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Research Paper

Numerical study of oxy-flame characteristics in a burner with three separated jets

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HIGHLIGHTS

- Numerical computations of diffusion oxy-methane flame in a triple jet burner.
- The longitudinal, transverse velocities and maximum temperature increases with the decreased of the equivalence ratio.
- The turbulence intensity increases promotes a better mixing quality.

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ABSTRACT

Oxy-flames from burners with separated jets present attractive perspectives because the separation of reactants generates a better thermal efficiency and reduction of pollutant emissions. The principal idea is to confine the fuel jet by oxygen jets to favor the mixing in order to improve the flame stability.

This paper investigates the effect of equivalence ratio on characteristics of a non-premixed oxy-methane flame from a burner with separated jets. The burner of 25 kW power is composed with three aligned jets, one central methane jet surrounded by two oxygen jets. The numerical simulation is carried out using Reynolds Average Navier-Stokes (RANS) technique with Realizable k-ε as a turbulence closure model. The eddy dissipation model is applied to take into account the turbulence-reaction interactions. The study is performed with different global equivalence ratios (0.7, 0.8 and 1). The validation of the numerical tools is done by comparison with experimental data of the stochiometric regime ($\Phi = 1$). The two lean regimes of $\Phi = 0.7$ and 0.8 are investigated only by calculations. The obtained results of the computational models with the experimental data are performed, and a good agreement is found. The velocity fields with different equivalence ratio are presented. It yields to increase of longitudinal and transverse velocity, promotes the fluctuation in interaction zone between fuel and oxygen also a better mixing quality and a decrease of the size of the recirculation zone.

1. Introduction

The evolution of pollution standards associated to strict regulations which motivate the fall of fuel consumption, lead to optimize combustion plants performances. Large reductions of nitric oxide emissions have been successfully achieved in the past, by using either low NOx technologies of air burner or oxy-combustion systems. Numerous studies have particularly shown that the NOx output can be reduced remarkably by the use of oxygen instead of air [1–3].

In air combustion, nitrogen brings about a low yield of combustion and high energetic consumption because the nitrogen contained in the air acts as energy ballast. The total substitution of air by oxygen permits the increase of the laminar combustion velocity up to 1300%, the improvement of the heat yield, the rise of the adiabatic temperature of flame (2200 K for CH_4-Air, 3090 K in oxy-combustion), the extension of the flammability limit up to 450%, the reduction of fuel consumption of 50% and from an environmental point of view, the decrease of the nitrogen oxide formation up to 95% [4,5].

Chahine [6] studied the effects of the oxygen enrichment on the flame characteristics, in particular, flame lift-off height, flame length, stability and instabilities at the bottom of the flame, front and top of the flame. His experiments, performed on a laminar

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flame in a coaxial burner, showed that oxygen enrichment has a very important role on the flame stability, on the energy efficiency, and thus enables to change the amplitude and frequency of instabilities. Beltrame et al. [7] studied experimentally and numerically a diffusion methane flame with against current using an air-oxygen mixture as oxidant. They performed a comparison between a methane/air flame and a methane/air flame enriched up to 68% of oxygen. This comparison is focused on the temperature variation and species between these two types of flame. For a methane/air flame, the maximum temperature is about 2200 K located at the stagnation plane.

A new generation of burners with separated fuel and oxidizer injectors shows attractive perspectives for industrialists. The basic idea of this burner consists of separating gas and oxygen injection to dilute the reactants with combustion products before the mixing of the reactants. Compared to classical co-flow type burners, a longer and larger flame with lower temperature level is expected [8]. The design of such burners implies a careful understanding of the turbulent oxy-flames properties developing in a furnace, especially at the flame base where combustion starts. There are many practical situations where the flames issued from burner with multiple jets (industrial furnaces, rocket engine, etc.).

Many studies have made it possible to demonstrate the effectiveness of this type of burner in terms of limitation of nitrogen oxide emissions and enhance of mixing of reactants. Salentey [8] was interested in the characterization the flames from multiple jets aligned through dynamic properties (speed of the jets and distance injectors) and the flame topology (stability, length, blow ...). Lesieur [9] has studied numerically the characteristics of a burner with three jets, focusing on the mixing of the jets, their dynamics and the pollutant emissions. In a previous work, we studied the effects of geometrical and dynamic parameters (exit velocities, separation distance between the jets, diameters) on the flame stability and its behavior. Previous works have proved the efficiency of oxy-burners in separated nozzles to control the jets in order to improve the mixing [10–12]. Boushaki et al. [13] research work has focused on two main areas for monitoring flow, passive control of changing the geometry of the burner affecting the dynamics flow; and active control requiring external energy intake through actuators while retaining the geometry of the combustion chamber. In their experimental study consisted in mainly characterizing experimentally the influence of the slope of the oxygen jets on the behavior of the oxy-flames [14]. The incline of lateral oxygen jets towards the central fuel jet presents double advantages: a better stabilization of flame and a strongly reduction of NOx. The flame stability is indicated by the decrease of lift-off height and its fluctuations according to the oxygen jets slope.

As emerged from the above review, only few works of the effect of equivalence ratios (in lean regime) on characteristics of non-premixed oxy-methane flames from burner with separated jets are investigated experimentally. However, these effects on oxy-flames diffusion have not been investigated numerically in the literature. To this reason and to the best of authors' knowledge, the aim of this contribution is to investigate numerically the effect of different equivalence ratio on the combustion characteristics of a diffusion methane oxy-flame in a stabilized separated burner. Fluent is used in this study with Reynolds Average Navier-Stokes (RANS) technique with Realizable k-ε as turbulence closure model. The EDM combustion model is used for the turbulence/chemistry interaction.

2. Experimental system

The burner depicted in Fig. 1 consists of three non-ventilated jets, one central of a natural gas and two laterals of pure oxygen jet. It is the same configuration studied in Ref. [14]. The internal

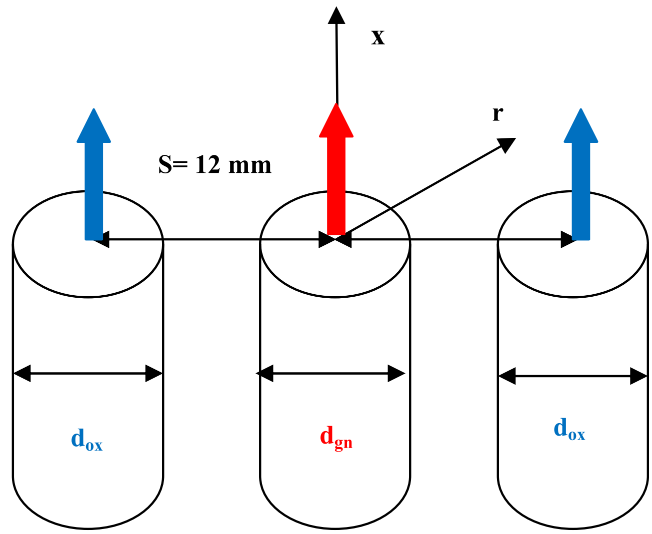

Fig. 1. Schematic view of the burner.

diameters d_g and d_{ox} are 6 mm. The separation distance between the jets (S) is fixed at 12 mm from axe to axe. The natural gas has used a density of 0.83 kg m^{-3} and a net calorific value of 45 MJ/kg. The oxygen is provided by Air liquid with a purity of 99.5% and a density 1.354 kg m^{-3} (at 1 atm and 15 °C). The flow rate and the exit velocity of natural gas are fixed whatever the configuration and correspond to the value calculated for a thermal power of 25 kW in stochiometric proportions ($\Phi = 1$), thus $m_g = 0.556$ g s^{-1} and Vg = 27.1 m s^{-1}.

The combustion takes place inside a square cross-section chamber of 60×60 cm^2 and 1 m in height. The lateral walls are refractory-lined inside and water-cooled outside of the combustion chamber. The chamber is finished with a convergent of 20 cm height and final section of 12×12 cm in order to limit the air intake by the top. Six windows are made in each face of the chamber, allowing optical access to all the flame zones.

The Particle Image Velocimetry technique has been used to characterize the experimental dynamic field. The PIV measurement requires the basic elements used in laser tomography, i.e. a laser sheet which clarifies the zone of studied flow, a camera CCD and a PC of acquisition and control of equipments. The laser used is Nd-YAG Bi-pulse of 532 nm wavelength and 10 Hz frequency. The laser sheet is formed by a first divergent cylinder lens, which spreads out the beam then by second convergent spherical lens, which refines the sheet. The signal of Mie scattering emitted by particles is collected by a camera CCD FlowMaster of Lavision (12 bits dynamics and 1280×1024 pixels^2 resolution).

3. Computational and simulation method

3.1. Governing equations

This section describes the numerical model which solves the steady equations for conservation of mass, momentum, energy, and species for a separated jet burner. The turbulence is modulated by second order turbulent equations for turbulence kinetic energy κ and its rate of dissipation ε. The general form of the elliptic differential equations for an axisymetric flow is given by Eq. (1),

Where S_Φ the source terms and Γ_Φ the transport coefficient.

$$\frac{\partial}{\partial x}(\rho U \Phi) + \frac{1}{r}\frac{\partial}{\partial r}(r\rho V \Phi) = \frac{\partial}{\partial x}\left(\Gamma_\Phi \frac{\partial \Phi}{\partial x}\right) + \frac{1}{r}\frac{\partial}{\partial r}\left(r\Gamma_\Phi \frac{\partial \Phi}{\partial r}\right) + S_\Phi \quad (1)$$