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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

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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 extent 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 m^3) 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 m^2) and height of 0.05 m. Two pairs of oxidant/fuel jets feed the combustion chamber in an anti-symmetric configuration thus realizing a