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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 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}.

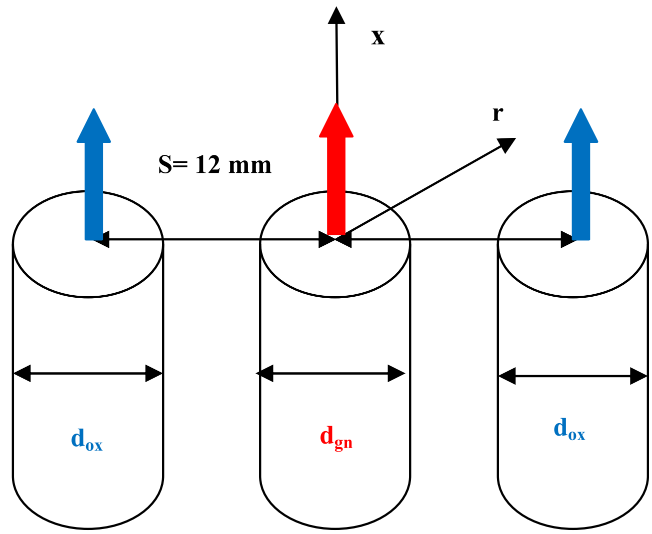

Fig. 1. Schematic view of the burner.

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.

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

where ρ is the density, P is the mean pressure and μ is the viscosity.

μ_e is the effective viscosity is determined from $\mu_e = \mu + \mu_t$, where μ_t is the turbulent viscosity, which is derived from the turbulence model and expressed by: $\mu_t = C_\mu \rho \frac{\kappa^2}{\varepsilon}$.

The Finite Rate/Eddy Dissipation Model (EDM) is used to address the turbulence chemistry interaction. The EDM is based on the hypothesis that the chemical reaction is fast in relation to the transport processes of the flow. The reaction rate is assumed to be proportional to a mixing time defined by the turbulent kinetic energy (k) and the specific dissipation rate (ε).

3.2. Simulation details

Simulations are performed using the CFD code FLUENT 6.3.26, which is based on finite volume discretization of the conservative governing equations using second order upwind. The scaled residual is used as indicator of convergence. In fact, convergence criterion of residuals is 10^{-6} for energy equation and 10^{-3} for all other equations. The Grid is constructed with the GAMBIT grid generator, the computational domain (half of the flame) was extended 100 cm in the axial direction and 30 cm in the radial direction. A total number of 28,700 quadrilateral cells were generated using non-uniform grid spacing to provide an adequate resolution near the jet axis and close to the burner where gradients were large. The grid spacing increased in the radial and axial directions since gradients were small in the far-field.

The aim of this study is to numerically investigate the effects of the global equivalence ratio (from 0.7 to 1). Table 1 summarizes the parameters of this study including methane and oxygen flow rates, the fuel and oxygen exit velocity and Reynolds. Note that the methane flow rate is kept constant for a given global equivalence ratio, whereas the oxygen flow rate increases.

Reynolds Number is defined by the following equation:

$$Re = \frac{\rho d_{gn} U_{gn}}{\mu} \quad (2)$$

A global equivalence ratio can be defined as the molar ratio of methane and oxidant at the injection to molar ratio methane and oxidant in stoichiometric conditions, as:

$$\text{Phi} = \phi = \left(\frac{Q_{CH_4}}{Q_{O_2}}\right) \Big/ \left(\frac{Q_{CH_4}}{Q_{O_2}}\right)_{stoichio} \quad (3)$$

where Q is the volumetric flow rate.

At the inlet, the methane is supposed to enter a pipe with a constant axial velocity profile (Table 1). At the axis of symmetry, r = 0, V = 0 and $\partial\Phi/\partial r = 0$ ($\Phi = U, \kappa, \varepsilon$). At the outlet, the fully-developed condition of pipe flow is adopted, $\partial\Phi/\partial x = 0$ ($\Phi = U, V, \kappa, \varepsilon$). At the wall, the velocities are assumed to be zero, and these no-slip boundary conditions are appropriate for the gas. These equations, called "wall functions", are introduced and used in finite difference calculations at near-wall points.

4. Results and discussion

4.1. Experimental and numerical comparison

Fig. 2 reports the experimental and numerical profile of the radial variation of the longitudinal velocity in the case of oxy-combustion of methane. The numerical results are obtained by the standard k-ε model. The profiles of the longitudinal velocity have a similar shape, having two maxima and minima velocity whose central peak corresponds to the injection of the fuel jet, while the two other peaks are relative to the annular jet of oxidant. For this a classical behavior of the multiple jets for the longitudinal velocity is found, i.e. the maximum ones in the jets centers and minima between the jets.

By comparing the numerical and experimental cases, remarkable differences appear. The difference may be due to the type of fuel used and the boundary conditions to the injection. Indeed, natural gas composed of 85% CH_4; 9% C_2H_6; 3% C_3H_8; 2% N_2; 1% CO_2 was used experimentally but pure methane was injected into the simulation. Also the injection velocities of the fuel and oxidant for the experimental are parabolic, against for calculations constant velocities were used.

In the combustion case a more important radial expansion is noted; the strong radial expansion is visible in presence of flame. This is due to the hot environment and reaction zone, which accelerates the flow. The effect of turbulence models does not appear on the peaks relating to the annular jet of combustion where the experimental and numerical data correspond.

The radial profiles of rms velocities (u′) at various heights of the flow are shown in Fig. 3. The numerical results indicate differences appear with the experimental results. Three turbulence peaks correspond to the mixing zones of jets are observed. The fluctuations on the order of 5.5 m/s near the burner are shown, two at the center corresponding to the mixing layers of the central jet and one at both sides of the central jet corresponding to the mixing layers of the side jets. These fluctuation peaks diminish along the flow with decreasing longitudinal velocity in the combined region of flow.

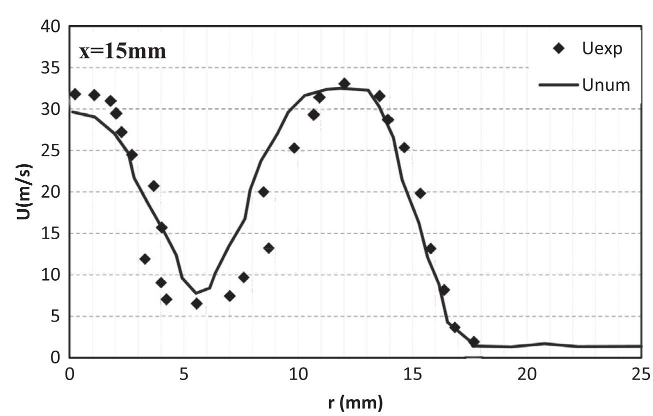

Fig. 2. Radial profile of the longitudinal mean velocity at x = 15 mm.

Table 1
Dynamic conditions of the burner.

Configuration	ϕ	$\dot{Q}_{CH_4}$ $[\frac{l}{s}]$	$\dot{Q}_{O_2}$ $[\frac{l}{s}]$	V_{gn} $[\frac{m}{s}]$	V_{O_2} $[\frac{m}{s}]$	Re_{gn}
Confi 1	1	0.767	1.534	27.13	27.13	12,272
Confi 2	0.8	0.767	1.917	27.13	33.86	12,272
Confi3	0.7	0.767	2.19	27.13	38.69	12,272

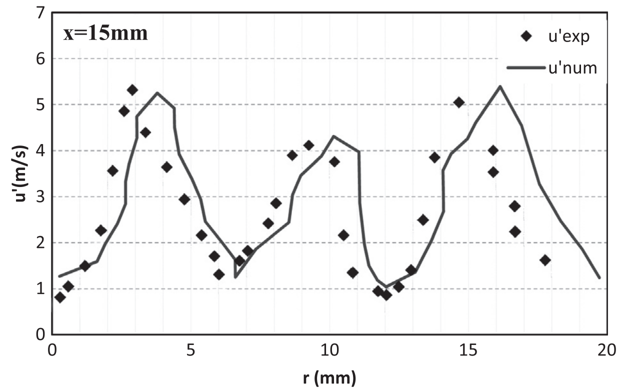

Fig. 3. Radial profile of the rms of longitudinal velocity at x = 15 mm.

4.2. Radial profiles of mean velocities and fluctuations

Fig. 4 shows the radial profiles of the mean longitudinal velocity (U) at different heights (x/D = 1.66, x/D = 8.33 and x/D = 16.66) for three global equivalence ratios. For the straight jets, a classical behavior of multiple jets is found for the distribution of longitudinal velocity, maxima in the center of jets and minima between the jets. In the initial zone, each jet follows its own evolution, and then the jets start to interact. In the near burner region (x/D = 1.66) and for the three global equivalence ratio ($\Phi = 1$ and $\Phi = 0.7$), it is observed that the longitudinal velocities of the jet central of fuel keep constant but the radial profiles of mean velocities of the lateral of pure oxygen jet show an increases with the decreases of the global equivalence ratio. It is noted, that for $\Phi = 1$ and $\Phi = 0.7$ the mean longitudinal velocities are respectively equal to 27 m/s and 38.57 m/s. with equivalence ratio increase, radial profiles of mean velocities show an increase of 30% of the maximum velocity. For the height of x/D = 8.33, the decrease of equivalence ratio rises the maximum of velocity of 33% (from U = 26 m/s to U = 39 m/s), and for x/D = 16.66, the velocity profiles in combustion are slightly flattened, more open and the mixing of the fuel jet with the oxidant and the surrounding fluid is significant, due to decrease of the global equivalence ratio in the oxy-fuel flame. The influence of the equivalence ratio on the longitudinal component U is less and less significant while the height in the flow increases. From an aerodynamics point of view, the decrease of equivalence ratio (for 1–0.7) modifies the longitudinal velocity of flow near to the burner but keep the flow velocity behavior in the combination zone.

Transversal velocity profiles are shown in Fig. 5 at different positions from the burner and for different global equivalence ratios. In the case of x/D = 1.66, the transversal velocity is low and ranges from −2 to 2 m/s, but its maxima decrease for x/D = 8.33 and x/D = 16.66 for the central jet and then increase for the oxidizer zone. The global equivalence ratio leads to an increase in the transversal velocity of the side jets, particularly since x/D = 8.33, the maximum value of V varies from 1 to 1.5 m/s when the global equivalence ratio varies from 1 to 0.7. As shown in figure, the velocity profile is composed of two parts, one positive and one negative with a passage by zero corresponding, respectively, to the side jets and the central jet of fuel. The expansion of the flow increases downstream the flow with when the global equivalence ratio varies.

The mean and RMS longitudinal velocity along the centerline of the jet, the turbulence intensity is studied in the convergence zone. The turbulence intensity equals to u′/U along the fuel jet. In Fig. 6, the radial distribution of the turbulence intensity, u′/U, according to the equivalence ratio is shown at different axial positions, x/D = 1.66, 8.33 and 16.66. Results of u_0/U highlight the interaction zones between the jets themselves.

The results of u′/U highlight the zones of interaction between the jets and the air surrounding and between the jets themselves. Two areas strong turbulence are observed. It takes place on the

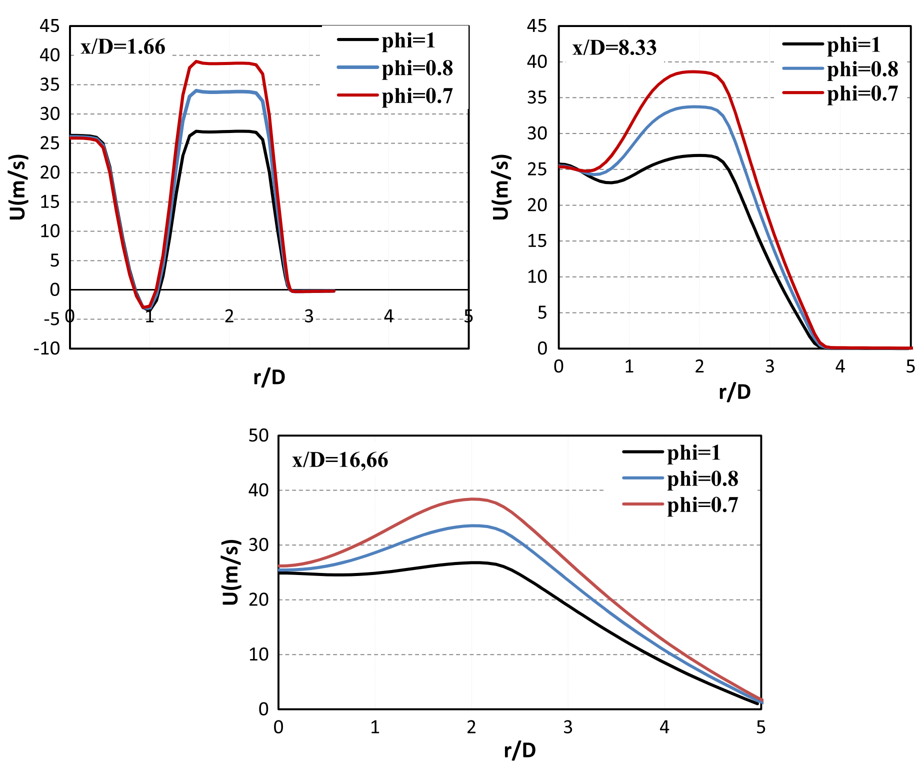

Fig. 4. Radial profiles of longitudinal velocity at different positions from the burner.

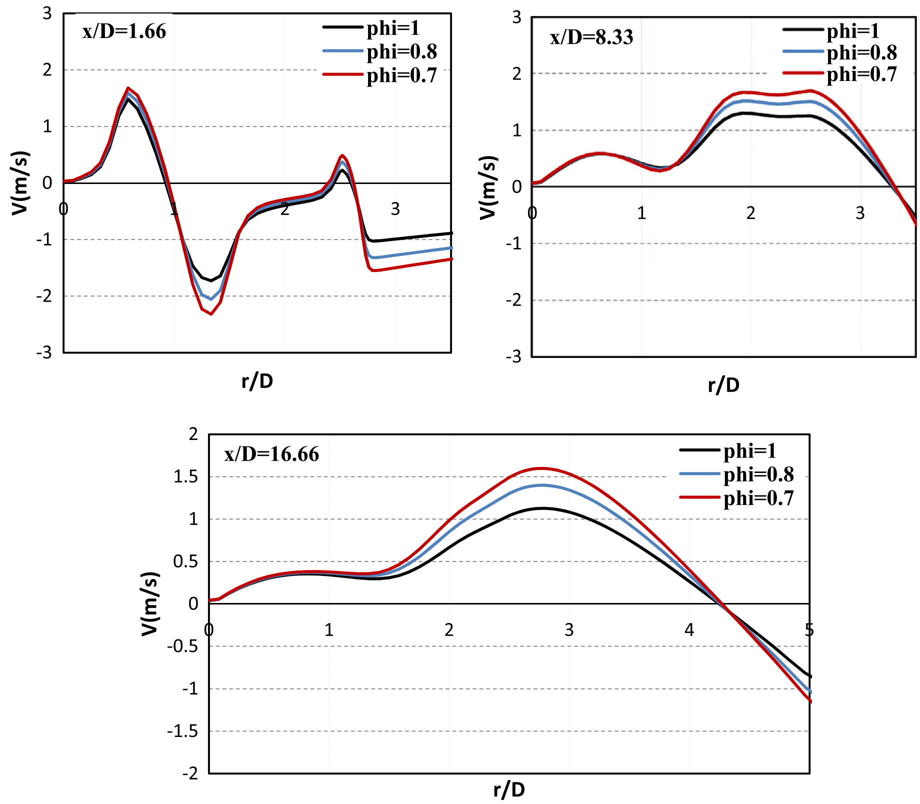

Fig. 5. Radial profiles of transversal velocity at different positions from the burner.

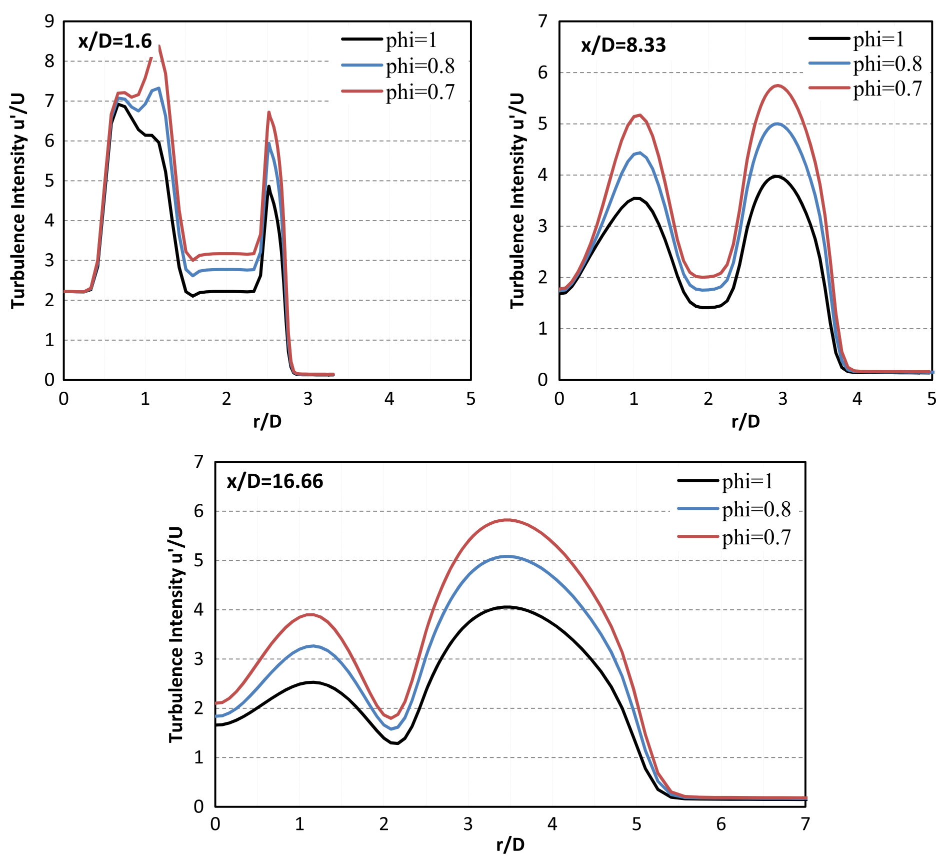

Fig. 6. Turbulence intensity at different positions from the burner.

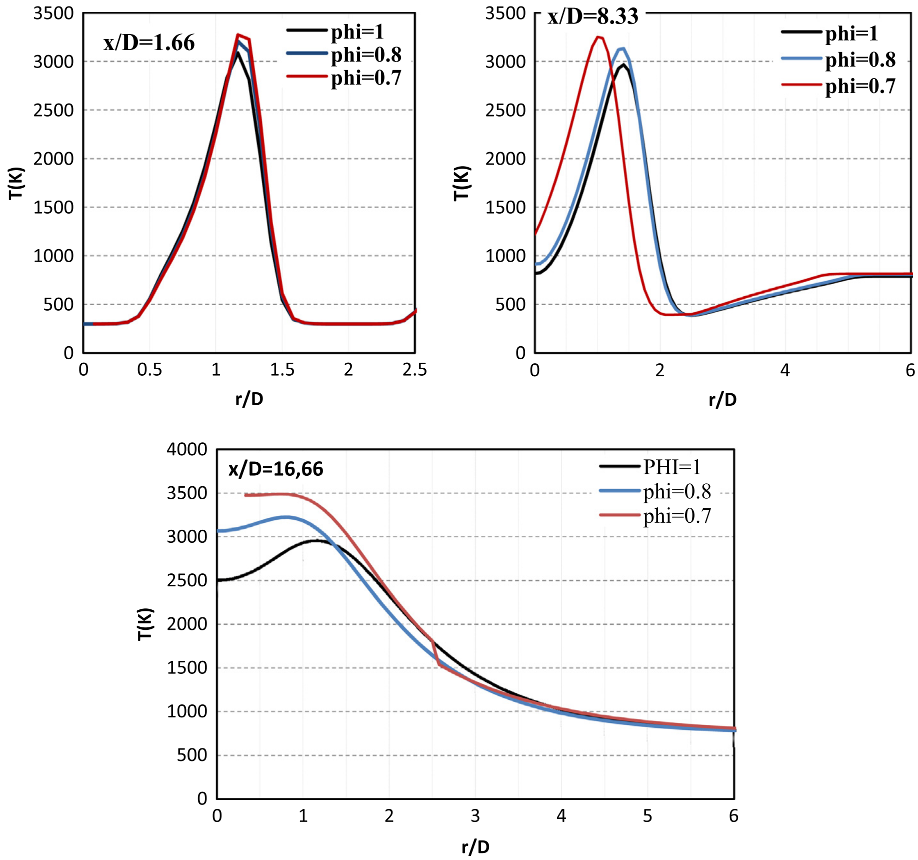

Fig. 7. Radial profiles of temperature at different positions from the burner.

outside of lateral jet and dilutes the oxygen jet with ambient air. The other area is located between the jets corresponding to the mixture jets there between.

In all areas and according to the decrease of the Φ, the external and internal zones of turbulence seem to be influenced by the decrease of the equivalence ratio. Further downstream, the jets will be merged and there are only external turbulence zones resembling characteristics of a single jet. The turbulence intensity of these two outer regions increases along the z height is noted and a radial expansion due to the opening of the jet.

As in reacting flow, in the initial zone of flow, the mixing layers generating turbulence are found, the inner zone at the interface of the natural gas-oxygen and the outer zone at the interface of the oxygen–ambient fluid.

4.3. Radial profiles of temperature

Fig. 7 shows the distribution of the temperature in different positions in the combustion chamber. For the zone close to the injector of gas, the temperature is represented as one peak with maximum values equal to 3000 °C. In fact, the region between the peaks represents the area of the fuel which is not yet burned and the peaks represent the zone of the reaction between the fuel and oxidant after mixing. The reaction takes place at the interface of jets between fuel and oxidant. Far the burner exit (x/D = 8.33) and for the global equivalence ratio 0.7, the peak converges in the central jet and the temperature profile keep constant to large r/D = 1.5 with a value equal to 3500 °C. Therefore, the flame is formed around the jet fuel in the zone of the chemical reaction between the reactants, which explains the evolution of the temperature from two peaks near the burner, to a single peak far from the burner (400 mm). At; x/D = 16.66 it is noted here that the temperature increases with the decreases of global equivalence ratio from 3000 °C to 3500 °C near the fuel jet. This increase is very remarkable in zone reaction.

5. Conclusion

The present study is a numerical investigation of development and structure of flow from an oxy-fuel flame generated by a burner constituted with three jets, jet central continued methane and surrounded by two oxygen jets.

This work consists in mainly characterizing numerically the influence of the global equivalence ratios of 0.7, 0.8 and 1 on the behavior of the oxy-flames. Validations of computational models with experimental data of the designed stable case are performed, and a good agreement is found using Realizable k-ε.

The results of radial profiles of mean velocities, fluctuations and temperature are represented with varying global equivalence ratio. From an aerodynamics point of views, the global equivalence ratio modifies the mean longitudinal velocity of flow near to the burner but keep the mean flow velocity behavior in the central jet. The study of the turbulence intensity along the jet shows that the global equivalence ratio increases the velocities fluctuation intensity. The global equivalence ratio is very efficient to increase the turbulence intensity and in consequence the mixing of the fuel jet with the oxidant and the surrounding fluid.

Acknowledgements

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References

[1] J.C. Sautet, T. Boushaki, L. Salentey, B. Labegorre, Oxy-combustion properties of interacting separated jets, Combust. Sci. Technol. 178 (2006) 2075–2096.
[2] T. Boushaki, S. Guessasma, J.C. Sautet, Predictive analysis of combustion burner parameter effects on oxy-fuel flames, Appl. Therm. Eng. 31 (2011) 202–212.
[3] B. Genies, L'oxydation, une solution attractive pour minimiser les émissions de NOx des procédés industriels, Combust. et procéd. Indust. Comment réduire les émissions de NOx, Rencontres et journées techniques A.D.E.M.E (1996) 153–196.
[4] Z. Riahi, M.A. Mergheni, C. Gobin, Experimental characterization of the velocity field in turbulent oxy-flame of a coaxial burner, Int. J. Fluid Mech. Res. 41 (4) (2014) 283–295.
[5] Z. Riahi, M.A. Mergheni, S. Ben Nasrallah, Numerical study of turbulent normal diffusion flame CH_4-air stabilized by coaxial burner, Therm. Sci. 17 (4) (2013) 1207–1219.
[6] M. Chahine, Etude des effets magnétiques et des effets de l'enrichissement en oxygène sur la combustion d'une flamme de diffusion laminaire CH_4-air. Optimisation de l'efficacité énergétique. Ph.D. Université d'Orléans, 2012.
[7] A. Beltrame, P. Porshnev, W. Merchan, A. Saveliev, A. Fridman, L.A. Kennedy, Soot and NO formation in methane-oxygen enriched diffusion flames, Combust. Flame 124 (2001) 295–310.
[8] L. Salentey, Etude expérimentale du comportement de brûleur à jets séparés: application à la recherche gaz naturel-oxygène pur Ph-D, University of Rouen, 2002.
[9] C. Lesieur, Modelisation de la combustion turbulente non premelangee dans un bruleur a jets separes: Application a la stabilisation d'une oxy-flamme, Ph. D. INSA of Rouen, 2003.
[10] M. Ditaranto, J.C. Sautet, J.M. Samaniego, Structural aspects of oxy-fuel flames, Exp. Fluids 30 (2001) 253–261.
[11] V. Faivre, T. Poinsot, Experimental and numerical investigations of jet active control for combustion applications, J. Turbl. (2004) 5–25.
[12] J.C. Sautet, L. Salentey, M. Ditaranto, J.M. Samaniego, Length of natural gas-oxygen nonpremixed flames, Combust. Sci. Technol. 166 (2001) 131–150.
[13] T. Boushaki, J.C. Sautet, B. Labegorre, Control of flames by radial jet actuators in oxy-fuel burners, Combust Flame 156 (2009) 2043–2055.
[14] T. Boushaki, M.A. Mergheni, J.C. Sautet, B. Labegorre, Effects of inclined jets on turbulent oxy-flame characteristics in a triple jet burner, Exp. Ther. Fluid Sci. 32 (2008) 1363–1370.