Impact of heat loss on the modelling of a cyclonic burner with high levels of internal recirculation

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Introduction

The development of thermal efficiency with fuel flexibility and ultra-low emissions is one of the most challenging subjects for combustion researchers. Among the modern technologies developed for this challenge, MILD combustion [1] seems to be one of the most promising. It is a combustion regime characterized by fuel oxidation in an environment with relatively low oxygen concentrations and high inlet temperatures. 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, very low NOx and CO emissions and ensure large fuel flexibility, also representing an ideal technology for low-calorific value fuels [2]. This combustion mode is achieved through the strongly burnt gases and heat recirculation, which is obtained through special designs of the feeding jets as well as of the combustion chamber. Despite the reasonable number of studies in the literature [3], the amount of detailed experimental data available for combustors operating under MILD/Flameless conditions is relatively scarce. In recent years, attention has been paid to MILD combustion modeling, due to its very strong coupling between turbulence and chemistry. Flue gas entrainment, indeed, increases the initial inert content of the fresh mixture and kinetics time scales become comparable to the mixing scales so that the turbulence/chemistry interaction needs to be considered with an appropriate turbulent combustion model [4]. Attractive strategies for including detailed chemistry effects using moderate CPU resources are tabulated chemistry techniques. Among them there is the Flamelet Generated Manifold (FGM) [5] technique, which is based on the flamelet assumption [6]. So, the present study involves the characterization of MILD combustion in a novel cyclonic burner [7] using the FGM model. In particular, the attention is focused on the influence of the heat exchange of the system, both externally and internally.

The cyclonic combustion chamber

In the left of Fig. 1, a sketch of a cross-section and the feeding configuration of the cyclonic burner used to investigate the MILD combustion process [7, 8] is reported. The burner consists of a prismatic chamber with a square section of 20x20 cm^2 and a height of 5 cm. It is fed with two pairs of coaxial oxidant/fuel jets placed in an anti-symmetric configuration thus realizing a centripetal cyclonic flow field. The round section outlet is placed at a central position, perpendicular to the cyclonic flow. The main oxidizer flow (composed by oxygen and diluent species) is preheated to 1000 K whereas the fuel stream (pure methane) is fed at the environmental temperature (300 K). The oxidant injector is located 2 cm from the lateral wall, whereas the fuel injector is located at 4.5 cm. The burner is equipped with two movable N-thermocouples in the mid-plane giving Tc and Tl (Fig. 1). The lateral one is placed 2 cm from the wall, while the central one is placed at the centerline of the combustion chamber (10 cm from the wall).

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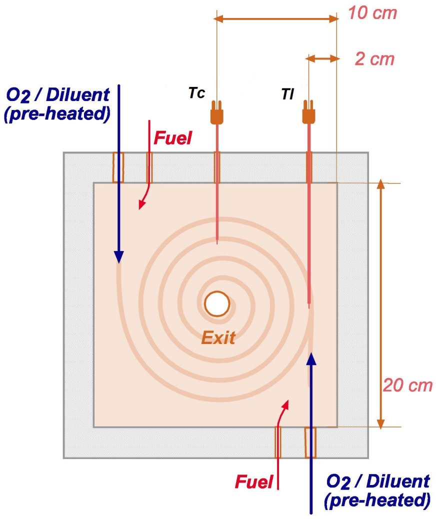
The exhausts were monitored at the exit and the major species emissions were analyzed by means of a GC analyzer. In the right of Fig. 1, the operating conditions investigated experimentally and numerically are listed, where d is the dilution level, Φ is the equivalence ratio and DIL is the diluent. Moreover, a global energy balance over the whole system was carried out to evaluate the total heat flux Q experimentally leaving the chamber.



RUN	DIL	Φ	d	Q [W/m^3]
1	N2	1	AIR	10000
1a	N2	0.7	AIR	10000
1b	N2	1.3	AIR	10500
2	CO2	1	AIR	9000
3	N2	1	80%	9000

Fig. 1 Sketch of the midplane section of the cyclonic configuration (left); list of the conditions investigated (right).

Methodology and numerical setup

In this study, the capability of flamelet-like models (FGM) for predicting MILD combustion in a chamber with a high internal recirculation is assessed. FGM is a chemistry reduction method, which is based on two assumptions: an 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 set of one-dimensional structures (flamelets) and tabulating the related quantities as functions of a few controlling variables (CVs). During a CFD simulation, only the transport equations for the CVs are solved and the rest of the required variables are looked-up from the so-called FGM look-up tables. CFD simulations were performed with commercial code ANSYS Fluent 18.1. Following the study from Sabia et al. [9], C1C3 reaction mechanism [10] and GRI30 [11] were used. The Flamelets were computed with the flamelet solver Chem1D [12]. An Igniting Mixing Layer (IML) structure [13] and a steady premixed flame (MIX) [5] were used. In the former, fuel and oxidizer are initially placed side-by-side and then mix by molecular diffusion and react in time. In the first step, an adiabatic table was built for both IML and MIX configurations with two CVs (100x100 points): A Progress Variable (CV1=PV), defined as a combination of the mass fractions of H_2O, CO_2 and HO_2 and the mixture fraction (CV2=Z), computed using Bilger's formula, to represent the molecular mixing between fuel and oxidizer are used. Afterwards, a non-adiabatic table was built, for the MIX flamelet, including total enthalpy (100x100x50 points). To do that, flamelets at lower enthalpy content were calculated decreasing the oxidizer inlet temperature. For turbulence-chemistry interaction, the presumed β-PDF approach was adopted.
Regarding the adiabatic tables, they were imported in Fluent 18.1 and 4D turbulent tables were created using the built-in FGM option. In this case, Fluent 18.1 couples the non-adiabatic effects in the flamelet library by freezing the species in adiabatic flamelets so that the temperature is recalculated with the enthalpy.

On the other hand, for the non-adiabatic table, the dimensions describing variances were added by in-house codes and the 5D turbulent table was stored in Fluent by means of User Defined Function.

The complete 3D geometry and the computational grid were realized using the software ANSYS ICEM 18.1. The mesh used is composed of around 400000 hexahedral elements, clustered near the inlets. Favre-averaged Navier–Stokes equations were solved using the RNG k-ε turbulence model with swirl dominated flow corrections to account for the high swirl in the combustor. The radiative heat transfer was considered on Fluent 18.1 by using a DO model to calculate the RTE and the WSGG domain-based for the absorption coefficient. The radiation was not included by using non-adiabatic table and UDF.

Results and Conclusions

First, the influence of kinetics and Flamelet configuration was evaluated by using adiabatic tables and Fluent-based FGM. The simulation results reported in Fig.2 show that, at steady conditions, there is no significant difference between the GRI mechanism and the more detailed C1C3 (POLI). Moreover, it was found that there is almost no difference between the premixed table (MIX) and the non-premixed one (IML) except for the near inlet position even if the real configuration is non-premixed. This result allows saying that for such a system the way of tabulating the chemistry does not have a noticeable effect.

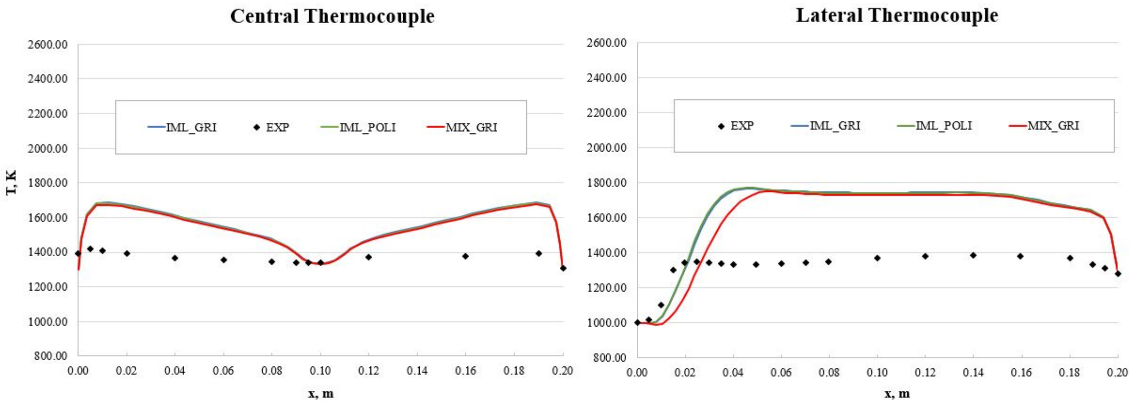


Fig. 2 Simulated temperature profiles along thermocouples Tc and Tl for run 1 using Fluent FGM with two different mechanisms.

Using the MIX configuration, a sensitivity study was then carried out changing the heat flux at walls with and without radiation. The resulting profiles are shown in Fig. 3. Note the high influence of the radiation for the heat flux of the system.

The high amount of heat loss through the walls Q (Fig.1 and Fig. 3) makes necessary the explicit inclusion of the total enthalpy as a controlling variable using the FGM model by UDF. In order to include the low enthalpy levels required in the table, the MIX configuration was used. The simulations performed using the non-adiabatic table and UDF underlines that the inclusion on the variance of the PV is negligible for this case whether the variance of Z has relevant effects just near the ignition (Fig. 4).

In general, the two methods used (adiabatic table and Fluent FGM and non-adiabatic table and UDF) give similar results except for the area near the inlets where the UDF method predicts a higher peak. This main difference lies in the different including enthalpy techniques used by the two procedures adopted.

In general, this study points out that under the conditions in which the cyclonic burner works, the heat loss by the system and the internal radiative effects seem to have a dominant role in reaching a very homogenous and almost isothermal thermal field, stabilizing the MILD regime.

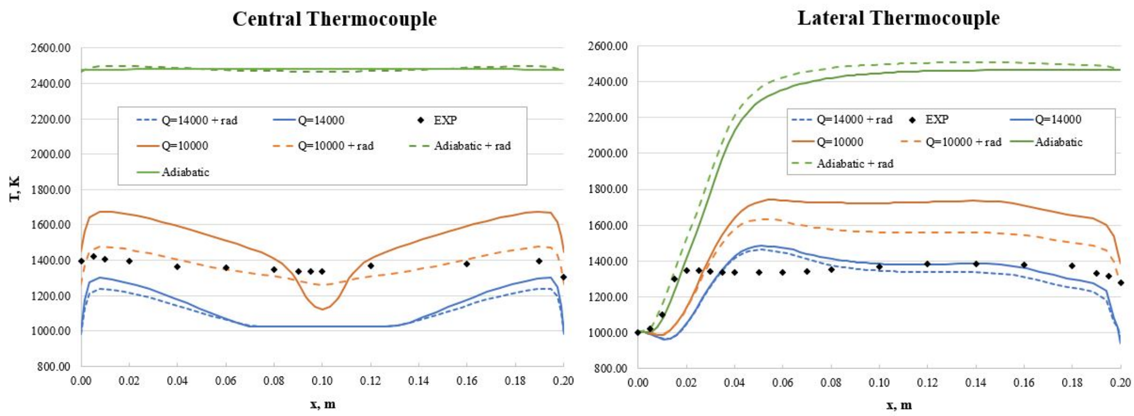


Fig. 3 Simulated temperature profiles along thermocouples Tc and Tl for run 1 using Fluent FGM with three different heat loss flux at walls and including radiation.

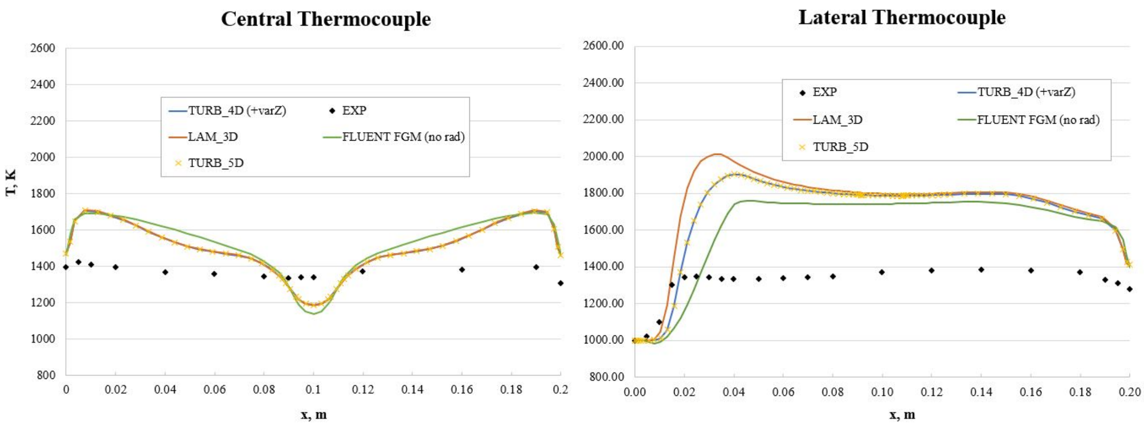


Fig. 4 Simulated temperature profiles along thermocouples Tc and Tl for run 1 using UDF with different non-adiabatic tables, and comparison with Fluent FGM.

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