Available online at www.sciencedirect.com

ScienceDirect

Energy Procedia 66 (2015) 141 – 144

Energy Procedia

The 12th International Conference on Combustion & Energy Utilisation – 12ICCEU

Development of a novel cyclonic flow combustion chamber for achieving MILD/Flameless Combustion

Giancarlo Sorrentino [a]*, Pino Sabia [b], Mara de Joannon [b], Raffaele Ragucci [b], Antonio Cavaliere [a], Ugur Göktolga [c], Jeroen van Oijen [c], Philip de Goey [c]

[a] *D.I.C.M.A.P.I, Università degli Studi di Napoli Federico II, P.le V. Tecchio 80, 80125 Napoli, Italy*
[b] *Istituto di Ricerche sulla Combustione, CNR, P.le V. Tecchio 80, 80125 Napoli, Italy*
[c] *Combustion Technology, Mechanical Engineering, Eindhoven University of Technology, 5600 MB Eindhoven, The Netherlands*

Abstract

The present study investigates the characteristics of MILD/Flameless Combustion in a prismatic (20x20x5 cm^3) laboratory-scale burner. The main pre-heated flow rate composed by diluent and oxygen and the fuel (at environmental temperature) 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 1200K) and equivalence ratio (lean to reach mixtures) to identify the combustion regimes in a non-premixed facility. A numerical simulation of fluid dynamics in the chamber was performed to give proper indications concerning the design of the chamber.

Peer-review under responsibility of the Engineering Department, Lancaster University

Keywords: MILD Combustion; Cyclone combustor; Large residence times, Numerical simulation

* Corresponding author. Tel.: +39-081-2391709

E-mail address: g.sorrentino@unina.it

1. Introduction

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, distributed reaction zone, relatively uniform temperatures, no visible flame, low noise, negligible soot formation, and very low NO*x* and CO emissions. 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 remains lower than mixture auto-ignition temperature [1]. Weber et al. [2] reported detailed measurements of velocity, temperature, gas species composition and radiation from flameless combustion

Peer-review under responsibility of the Engineering Department, Lancaster University
doi:10.1016/j.egypro.2015.02.079

in a natural gas-fired semi-industrial furnace, and concluded that the furnace was operating under conditions resembling a well-stirred reactor. Szegö et al. [3] reported measurements of temperature and flue-gas composition from a MILD laboratory combustion furnace. More recently, Mi et al. [4] 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. In spite of a number of activities for industrial furnaces, the application of flameless combustion in gas-turbine combustion systems is in the preliminary phase [5]. Luckerath et al. investigated flameless combustion in forward flow configuration in elevated pressure up to 20atm for application to gas turbine combustors [6]. Gupta et al. demonstrated the concept of colorless distributed combustion for gas turbine application [7]. Despite that, the amount of detailed experimental data under flameless conditions is relatively scarce. The present investigation aims to extend the present database on MILD combustion and to improve the understanding of sub-processes. To this end, experiments have been performed in a propane-fired small-scale cyclone combustor. The cyclonic flow pattern inside the chamber provides large residence times and better mixing between the reactants. Focus here is on achieving flameless and distributed combustion conditions. Sustainability of MILD combustion for nitrogen dilution is observed under several operating conditions.

2. Geometry of the combustor and numerical computation

Fig. 1a shows a photograph and Fig. 1b shows a sketch of the non-premixed configuration of the (20x20x5 cm^3) laboratory-scale burner used to investigate MILD/Flameless combustion for a $C_3H_8/O_2/N_2$ mixture. The combustor is designed to operate at a nominal heat load of 2 kW. It has optical access through a quartz window on the front side. The main pre-heated flow rate composed of 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.

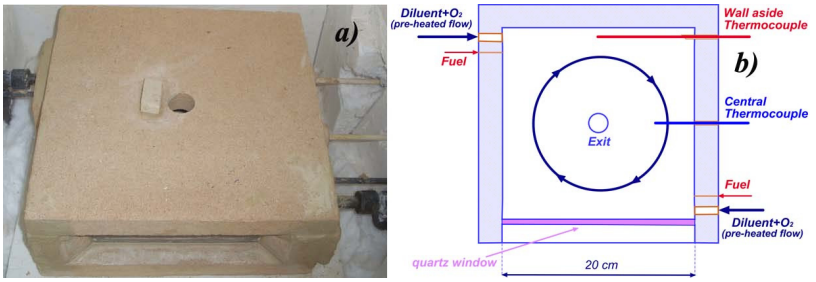

Figure 1. Photograph (a) and sketch (b) of the cyclonic combustion chamber

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 shown in Fig. 1b. Fuel jets are adjacent to the combustor wall and oxidizer is injected between the fuel jet and centerline of the combustor. The gases are expected to recirculate downwards along the combustor centerline. The chamber is made of vermiculite. The combustor was operated using C_3H_8/N_2 as the fuel at environmental temperature. A pre-heated O_2/N_2 mixture was fed to the reactor and the operating pressure was 1 atm. 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 for the cold flow field (V_{fuel}=50 m/s and $V_{oxidizer}$=39 m/s). Moreover, simulations were performed also in reactive conditions for a selected condition (T_{in}=1025K and C/O=0.3). The computed temperature profiles are shown in Fig. 2-b and 2-c and they were obtained by means of two different turbulence-chemistry interaction models using San Diego chemical mechanism. 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). At the same time the chemical equilibrium approach results were reported in Fig. 2-c and in this case the maximum increase of temperature is higher than EDC.

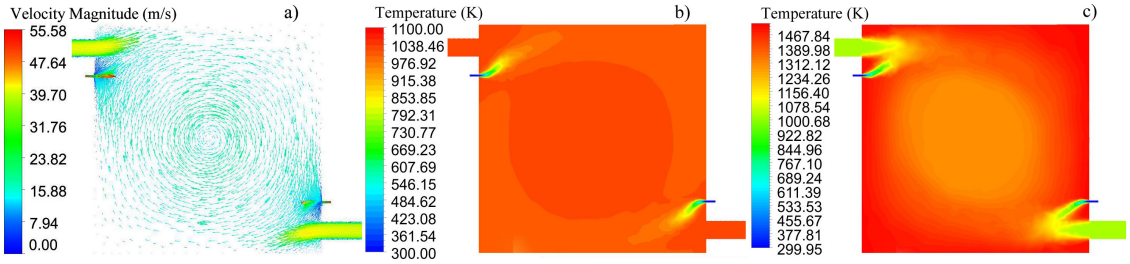

Figure 2. Numerical computation of velocity field for cold flow conditions (a); Numerical computation of the temperature profile for reactive conditions using the EDC (b) and chemical equilibrium approach (c)

3. Experimental results

To evaluate the effect of mixture composition and inlet temperatures on the combustion regimes, experimental tests were carried out varying the 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. Temperature profiles were measured inside the reactor by means of two 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. 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). 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.

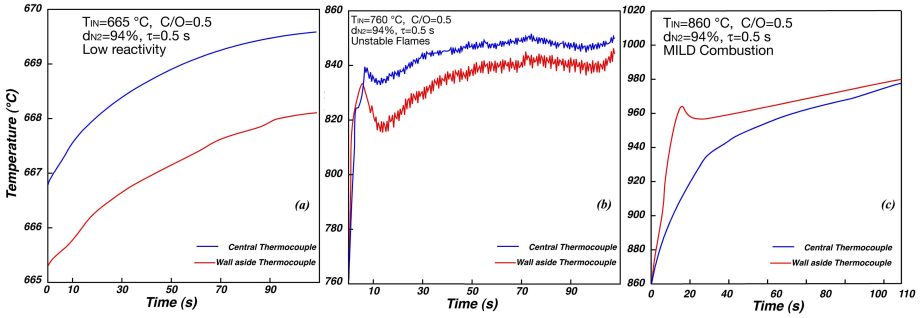

Figure 3. Temporal temperature profiles reported for different operative conditions

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 is lower than 10 K. Such a case was named "Low Reactivity. 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. 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 (Fig. 3c). 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. 4 for N_2 dilution of 94% and τ=0.5 s. 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”.

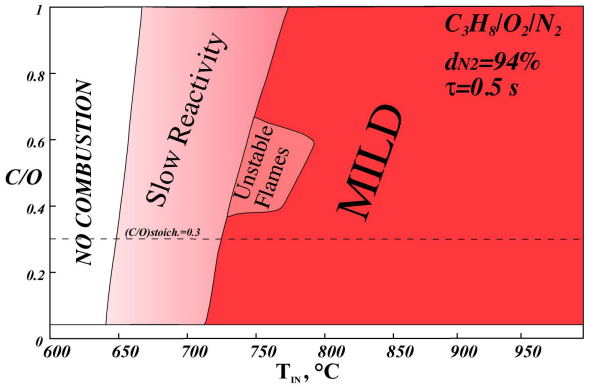

Figure 4. Experimental map of behaviour for mixtures diluted up to 94% in nitrogen.

For temperature higher than 660 °C and lower than 725 °C the mixtures ignite and then stabilize with a typical “slow reactivity” regime. For temperatures higher than 725 °C the system shows different phenomena. For high C/O, slow reactivity is still observed. For $0.35 < C/O < 0.7$ and $725 < T_{in} < 800$°C the map shows unstable flame 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 become uniform.

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. 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. The experimental results were compared with the computational ones using EDC and chemical equilibrium approaches. The former showed an under-prediction of temperatures for the analyzed operative condition. Such results were thought to stem from the turbulence-chemistry interaction model.

References

[1] A. Cavaliere, M. de Joannon, Mild combustion, Prog. Energy Combust. 30 (2004) 329-366.

[2] R. Weber, S. Orsino, N. Lallemant, A. Verlaan, Combustion of natural gas with high-temperature air and large quantities of flue gas, Proc. Combust. Inst. 28 (2000) 1315-1321.

[3] G.G. Szegö, B.B. Dally, G.J. Nathan, Scaling of NOx emissions from a laboratory scale mild combustion furnace, Combust. Flame 154 (2008) 281-295.

[4] J. Mi, P. Li, B.B. Dally, R.A. Craig, Importance of initial momentum rate and air-fuel premixing on moderate or intense low oxygen dilution (MILD) combustion in a recuperative furnace, Energy Fuels 23 (2009) 5349-5356.

[5] Li P, Mi J, Dally B, Wang F, Wang L, Liu Z, Chen S and Zheng C (2011) Progress and Recent Trend in Mild Combustion. SCIENCE CHINA Technological Sciences. 54: 255-269.

[6] Luckerath R, Meier W and Aigner M (2008) Flox Combustion at High Pressure with Different Fuel Compositions. Journal of Engineering for Gas Turbines and Power. 130: 011505.

[7] Khalil AEE and Gupta AK (2011) Distributed Swirl Combustion for Gas Turbine Application. Applied Energy. 88: 4898-4907.