Experimental characterization of an industrial burner operated with simulated EGR

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Abstract

This work presents the results of an experimental campaign investigating the behavior of an industrial burner operated with simulated Exhaust Gas Recirculation (EGR). EGR is recreated by diluting standard air with CO2, and tests are performed at ambient pressure using natural gas as fuel.

Burner characterization has been performed in terms of emission measurements both in standard conditions and with CO_2 vitiated air. Flame topology has been studied with OH* chemiluminescence, evaluating the effect of fuel split and CO_2 addition.

CO_2 addition has been found to trigger thermoacoustic instabilities up to a certain threshold, therefore limiting the EGR operability window.

Introduction

While the employment of Exhaust Gas Recirculation (EGR) is a well-established technique in Internal Combustion Engines to limit NOx emissions, its adoption in Gas Turbine engines hasn’t yet found a practical application due to its expensive and complex installation that doesn’t justify the emissions reduction when compared to already established DLN combustion technologies. EGR becomes an interesting option in GT engines considering the possibility of increasing the CO_2 content of the exhaust gases to improve the efficiency of Carbon Capture and Storage (CCS) units. However, the decrease in oxygen content of the combustion air is extremely challenging in terms of combustion stability. CO and UHC emission increase therefore limits the achievable EGR level [1-2]. Different strategies can be explored in order to extend the combustor operability window. The optimization of the burner design can benefit from less stringent limitations for NOx emissions, which are already lowered by EGR. Therefore, pilot flames can be exploited to help the flame stabilization, even with local injections of hydrogen.

European project TRANSITION (fuTure hydRogen Assisted gas turbiNeS for effective carbon capTure IntegratiON) fits in this context with the purpose of developing advanced combustion technologies for natural gas fired Gas Turbines to permit engine operations with high EGR rates leading to an increase of the CO_2 content in the exhaust gases and a drastic reduction of the CCS costs and units' size

[3]. The present work describes the results of the first experimental campaign within the project, performed on the baseline burner at ambient pressure. Experimental data will be used to calibrate CFD models employed to optimize the burner design, in order to enlarge the operability window with EGR by improving the flame stability.

Test Rig and burner

The burner was investigated in the reactive test cell of the THT Lab of the University of Florence, whose schematic layout is outlined in Figure 1a. The same test cell has been exploited in the past for investigations on novel low NOx burners for heavy duty gas turbines [4].

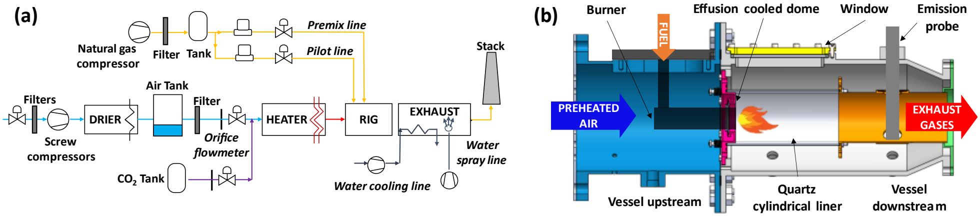

Figure 1. Combustion test rig (a) and close-up of the combustor set-up (b).

Two screw compressors supply the filtered and dried airflow to the test rig, and an electric heater is used to regulate the inlet flow temperature. A water jacket exhaust duct is placed right after the rig. It is equipped with water sprayers used to quench the hot gases and control the flow exit temperature.

Recreating real EGR conditions in lab scale is quite challenging because of the associated costs and plant complications. CO_2 addition in the airflow feeding the burner has been chosen to reproduce EGR condition, because it offers the opportunity to manage storage better than mixtures with nitrogen, while preserving the purpose of the investigation. CO_2 is stored in a pressurized tank and injected in the main air flow line upstream the electric heater, in order to deliver to the test section a homogeneous mixture, both in terms of temperature and composition.

The test cell is equipped with two fuel lines that deliver natural gas taken from the domestic line. The fuel composition is analyzed after each test.

The test rig is designed to allow optical measurements on the flame region.

A cross-section of the test article is shown in Figure 1b. The external casing consists of an upstream vessel, through which the burner enters the test article, and a downstream vessel, equipped with two perpendicular optical windows for the flame visualization. The combustor is made of a 2.5 mm thick cylindrical quartz liner, held in place thanks to a blocking system made of four tie rods and four springs that connect the dome to the following duct, used to convey the exhaust gases towards the test rig exhaust system. The quartz cylinder is approximately 2.5 diameters long, to ensure a complete flame development for a proper flame visualization. The flame tube is cooled by forced convection of a fraction of the incoming air that flows in the annulus between the liner and the confining vessel, not used in the combustion process. The dome plate is cooled through a series of inclined effusion holes.

The investigated burner is a lean premixed burner developed by Baker Hughes for industrial gas turbine applications. A thorough description of the burner geometry and its design can be found in [5]. It is composed by two counter-rotating swirlers and a center body with an air purge. Two independent fuel lines are present: the pilot line injects the fuel directly in the combustor chamber through circumferentially equally spaced holes, helping the flame stabilization. The premixed line delivers the fuel at the tip of the inner swirler, so that it mixes with the airflow thanks to the strong turbulence created by the shear layer generated between the two swirlers.

Operating conditions and measurement techniques

The experimental campaign has been performed at ambient pressure with natural gas as fuel. As anticipated EGR-like conditions have been reproduced by diluting the airflow entering the test rig with CO_2. The lower oxygen content in the oxidizer due to EGR strongly affects the combustion process. EGR condition is here defined by the inlet oxygen molar fraction x_{O2}, which is a key similarity parameter between real EGR and simulated conditions. All the presented results have been obtained at the same adiabatic flame temperature. The inlet oxygen content has been varied to simulate different EGR levels. The inlet temperature of the oxidizer has been kept constant at 300°C and the burner pressure drop is 4.2%. The ratio of the fuel flow injected with the pilot line and the total fuel flow rate is denoted as PLT. It has been scaled with a reference value for proprietary reason. PLT/PLT_{ref} covers a range from 0 to 1, going from a premixed flame towards a more diffusive flame. The fuel split has been varied in order to study the combined effect of this parameter with the oxygen depletion due to EGR.

Concerning the rig instrumentation, the test article is equipped with various thermocouples and static pressure ports to monitor the flow conditions. An emission probe is employed to analyze the exhaust composition through a HORIBA PG350. The probe is made of several radially spaced holes, and it is plunged into the flame tube to extract the exhaust gases. After being extracted, the gases flow through a thermally insulated pipeline kept at 150°C, are dried by a HORIBA PSS-5H refrigerator and finally reach the gas analyzer. The gas analyzer is properly calibrated right before each test employing a rack of calibrated gas mixture tanks.

Chemiluminescence of the OH* radical was employed to detect the reaction zone and its position in various operating conditions. For OH* chemiluminescence measurements a high-speed camera (Phantom M340) was coupled with the Hamamatsu image intensifier through a relay lens. In addition, a UV lens and bandpass filter (CWL=310 +/- 5nm) were mounted on the image intensifier to be able to capture the OH* transition, which has its peak emission intensity in the UV spectrum at around 310 nm. Images were acquired at 1000 Hz with a 0.5 ms intensifier gate.

A dynamic pressure sensor (PCB) is also installed on the test rig to monitor pressure oscillations, with an acquisition frequency of 12.8 kHz.

Results and discussion

The burner flame structure and position have been investigated through OH* chemiluminescence measurements at different operating conditions in terms of fuel split and inlet oxygen content, keeping the flame temperature (Tflame) constant. Figure 2 presents the time averaged maps of OH* intensity.

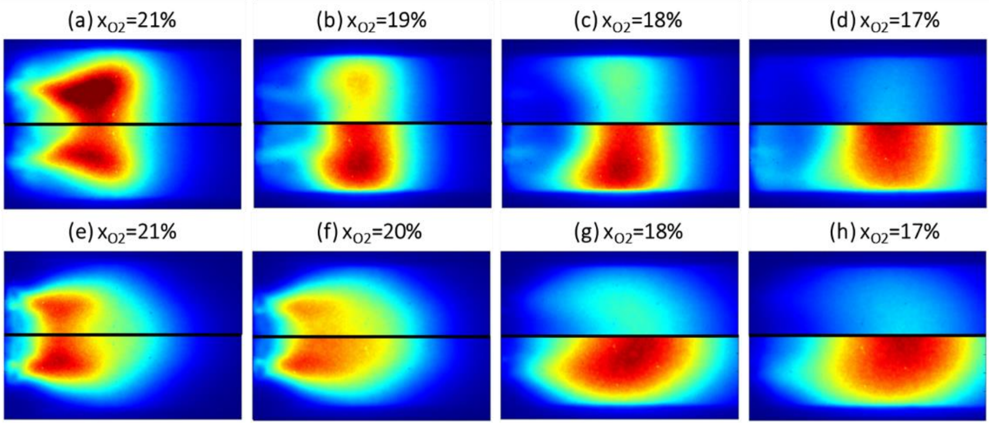

Figure 2. Time-averaged OH* chemiluminescence images at Tflame=constant for PLT/PLT$_{ref}$=1 (a-b-c-d) and PLT/PLT$_{ref}$=0.3 (e-f-g-h). (Upper halves: absolute OH* intensity, lower halves: normalized with each own maximum)

Considering at first the results with standard air, fuel split significantly influence the flame shape: when the fuel split is fully diffusive the flame stabilizes in correspondence of the pilot jets, which are clearly distinguishable near the burner exit (Fig 2a). As the fraction of fuel injected with the premixed line increases the flame “closes” toward the centerline, and OH* intensity decreases. Looking at the absolute OH* intensity CO_2 addition significantly lowers the flame reactivity. The flame lifts off from the burner exit and shifts downstream. The oxygen content depletion leads to a slowdown of the reaction process. Indeed, the reaction zone becomes more widespread, reaching an extension that almost covers the whole combustion chamber (Fig 2c-d-g-h).

The significant reduction of the flame reactivity is confirmed by emission levels.

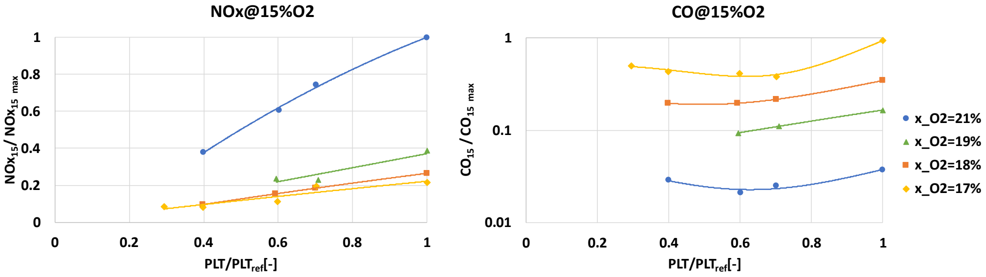

Figure 3. NOx and CO emission measurements at Tflame=constant

Figure 3 shows the results of NOx and CO emission measurements, which have been corrected with the following expression in order to take into account the lower inlet oxygen content [1] (same for CO). Values were then scaled with the maximum emission level for proprietary reasons.

$$NO_{x\,15} = NO_{x\,dry} \cdot \frac{0.2095 - 0.15}{2 - 0.2095} \frac{2 - x_{O2\,inlet}}{x_{O2\,inlet} - x_{O2\,dry}}$$

As expected, simulated EGR strongly reduces NOx emissions, but at the same time CO levels are extremely high. Despite the fact that all the points have the same adiabatic flame temperature, OH* images showed that the flame reactivity strongly decreases with lower oxygen content of the oxidizer. CO increase could also be linked with the downstream shift of the reaction zone, which doesn't allow the reaction to be completed at the probe location (about 2.5 diameters downstream of the burner exit). CO_2 addition reduces the effect of fuel split on NOx emissions, which, however, remain growing with pilot split. After an important drop of NOx levels with the first level of oxygen reduction, a further decrease has a limited effect on NOx, while CO continues to increase.

During the reactive tests strong tonal pressure oscillations have been observed as soon as the oxidizer composition changes from standard air. The amplitude of these oscillations quickly grows with the CO_2 fraction in the oxidizer, reaches a maximum, and eventually decreases, going back to the levels corresponding to standard air, or even lower in some cases. This last condition is near the flame extinction, as showed by very high CO levels. This behavior has been observed for all the tested fuel splits, but the oscillation amplitude increases with the fraction of fuel supplied with the premix line. Figure 4a shows this trend, while Figure 4b reports the frequency spectrum of these pressure oscillations. The peak frequency is around 330 Hz and decreases with lower oxygen inlet content, as the mixture composition changes, and the reaction becomes more widespread.

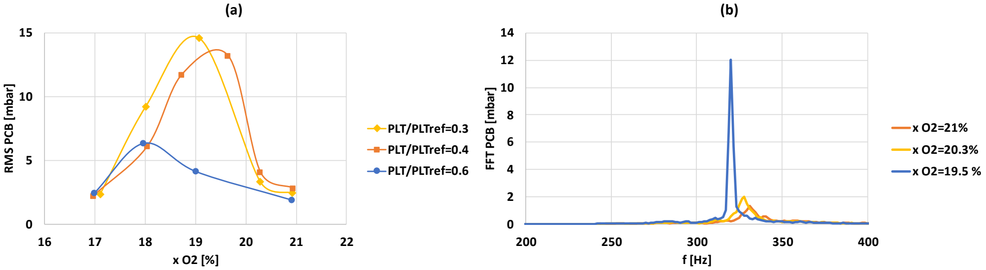

Figure 4. Amplitude of pressure oscillation as a function of inlet oxygen molar fraction (a) and frequency spectrum of pressure oscillation at $PLT/PLT_{ref}=0.4$ (b)

Thermoacoustic instabilities triggered by CO_2 have also been detected with OH* chemiluminescence: the frequency spectrum of the OH* intensity averaged over the whole measurement area captures the pressure oscillation peaks detected with the PCB. Figure 5a reports some instantaneous OH* images, where it can be seen the flame subjected to intense longitudinal fluctuations. Figure 5b shows the standard deviation of the OH* intensity over time in comparison to the corresponding case with standard air (upper half). The fluctuation of OH* emission is much more intense in the case with CO_2 addition, and the area where these fluctuations occur extends further downstream.

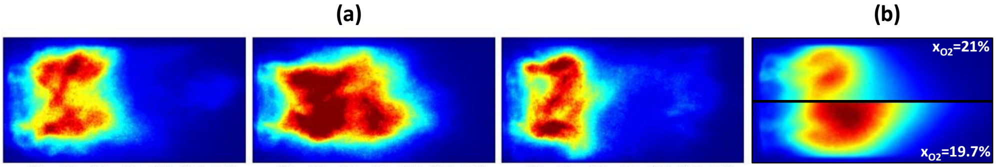

Figure 5. Instantaneous OH* images (f=1000 Hz) (a) and standard deviation of OH* intensity (b) for $PLT/PLT_{ref}=0.4$ $x_{O2}=19.7\%$ compared with case with standard air ($x_{O2}=21\%$, upper half)

Conclusion

In the present work the experimental characterization of an industrial burner operated at ambient pressure with reduced inlet oxygen level caused by the dilution of standard air with CO_2 has been presented. Emission measurements revealed very high CO levels (correlated to both air vitiation and the reduced residence time of the rig), progressively increasing with CO_2 addition, while NOx emissions decrease. OH* chemiluminescence images showed very different flame structures varying the fuel split and oxidizer composition. The outbreak of thermoacoustic instabilities with CO_2 vitiated air strongly limits the burner operating window at intermediate EGR-like conditions, pointing out to the necessity of finding a different strategy to help the flame to stabilize in such conditions.

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