# LES validation of an industrial burner flame extinction operated with highly vitiated oxidizer

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## Abstract

In this paper an enhanced Thickened Flame Model (TFM) is leveraged to reproduce the extinction limit of an industrial burner operated at atmospheric pressure along a vitiated oxidizer: $CO_2$ is employed to dilute the air and mimic an Exhaust Gas Recirculation (EGR). It is found that the TFM is able to reproduce the Lean Blow-Out (LBO) at exactly the same oxidizer composition detected experimentally. Additionally, approaching the extinction limit, the numerical model manifests the same dynamics observed during the test with the flame propagating backward to the burner from an extremely elongated position.

## Introduction

The EGR technology in GT power plants doesn’t find application because of the high installation costs that do not justify the benefit in terms of $NO_x$ reduction. Moreover, a high EGR content can strongly compromise the flame stability that can lead to undesired emissions of CO/UHC [1-3]. Nevertheless, if the LBO resistance of the combustor is enhanced and the rate of EGR consequently increased, such technology can pave the way for a more efficient capture of the $CO_2$. Increasing the carbon-dioxide content could not only reduce the total energy consumption of standard amine-based carbon capture units but even enable the adoption of new capture processes (adsorption or membrane separation [4]). The enlargement of the operability window can be achieved in several ways. The first one can be done through an optimization of the premixer design [5]. The second could be represented by the doping of the fuel gas with $H_2$ able to increase the extinction strain rate and/or its injection in controlled quantities through a pilot line. In this context, this paper will show the experimental findings characterizing the LBO resistance without any $H_2$ addition of an industrial burner when it is operated with an oxidizer having a high $CO_2$ content. The vitiation of the oxidizer through $CO_2$ to mimic EGR is due to storage limitations of the experimental facility. Despite that, since operating with $CO_2$ dilution is a more severe condition in terms of combustion stability, the findings are fully representative and still valid in case the same design is operated with EGR. These results will allow to plane an optimization of the design to further extend its extinction limits. The optimization can be performed through a dedicated CFD models whose validation will be here presented as well. The manuscript is organized as follows: the next section describes the test facility while the numerical model is introduced in the following paragraph. The experimental sequence leading to the LBO and reproduced numerically will introduce the results and discussion section.

## Test Rig and Measurement Techniques

Figure 1-a) shows a sketch of the rig where the tests are executed. The facility is able to run at a maximum pressure of 10 bar delivering up to 1 kg/s of the oxidizer. An electric heater of 600 kW rises the temperature of the oxidizer up to 300 °C after that the same is filtered and the humidity removed. When the $CO_2$ is used to dilute the air, it mixes before entering the heater such that a homogeneous temperature and composition of the mixture can be assumed at the combustor inlet. The facility has up to three independent fuel gas lines (up to 90 $Nm^3/h$ at 16 bar of pressure).

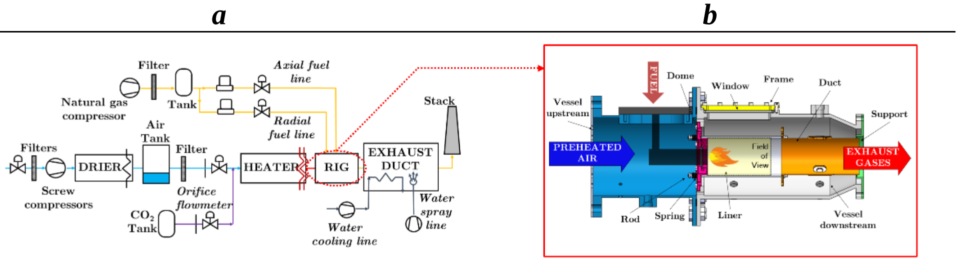


**Figure 1.** Combustion test rig (a) and close-up of the combustor set-up (b).

Figure 1-b) side shows a close-up of the combustor with the external casing that, in the flame region, is equipped with two perpendicular optical accesses allowing to visualize the 2.5 mm thick quartz liner. The latter is cooled by a fraction of the oxidizer passing through the dome and entering the annulus between the external casing and the flame tube. The dome plate is instead cooled by effusion holes fed through a second fraction of the oxidizer coming from the upstream vessel. Regarding the standard instrumentation, the rig counts on thermocouples monitoring the temperature of the dome and the liner downstream the quartz and static pressure probes to quantify the pressure drop across the burner. A dynamic pressure probe is used to detect any thermoacoustic instability may rise. The flue gas is sampled at the end of the metal liner for the measure of the pollutant emissions through a HORIBA PG300: the sample is kept at 150 °C before reaching the gas analyzer and then cooled to remove the water vapor. A Phantom MIRO M340 camera coupled with an intensifier is used for OH* recording; the intensifier is equipped with a Nikon UV lens with a bandpass filter set at 310±2 nm; the gain and the acquisition frequency are fixed to 5 and 500 Hz. Concerning the burner, it is composed by two counter-rotating swirlers ensuring a good mixing of the main fuel gas that is injected at the tip of the inner swirler. The pilot line delivers the fuel into the primary zone of the combustor through circumferentially equally spaced holes for flame stability. In this study, the burner is operated injecting the entire fuel from the pilot line. More information about the fuel nozzle and its flame stabilization can be found in [5].

## Enhanced-Thickened Flame Model and Numerical Settings

The application of the TFM, theoretically valid for premixed and partially premixed flames, is here justified by the lifted nature of the piloted flames [6-7]. This is even more effective when the oxidizer is vitiated through $CO_2$ leading to a high lift-off. Nevertheless, where the flame is characterized by a diffusive regime (especially when the air is the oxidizer) the original formulation of the combustion model [9] is modified such that the chemical source term of each species-related transport equation is a function of the local flame index. For positive flame-index (premixed regime), the original TFM formulation is applied; when it is negative, the thickening of the flame is not applied, a finite rate closure is adopted and the species diffusivity not altered. Being $\varphi$ the vector of the species mass fractions (a 19 species-62 reactions skeletal mechanism calculated ad-hoc is used), the corresponding transport equations can be written as:

$$\frac{\partial\bar{\rho}\,\widetilde{\varphi_\alpha}}{\partial t}+\frac{\partial\bar{\rho}\,\widetilde{u_j}\,\widetilde{\varphi_\alpha}}{\partial x_j}=\frac{\partial}{\partial x_j}\left(\bar{\rho}(EFD_\alpha+(1-\Omega)D_t)\frac{\partial\widetilde{\varphi_\alpha}}{\partial x_j}\right)+\frac{E}{F}\dot{\omega}_\alpha(\tilde{\varphi}) \qquad (1)$$

with $E, F$ and $\Omega$ the efficiency function, the dynamic thickening factor and the flame sensor, respectively [9]. The dynamic thickening factor $F$ is a function of the number of points $N$ in the flame thickness $\delta_{th}$. Since the latter parameter changes along the different oxidizer compositions, $N$ is dynamically accommodated to maintain an almost constant thickening factor along the entire flammability range and equal to 5 at stoichiometric conditions. Regarding the mentioned computational grid, Figure 2 shows a longitudinal cut with a resolution inside the flame tube equal to 0.6 mm and 0.2 mm where the pilot jets enters the combustor (important mainly when the oxidizer is air and the flame stabilizes primarily around the pilot jets).

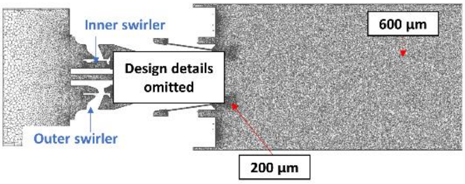


**Figure 2.** Mesh size at the main locations of the computational model.

As for the quartz thermal boundary conditions, a heat transfer coefficient equal to 35 $W/m^2$-K and a bulk temperature of 577 K is used to model the heat loss. Discrete Ordinate is adopted for radiation with semi-transparent boundary for the quartz and the gas modelled as optically thick. Regarding the numerical setting, the Dynamic-Smagorinsky closure is used to model the sub-grid scale turbulent structures along the LES. All the transport equations are resolved at the second discretization order as well as the bounded time step advancement.

## Results and Discussion

Experimentally, the LBO limit is found increasing the $CO_2$ content through several steps. Numerically, the same process is simplified considering two steps of $CO_2$ rising, summarized in Figure 3. The investigation starts with pure air and then the $CO_2$ is increased to have 18.6% $O_2$ vol. and eventually16.2% $O_2$ vol, respectively.

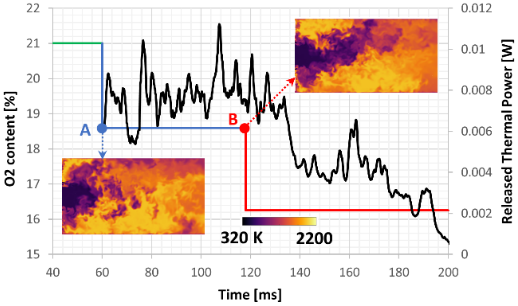


**Figure 3.** $O_2$ reduction steps and the volume-average released power till LBO.

The same Figure 3 reports the trend of the volume-average released thermal power from the combustor. It can be seen that the first oxygen reduction doesn't have an impact onto the global fuel consumption rate with the thermal power remaining approximately constant, as demonstrated by the contour plot of the temperature field at the beginning and at the end of the first step. Conversely, once the second oxygen reduction starts interacting with the pilot flames (at135 ms, after about 15 ms from the beginning of its injection in the domain), the heat release drops. The simulation takes approximately 60 ms to completely push the flame outside the combustor.

Focusing the attention on the time window between 60 ms and 120 ms, it is useful to compare the numerical results with the experiments in terms of CO and combustion instability, whose main finding are summarized in Figure 4. Regarding the CO, it can be observed that an excellent prediction is achieved working with pure air while an overprediction is achieved with $O_2$ at 18.6%. At the same time, the TFM model is able to predict the higher instability recorded experimentally if compared with the operation with air (not shown here): experimentally only the L=2 tone is triggered, while numerically also a lower frequency tone (150 Hz) is observed, denoting a propensity through LBO related to colder spot release from the flame [6].

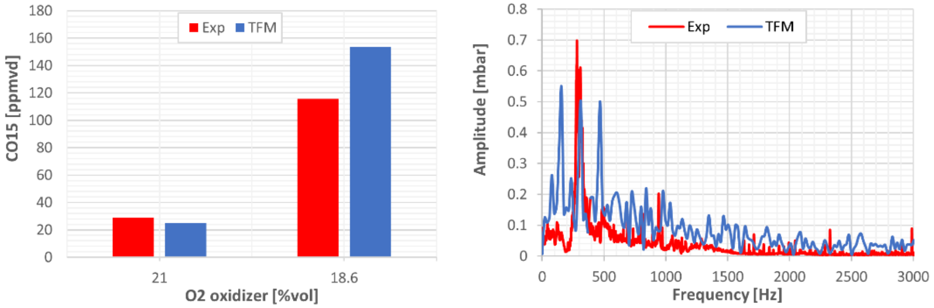
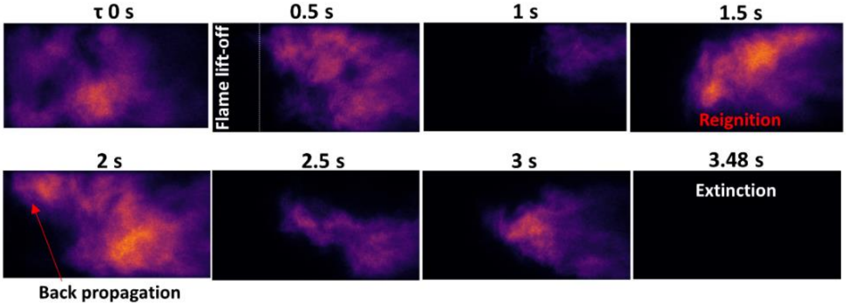


**Figure 4.** CO (left) and FFT of the acoustic pressure inside the combustor (right).

Focusing on the transitory phase leading to the flame extinction (numerically $\tau > 135\ ms$), Figure 5-a shows the experimental sequence of the last 3.5 seconds before the flame out and Figure 5-b the numerical highlights. During the test, the flame moves cyclically from an extremely detached position toward the pilot jets. A similar behavior can be observed numerically: for example a backpropagation is detected at 0.15 s and 0.18 s after that the flame presents a significant lift-off with the heat release rate region placed even in the middle of the liner.

**a) Experimental LBO sequence**



**b) TFM LBO sequence**

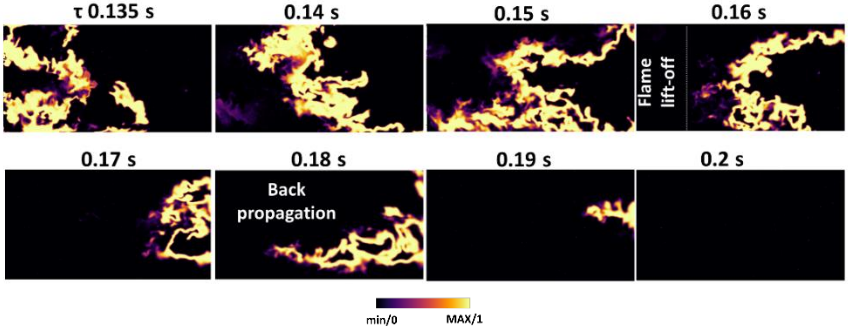


**Figure 5.** Experimental Line of Sight OH* (a) and numerical Ω sensor [0-1] (b).

In order to provide an insight of the complex mechanism leading to the extinction, Figure 6 correlates the flow field (through its vectors) with the radical OH at four instants after the $O_2$ final depletion. As a general result, it can be observed that the

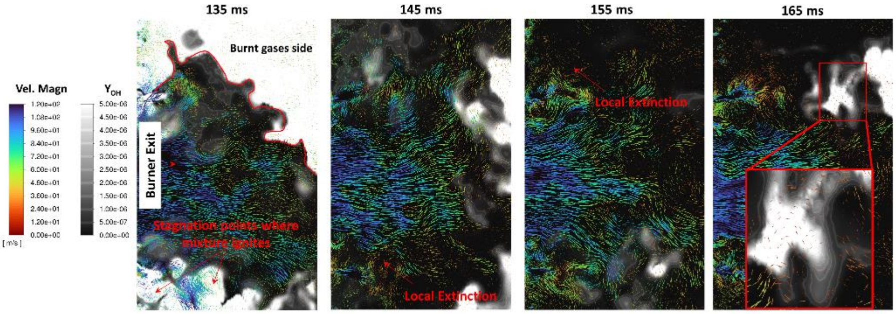


**Figure 6.** Velocity magnitude vectors for stagnation point detection overlapped to the OH mass fraction (gray scale) right downstream the burner exit.

flame gets preferentially anchored in the outer recirculation zones and in particular where the stagnation points are located. Those stabilization locations are lost quite immediately once the $CO_2$ rate is increased (i.e., at 145 ms) causing local extinctions. Even if localized ignition events are still present, like the one depicted by the close up at 165 ms, such events happen quite far from the pilot line where the regime is leaner and consequently the laminar flame speed can't sustain the flame stabilization.

## Nomenclature

| | | | |
|---|---|---|---|
| *CFD* | *Computational Fluid Dynamics* | *LES* | *Large Eddy Simulation* |
| *EGR* | *Exhaust Gas Recirculation* | *LBO* | *Lean Blow-Out* |
| *FFT* | *Fast Fourier Transform* | *TFM* | *Thickened Flame Model* |
| *GT* | *Gas Turbine* | *UHC* | *Unburnt Hydro-Carbon* |
| *Subscripts* | | | |
| F | Fuel | *ox* | Oxidizer |

## Conclusion

The present work reports the findings of a TFM-based combustion model in predicting the flame extinction of an industrial burner experimentally operated with a highly-$CO_2$ vitiated oxidizer. The model reproduces quite accurately the behavior of the burner during a first $O_2$ reduction, with similar CO emission and acoustic fluctuations. Also the phenomenology leading to the LBO seems to be captured by the numerical model showing a back-propagation behavior toward the pilots.

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