PERFORMANCE OF A CYCLONIC BURNER FOR TECHNOLOGIES WITH HIGH LEVEL OF DILUTION AND INTERNAL RECIRCULATION


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Abstract
The present study describes the performance and stability characteristics of lab-scale burner with high level of dilution and strong internal gas recirculation. A cyclonic flow is realized inside the combustor and it could represent a very effective system in realizing mixing processes in very short time and small size while allowing for a reasonable long residence time for the development of combustion reactions. The stabilization process of MILD combustion for propane/oxygen/nitrogen mixtures was studied varying the system external parameters, namely inlet temperature \( T_{\text{in}} \), equivalence ratio \( \Phi \) (lean to reach mixtures) and inlet oxygen percentages \( X_{O_2} \) (from 8% to 18%). The process features were characterized by means of temperature measurements inside the chamber, a quartz window and gas sampling analysis at the stack of the burner. Different combustion regimes were achieved and characterized: low reactivity, dynamic regimes and MILD Combustion. The last regime showed a uniform temperature distribution within the chamber with a stable volumetric combustion characteristics and very low pollutant emissions in the exhaust gases. MILD regimes were established for inlet preheating temperature higher than about 900 K for each mixture composition. The main contributing factor for combustion stability was found to be pronounced internal recirculation. Moreover, once achieved MILD operating condition, it was possible to maintain this regime by decreasing the preheating temperature of the reactants, thus identifying a hysteresis behavior. As matter of fact, for the stoichiometric condition the present burner configuration proved to operate without the need for external preheating, and achieved a high degree of temperature uniformity with low emissions. Such results suggest that the advantages of MILD can be partly achieved without the preheating of combustion air and with moderate flue gas recirculation. This enables a simplified and more economical construction, applicable for instance in small-scale boilers and CHP systems.
1. INTRODUCTION
MILD combustion [1] also called FLameless OXidation (FLOX®) or High Temperature Air Combustion (HiTAC) [2, 3] is a combustion regime characterized by fuel oxidation in an atmosphere with relatively low oxygen concentration and high inlet temperatures featuring 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 NOx and CO emissions [4]. In MILD combustion, the inlet temperature of reactants is higher than the autoignition one and, at the same time, the maximum temperature increase due to oxidation reactions remains lower than the mixture auto-ignition temperature [5] because of high dilution levels.

Existing industrial MILD Combustion systems usually reach the autoignition conditions by re-circulating efficiently the product gases into the incoming fresh reactants [6]. The design of MILD systems has been the subject of several studies [2]. Despite considerable efforts to extend the MILD combustion technology to other heat and power systems, such as boilers and gas turbines [7], critical operational parameters still require further investigation.

In this context numerous studies have shown that the stabilization and optimization of MILD combustion technology depends on a range of external operating parameters [8, 9]. These include the fuel type and composition, local oxygen concentration, the initial preheating temperature [9]. Flameless oxidation has been studied in various furnace systems differing in thermal power output and design [9] and [10]. In this context the present work investigates the performance and stability characteristics of a novel Laboratory Unit CYclonic (LUCY) burner operating under MILD combustion conditions.

2. EXPERIMENTAL SETUP
Fig. 1 shows a picture (a) and a sketch of the section (b) of the non-premixed configuration of the (20x20x5 cm³) LUCY burner used to investigate the MILD combustion process [11].

![Figure 1. Photograph (a) and sketch of the section (b) of the cyclonic combustion chamber](image)
The combustor is designed to operate in the range of nominal thermal power between 0.5 and 5 kW for the operating conditions reported in this manuscript. Two pairs of oxidant/fuel jets feed a 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 diluent) is fed inside the combustion chamber parallel to the fuel jet. The feeding configuration is reported in Fig. 1b.

The exhaust is sampled by a GC analyzer, averaged over a 5-min duration for each operating condition studied. NO and NO\textsubscript{2} (NO\textsubscript{x}) are measured through an ABB flue gas analyzer. The high gas recirculation rates promote the attainment of high temperature low oxygen concentration condition required for the stable autoignition of MILD mixture [3].

3. RESULTS AND DISCUSSION
Experimental tests were carried out for C\textsubscript{3}H\textsubscript{8}/O\textsubscript{2} mixtures, at environmental pressure and residence time of 0.5 s, diluted in N\textsubscript{2} varying the external operating parameters of the system. The external parameters such as the inlet temperatures of the main flow (T\textsubscript{in}), the initial oxygen mole fraction (X\textsubscript{O\textsubscript{2}}), and the overall equivalence ratio (\Phi) were varied parametrically in order to investigate the combustion behavior of the system.

During the experimental campaign two different operational procedures were used: the “standard” procedure, performed by increasing the inlet temperature of the oxidizer (by means of external preheating systems) from a chemically frozen state, and the “inverse” mode without external preheating was performed from burnt state and decreasing the inlet temperature of the oxidizer in order to investigate the occurring of extinction conditions and the sustainability of the process.

3.1 Effect of inlet preheating temperature (T\textsubscript{in})
Figs. 2a reports the measured maximum values of temperature and \Delta T in the mid-plane of the chamber for a stoichiometric condition and oxygen percentage equal to 10\% as a function of the inlet oxidizer flow temperature (T\textsubscript{in}).

![Figure 2](image-url)

**Figure 2.** Maximum temperature and \Delta T profiles (a), CO, NO\textsubscript{x} emissions (b) for both the operational procedures as a function of T\textsubscript{in}
The open symbols represent the standard operational mode, i.e. with the external preheating of the oxidizer, while the closed ones are relative to inverse operational modes. Figure 2a is relative to a standard operational mode, i.e. with the external preheating of the oxidizer, and to an inverse procedure where the system evolves on the equilibrium branch by decreasing the $T_{in}$ values.

In particular, as showed in Fig. 2a, the minimum preheating temperature that led to reactive conditions is about 930 K for the standard procedure showing a transition between the chemically frozen and the fully burning states. In this case the transition between the low reactivity and high reactivity branch is characterized by instability behaviors where unstable diffusion flames occurs during the time before the stabilization of MILD combustion conditions with homogeneous thermal fields.

Figs. 2b reports the carbon monoxide and nitrogen oxides emissions corrected to 15% of oxygen level at the exhaust as a function of the inlet oxidizer flow temperature ($T_{in}$).

As reported in Fig. 2b, for the inverse procedure, NO$_x$ emissions increase with $T_{in}$ but they are always lower than 8 ppm. In the range of $600<T_{in}<900$ K, CO production is around 250 ppm, increasing for $T_{in}$ values lower than 600 K. This behavior is ascribable to a lowering of the system reactivity.

### 3.2 Effect of equivalence ratio ($\Phi$)

Figure 3a and 3b shows the effect of the equivalence ratio on $T_{max}$ and $\Delta T$ profiles, CO and NO$_x$ emissions respectively at $T_{in} = 920$ K and for $X_{O_2}=0.1$. Maximum value of temperature increase $\Delta T$ is about 500 K, corresponding to a maximum temperature $T_{max} = 1400$ K and it is obtained for an equivalence ratio around the stoichiometric value, as expected. Figure 3b shows the effect of the equivalence ratio on CO and NO$_x$ emissions at $T_{in} = 900$ K and $X_{O_2}=0.1$.

NO$_x$ emissions values vary in the range $0<NO_x<7$ ppm for equivalence ratios varying from $\Phi=0.3$ to $\Phi=2.3$. On the other hand CO emissions are close to 0 ppm at $\Phi<0.3$ and increase until 11000 ppm to $\Phi=2.0$. Highest values of NO$_x$ emissions are measured between the equivalence ratio $\Phi=0.6$ and the stoichiometric value, while CO production is very low in the range $0.3<\Phi<1$, about close to zero for equivalence ratio values lower than $\Phi=1$ and it increases for equivalence ratio values above the stoichiometric one.

Therefore, NO$_x$ and CO emissions are very low for a wide range of equivalence ratio values (the best operational windows seems to be in the range $0.7<\Phi<0.9$).
3.3 Effect of initial oxygen level ($X_{O_2}$)

Figure 4a and 4b shows $T_{\text{max}}$ and $\Delta T$ profiles, CO and NO$_x$ emissions for different values of inlet oxygen percentage $X_{O_2}$.

Figure 4. Maximum temperature and $\Delta T$ profiles, CO, NO$_x$ emissions for both the operational procedures as a function of $X_{O_2}$

$T_{\text{max}}$ increases from a value of 1600K to 1300K increasing $X_{O_2}$ from 10% up to 18% (figure 4a). NO$_x$ concentration (figure 4b) increases for higher $X_{O_2}$ values from 7 ppm to 18 ppm and hence the burner performances are lowered in terms of emissions (the system does not satisfy the one-digit requirement for $X_{O_2} > 12\%$). Moreover, CO concentration levels decreases from 290 ppm to a value close to zero at 16 $O_2\%$, due to the higher reactivity for temperatures higher than 1100 K for $X_{O_2} > 0.1$. Similar trends are achieved for both operational modes.

4. CONCLUSIONS

The operational characteristics of LUCY burner were investigated through temperature and exhaust gas emission measurements. Results of the influence of equivalence ratio, oxidizer preheating temperature and initial oxygen level on
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system performance were presented. The key conclusions drawn from this study are: MILD Combustion was achieved for a wide range of external parameters with reduced combustion peak temperatures and very low NO\textsubscript{x} and CO emissions. The occurrence of hysteresis behavior permits to stabilize MILD combustion regimes not achievable from frozen conditions. Flexibility, stability and efficiency in a wide range of operative conditions make the LUCY burner a very interesting device in view of power generation applications like small-scale boilers and CHP systems.

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