

Experimental investigation of MILD/Flameless Combustion in a lab-scale cyclonic burner.

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Abstract

The present study investigates the characteristics of MILD/Flameless Combustion in a lab-scale burner. The main pre-heated flow rate composed by diluent and oxygen and the fuel are fed inside the combustion chamber from one side. Diametrically opposed the feeding configuration is reproduced, thus realizing a cyclonic flow field inside the reactor. The outlet is located on the top of the chamber. The system is provided with a quartz window and some thermocouples to measure the temperature profiles inside the burner. The oxidation process of C_3H_8/O_2 mixtures diluted in N_2 was studied varying external parameters of the system, namely inlet temperatures (up to 1300K) and equivalence ratio (lean to rich mixtures) to identify the combustion regimes in a non-premixed facility.

Introduction

Moderate or intense low oxygen dilution (MILD) combustion [1, 2] also called Flameless oxidation (FLOX) or HiTAC [3-4] 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 NO_x and CO emissions [5, 6]. 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 [7, 8]. 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 [9-11]. These conditions are reached by re-circulating the product gases into the incoming fresh reactants efficiently [12,13]. The gas recirculation serves two purposes: (i) raise the reactant temperature (heat recovery) (ii) reduce the oxygen concentration (dilution). In general, low oxygen concentration and moderate temperature levels lead to slower reaction rates and the Damköhler number approaches unity [14, 15]. 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 [16, 17]. Previous experimental studies on this subject [18] reported instantaneous measurements of temperature and OH concentration from a combustion chamber and concluded that, under flameless oxidation conditions, combustion takes place in a regime similar

to that of a well-stirred reactor, where no ignition and quenching events occur, which explains the low level of the combustion noise associated with this combustion regime. The measurements showed that the temperature rises smoothly and continuously along the furnace and that the OH is homogeneously distributed in the burnt side of the flame. Weber et al. [19] 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 O₂. Dally et al. [20] studied the effects of the fuel dilution with CO₂ and N₂, 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 NO_x emissions. Simultaneous imaging of OH and temperature confirmed that the reaction zone is rather distributed under flameless oxidation conditions. Szegő et al. [21] 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 et al. [22] 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. 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 [23]. Luckerath, R. et al., investigated flameless

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combustion in forward flow configuration in elevated pressure up to 20atm for application to gas turbine combustors [24]. In a novel design of Costa et al. that named FLOXCOM, flameless concept has been proposed for gas turbines by establishing large recirculation zone in the combustion chamber [25]. Lammel et al. developed a FLOX combustion at high power density and achieved low NO_x and CO levels [26]. Gupta et al. have demonstrated the concept of colorless distributed combustion for gas turbine application in a number of publications [27, 28].

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 present 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 key factors associated with such arrangement can be summarized as follows:

- (1) Longer residence time inside the combustor
- (2) Recirculation zones and turbulence generated internally by shear between differing fluid
- (3) 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.

Geometry of the burner and experimental setup

Fig. 1a shows a photograph of the combustor and Fig. 1b shows a sketch of the non-premixed configuration of the (20x20x5 cm³) laboratory-scale burner used in this study to investigate MILD/Flameless combustion for a C₃H₈/O₂/N₂ mixture.

The combustor was operated at a nominal heat load of 2 kW with diluents (N₂) 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 94% 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 20-1000 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.

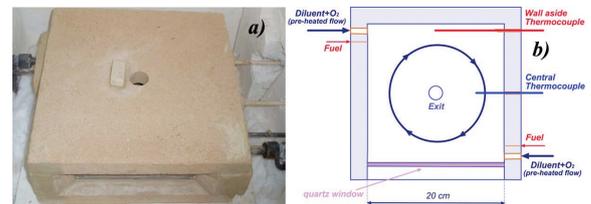


Figure 1. Photograph (a) and sketch (b) of the cyclonic combustion chamber

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 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 and a nominal heat load of 2 kW.

Numerical simulations were performed for this configuration to give properly indications concerning the design of the chamber (Fig. 2-a). Fig. 2-a shows the (mean) velocity vectors in the mid-plane of the combustor for the cold flow field for a fuel injection velocity of 50 m/s and an oxidizer velocity of 39 m/s. Simulations showed that the velocity decreased as we move towards the center of the combustor. Moreover, numerical simulations were performed also in reactive conditions for a selected operative condition ($T_{IN}=1025K$ and $C/O=0.3$). The computed mean

temperature profiles are shown in Fig. 2-b and 2-c and they were obtained by means of two different turbulence-chemistry interaction models. Fig. 2-b shows the thermal field obtained with the EDC model and it predicts a maximum increase of temperature of about 65K (for the same conditions the maximum increase of temperature observed experimentally was about 130 K). The computations were performed using the San Diego chemical kinetic mechanism.

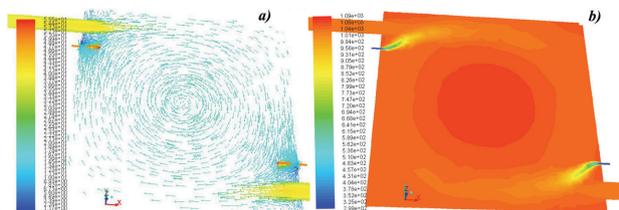


Figure 2. Numerical computation of velocity field for cold flow conditions (a); Numerical computation of the temperature profile for reactive conditions using the Eddy Dissipation Model Concept (b)

Experimental results

To evaluate the effect of mixture composition and inlet temperatures on the combustion regimes established inside the chamber, experimental tests were carried out varying the carbon/oxygen (C/O) ratio from 0.025 up to 1 and inlet temperatures (T_{in}) from 600 to 1000 °C. At the same time, the mixture was diluted in nitrogen up to 94%. The average residence time (τ) was fixed to 0.5 s. The inlet fuel injection velocity was fixed to 50 m/s and the oxidizer injection velocity varied from 30 m/s to 40 m/s as a function of the operating parameters (T_{in} , τ). 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. An evaluation of the system behavior 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 the chemical evolution of the system came from the analysis of the shapes and trends of the axial temperature profiles measured for the different experimental conditions. More specifically, several main typologies of temperature profiles were recognized and associated to characteristic system behavior. The temperature profiles reported in Fig. 3 are exemplifications of the several reaction modes experimentally detected.

The profile corresponding to case Fig. 3(a) refers to a condition where the reactivity of the system is slow and the maximum temperature increase ($\Delta T = T_{max} - T_{in}$) is lower than 10 K. Such a behavior was associated to a

“Low Reactivity” condition. The temperature profile Fig. 3(b) is representative of a dynamic phenomenology with ignition/extinction phenomena, characterized by temperature oscillations. Such a behaviour was named the “Unstable Flames” regime. These flames were unstable and had the marks of a non-premixed flame, which appeared blue in color close to the jet exit turning yellow further downstream. The temperature profile Fig. 3(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. In fact, the maximum temperature detected by the two thermocouples is almost the same (Fig. 3c).

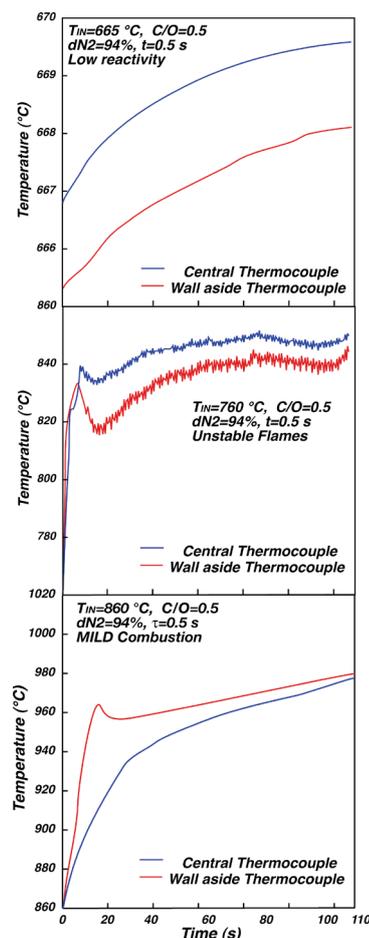


Figure 3. Temporal temperature profiles reported for different operative conditions

The different operative conditions led to different phenomenologies observed by means of the quartz windows located on the front of the burner.

It is possible to distinguish several phenomena as a function of the operative conditions as showed in Fig. 4. In particular the first and the second images are relative to “Unstable Flames” condition in which a non-premixed flame is observed inside the burner.

Furthermore “Low Reactivity” regime is observed in the third image for lower inlet temperatures and it appears

with a very low luminosity indicating that the oxidative activity is very small inside the combustor.

Finally, the fourth image is relative to “MILD” Combustion conditions. A Flameless mode is clearly obtained through the quartz window and the reaction zone becomes distributed.

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 Fig. 5 for N_2 dilution of 94% and $\tau=0.5$ s. In particular, it refers to a temperature range between 600 and 1000 °C and a C/O from 0.025 up to 1.

It is possible to distinguish several areas represented by different color that were related to different typical temporal profiles. For low inlet temperatures (from ambient temperature up to about 660 °C) 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.

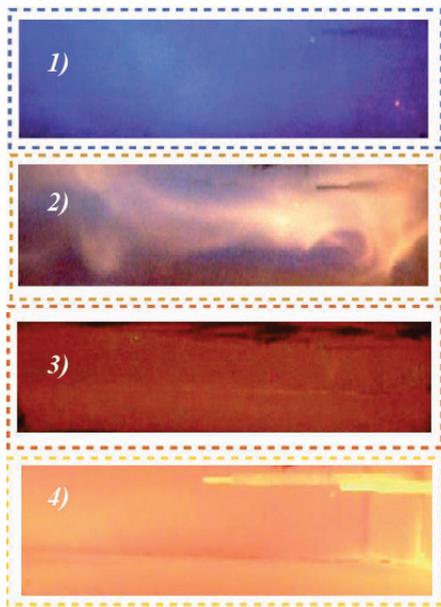


Figure 4. Images showing the in-furnace appearance of propane combustion for different operative conditions.

For temperature higher than 660 °C and lower than 725 °C the mixtures ignite and then stabilize with a typical “Low reactivity” regime. The latter establishes with a temperature gradient lower than 10 K with respect to the isothermal inlet condition. For temperatures higher than 725 °C the system shows different phenomena. For high C/O, low reactivity is still observed. For $0.35 < C/O < 0.7$ and $725 < T_{IN} < 800^\circ\text{C}$ the map shows “Unstable flames” behaviour. Below such a region, 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.

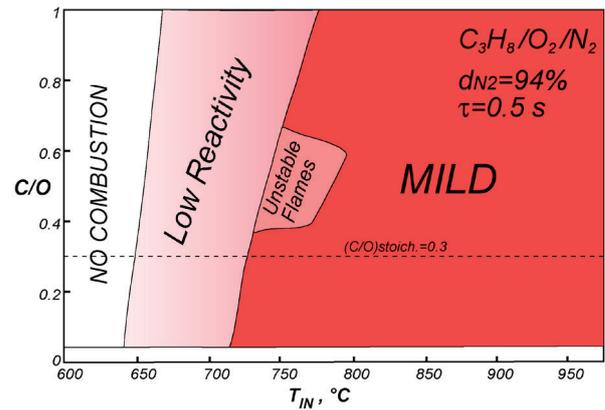


Figure 5. Experimental map of behaviour for mixtures diluted up to 94% in nitrogen.

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.

Experiments have demonstrated that MILD combustion in the present combustor can be achieved for mixtures diluted in nitrogen up to 94%. When MILD combustion is established flameless conditions was observed into the chamber. For the present non-premixed configuration flameless combustion can be established for $T_{IN} > 750^\circ\text{C}$ for each value of C/O ratio. 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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