Experimental and numerical investigation of a 20 kW flameless burner fired by natural gas

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Introduction

MILD combustion (Moderate or Intense Low-Oxygen Combustion) [3], known as Flameless Oxidation, is a very high efficiency novel combustion technology, successfully applied on industrial furnaces to have very low pollutant emissions, stable working conditions and significant energy savings. The technology needs the reactants to be preheated above their self-ignition temperature and enough inert combustion products to be entrained in the reaction region, in order to dilute both reactants and flame. The system is characterized by a more uniform temperature field than in traditional non-premixed combustion, and by the absence of high temperature peaks, thus reducing NOx and CO formation. This combustion technique is particularly interested for low LHV fuels, such as biogas, coke oven gas (COG), syngas, allowing fuel flexibility.

Preliminary experimental tests have been conducted on a 20 kW nominal power flameless unit (Figure 1) with integrated metallic finned heat exchanger to extract energy from the hot gases to pre-heat the combustion air. It is able to reproduce some of the main features of industrial furnaces (injection geometry, air excess, fuel and air velocity, variable load). Both the gas injections (air and fuel) and the outlet (hot gases) are placed in the bottom part of the chamber, therefore the combustion products can recirculate within it and dilute the reactants. The plant is provided by an air cooling system, whose dimensions are fixed, while the mass flow rate can be changed. In this way the combustion chamber is able to work at different working conditions, simulating an industrial load within it.

On each side of the combustion chamber there is a slot for measurements. It can be equipped with a quartz window allowing optical access to the chamber for OH* chemiluminescence imaging or it can be closed allowing thermocouples access to measure wall temperature profiles. In the first case, the window can be fixed in the upper or in the lower side of the slot, allowing a complete access to the reactive zone.

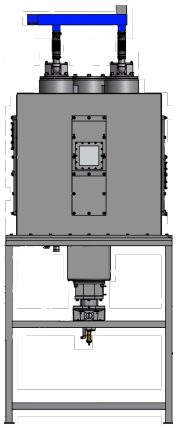

Figure 1: Flameless burner

Experimental results

The 20 kW flameless burner has been preliminary tested to burn in flame and flameless mode natural gas. The air flow rate has been set in order to have 16% excess air into the furnace. Different powers in the range 15-25 kW and different set-point temperatures (temperature of the combustion chamber in the upper part), in the range 900-970 °C, have been tested and a steady-state has been correctly reached. Furthermore, also the air cooling flow rate values have been investigated in order to limit the cooling air-outlet temperature and to maintain the set-point within the expected range, as simulating an industrial load inside the combustion chamber. Several parameters have been detected during test-

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ing, such as the four cooling air-outlet exit temperatures, the wall temperatures in three positions on one side of the combustion chamber, the temperature and composition of the exhaust gases. In particular, Figure 2 provides the evolution on time of NOx concentration in the flue gases, highlighting the sudden drop, up to few ppm, associated to the switch from flame to flameless operation. Figure 3 shows the evolution on time of the wall temperatures measured on different levels of the combustion chamber. After switching to flameless operation, they maintain a quasi constant value, proving that the temperature is quasi homogeneous adopting this combustion technique.

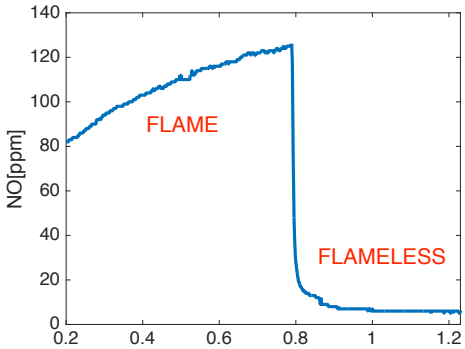

Figure 2: Time evolution of exhaust gases NOx concentration. The sudden drop of NOx concentration is associated to the switch from flame to flameless operation.

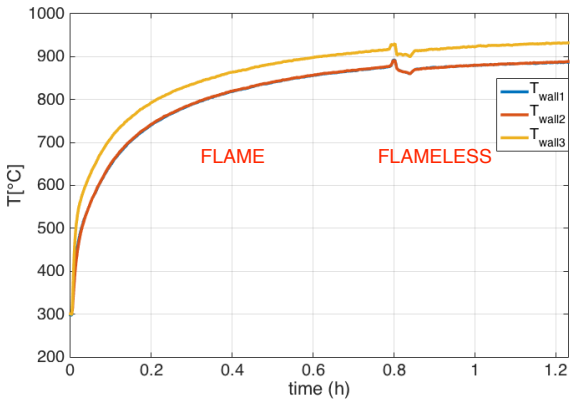

Figure 3: Time evolution of the wall temperatures on different levels. They maintain a quasi constant value after switching to flameless operation.

Numerical Validation

Considering flameless combustion is characterized by a very strong interaction between mixing and chemistry, indicated by characteristic Damkohler number approaching unity, a finite-rate approach is needed simulating it. Indeed, a first numerical validation of the experiments has been conducted using the edcSMOKE solver of OpenFOAM, capable of using detailed chemical reaction mechanisms. It is based on the EDC combustion model, in order to manage the interaction between chemistry and turbulence and coupled with the OpenSMOKE library [1] to manage large kinetic schemes. The interactions between edcSMOKE, OpenSMOKE library and OpenFOAM software are of paramount importance. The kinetic mechanism is interpreted by the solver, that transforms the CHEMKIN format in the XML format, used by OpenSMOKE. At the same time, all the other fields (velocities, enthalpy and mass balance) are generated and the code starts to solve all the variables. Once these variables are established, the problem is solved by coupling edcSMOKE with the OpenFOAM framework. In particular the detailed kinetic scheme GRI 3.0 [2] (53 species, 325 reactions) has been chosen. The meshing process of the combustion chamber has been performed with the snappyHexMesh OpenFOAM utility, which creates an unstructured grid.

Acknowledgments

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