[6] Lefebvre, A. H., Gas Turbine Combustion, 2nd ed., Taylor and Francis, Philadelphia, PA, 1998.

[7] Baulch, D. L. and Drysdale, D. D., "An Evaluation of the Rate Data for the Reaction CO + OH → CO_2 + H," *Combustion and Flame*, Vol. 23, 1974, pp. 215-225.

[8] Bowman, C. T., "Chemistry of Gaseous Pollutant Formation and Destruction," *Fossil Fuel Combustion*, edited by W. Bartok and A. F. Sarofim John Wiley & Sons, New York, 1991, pp. 215-260.

[9] Westenberg, A. A. and deHaas, N., "Steady-State Intermediate Concentrations and Rate Constants. Some HO_2 Results," *Journal of Physical Chemistry*, Vol. 76, No. 11, 1972, pp. 1586-1593.

[10] Westbrook, C. K. and Dryer, F. L., "Chemical Kinetics and Modeling of Combustion Processes," *Proceedings of the Combustion Institute*, Vol. 18, 1981, pp. 749-767.

[11] Elkady, A.M., Evulet, A.T., Brand, A., Ursin, T.P. and Lynghjem, A., "Exhaust Gas Recirculation in DLN F-class Gas Turbines for Post-Combustion CO2 Capture", *Proceedings of GT 2008*, ASME TurboExpo 2008: Power for Land, Sea and Air, June 9-12, 2008, Berlin, Germany.