Experimental and numerical study of the effect of CO_2/N_2 dilution to simulate EGR in GT combustor

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Abstract

This work presents the experimental comparison between the use of CO_2 or N_2 to dilute combustion air, in order to simulate Exhaust Gas Recirculation in a gas turbine combustor. Tests have been performed on an industrial burner operated in a tubular single sector test rig at ambient pressure with natural gas as fuel. Comparison is made in terms of flame shape with OH* chemiluminescence imaging, pollutant emissions and dynamic behavior. Significant differences have been observed in terms of CO emissions, and data have been used to validate a reactor network with Cantera, in order to study what happens with intermediate compositions of the oxidant, targeting real EGR conditions.

Introduction

While the employment of Exhaust Gas Recirculation (EGR) is a well-established technique in Internal Combustion Engines to limit NO_x 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].

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, eventually leading to an increase of the CO_2 content in the exhaust gases. Achieving this goal would allow a drastic reduction of the CCS costs and units' size [2].

Recreating real EGR composition in lab scale is quite challenging because of the associated costs and plant complications. During the experimental campaign CO_2 addition in the airflow feeding the burner has been chosen to reproduce EGR, because it offers the opportunity to manage storage better than mixtures with nitrogen. In the present work the effect of such choice is evaluated, comparing the behavior of an industrial burner fueled with natural gas when combustion air is diluted with CO_2 or N_2 in order to match the same inlet oxygen level, which is a key similarity parameter between real and simulated EGR.

Test rig and burner

The burner was investigated in the reactive test cell of the THT Lab of the University of Florence, with the single sector tubular test rig, reported in Figure 1a. The external vessel is equipped with two perpendicular optical windows for the flame visualization. The combustion chamber is made of a 2.5 mm thick cylindrical quartz liner, cooled by forced convection with 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.
Combustion air is diluted with CO_2 or N_2 to reach a certain inlet oxygen content. Inert gases are injected in the main air flow line upstream of the electric heater used to increase the flow inlet temperature, in order to deliver to the test section a homogeneous mixture, both in terms of temperature and composition. Natural gas is taken from the domestic line, and fuel composition is analyzed after each test.

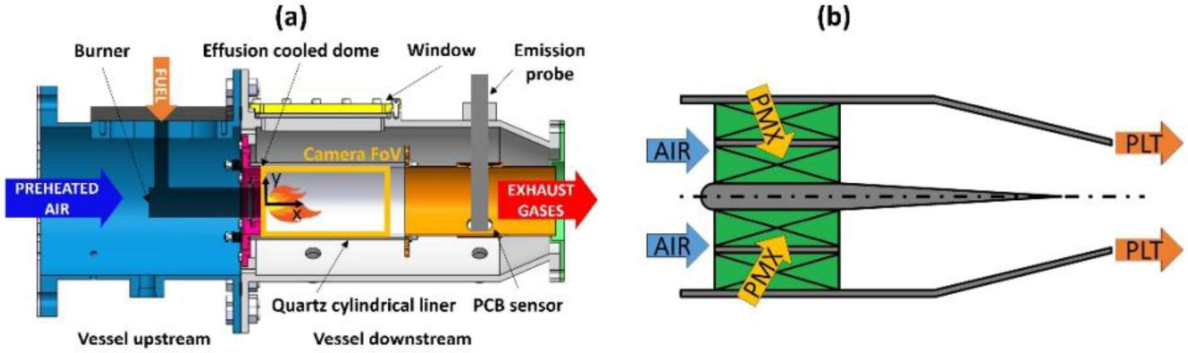

Figure 1. Cross section of the reactive test rig (a) and burner schematic (b)

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 [3], and a sketch is reported in Figure 1b. 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 (PLT) injects the fuel directly in the combustor chamber through circumferentially equally spaced holes, helping the flame stabilization. The premix line (PMX) 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. The purpose of the investigation is to evaluate the effect of the oxidizer composition in reproducing the lack of oxygen due to EGR, diluting the airflow entering the test rig with CO_2 or N_2. Comparison between the two conditions is made by targeting the same inlet oxygen mass fraction Y_{O2}, which has been varied to simulate different EGR levels. Test are performed with constant thermal power, leading to decreasing adiabatic flame temperature with lower Y_{O2}, especially for the CO_2 case, while differences are lower for the N_2 dilution (see Fig. 3c). The ratio of the fuel flow injected with the premix line and the total fuel flow rate is denoted as PMX%, and has been kept constant at 40%, as well as the inlet temperature of the oxidizer at 300°C and the burner pressure drop at 4.2%.

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 before each test with 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.

Cantera reactor network and thermo-kinetic study

In order to gain a comprehensive understanding of how the oxidizer composition affects the thermo-kinetics of the combustion process, Laminar Flame Speed (Sd), and Extinction Strain Resistance (ESR) were evaluated with Cantera. The first was done with FreeFlame class, while the CounterflowDiffusionFlame function was employed to model the counterflow diffusion flame and determine the maximum extinction strain rate. The evaluation of S_d and ESR was done targeting a constant adiabatic flame temperature.

Additionally, experimental data in terms of pollutant emissions have been used to tune and validate a reactor network representing the combustor with CO_2 or N_2 dilution, in order to be able to study intermediate oxidizer composition, and therefore the real EGR case. Three distinct Perfectly Stirred Reactors (PSRs) were implemented to represent the main flame, pilot flames, and corner regions of the combustor, while two Plug Flow Reactors (PFRs) were utilized to model the dilution zone. Experimental conditions were targeted for the CO_2 and N_2 dilutions cases, while an in-house algorithm was utilized to estimate the mixture composition for the real EGR case (dry), matching the inlet oxygen mass fraction and thermal power. Furthermore, the CO_2 dilution case was run also considering the CO_2 at the inlet as inert.

Results and discussion

Figure 2 presents the laminar flame speed and extinction strain rate, estimated with Cantera. With CO_2 dilution laminar flame speed is lower, with increasing difference with respect to real EGR as the inlet oxygen content decreases. Considering as first approximation that turbulence remains unaltered, the lower laminar flame velocity of CO_2 dilution case leads lower Damkohler numbers, thus moving toward diffuse combustion regimes, with a thickening of the flame front.

Regarding the extinction strain rate, as expected it decreases with lower inlet oxygen fraction, and with CO_2 dilution flame extinction is reached for lower values of the strain rate, thus indicating a reduced combustion stability. Therefore, CO_2 dilution creates more challenging conditions for flame stability compared to N_2 dilution or real EGR, which results in an intermediate condition.

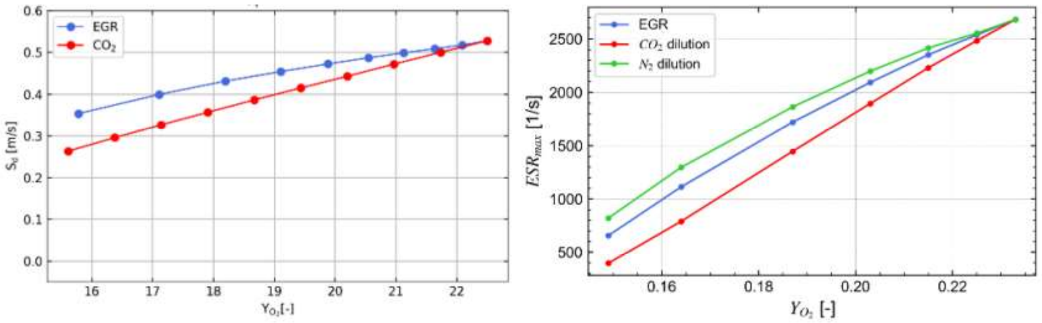

Figure 2. Comparison of Laminar Flame Speed (S_d) and Extinction Residence Time (ESR)

Figure 3 shows the results of CO and NO_x emission measurements (EXP profiles), together with the results of the reactor network (RN profiles). Experimental data highlight significant differences in CO levels between N_2 and CO_2 dilution, especially at low Y_{O2}. The reactor network is able to capture the two different exponential trends, with values close to the measured ones. If the CO_2 at the inlet is considered as inert, CO values are much smaller and comparable to the ones of N_2 dilution case. Therefore, the thermal effect has very little impact, and very high CO levels for the CO_2 dilution case are due to equilibrium effects for high CO_2 concentration. Real EGR case turns out to be much closer to the N_2 dilution curve, indicating that testing with CO_2 is a very conservative condition in terms of CO emissions.

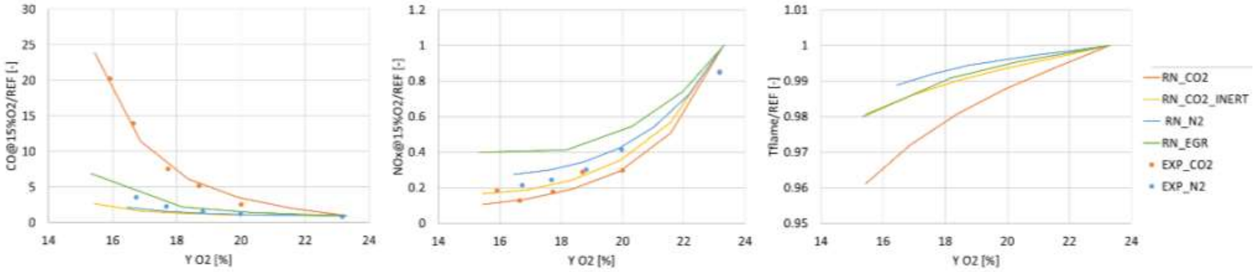

Figure 3. CO and NOx emission measurements (EXP) compared with the results of the reactor network (RN), and adiabatic flame temperature

Regarding NO_x emissions experimental values are slightly higher in the case of N_2 dilution, because of the higher adiabatic flame temperature. The reactor network confirms this trend and shows even higher values in the case of real EGR, since NO_x are also recirculated.

The time averaged OH* chemiluminescence maps identifying the burner flame structure and position are reported in Figure 4. As observed in previous works [4] the flame lifts off from the burner exit and shifts downstream with CO_2 dilution. The oxygen content depletion leads to a slowdown of the reaction process, as showed by the decrease in laminar flame speed. Indeed, the reaction zone becomes more widespread, reaching an extension that almost covers the whole combustion chamber.

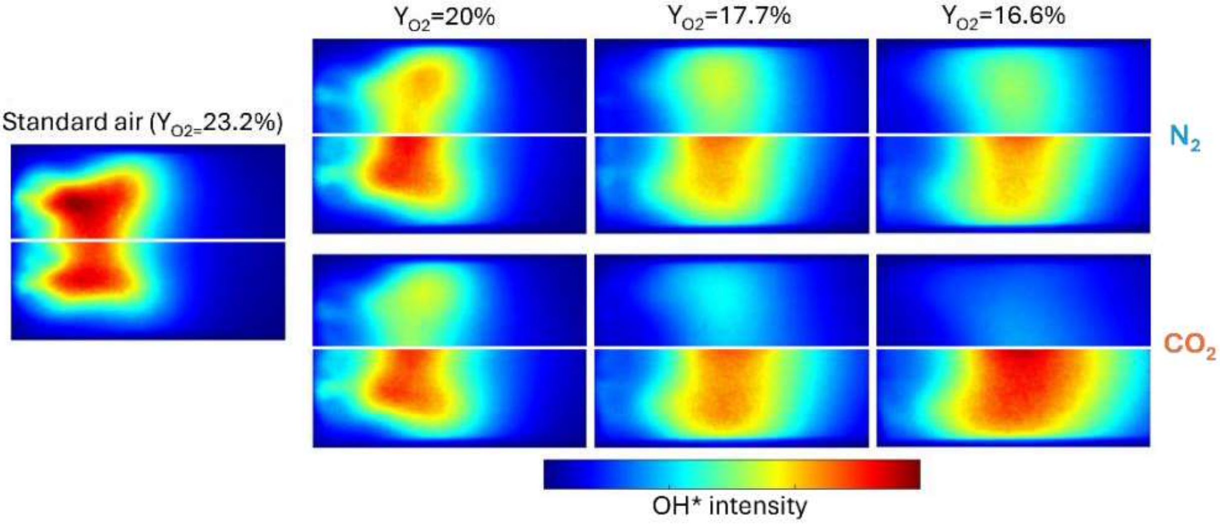

Figure 4. Time-averaged OH* chemiluminescence images (Upper halves: absolute OH* intensity, lower halves: normalized with each maximum)

Comparing the upper halves of the images, the reduction of OH* intensity with lower inlet oxygen content is much more evident with CO_2 dilution, but considering normalized images the differences become negligible, and the shape and position of the reaction zone is approximately the same. Only at very low inlet oxygen content length of the reaction zone increases with CO_2 dilution, but this is an effect related to the lower values with which the images are normalized.

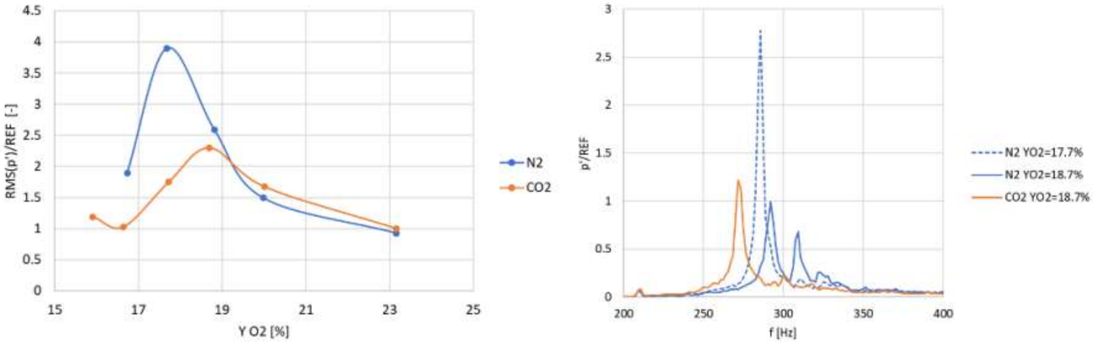

Figure 5. Measured RMS of pressure oscillation amplitude as a function of inlet oxygen level (a) and frequency spectrum (b)

The dynamic behavior is also affected by the oxidizer composition, as shown by Figure 5. A non-monotonic trend of the amplitude of pressure oscillations with inlet oxygen level has been observed with CO_2 dilution. A maximum is still present also with N_2 dilution, with higher peak and shifted to lower values of O_2 mass fraction. This effect is still related to the lower laminar flame speed in the case of CO_2 dilution, which gives rise to a more distributed flame, which partially dampens the oscillations and slightly reduces their peak frequency.

Conclusion

In the present work differences in terms of pollutant emissions, flame structure, and dynamic behavior due to oxidant composition were investigated, in order to evaluate the effect of the experimental strategy of reproducing the absence of oxygen due to EGR by diluting the combustion air with CO_2 or N_2.

Emission measurements revealed very high CO levels with CO_2 dilution, and the Cantera reactor network is able to reproduce the trend of the experimental data, showing that with real EGR CO values would be closer to the one's measured with N_2 dilution. OH* chemiluminescence intensity reduction is more pronounced with CO_2 dilution, but normalized images show that the shape and position of the reaction zone is very similar. The dynamic behavior is also affected by the oxidizer composition, with higher pressure fluctuations with N_2 dilution for the investigated conditions.

These results support the validity of the experimental strategy to use CO_2 dilution to reproduce EGR, in the perspective of a general preliminary screening, considering different burners and various solutions to improve flame stability. In fact the choice turns out to be very precautionary in terms of CO emissions, while in terms of thermoacoustic instabilities N_2 dilution with nitrogen is more critical.

Acknowledgement

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References

[1] ElKady, A. M., Evulet, A., Brand, A., Ursin, T. P., Lynghjem, A. "Exhaust Gas Recirculation in DLN F-Class Gas Turbines for Post-Combustion CO2 Capture". *Proc ASME Turbo Expo*, pp. 847–854 (2008)

[2] Tabbi Wilberforce, A.G. Olabi, Enas Taha Sayed, Khaled Elsaid, Mohammad Ali Abdelkareem, "Progress in carbon capture technologies", Science of The Total Environment, Vol 761, 2021

[3] M. Cerutti, N. Giannini, G. Ceccherini, R. Meloni, E. Matoni, C. Romano, G. Riccio, "Dry low NOx emissions operability enhancement of a heavy-duty gas turbine by means of fuel burner design development and testing", Proc of ASME Turbo Expo, GT2018-76587, Oslo, Norway, 2018

[4] Galeotti, S., Picchi, A., Becchi, R., Meloni, R., Babazzi, G., Romano, C., and Andreini, A. "Experimental characterization of an industrial burner operated with simulated EGR", Applied Thermal Engineering, 2024