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An experimental and numerical study of MILD combustion in a Cyclonic burner

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Abstract

The implementation of MILD combustion systems is limited by a lack of fundamental insight into such combustion regime and therefore novel tools are indispensable compared to traditional combustion systems. In this context CFD simulations for the prediction of the burner behaviour and for design and optimization appears essential for a successful introduction of such concept in some industries. Detailed chemistry has to be included in fluid-dynamics simulations in order to account for the strong turbulence-chemistry interaction in the MILD regime. An effective strategy to overcome this aspect is represented by tabulated chemistry techniques. In particular the implementation of Flamelet Generated Manifold with IML tabulation seems to be a promising tools for MILD systems and therefore high fidelity and comprehensive experimental data are needed for the assessment of such model. The present study is framed in this context and it investigates the characteristics of MILD Combustion in a Cyclonic lab-scale burner that operates with high level of internal recirculation degrees induced by a cyclonic fluid-dynamic pattern obtained by the geometrical configuration of the reactor and of the feeding system. Experimental tests were realized varying the mixture composition. Detailed measurements of local mean temperatures and concentrations of gas species at the stack for several operating conditions were used to validate the FGM model under such unconventional operating conditions. Results suggest that FGM with IML is a promising tool for modeling the complex flame structures of cyclonic MILD burner, with many aspects that need to be further investigated.

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Keywords: MILD combustion; Cyclonic flow; Internal recirculation; FGM; Igniting Mixing Layer

1. Introduction

Reducing pollutant emissions, increasing the fuel flexibility and improving burners efficiency has brought to the development of new combustion concepts. Among these new technologies, MILD combustion [1, 2], also called

FLameless OXidation (FLOX[®]) [3, 4] seems to be one of the most promising. This is a combustion regime characterized by fuel oxidation in an environment with relatively high dilution and preheating levels. Such operating conditions feature a process with a distributed reaction zone, relatively uniform temperatures within the combustion chamber, no visible flame, low noise, negligible soot formation and very low NO_x and CO emissions [5, 6]. In MILD combustion, the inlet temperature of the reactants is higher than the auto-ignition temperature of the mixture and, simultaneously, the maximum temperature increase due to oxidation reactions remains lower than the mixture auto-ignition temperature [7, 8] because of high dilution levels.

Although MILD combustion systems have been successfully introduced in some industries, broad implementation is hampered by a lack of fundamental insight into this combustion regime [9].

A key point necessary for efficient design of a MILD combustor is to ensure good mixing between the incoming fresh fuel/air mixture and the hot burnt gases. This can be achieved by designing combustor aerodynamics with strong recirculation that redirects the hot products towards the injection nozzle. MILD combustion modeling requires different tools compared to traditional combustion simulation. Attractive strategies for including detailed chemistry effects using moderate CPU resources are tabulated chemistry techniques. Among such models are flamelet generated manifold (FGM) [10] techniques, which are based on flamelet assumption [11]. They have been applied to MILD combustion successfully [12]. FGM is a chemistry reduction method, which is based on two assumptions: *n*-dimensional composition space can be represented by a lower dimensional manifold, and a turbulent flame is an ensemble of laminar flames. The lower dimensional manifold can be constructed by solving a one-dimensional flame and tabulating the related quantities as functions of a few controlling variables (CV). During a CFD simulation, only the transport equations for CV are solved and the required variables are looked-up from the so-called FGM tables. Important selections to be made in an FGM study are the determination of CV and the type of 1D flame to be solved. In non-premixed combustion, the traditional approach is to use mixture fraction (*Z*) and a reaction progress variable (PV) as CV, and to select PV as combination of products and/or reactants mass fractions [13]. It was shown in engine related studies [14] that addition of precursors to the classical definition of PV is required to capture the autoignition. As for the 1D flame type, although the common practice is to use counter-flow (CF) type flames [15], Abtahizadeh et al. [16] showed that igniting mixing layers (IML) type flame is a better option in representing MILD combustion in a jet in hot coflow (JHC) burner. The elucidation of the above topics needs high fidelity and comprehensive experimental data to validate the numerical models. JHC setups from Adelaide [17], and Delft [18], and the Cabra flame [19] have been conceived to emulate flameless conditions by feeding diluted and hot streams to the burner. However, in the industrial practice, MILD Combustion conditions are obtained by means of the massive internal recirculation of flue gases, which allows diluting the fresh gases before they reach the reaction zone. Such recirculation is generally achieved through special designs of the feeding jets as well as of the combustion chamber. The recirculation affects both mixing and chemical timescales, so that conceptually these burners are different from JHC and Cabra flames, which act solely on the chemical timescale. Despite the reasonable number of studies in the literature [20, 21, 22], the amount of detailed experimental data available for combustors operating under flameless conditions is relatively scarce and, in general, when reported, is for very few and narrow combustor operating conditions. The present investigation aims to extend the present database on MILD Combustion and thereby to improve the understanding of the processes, which occur during this combustion regime. To this end, experiments have been performed in a propane-fired small-scale combustor, and include detailed measurements of local mean temperatures and concentrations of gas species at the stack for several operating conditions. In this article, the combustion process in a cyclonic burner that operates in MILD combustion conditions is investigated experimentally and by means of RANS simulations with FGM sub-model in order to prove and validate the capability of the numerical model to represent the underlying physics of this combustion regime in the present combustion chamber.

2. Experimental setup

Experimental tests were conducted in a laboratory-scale cyclonic flow reactor. Fig. 1 shows a sketch of the non-premixed configuration of the (0.2x0.2x0.05 m³) laboratory-scale burner used to investigate the MILD/flameless combustion process [23–26]. It is a prismatic chamber with a square section (0.2x0.2 m²) and height of 0.05 m. Two pairs of oxidant/fuel jets feed the combustion chamber in an anti-symmetric configuration thus realizing a

centripetal cyclonic flow field with a top-central gas outlet. The main pre-heated flow (composed by oxygen and nitrogen) is fed inside the combustion chamber parallel to the fuel jet.

The fuel stream is propane at environmental temperature (T_0). The oxidant injector is 0.02 m from the lateral wall, whereas the fuel injector is at 0.045 m. The feeding configuration is shown in Fig. 1b. The gas exit is located on the top of the chamber.

The high gas recirculation rates promote the attainment of high temperature low oxygen concentration condition required for the stable autoignition of MILD mixture.

The main oxidizer flow passes through heat exchangers located within the electrical ceramic fiber heaters to raise the temperature to the desired values, while the fuel is injected at environmental temperature.

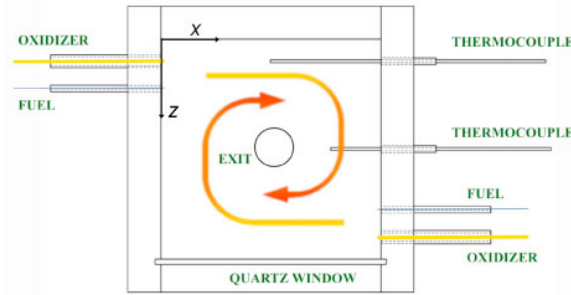


Fig. 1. Sketch of the mid-plane section of the cyclonic configuration

The cyclonic burner is equipped with a set of thermocouples (type N) and an optical access (a quartz window) (Fig. 1). Two movable thermocouples are located at the mid-plane of the reactor. The lateral is placed near the wall (0.02 m from the wall) and the central is placed at the centerline of the combustion chamber (0.1 m from the wall, see Fig. 1a). The thermocouples can be moved across the reactor. Further details on the experimental apparatus can be found in previous literature works [23–25]. The exhausts were monitored at the exit of the combustion chamber through a water-cooled probe. The major species emissions were analyzed by means of a GC analyzer, averaged over a 5-min duration for each operating condition studied. NO and NO₂ (NO_x) were measured through an ABB flue gas analyzer.

The full list of the experimental runs performed is summarized in Table 1. For all measurements, the global inlet content of nitrogen is taken into account by means of the dilution level parameter (d) that in this paper is fixed at 94% whereas the mean residence time in the reactor is kept constant at 0.5 s (volume/flow rate) and the pressure of the system is atmospheric. Therefore the inlet oxygen level (YO_2) is a function of the inlet equivalence ratio (Φ).

Table 1 List of the experimental conditions investigated in this study

RUN	T_0 (K)	T_{in} (K)	Φ	Dilution level (d)
CL1045	300	1045	0.33	0.94
CS1045	300	1045	1	0.94
CR1045	300	1045	1.67	0.94

During the experimental campaign the autoignition of the fresh oxidizer charge was reached by increasing the inlet temperature of the oxidizer (by means of external preheating systems) from the environmental temperature to

the desired value T_{in} . The effect of the global equivalence ratio on the combustion behavior was studied in this paper.

3. Numerical method

As mentioned in Section 1, an important part of an FGM simulation is to select an appropriate 1D flame type to be used in table generation. Counter-flow (CF) configuration is a commonly used one, where two opposing jets are issued on to each other and the flame develops at the stagnation plane. However, as seen in Fig. 1, the current configuration does not have such opposing jets, but rather has co-flowing jets. In the igniting mixing layer (IML) approach proposed in [16], the fuel and oxidizer are placed side-by-side initially; they mix by molecular diffusion, and react in time. Evolution of temperature in a sample IML simulation is shown in Fig. 2.

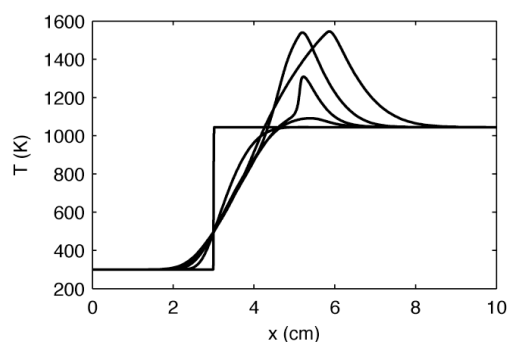


Fig. 2. Evolution of temperature profile for a sample IML case

Since the structure of co-flowing inlet jets in the present burner is similar to IML, it is selected as the 1D flame type in this study. It can be argued that the use of homogeneous reactors would be a better option considering the uniform flame structure in MILD combustion. However, the pre-ignition chemistry takes place as the jets start to mix and this cannot be captured with 0D models. The boundary conditions in 1D calculations follow from the experiments as reported in Table 1. Following the study from Sabia et al. [27], C1C3 reaction mechanism [28] was used in IML simulations. Progress variable (PV) was selected as a combination of Y_{H_2O} , Y_{CO_2} and Y_{HO_2} . Mixture fraction (Z) computed using Bilger's formula was used as the second CV to represent the molecular mixing between the fuel and oxidizer. Although there is heat loss from the burner to the surroundings, this was not accounted for in FGM table creation to limit the table dimension and thus reduce computational needs. In the CFD simulations, ANSYS Fluent was used as the solver. RANS equations were solved using RNG k- ϵ turbulence model with swirl dominated flow corrections to account for high swirl in the combustor. For turbulence-chemistry interaction, presumed β -PDF approach was adopted. A total of four transport equations for the means and variances of CVs were solved for the FGM part using built-in FGM option in ANSYS Fluent. A 4D FGM table was constructed using $101 \times 101 \times 11 \times 11$ points in the mean and variance of CVs, respectively. Although heat loss was not used in manifold creation, it was included in the CFD runs. A heat transfer coefficient of $10 \text{ cal}/(\text{m}^2 \text{ s K})$ and $T_{\text{ambient}} = T_{in}$ were prescribed at the walls as the thermal boundary condition [23–26]. This way, the effect of heat loss could be reflected on the prediction of temperature and thermodynamic properties, but not on the reaction rates and heat release. For the simulations presented in this paper, we use eight processors of an Intel computer. Total computing time is about 5 h per processor.

The computational mesh used is composed of 411064 hexahedral elements, clustered near the inlets. Velocity inlet BCs were used for the fuel and oxidizer jets, while pressure outlet BC was used for the outlet. Pressure-velocity coupling was ensured using SIMPLE scheme, and second order upwind discretization was used for all the transported variables. The temperature slice from the mid plane and the surface mesh of the whole domain from the simulation with stoichiometric conditions and $T_{in} = 1045 \text{ K}$ is given in Fig. 3 to provide an idea on how the simulations look like.

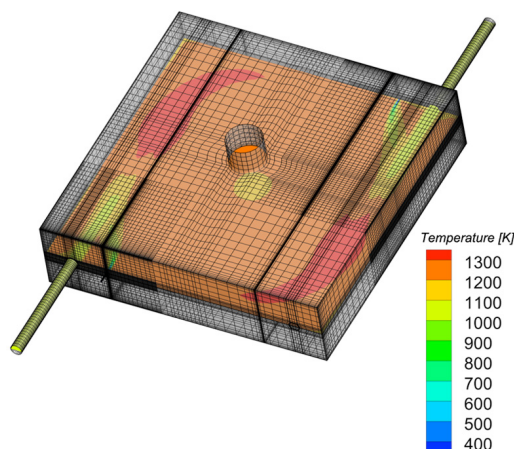


Fig. 3. Computational mesh and mid-plane temperature profile for the Run CS1045

4. Results

Experimental tests were carried out for $C_3H_8/O_2/N_2$ mixtures, at environmental pressure and mean residence time of 0.5 s inside the combustor. The external parameter such as the overall equivalence ratio (Φ) at the inlet was varied parametrically in order to investigate the combustion behavior of the system. The overall external dilution level is kept constant at 94% for all the investigated conditions.

The results of the comparison between experimental and CFD analysis of the cyclonic burner are presented and discussed in this section with two main objectives:

- i) to assess the performance of the chosen tabulated chemistry model (FGM with IML configuration) and evaluate the adequacy of the kinetic mechanism
- ii) to examine the effects of the operating parameters (T_{in} and Φ) on the temperature distributions and species emissions, as well as on the accuracy of the numerical predictions.

Experimental results on temperature distribution obtained for various equivalence ratios at atmospheric pressure and $T_{in}=1045$ K are presented here and compared with the numerical ones.

The inlet mixture composition is a crucial parameter, which affects the thermal field and the species production. To investigate these effects, firstly the temperature profiles at the mid-plane were examined. The left part of Fig. 4 (a-c) shows the values measured at the lateral location ($z=0.02$ m, with the movable lateral thermocouple) along the burner axis at the mid-plane when increasing the inlet equivalence ratio Φ (see Table 1) while keeping T_{in} at 1045 K. The experimental thermal field demonstrates an important characteristic of MILD combustion regime: the temperature uniformity. The difference between the maximum temperature in the burner and the average one is less than 40 K for the three examined cases. Few inhomogeneities in the thermal field are detected only in a small region very close to the oxidizer and fuel nozzles where ignition occurs ($0 < x < 0.02$ m).

It is possible to note (Fig. 4b) that the position of the maximum temperature is located close to the oxidizer nozzle at $x=0.02$ m for the stoichiometric condition and the temperature profile shows a steep increase before reaching an almost constant value of $T=1283$ K. Similar trends are obtained for fuel-lean and fuel-rich cases. It is worthwhile to note that the maximum value of ΔT ($\Delta T = T_{max} - T_{in}$) is obtained for the Run CS1045 where the inlet stoichiometric conditions results in a higher reactivity of the system. Therefore the main effect of the overall equivalence is observed in the increasing of the maximum temperature inside the chamber while the trend of the thermal field remains the same in all three cases.

The high dilution of the fresh mixture in conjunction with the large internal recirculation degrees due to the configuration helps to mitigate the temperature increases thus confirming that the present combustor is in the MILD Combustion regime for all the investigated conditions.

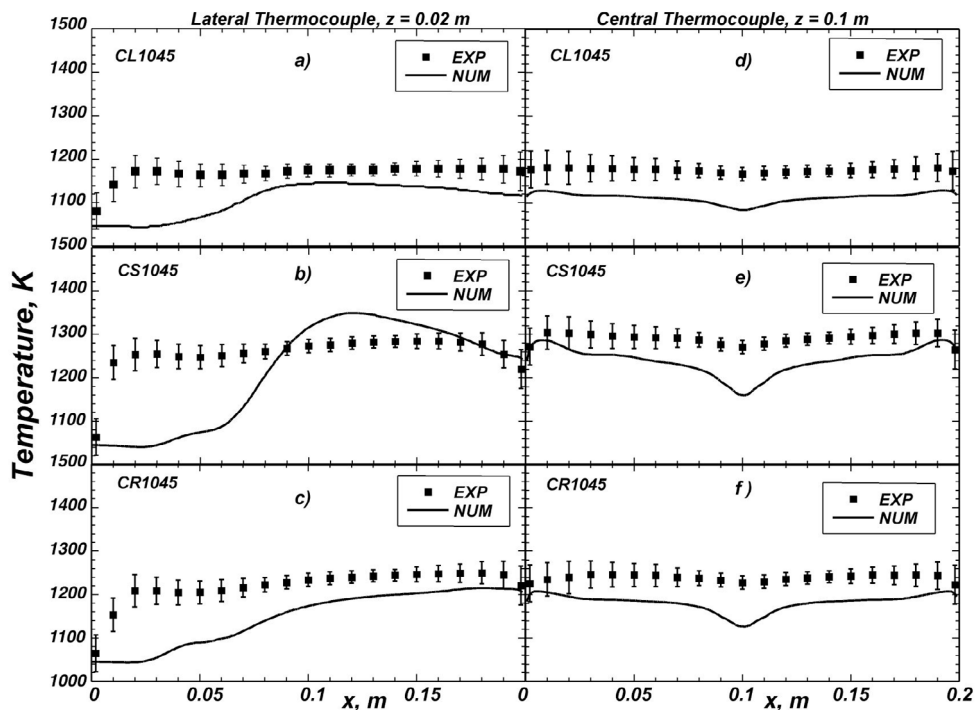


Fig. 4. Axial profiles of the measured and predicted temperature profiles parametric in the equivalence ratio (Lateral and Central thermocouples)

Experimental results have been also corroborated by the modeling activity. In the left column of Fig. 4 the axial temperature profiles obtained with the FGM-IML computations are reported with a black solid line for the three equivalence ratio values in order to compare and validate the model against the experimental data. The small increase of temperature measured along the axial direction is reasonably predicted quite-well when lean or fuel-rich inlet mixture compositions are used, although the temperature rise happens earlier in the experiments compared to the model. This is because the lateral thermocouple is positioned at the centerline of the oxidizer inlet, whereas the reactions start to occur between the fuel and oxidizer inlets in the simulations. There is a slight overshoot of temperature at the stoichiometric condition, which corresponds to the most reactive condition in the simulation. The simulated results show that the ignition starts between oxidizer and fuel jets thus partially explaining the under-prediction of the model close to the nozzles. In fact the present tabulated model does not account for product gas dilution by means of internal recirculation. Previous works have emphasized the significance of dilution in the non-equilibrium chemistry and flame stabilization for internal recirculation systems [29] but the addition of dilution parameter as another controlling variables implies higher table dimensions and CPU costs. Axial profiles of temperature are reported in Fig. 4 (d-f) for the central thermocouple ($z=0.1$ m). The temperatures obtained with FGM are in quite good agreement with measurements for all the cases and they show the same trend. In particular, in proximity of the center of the burner FGM results produce a slight under-prediction on the order of maximum 6 % at stoichiometric conditions whereas it is lower for other conditions. In order to obtain a further assessment of the numerical model the major (CO_2 , CO , H_2 , O_2) and minor (CH_4 , C_2H_2 , C_2H_4 , C_2H_6) combustion products for each case at the exit of the burner were measured and compared with the numerical results in Fig.5 for $T_{\text{in}}=1045$ K.

It is possible to observe that the CO and UHC emissions are very low in lean and stoichiometric conditions confirming another important characteristic of MILD Combustion. They increase for fuel-rich conditions as expected. Figure 5 compares the species volumetric concentration (%vol. on a dry basis) measured at the exit of the burner with those obtained through FGM modeling at the outlet. They are reported as a function of the inlet equivalence ratio.

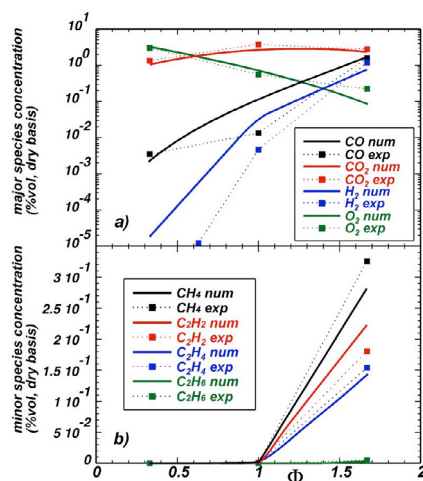


Fig. 5. Species Volumetric concentration parametric in the equivalence ratio (Major and minor species)

Predictions of major species concentrations (Fig. 5a) are in quite good agreement with the model especially for CO₂ and O₂ and they reflect the one observed for the temperature. Predictions of minor species concentrations (Fig. 5b) are consistent with those obtained for major species and few discrepancies are obtained only for CH₄ and C₂H₂ under fuel-rich conditions. An overestimation of CH₄ is noticeable at $\Phi=1.67$ whereas the C₂H₂ is underestimated in the same condition. These discrepancies may be attributed to the C1C3 chemical kinetics mechanism that under fuel-rich conditions partially fails to describe accurately the C₂-recombination channel [27].

5. Conclusions

In this work, both experimental and numerical investigations were conducted for a novel Cyclonic burner under MILD Combustion conditions. The combustor is fuelled with C₃H₈ and a mixture of N₂ and O₂ as oxidizer. The Flamelet Generated Manifold (FGM) model based on Igniting Mixing Layer (IML) configuration was used in order to predict the MILD Combustion characteristics of the considered chamber and validations were driven using the experimental results. A certain range of equivalence ratio was investigated, since the characteristics of MILD Combustion regime (i.e. temperature homogeneity and pollutant emissions) are influenced by such operating parameter. The combustion process was investigated in detail by measuring the temperatures and emissions, and comparing them with those from the numerical model. Experimental and numerical results show a quite good agreement and the numerical model is capable of predicting very similar trends of temperature and also the overall species production. However, there are still some discrepancies to be addressed. Firstly, the temperature close to the oxidizer nozzle exit is under-predicted by the numerical model. This can be attributed to the internal recirculation in the experiments. Another slight disagreement is observed in the prediction of the mole fractions of species like H₂ and CO, which is believed to be the result of not translating the effects of heat loss on the chemistry. This is also amenable at the effect of the chemical kinetics mechanism. The numerical results of this work demonstrated that FGM with IML is a promising tool for modeling the complex flame structures of cyclonic MILD burner, with lots of room for improvement. Many aspects like inclusion of a dilution parameter and/or heat loss in the manifold generation, reevaluation of heat transfer coefficient at the walls, usage of a different chemistry mechanism and flamelet type will be considered in the future.

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