An Experimental Study on MILD combustion of alcohols in a Cyclonic burner

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Introduction

Moderate or intense low-oxygen dilution (MILD) combustion is a very promising technology to abate CO, NO_x and other emissions while maintaining stable combustion and high thermal efficiency [1]. Reactant temperatures above the self-ignition temperature and very low local oxygen levels [2] lead to a moderate temperature rise across the reaction zone, suppressing the formation of NOx, CO and soot significantly [3]. These features of MILD combustion are favored in a wide range of industrial combustion systems.
Numerous studies have shown that the stabilization and optimization of MILD combustion with gaseous fuels depends on a range of operating parameters [4].
Most previous studies [5, 6] on gaseous fuels use hydrogen, methane and other short-chain alkanes. Whilst is it true that previous studies have shown that MILD combustion is not heavily dependent on the type of fuel with hydrogen addition [7] the literature is very sparse on oxygenated or long-chain hydrocarbons.
Hence, ethanol, is here considered to investigate alcohol MILD Combustion in the current study. Considerable differences in performances for various liquid fuels under MILD combustion conditions have been reported in the literature [8, 9]. In particular, higher emissions were found for some fuels, such as heavy fuel oil and biodiesel fuel. The parameters controlling the stabilization and optimization of MILD combustion of liquid fuels are not fully understood. In addition, a better understanding of the impact of mixing on MILD combustion of liquid fuels is required to extend MILD combustion technology to industrial combustors operating with liquid fuels.
In this study experiments are conducted to understand the impact of various parameters on the stabilization and optimization of MILD combustion with prevaporized liquid fuels burning in a cyclonic-flow MILD combustor. The cyclone configuration applied in the present study has been proven to be effective in the establishment of MILD combustion of gaseous fuel and is well described in previous publications [10].
The prevaporization of liquid fuels allows the current study to ignore the complexity of spray development and focus on the impact of chemical kinetics, mixing, fuel type and heat transfer. The parameters investigated in the present study are the equivalence ratio and the nominal thermal power. Measurements and observations regarding the emissions, temperatures and the combustion stability under different operating conditions are presented and discussed.

Experimental methods

The experimental campaign was carried out in the Laboratory Unit CYclonic (LUCY) burner reported previous publications of this research group [11, 12]. It consists of an alumina prismatic chamber (20x20x5 cm^3) externally covered with a heat-insulating material. It is located inside an AISI 310s stainless flanged case that can be easily opened for inspection operations. Several shielded thermocouples (type N) are used to monitor the combustion process. The flow injection configurations and the position of the exit (in the center of the bottom face of the chamber) induce a toroidal flow-field. The oxidizer flows are preheated by means of two heat exchangers

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to the desired inlet temperature (T_{in}) before entering the reactor. Fuel is fed into the combustion chamber at environmental temperature. The burner is located within electrical ceramic fiber heaters to minimize heat exchange towards the surroundings. The mixture inlet equivalence ratio can be easily changed (from ultra-lean to very rich conditions). The exhaust gases are sampled from the central outlet by a cooled probe and are analyzed through a portable Agilent micro-GC analyzer that allows to measure O_2, CO, CO_2, C2-species, H_2, N_2. NO and NO_2 are measured by means of both a flue gas analyzer (TESTO 350) and a dedicated ABB analyzer. NOx concentrations are normalized to 15% O_2.

Results

The experimental campaign was carried out by operating LUCY burner with ethanol/air mixtures at atmospheric pressure. The performance of the cyclonic burner has been characterized in terms of system working temperatures (T) and pollutant emissions (CO, NO_x) for several equivalence ratio (Φ) values of the mixture, in accordance with previous works [11]. Results were obtained at environmental inlet temperature. Experimental tests were realized for a fixed value of the nominal thermal power P=5 kW, as a reference value for efficient working conditions identified in previous works with several hydrocarbon fuels [12, 13]. Figure 1 shows the mean system working temperature (T) and the maximum one (T_{MAX}) by varying the equivalence ratio. As it is possible to note, the sustainability of the combustion process is ensured at 5 kW when the working temperature is higher than about 1100 K in the whole range of inlet preheating temperature and equivalence ratio here investigated. Working temperatures lower than 1100 K (dashed lines) should be avoided because of the occurrence of extinction phenomena.
Noticeably, such threshold is similar in the case of methane-air combustion and therefore it could be stated that this behavior is related to the switch on high temperature kinetic branching of hydrocarbons chemistry.

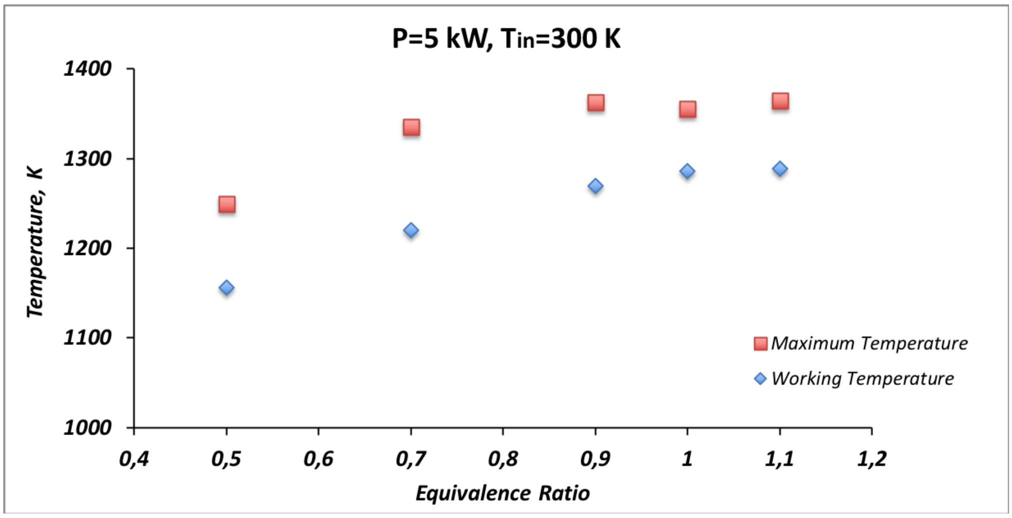

Fig. 1 Working and Maximum temperatures for ethanol-air mixtures as a function of Φ at P = 5 kW.

Thus, Figure 1 shows that at environmental conditions (T_{in} = 300 K) a stable oxidation process has been obtained in the range 0.5 < Φ < 1.1. The mean working temperature inside the chamber increases toward the stoichiometric value and it is kept to almost constant values. It passes from 1150 K at Φ=0.5 to 1300 K at Φ=1. Maximum temperature follows the same trend.
Figure 2 reports CO and NO_x emissions at the exhaust for the same condition (P = 5 kW) by varying the equivalence ratio of the mixture, for ambient inlet temperatures. It shows that the

NOx emission levels are decreased toward stoichiometric/rich mixture compositions. In particular NOx emissions ranged from 12 ppm under lean conditions for to 4 ppm at Φ = 1.1.
It is possible to observe that NOx emissions significantly decrease moving toward stoichiometric/fuel rich conditions for the case here investigated. Figure 2 shows that very lean ethanol-air flames emit high levels of NOx. Thus, the stoichiometry is seen to have a major impact on the NOx formation. Such results are in accordance with several literature works for alcohols-air combustion in model combustors [14-16].
On the other hand, CO emissions follow an opposite trend with respect to NOx ones. They increase to values higher than 100 ppm for Φ>0.95. They are very low for fuel-lean mixtures.
It is worth to note that the minimum joint emission levels are reached in the operational windows around Φ=0.9 where both the CO and NOx emissions are minimized.
The results reported in Figure 2 show that high values of the inlet equivalence ratio allow to lowering NOx emissions at 4 ppm, while the opposite effect is obtained with respect to CO ones.

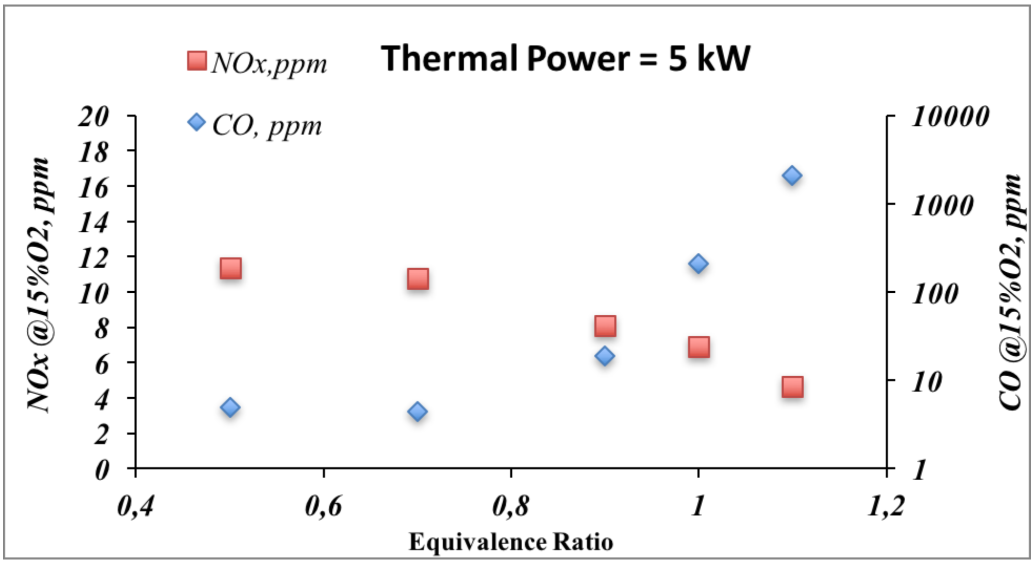

Fig. 2 CO and NOx emissions for ethanol-air mixtures as a function of Φ for several at P = 5 kW.

The stabilization mechanism related to burned gas recirculation in the combustion chamber is ensured when reactor temperature is highly enough to sustain high-temperature chain-branching reactions for ethanol combustion.

Conclusions

MILD combustion of prevaporized ethanol, was successfully established in a MILD combustor with a cyclonic-flow configuration over a broad range of equivalence ratios.
The main operational characteristics of ethanol/air combustion in a cyclonic burner were investigated through temperature and exhaust gas emission measurements. Results of the influence equivalence ratio on system performance were presented. The appearance of flameless combustion conditions and the temperature values were used to investigate the stability characteristics.
In particular, MILD Combustion regime was achieved for a wide range of external parameters with reduced combustion peak temperatures and very low CO and NOx emissions in a wide operational window. Remarkable performance in terms of stabilization of the oxidation process and low pollutants has been verified in a wide range of operating conditions.
The sustainability of the combustion process with ethanol/air without external preheating is ensured when the working temperature is higher than about 1100 K for each condition investigated in this manuscript.

The critical equivalence ratio above which there is a decrease in NOx emissions was found to be around the stoichiometric value ($\Phi = 1$).
CO emissions follow an opposite trend and they showed a steep increase for equivalence ratio higher than 0.9, passing from 4 to 1300 ppm for rich mixtures.
The joint regime of low CO and NOx emissions is located at $\Phi = 0.9$ where both the CO and NOx emissions are in the single-digit limit.

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