Numerical investigation of the global equivalence ratio effects on the dynamic behavior of turbulent swirling diffusion flame

S. Chakchak[1,2,3], A. Hidouri[2], M. Chrigui[4] and T. Boushaki[1]

[1] ICARE CNRS, Orléans, France
[2]Research Unit MEER, Faculty of Sciences of Gafsa, Tunisia
[3]National Engineering School of Monastir, Tunisia
[4]National Engineering School of Gabes, Tunisia

1 Introduction

The development of the combustion systems is mainly based on the burner configuration, the type of fuel injection and the dynamic parameters. Many studies have focused on the effect of inlet velocity, the flow rate and global equivalence ratio on the combustion characteristics [1]. Mergheni et al. [2] studied numerically the effect of equivalence ratio on oxy-flame characteristics in a burner with three separated jets under stoichiometric and lean conditions. The results show that the equivalence ratio influences the mean longitudinal velocity of flow near to the burner. Chakchak et al. [3] studied numerically the effect of velocity ratio of non-premixed flame stabilized over a swirler coaxial burner. They concluded that increasing the velocity ratio improves the mixing and reduces the CO emissions caused by the temperature variation. Their results showed also that the radial fuel injection results a partial premixing between reactants, which affects the flame behavior, in particular the flame stabilization. Zouhaier et al. [4] investigate experimentally the non-premixed flame generated by a simple coaxial burner constituted with a central natural gas jet surrounded by annular oxygen jet. They found that the variation of equivalence ratio effects the velocity fluctuations, the turbulence intensity and the kinetic energy. Studies focusing on the effect of global equivalence ratio on dynamic behavior of the flame are very limited. However, these effects on turbulent diffusion flame provided by a coaxial swirl burner with radial fuel injection have not been investigated numerically in the literature.

The aim of this paper is to study numerically the effect of global equivalence ratio (0.5, 0.8,1, 1.2 and 1.3) on the dynamic characteristics of a turbulent non-premixed flame in a coaxial burner stabilized by a swirl with a radial fuel injection. Simulations are performed using the ANSYS-Fluent CFD (computational fluid dynamic) code. Reynolds averaged Navier-Stokes (RANS) is used to capture the turbulence and the eddy dissipation combustion model (EDM) to resolve the turbulence/chemistry interaction.

2 Numerical modeling

Simulation was performed using the ANSYS-Fluent CFD software. It bases on the finite volume method to solve the governing equations. The realizable K-ε used as the turbulence model in order to close the

Correspondence to: sawssen.chakchak@cnrs-orleans.fr

system of Reynolds Navier-Stokes equations. The eddy dissipation combustion model is used to study the reaction rate and take account of the turbulence-reaction interaction.

2.1 Governing equations

The numerical modeling of turbulent reactive flow is carried out by the resolution of the partial differential equation of conservation of mass, momentum, energy and species [5].

The mass conservation equation is written as follows:

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_j}(\rho V_j) \tag{1}$$

Where ρ represents the density and V_j is the component of the instantaneous velocity in the three directions (j=1, 2, 3). In the general case.

The momentum conservation equation can be given by:

$$\frac{\partial}{\partial t}(\rho V_j) + \frac{\partial}{\partial x_j}(\rho V_i V_j) = -\frac{\partial P}{\partial x_i} + \frac{\partial \tau_{ij}}{\partial x_j} + \frac{\partial}{\partial x_j}(-\rho\overline{V_i' V_j'}) + F_j) \tag{2}$$

Where P is the pressure, τ_{ij} represents the stress tensor and $-\rho\overline{V_i' V_j'}$ is the component of the tensor of Reynolds stresses.

The energy equation is written as follows:

$$\frac{\partial(\rho h)}{\partial t} + \frac{\partial}{\partial x_j}(\rho V_j h) = \frac{\partial}{\partial x_j}(\rho D_h \frac{\partial h}{\partial x_j} - \rho\overline{h' V_j'}) \tag{3}$$

Where: $D_h = \frac{\lambda}{\rho c_p}$ represents the thermal diffusivity, $-\rho\overline{V_i' V_j'}$ is the correlation term between the velocity fluctuation and h is the specific enthalpy.

The equation of species conservation is given by:

$$\frac{\partial(\rho Y_K)}{\partial t} + \frac{\partial(\rho V_i Y_K)}{\partial x_j} = -\frac{\partial J_j^K}{\partial x_i} + \rho\dot{W}_K \tag{4}$$

Where Y_K , J_j^K and $\dot{W}_K$ represent respectively the mass fraction, the mass diffusion flux k in the j direction and the production rate of the species k.

2.2 Boundary Conditions

In this study, the equivalence ratio ϕ varies from 0.5 to 1.3 as shown in the Table.1. A detailed description of the burner configuration and the combustion chamber was reported by Chakchak et al. [4]. At the fuel inlet, the CH_4 is supposed enter with a constant mass flow $\dot{m}$fuel (0.00017 Kg/s) and fixed velocity V (4.98 m/s). At the air inlet, a mass flow boundary condition $\dot{m}$air is used. This variable depends on the variation of global equivalence ratio as indicated in Table 1.

Table 1: Boundary conditions

ϕ	Qair (Nl/min)	Qfuel (Nl/min)	$\dot{m}_{air}$ (Kg/s)	$\dot{m}_{fuel}$ (Kg/s)	V_{air} (m/s)	V_{fuel} (m/s)

1.3	115.38	15.75	0.0024	0.00017	2.16	4.98
1.2	125	15.75	0.0026	0.00017	2.34	4.98
1	150	15.75	0.0032	0.00017	2.8	4.98
0.8	187.5	15.75	0.004	0.00017	3.5	4.98
0.5	266	15.75	0.0056	0.00017	4.98	4.98

3 Results and discussion

3.1 Validation

The results of experimental and numerical investigations are presented. The computed results of axial and tangential velocity are compared to the experimental data obtained using Stereo-PIV technique under stoichiometric conditions (ϕ=1) at Z=20 mm downstream the burner exit (Figure 1). Globally, a satisfactory agreement is assigned. A difference is observed in particular in the central region of the flow.

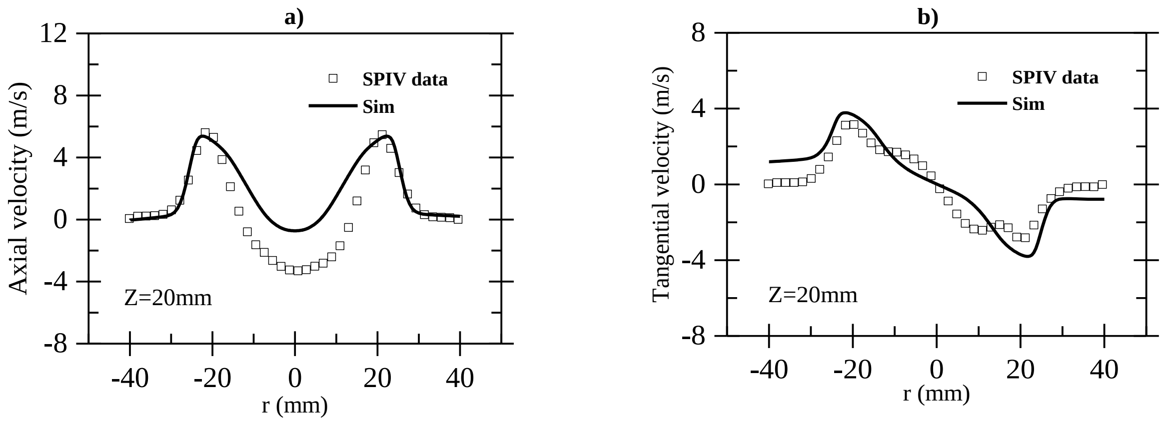

Figure 1: computations vs. measurement: radial profiles of mean axial velocity a) and mean tangential velocity b) at Z=20mm

The Central Recirculation Zone (CRZ) and the Swirling Jet region (SJ), due to the presence of the swirl, are well predicted by the simulations (see Figure 2.a). The CRZ is represented by the minimum value of axial velocity and due to the vortex breakdown phenomena. The swirl jet is represented by the maximum velocity value. The numerical peak positions are in good agreement with the Stereo-PIV peaks. The numerical and experimental profiles of the tangential velocity show in figure 2.b) are in good agreement. Comparison of the computed results and the experimental data showed that the RANS results were capable of predicting the swirling flow.

3.2 Axial velocity

Figure 2 shows the mean fields of axial velocity for different velocity ratios ranging from 0.5 to 1.3. The variation of the global equivalence ratio modifies the axial component of the velocity and more particularly on the Central Recirculation Zone region. The axial recirculation velocity, which is represent by the negative values, increase with the increment of ϕ. In lean regime (ϕ=0.5 and ϕ=0.8), the decrease of equivalence ratio leads to a greater radial expansion.

Figure 3 illustrates the radial profile of mean axial velocity for various equivalence ratios at two different positions Z=10mm and Z=60mm. three configurations are presented in this section; two configurations under lean conditions (ϕ= 0.5 and ϕ=0.8), one configuration in the stoichiometric condition (ϕ=1) and two configurations at the rich combustion mode (ϕ= 1.2 and ϕ=1.3).The global equivalence ratio does not modify the profile of axial velocity, it remains symmetrical from the burner axis (r=0 mm) for the different configurations and at the two positions (Z=10 mm and Z=60 mm). However, the decrease of equivalence ratio leads to an important increase in the maximum value of the axial velocity. At the height Z=10mm, the axial velocity varied from 6 m/s for ϕ=1.3 to 12 m/s for ϕ= 0.5. The radial profile of mean axial velocity shows an increase of 50% of the maximum velocity. The increasing of the mean velocity is caused by the variation of the mean density of the mixture. Further downstream from the burner exit (Z=60mm), the variation of equivalence ratio modifies the peak position of axial velocity which result by the modification of CRZ (Figure2). Figure 3.b shows that the decrease of equivalence ratio leads to an important increase in the maximum value of the axial velocity even for positions far from the burner exit.

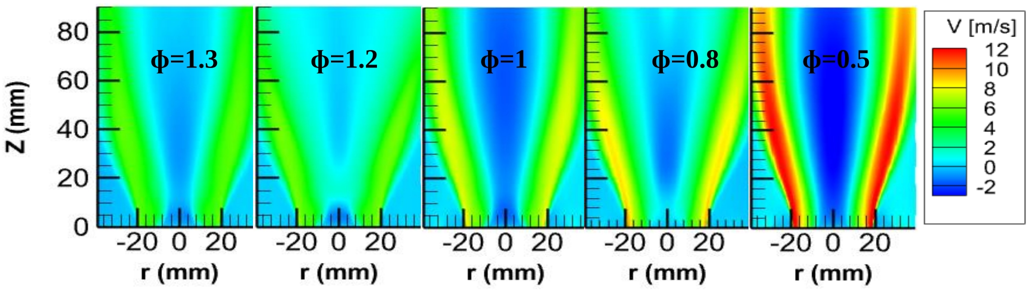

Figure 2: Simulated mean fields of axial velocity (V) for different equivalence ratios (0.5-1.3).

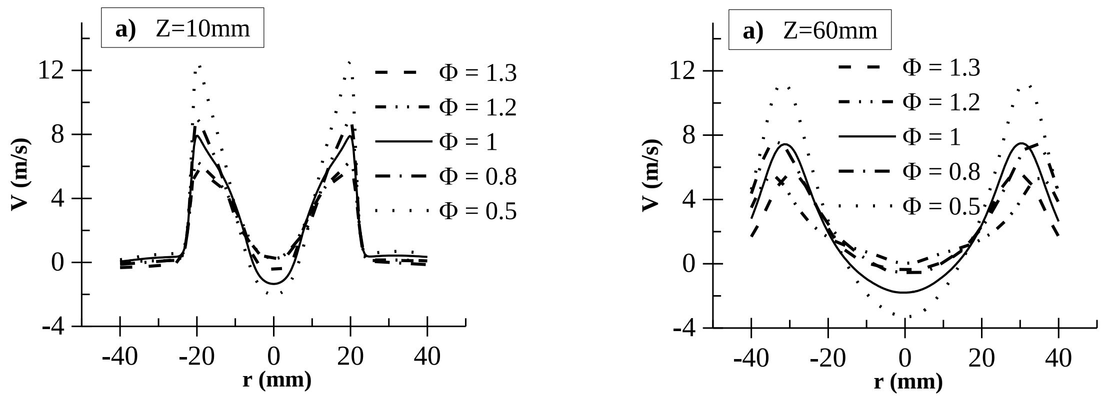

Figure 3: Radial profiles of mean axial velocity for different equivalence ratios (1.3, 1.2, 1, 0.8 and 0.5): a) Z=10 mm, b) Z=60 mm

3.3 Tangential velocity

The mean field of tangential velocity for different equivalence ratios ranging from 0.5 to 1.3 at two positions Z=10 mm and Z= 60mm are presented in Figure 4. The mean fields of tangential velocity are symmetrical from the axis of the burner. The variation of equivalence ratio does not affect this behavior. However, the value of tangential velocity is gradually increase by the decrease of equivalence ratio.

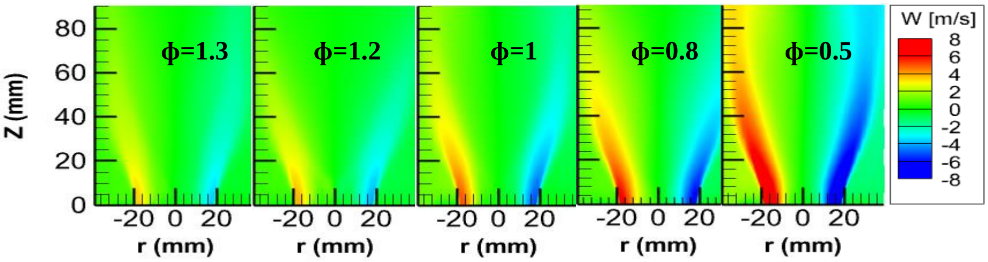

Figure 4: Mean fields of tangential velocity (W) for different equivalence ratios (1.3, 1.2, 1, 0.8 and 0.5)

Figure 5 shows the radial profile of mean tangential velocity for different equivalence ratios (1.3, 1.2, 1, 0.8 and 0.5) at Z=10 mm and Z=60 mm.

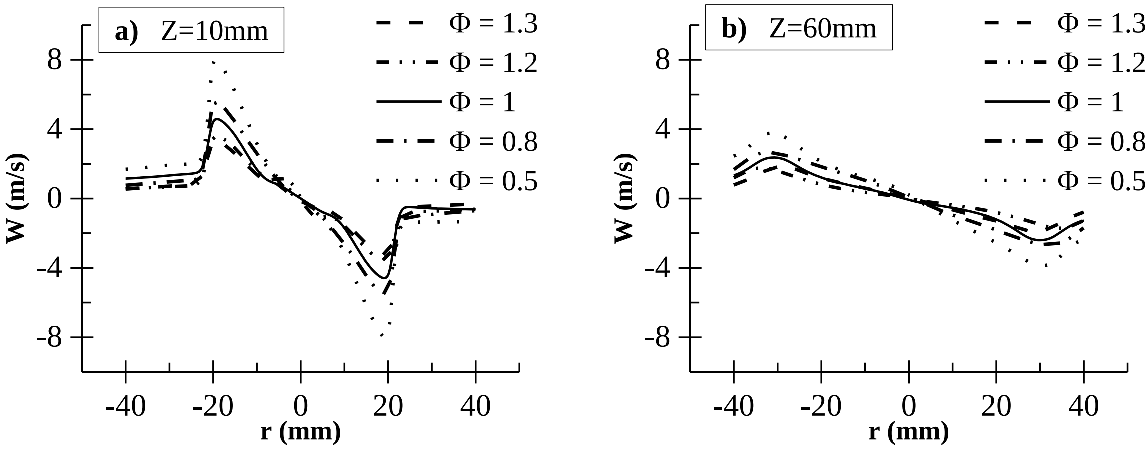

Figure 5: Computed radial profiles of mean tangential velocity for different equivalence ratios (1.3, 1.2, 1, 0.8 and 0.5) obtained at Z=10 mm, and at Z=60 mm.

At a position near of the burner exit (Z=10mm), the maximum tangential velocity varies from 3 m/s for ϕ= 1.3 to 8 m/s for ϕ=0.5. However, the influence of global equivalence ratio diminishes moving away from the burner exit. Figure 5.b shows that the maximum tangential velocity varies from 2 m/s for ϕ= 1.3 to 4 m/s for ϕ=0.5.

3.4 Turbulent kinetic energy

Figure 6 illustrates the turbulent kinetic energy for different equivalence ratios at Z=10mm and Z=60mm. The TKE is proportional to the fluctuations, since it is calculated based on the following equation:

$$TKE = \frac{1}{2}\left[(U')^2 + (V')^2 + (W')^2 \right] \quad (5)$$

The fluctuations reflect the degree of interaction between the different jets. They are generated by the velocity gradient between the different jets [3]. The maximum in the profile of turbulent kinetic energy (TKE) represents the interaction zone between the two jets. This maximum decrease when the height along Z increases. The maximum value of TKE has in important increase for ϕ=0.5 and reaches 28 m^2/s^2. The increase of global equivalence ratio leds to an increase of TKE and hence increases of the velocities fluctuation.

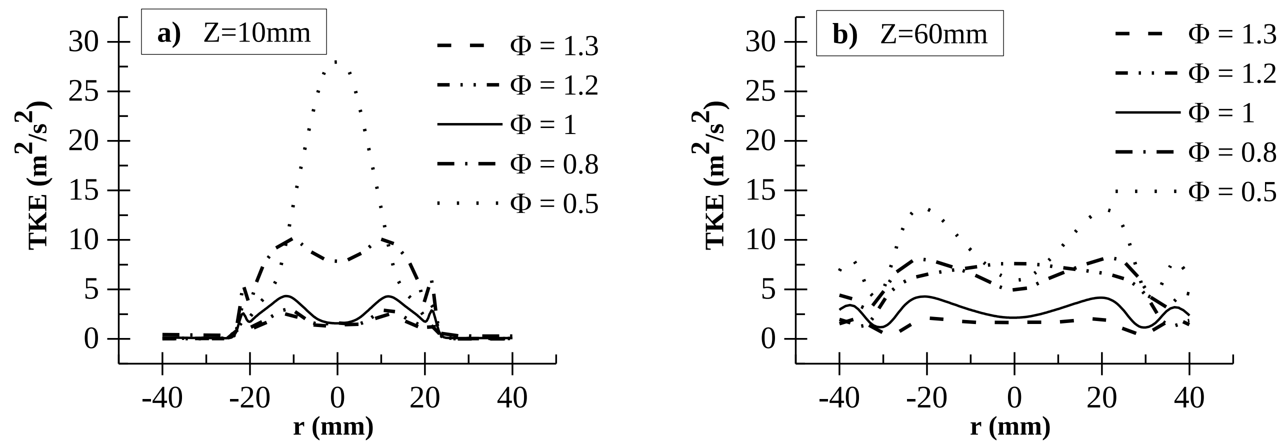

Figure 6: Turbulent kinetic energy for different equivalence ratios (1.3, 1.2, 1, 0.8 and 0.5): a) Z=10 mm, b) Z=60mm

4 Conclusions

This work presents a numerical investigation of turbulent diffusion flame provided by a swirl coaxial burner with radial fuel injection. The study consists in the influence of global equivalence ratio under lean, stoichiometric and rich conditions on the dynamic behavior of non-premixing swirling flame. The results of mean axial and tangential velocities and turbulent kinetic energy are presented for various equivalence ratios (0.5, 0.8, 1, 1.2, 1.3) at two different positions (Z=10mm and Z=60mm). The decrease of equivalence ratio affects the Central Recirculation Zone and leads to an important increase in the maximum value of mean axial velocity by around 50% at the two positions downstream from the burner exit. However, decreasing the equivalence ratio entrains an increase of mean tangential velocity near to the burner exit. The results of turbulent kinetic energy show the mixing zone between the two jets. The decrease of global equivalence ratio increases the TKE and hence increases the velocities fluctuations.

Acknowledgements

The authors are grateful for the financial support of this work provided by the Tunisian state to the stay of S. Chakchak in France and the CAPRI project from the Region Centre Val de Loire.

References

[1] Gheraissa N, Bouras F, Khaldi F, Hidouri A, Ferhat Rehouma F, Dogga A. (2121). A comparative study of the combustion supplied by multi-fuels: Computational analysis. Energy Reports 7 3819: 3832
[2] Mergheni MA, Boushaki T, Sautet JC, Ben Nasrallah S. (2019). Numerical study of oxy-flame characteristics in a burner with three separated jets, Applied Thermal Engineering.

[3] Chakchak S, Hidouri A, Zaidaoui H, Chrigui M, Boushaki T. (2021). Experimental and Numerical Study of Swirling Diffusion Flame Provided by a Coaxial Burner: Effect of Inlet Velocity Ratio. Fluids. 6(4):159.

[4] Riahi Z, Mergheni MA, Gobin C. (2014). Experimental characterization of the velocity field in turbulent oxy-flame of a coaxial burner, Int. J. Fluid Mech. Res. 41 (4) 283:295.

[5] Moussa O, Driss Z. (2017). Numerical investigation of the turbulence models effect on the combustion characteristics in a non-premixed turbulent flame methane-air Am. J. Energy Res. 5 85,