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Design and Development of a Lab-Scale Burner for MILD/Flameless Combustion

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This paper discusses the design and development of a burner for MILD/Flameless Combustion processes. Computational Fluid Dynamics was used to simulate preliminary designs for the burner and to obtain a characterization of the combustor for non-reactive conditions.
MILD or Flameless combustion is a stable combustion process without the presence of visible flame, defined by the recirculation of hot products of combustion inside the chamber volume.
The combustor presented in this work was built in vermiculite and it has a prismatic shape to ensure the optical accessibility. A preheated main flow of diluent and oxygen and the fuel flow are fed inside the combustion chamber from one side. Diametrically opposed the feeding configuration is reproduced, thus realizing a spiral flow field inside the combustion chamber. The system is provided with a quartz window. The oxidation process of fuels/oxygen mixtures diluted in N_2 can be studied varying external parameters of the system, namely inlet temperatures (up to 1200K), equivalence ratio (lean to reach mixtures), residence times and mixture dilution levels. Temperature measurements inside the chamber are realized.
Rapid mixing between the injected fuel and hot oxidizer has been carefully explored for autoignition of the mixture to achieve volumetric combustion reactions. Distributed reactions can be achieved for a non-premixed configuration with sufficient entrainment of hot species present in the flame and their rapid turbulent mixing with the reactants.
Experimental tests, realized for C_3H_8/O_2 mixtures diluted in N_2, showed that for inlet temperatures higher than 900 K, MILD combustion condition is established for an overall dilution level of 90 % in nitrogen.
Increasing the preheating temperature, MILD occurs and combustion becomes invisible and homogeneous.

1. Introduction

Moderate or intense low oxygen dilution (MILD) combustion also called Flameless oxidation (FLOX) is a combustion regime characterized by oxidation of the fuel in an atmosphere with relatively low oxygen concentration, due to previous mixing between the oxidizer and the combustion products, a distributed reaction zone instead of a thin flame front, relatively uniform temperatures, no visible flame, low noise, negligible soot formation, and very low NOx and CO emissions (Cavaliere. and de Joannon, 2004). This technology has been successfully applied in heating and heat-treating furnaces of the metal and steel industry and has potential for implementation into many other applications. This requires a better understanding of the flameless oxidation phenomena, which can be achieved through fundamental studies. In MILD combustion, the inlet temperature of reactants remains higher than auto-ignition temperature of the mixture and, at the same time, the maximum temperature increase achieved during combustion usually remains lower than mixture auto-ignition temperature (Cavigiolo et al., 2003). These conditions are reached by re-circulating the product gases into the incoming fresh reactants efficiently. The gas recirculation serves two purposes: (i) raise the reactant temperature (heat recovery) (ii) reduce the oxygen concentration (dilution). In general, low oxygen

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concentration and moderate temperature levels lead to slower reaction rates and the Damköhler number approaches unity. Hence, for flames in the MILD regime finite rate chemistry is very important. At the same time mixing process remains essential: on one hand the mixing process of products with either fuel or air, on the other hand the entrainment of the diluted fuel and oxidizer streams. Weber et al. (2000) reported detailed measurements of velocity, temperature, gas species composition and radiation from flameless combustion in a natural gas-fired semi-industrial furnace, and concluded that the furnace was operating under conditions resembling a well-stirred reactor, with almost all furnace volume filled with combustion products containing 2 – 3 % of O_2. Dally et al. (2004) studied the effects of the fuel dilution with CO_2 and N_2, in a recuperative furnace, on the structure of the flameless oxidation. The results showed that the dilution of the fuel stream with inert gases might help to achieve flameless oxidation conditions and to reduce NOx emissions. Simultaneous imaging of OH and temperature confirmed that the reaction zone is rather distributed under flameless oxidation conditions. Szegö et al. (2008) reported measurements of temperature and flue-gas composition from a MILD laboratory combustion furnace. They found that air preheating is not required to achieve MILD combustion, even with 40% of useful heat being extracted through a cooling loop. More recently, Mi reported an investigation on the effects of the air-fuel injection momentum rate and the air-fuel premixing on the MILD combustion in a laboratory recuperative furnace (Mi et al., 2009). It was concluded that, above a critical momentum rate of the inlet fuel-air mixture below which MILD combustion cannot occur, both the inlet fuel-air mixedness and momentum rate impose insignificant influence on the stability of and emissions from the MILD combustion.
In spite of a number of activities for industrial furnaces, the application of flameless combustion in the gas-turbine combustion system is in the preliminary phase. Lammel et al. (2010) developed a FLOX combustor at high power density and achieved low NO_x and CO levels. The group of Gupta have demonstrated the concept of colourless distributed combustion for gas turbine application in a number of publications (Arghode and Gupta, 2010).
Despite the reasonable number of studies in the literature, 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 database on MILD Combustion and thereby to improve the understanding of the processes that occur during this combustion regime. To this end, experiments have been performed in a propane-fired small-scale cyclone combustor, and include detailed measurements of local temperatures for different operating conditions. The cyclonic flow pattern inside the chamber provides large residence times and better mixing between the reactants. The recirculation zones and turbulence generated internally by shear between differing fluid enhance the mixing and generate large toroidal recirculation zone with high level of turbulence.
Focus here is on achieving flameless and distributed combustion conditions. Sustainability of MILD combustion for nitrogen dilution is observed for different operating conditions.

2. Geometry and design of the combustor

As reported in the introduction, design of a novel cyclonic burner for the study of MILD/Flameless combustion conditions has to address several constraints:
- long residence time of gas flow, compatible with chemical kinetic times;
- strong and fast mixing between inlet streams and recirculated fluid for combustion process stabilization;
- maximization of mixing process, for geometrical reactor optimization.

A CFD analysis with FLUENT 6.3 software was performed in order to design a novel MILD cyclonic burner configuration in which a strong and well/controlled recirculation is achieved.
Firstly, an analysis of the mass and energy balances was done. The nominal power of the experimental test rig was varied between 0.5 and 5 KW (by varying the average residence time). Considering a $C_3H_8/O_2/N_2$ mixture at stoichiometric conditions, with an overall nitrogen dilution equal to 90 % and an inlet oxidizer temperature of 1,045 K, the total flow rate is changed by varying the average residence time (τ) values from 0.2 to 1. The inlet fuel temperature is 300K. In Table 1 the different configurations are reported and the inlet oxidizer jet velocity (diluent/oxygen) is reported basing on the average residence time and by fixing the fuel jet velocity at 50 m/s for all the configurations.
Full hexahedral grid was used to minimize the grid size and appropriate refinement of the grid was undertaken in the region with high gradients.
In grid independence study, the velocity vectors and fuel mass fraction along the fuel jet centerline were carefully compared. The mixing field was solved using a steady state, implicit, finite-volume based compressible solver, and the Reynolds stress model (RSM) with non-equilibrium wall functions was used to model turbulence in high highly swirling flows condition. Reynolds stress model (RSM) has been shown to

provide more accurate prediction of the mixing flow field for swirling flow-fields (Vondál and Hájek, 2012). Turbulence intensities of the mass flow inlets and pressure outlet were set to 0.05 while SIMPLE algorithm was used for pressure velocity coupling. A second-order upwind discretization scheme was used to solve all governing equations. Convergence was obtained when the residuals for all the variables were less than 10^{-4}.

Table 1: Summary of the investigated configurations

Case	Configuration	J	Nominal heat load (kW)	Average Residence time (s)	Oxidizer Velocity (m/s)
1	A1	382	4	0.2	98
2	A2	58	1.6	0.5	38
3	A3	16	0.9	0.9	20

In the present burner configuration exhibited in Fig. 1, the oxidizer and fuel stream are injected at high speed to induce a spiral flow and so enhance gas recirculation inside the combustor. Strong exhaust gas recirculation aids in the spontaneous ignition of uniformly distributed reactants as well as the growth of reactants oxidation rate so that the CO emission level is reduced.
Figure 1a shows a photograph of the combustor and Figure 1b shows a sketch of the non-premixed configuration of the (20x20x5 cm^3) laboratory-scale burner used in this study to investigate MILD/Flameless combustion for a $C_3H_8/O_2/N_2$ mixture.

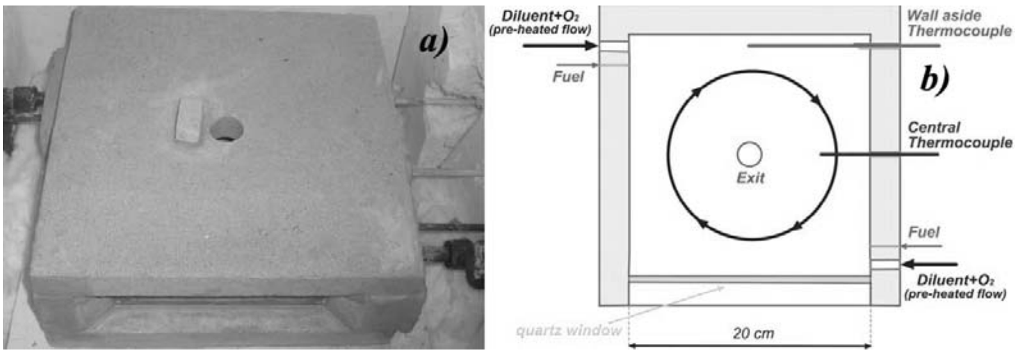

Figure 1: Photograph (a) and sketch (b) of the cyclonic combustion chamber

The combustor was operated at a nominal heat load of 0.5-5 kW with diluent (N_2) composition in both jets changed for each operative condition to regulate the total equivalence ratio whilst maintaining constant the oxidant/fuel momentum ratio for each heat load value.
The total dilution of the system is fixed to 90% and hence the nominal heat load changes with the average residence time of the burner.
The combustor has an optical access with a quartz window on the front side. The main pre-heated flow rate composed by nitrogen and oxygen and the fuel (propane diluted with nitrogen) are fed inside the combustion chamber from one side. Diametrically opposed the feeding configuration is reproduced, thus realizing a cyclonic flow field inside the combustion chamber. The combustion product gas exit is from the top side with a diameter of 0.025 m.
The oxidant jet diameter is 0.008 m while the fuel one is 0.0008 m thus achieving high disproportion between primary (oxygen and nitrogen) and fuel jet.
It may be noted that the oxidant jet is the dominant one as the momentum ratio variation of oxidant/fuel jets is 10 - 400 and it changes with the nominal heat load. In the non-premixed mode the oxidizer is supplied with a jet adjacent to the fuel injector. The location of fuel and air injection is reported in Fig. 1b. Oxidant jets are adjacent to the combustor wall (the distance between the wall and the oxidant jet is 0.02 m) and fuel is injected between the oxidant jet and centerline of the combustor (the distance of the fuel jet from the oxidant one is 0.025 m). The gases are expected to recirculate downwards along the combustor centerline thus aiding in entrainment of the fuel jet and to move along the length of the combustor adjacent to the combustor wall.
The combustion chamber is made of vermiculite that is an easily machinable refractory thus allowing for the realization of different geometries. It has excellent resistance to high temperatures and excellent insulating capacity to reduce heat losses from the combustor. Moreover ceramic fiber heaters surround the reactor

chamber to minimize heat fluxes from the combustor walls to the ambient. The combustor was operated using propane as the fuel and a mixture of propane and nitrogen was injected inside the chamber through the fuel injector at environmental temperature. A pre-heated mixture of oxygen and nitrogen (at $T=T_{in}$) was fed to the reactor and the operating pressure was 1 atm.

The combustion regimes that occur by varying the inlet preheating temperature of the oxidant (T_{in}) are explored for different C/O ratio (i.e. from fuel-lean to fuel-rich mixtures) for a fixed oxidant/fuel momentum ratio (J) and nominal heat load. J is the product between the mass flow rate and the jet inlet velocity.

Figure 2 presents the tangential velocity profiles for the configurations reported in Table 1 along the burner centerline (Z coordinate). A recirculation flow zone and a strong swirl covering the entire combustion chamber are observed inside the combustor for low residence times. Due to the higher oxidizer injection momentum than the fuel injection momentum (see Table 1) and due to the position of the exit on the top, the strong swirl is mainly induced by the high speed oxidizer jet, which induces entrainment and recirculation.

Moreover, because the fuel flows at the inlet is in the same direction as the oxidant stream, the high speed fuel jet also enhances the oxidant jet dominated flow field. As reflected by the profiles of Figure 2, stronger swirl is observed for configuration A1 and A2 with maximum tangential velocity of 22 and 8 m/s respectively. This is attributed to the higher oxidizer injection velocity. It can be observed that for the preheating and dilution effect of recirculated combustion products, high gas recirculation rates promote the attainment of high temperature low oxygen concentration condition required for the stable autoignition of MILD mixture (De Joannon et al., 2012). In this sense the average residence time inside the burner cannot be too low because mixing characteristic times have to be comparable with chemical ones that in MILD cases are longer than traditional combustion systems (Sabia et al., 2014).

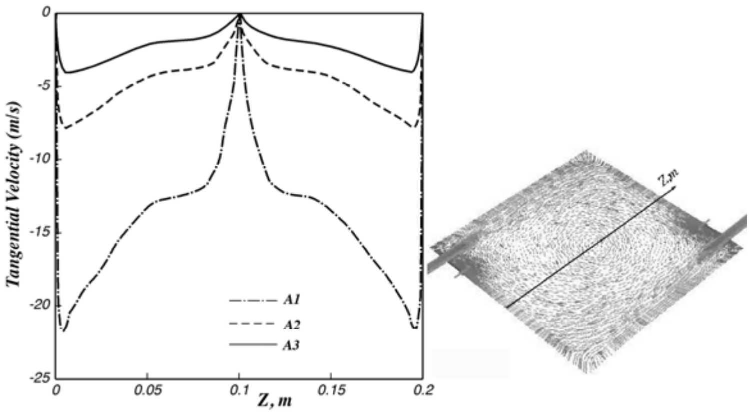

Figure 2: Tangential velocity along the burner centerline for the different configurations of Table 1

It is recognized that the flow field and mixing behaviour will be different under reacting flow conditions; however, comparative study of the non-reacting condition among various configurations provides important insights into the effect of oxidizer/fuel momentum flux ratio on the jet profile and gas recirculation characteristics.

In this sense, the configuration A2 (τ=0.5 s) was chosen as the reference one for this study because it represents a good trade-off between mixing time and recirculation pattern. Lower residence time values, in fact, involve high swirl with mixing times that are no more comparable with the chemical ones for stabilization of MILD/Flameless combustion conditions.

3. Experimental results

To evaluate the effect of mixture compositions and inlet temperatures on the combustion regimes established inside the chamber, the experimental tests were carried out varying the carbon/oxygen (C/O) ratio from 0.025 (fuel-lean conditions) up to 1 (fuel ultra-rich condition) and inlet oxidant temperatures (T_{in}) from 800 to 1000 K. At the same time, the mixture was diluted in nitrogen up to 90%. The average residence time (τ) was fixed to 0.5 s (configuration A3 as reported in Table 1). The inlet fuel injection velocity was fixed to 50 m/s and the oxidizer injection velocity was 38 m/s. The combustor was allowed to run for about 2 min in each experimental test before taking the data. Temperature profiles were measured inside the reactor by means of two movable thermocouples. The first one is placed aside the wall and the other at the centerline of the combustion chamber. Another thermocouple is placed at the outlet of the combustion chamber. A 16-Channel thermocouple module, supplied by National Instruments, was installed and interfaced to a PC to monitor and store temperature data. The evaluation of system behaviour was carried out on the systematic analysis of temperature profiles as a function of inlet pre-heating temperatures and mixture compositions (C/O ratio). First fundamental information on chemical evolution of the system came from the analysis of the shapes and trends of the axial temperature profiles measured in the different experimental conditions. More specifically, several main typologies of temperature profiles were recognized and associated to characteristic system behaviours. The temperature profiles reported in Figure 3 are exemplifications of the several reaction modes experimentally detected.

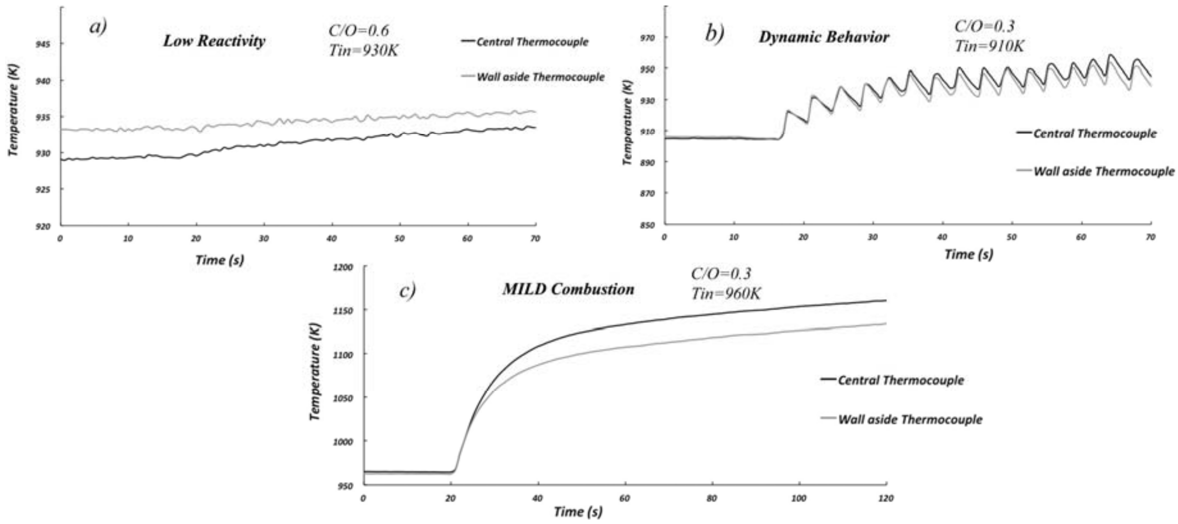

Figure 3: Temporal temperature profiles reported for different operative conditions

The profile corresponding to case 3-a) refers to a condition where the reactivity of the system is low and the maximum temperature increase ($\Delta T = T_{max} - T_{in}$) is lower than 10 K. Such a behaviour was associated to a "Low Reactivity" condition. The temperature profile (b) is representative by a dynamic phenomenology with ignition/extinction phenomena, characterized by temperature oscillations. Such behaviour was named "Dynamic Behavior" regime. These flames were unstable and had the marks of a non-premixed flame, which appeared blue in colour close to the jet exit turning yellow further downstream. Closer observation revealed some downstream propagation from an upstream location toward the fuel exit. The temperature profile (c) shows that T slowly increases reaching a maximum value. This profile corresponds to a "MILD Combustion" condition. In this case the thermal field in the combustion chamber is uniform and homogeneous (De Joannon et al., 2012).

On the basis of such a classification of temperature profiles, a map of behavior on a C/O–T_{in} plane was built up and reported in Figure 4 for N_2 dilution of 90 % for the configuration A2. In particular, it refers to a temperature range between 800 and 1,000 K and a C/O from 0.025 up to 1.

It is possible to distinguish several areas that were related to different typical temporal profiles. For low inlet temperatures (from temperatures up to about 890 K) the system does not ignite in the whole C/O range investigated.

The area is indicated as "No-Combustion" and temperature profiles acquired for such conditions show no temperature increase and remain equal to the inlet value. For temperature higher than 890 K and C/O>0.4 the mixtures ignite and then stabilize with a typical "Low reactivity" regime. The latter establishes for with a temperature gradient lower than 10 K with respect to the isothermal inlet condition. For C/O lower than 0.4 and 890<Tin<940 K the "Dynamic Behavior" regime is identified. For temperature higher than 940 K the system shows different phenomenologies. For high C/O, low reactivity is still observed. For C/O < 0.6 it is possible to recognize the "MILD combustion" regime. Increasing T_{in}, it enlarges up to cover the whole C/O range. In this regime the system approaches distributed combustion conditions and the temperatures in the combustion chamber become uniform. As the inlet temperature is increased the system reaches stable combustion conditions and in particular the maximum increase of temperature is observed around the stoichiometric condition.

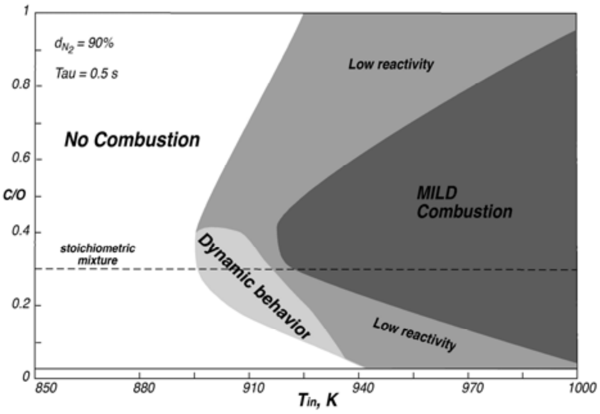

Figure 4: Experimental map of behaviour for mixtures diluted up to 90% in nitrogen.

4. Conclusions

The present study has investigated the global characteristics of MILD combustion of propane using a cyclonic pattern of fuel and oxidant streams in a laboratory-scale burner. The characteristics of the MILD regime have also been investigated. Specifically, the influences of inlet mixture composition (C/O) and inlet pre-heating temperature (T_{in}) have been examined for a specific configuration that was optimized on the basis of non-reactive simulations of mixing pattern.

Experiments have demonstrated that MILD combustion in the present combustor can be achieved for mixtures diluted in nitrogen up to 90 %. When MILD combustion is established flameless conditions was observed into the chamber. For the present non-premixed configuration flameless combustion can be established for inlet temperatures higher than 920 K. As the pre-heating temperature is decreased, the characteristic Damkohler number (Da) changes leading to unstable flames conditions. High scalar dissipation is essential at the vicinity of the jet to ensure the establishment of MILD combustion. This is equivalent to a short residence time in the vicinity of the jet exit. If this is not the case, flame propagation from regions further downstream can occur toward the exit plane.

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