Detached Eddy Simulation of High Turbulent Swirling Reacting Flow in a Premixed Model Burner

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1 Introduction

The dynamics of swirling flows and swirl-stabilized premixed flames are still open fields of research. In modern gas turbine (GT) combustors the swirling motion is a desirable choice since it offers a possibility of enhanced mixing, controlled flame temperature and reduced NOx emissions [1]. The expansion of the swirling jet in the combustion chamber results a Vortex Breakdown (VB). This VB depends strongly on a critical level of swirl motion and burner geometry. The VB appears around the center region close to the expansion and provide a low pressure region. This region induces an axial backflow which provide storage of heat and chemically active species to sustain combustion [2,3], no need for bluff bodies to hold the flame. The flow field of turbulent swirl flames contains turbulent velocity fluctuations and in many cases also features unsteady coherent vortex structures. The most common coherent vortex structure in swirl combustors is the so-called precessing vortex core (PVC) [4]. The PVC by itself takes the role of a source of excitation for the flame front and a source of thermoacoustic fluctuations.

On the one hand, in swirl-stabilized combustor, understanding the turbulence-chemistry interaction (TCI) is important. Meier et al [5] carried out an experimental investigation of TCI in a gas turbine model combustor. Three swirling CH_4/air diffusion flames are studied at different thermal powers and air/fuel ratios. They reported that the flames exhibited different behaviors with respect to its instabilities. Their results revealed very rapid mixing of fuel and air, accompanied by strong effects of turbulence–chemistry interactions in the form of local flame extinction and ignition delay. The flames are not attached to the fuel nozzle, and are stabilized approximately 10 mm above the fuel nozzle, where fuel and air are partially premixed before ignition.

On the other hand, in swirl-stabilized combustor, coherent vortices-flame interaction is very important to study, characterize and understand. A state of the art review of the role of PVC in swirl combustion system is performed by Syred [6]. Initially, he reviewed the studies of the occurrence of the PVC in free and confined isothermal flows. Then, he mentioned the complexity of the PVC behavior under combustion conditions. He noticed that the premixed or partially premixed combustion can produce large PVC structure, and he illustrated and analyzed oscillations and instabilities in swirl burner/furnace systems. The flow pattern and frequency of PVC and their interaction with a flame have been studied by Stöhr et al [7]. They used experimental techniques to investigate a gas turbine combustor which operates with air and methane at the atmospheric pressure and thermal powers from 10 to 35 kW. They found for all operating conditions, PVC is detected in the shear layer of the IRZ, and a co-rotating helical vortex in the outer shear layer (OSL) is found. Their results show that the flames are mainly stabilized in the ISL, where also the PVC is located. In addition, the PVC causes a regular sequence of flame roll-up, mixing of burned and unburned gas, and subsequent ignition of the mixture in the ISL.

The main goal of this work is to contribute to the understanding of the dynamics of unsteady swirling flames. In addition to clarify the characteristics of the PVC and its role in flame stability. To do so, a numerical approach and perform Detached Eddy Simulations (DES) is chosen which guarantees the adequate resolution of turbulence in both space and time [8], enabling to resolve the dynamics of the flow and the flame. DES is defined as the hybrids of Reynolds Averaged Navier-Stokes (RANS) and Large Eddy Simulation (LES). As an investigated configuration of a swirled lean premixed combustor is studied, that was used by Anacleto et al [9]. Initially, the investigated configuration and its operating conditions are presented. Then, the DES computational model is described with the employed numerical procedures. Next, the obtained results are discussed which contain, visualization of the flow, validation with experimental data, the flame dynamic and identification of large scale coherent structure PVC. Finally, concluding remarks are noted with some perspectives.

2 Investigated configuration

2.1 Geometry

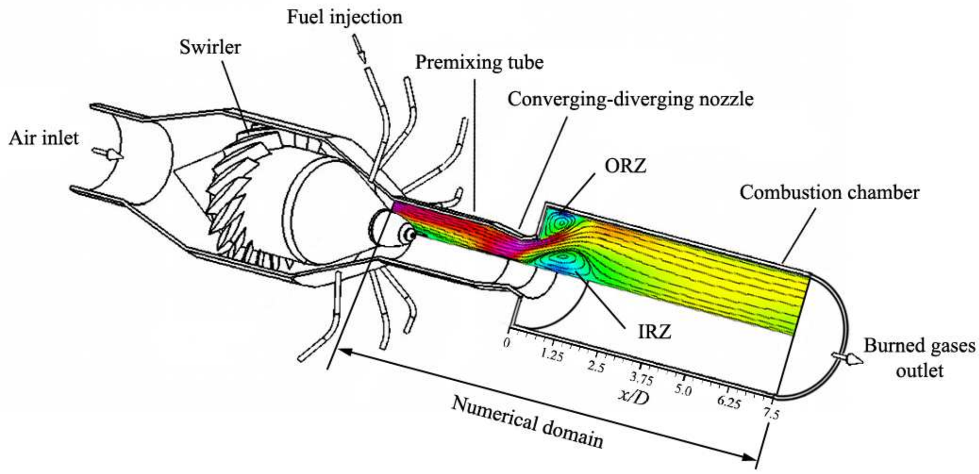

Figure 1. Schematic view of the swirl premixed burner and limits of the computational domain.

The studied burner configuration is that used by Anacleto et al. [9]. A schematic view of the burner is shown in Figure 1. The atmospheric pressure model combustor consists of a swirler, premixing tube (PT), a converging-diverging nozzle and combustion chamber (CC). Because of the sudden expansion downstream of the contraction, a vortex breakdown is obtained and the flame is stabilized at the expansion plane. The swirl generator has a variable blades angle, able to change between 0° and 60° in order to give the flow the desired swirl. The throat diameter $D = 40\ mm$ is used to calculate the non-dimensional data presented in the paper. The premixing duct is a cylindrical tube with inner diameter $1.25D$ and length of $4.14D$ including the converging-diverging nozzle. The combustion section is a cylindrical tube with inner diameter of $2.75D$ and total length of $8.4D$. As sketched in Figure 1, the model combustor is axisymmetric and the computational domain covers a fraction of the experimental configuration. It includes the premixing tube, the contraction and the combustion chamber.

2.2 Operating conditions and mesh modeling

In the burner, the flame operates with a perfect mixing of propane and air, for a equivalence ratio $\Phi = 0.5$ at the atmospheric pressure and precessing frequency $f = 800\,Hz$. The unburned gas temperature at the inlet is $T_0 = 573\,K$. Typical averaged velocity in the nozzle $u_0 = 37\,m/s$, corresponding to $R_e = 8 \times 10^4$ is used as reference of calculated non-dimensional data. The swirler configured at blade angle $\varphi = 50°$, which provides a swirl number $S_n = 1.05$.

A grid sensitivity analysis has been conducted for three computational structured grids (coarse, medium and a fine) in a previous study [10] .The computational structured grid used in the present work consists of 3 million hexahedral grid cells. Near the walls, the first spacing is related to wall distance vector is made to be $y^+ = 1$.

3 Detached Eddy Simulation and numerical details

3.1 DES modeling

Generally DES is not bounded on a certain underlying statistical turbulence model. Spalart introduced a DES approach which is based on a one equation RANS model [8]. The model of Strelets [11], which is used in this work, combines the two equation SST model with elements of LES methods. The SST model is used to cover the boundary layer and switches to a LES mode in regions where the turbulent length L_t predicted by SST model is larger than the local mesh size Δ. In this case the length scale used to compute the dissipation rate in the equation for the turbulent kinetic energy is replaced by the local mesh size Δ. In contradiction to the SST model the destruction term in the k-equation depends on the turbulent length scale.

$$\frac{\partial(\rho k)}{\partial t} + \frac{\partial(\rho \bar{U}_j k)}{\partial x_j} = P_k - \beta^* \rho k \omega F_{DES} + \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\tilde{\sigma}_k}\right)\frac{\partial k}{\partial x_j}\right]$$

The factor F_{DES}which is the multiplier to the destruction term in is defined as:

$$F_{DES} = \max\left(\frac{L_{t,SST}}{L_{t,DES}}\right); L_{t,SST} = \frac{\sqrt{k}}{\beta\omega}; L_{t,DES} = C_{DES}\Delta$$

3.2 Numerical details

For modeling turbulence-chemistry interaction the Finite-Rate/Eddy Dissipation model is used [12,13] and reduced chemical kinetics to three-step schemes for the combustion of premixed propane-air mixture [14]. A patch of temperature about 1000 K is used on the reaction zone in order to ignite the flame. Simulations were performed using the ANSYS-Fluent 14 software. The solver is based on finite volume formulation. The SIMPLE algorithm is applied for the pressure–velocity coupling. A second order upwind scheme is used for all parameters. Convergence criteria are set to 10^{-5} for all equations. A second order upwind scheme is used for all parameters. Initial calculation were done using RANS model until the solution is completely converged, and then the calculation switched to DES. The time step used is $\Delta t = 4 \times 10^{-6}$ chosen such that the precessing frequency is $800\,Hz$. Calculations were performed for about four flow-through times after the flow field had reached its stationary state to obtain statistically meaningful data for analyzing the flow dynamics.

4 Results and discussion

4.1 Flow topology along the burner

The mean flow field over the burner is illustrated in Figure 2.a, using streamline patterns colored by the mean axial velocity. As expected from a turbulent swirling flow in sudden expansion burner, two distinct regions must be present. The first, a cone-shaped inner recirculation zone (IRZ) appears as a result of the vortex breakdown. This recirculation region is deeply involved in the flame stabilization process as it constantly puts hot burnt gases in contact with fresh gases allowing permanent ignition. The second, a weak outer recirculation zone (ORZ) comes out above the mixing layer (Swirling jet) and takes it shape from the neighboring boundary walls.

Figure 2.b shows the instantaneous flow topology presented by streamline patterns and colored by mean axial velocity over the burner. It is shown that the instantaneous flow contains distinctive elements that are not present in the mean flow field. First, the black dots which are an arrangement of strong vortices in ISL. This arrangement indicates the presence of a 3D coherent vortex in the ISL. It is commonly named precessing vortex core (PVC) and it is often found in swirl flames. Second, distinctive features are the stagnation point and the stagnation line which are marked by a red dot and a dashed line respectively. Those features are located also in the ISL and they came from the collision between the vortices. Generally the dynamics of stagnation points is coupled to the arrangement of vortices; this demonstrates that the PVC induces distinct unsteady stagnation points. Other features appear in the OSL (marked by grey dots) present less strong vortices, obviously are associated with the corner wall.

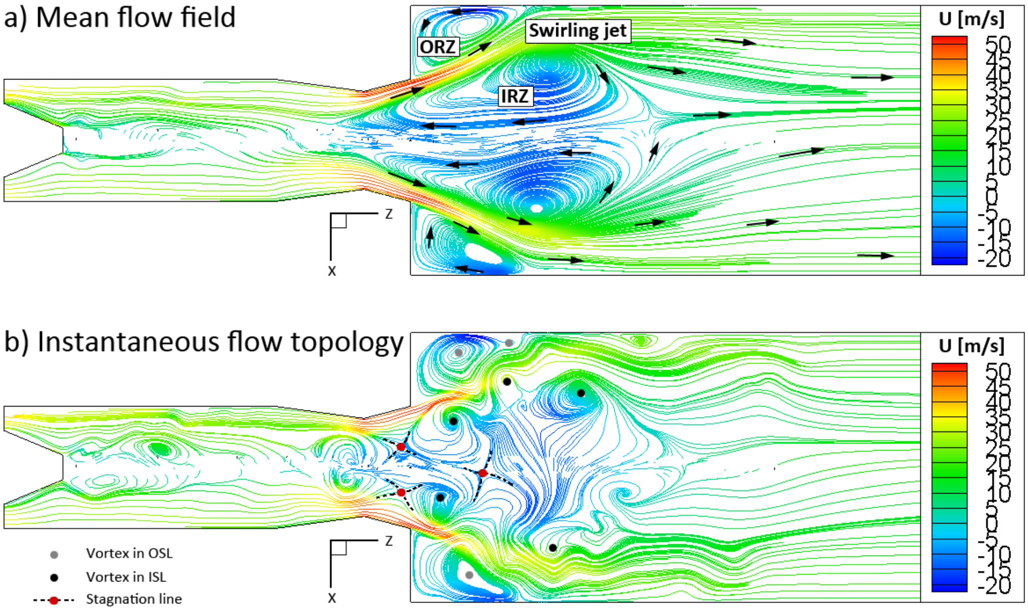

Figure 2. a) Mean flow field and b) instantaneous flow topology

4.2 Validation with experimental data

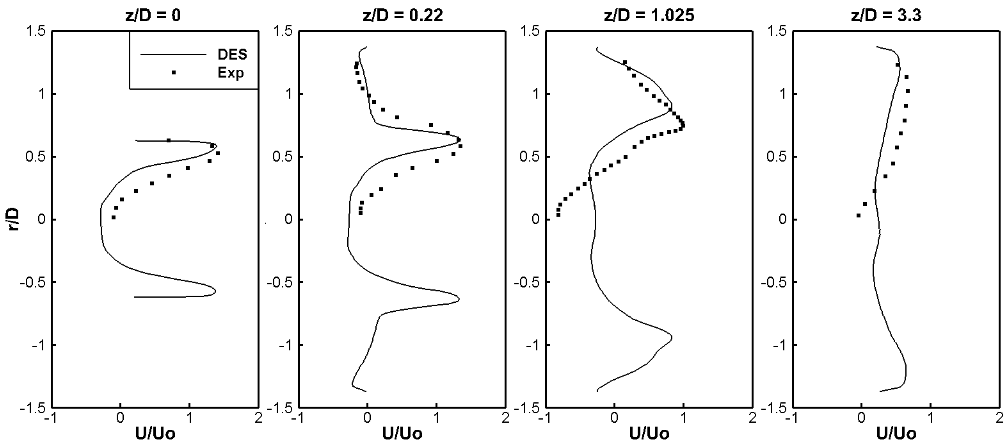

Figure 3. DES versus LDA data: radial profiles of the averaged axial velocity

Figures 3 shows a comparison between LDA (Laser Doppler Velocimetry) measurements and present numerical results of mean axial velocity profiles, at several axial locations in the combustion chamber. The employed DES model can predicts clearly the IRZ and the ORZ. For both measured and predicted profiles a similar tends are shown. Furthermore, the measured and the predicted velocity peaks mostly have the same values. For example, at $z/D = 0$ the velocity peak is about $1.5\ u_0$ which occurs away from the center line $\sim r/d = 0.5$ for both measured and predicted results. However, the employed DES model presents and adequate predictions on mean axial velocity profiles in each location.

4.3 Instantaneous temperature distribution

Figure 4 illustrates the detailed distribution of the instantaneous temperature in the combustion chamber. The burned gases reach a maximum temperature of 1700 K. Near the expansion plane the thin temperature gradient presents the reaction zone of the flame front. It is clearly seen that the flame front is wrinkled with both small and large scale structures. It assumes the typical shape for swirl-stabilized flames. It should be remarked that the leading edge of the flame is inside the contraction, and shows a tendency to flashback into the premixing tube.

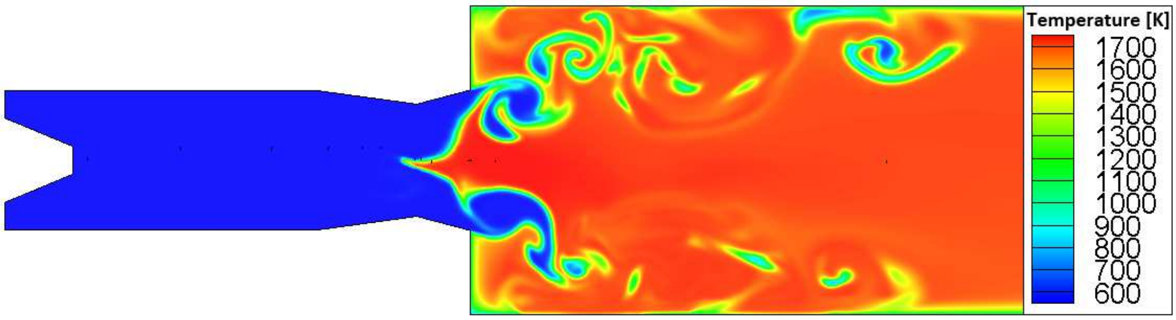

Figure 4. Instantaneous temperature distribution in the combustion chamber

4.4 Characterization of the PVC

Since the vortex breakdown appears around the center of the combustion chamber and provides a low pressure region. It is therefore possible to visualize the 3D flow structure of the PVC by plotting an iso-surface of a low pressure as sketched in Figure 5. It can be seen that the PVC performs a rotational motion around the central axis. The PVC extends to the radial direction in the combustion chamber .It is also a double coherent structure which branched in the converging-diverging nozzle. This explains why the leading edge of the flame appears in the contraction, because it is hanged in the branching of the double PVC.

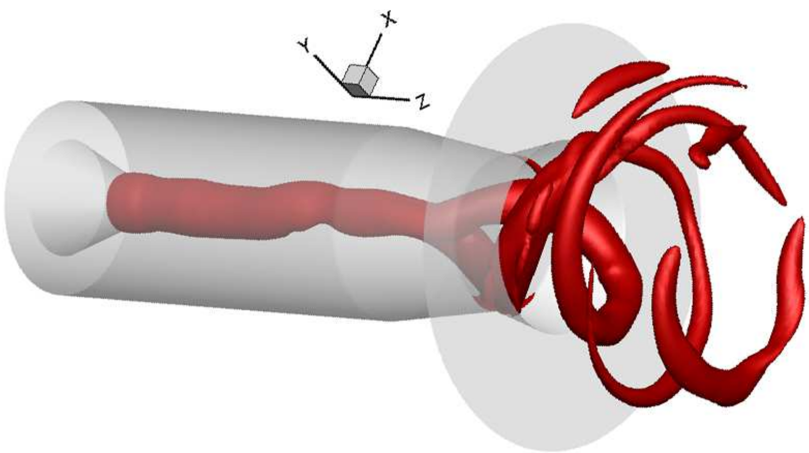

Figure 5. 3D Coherent structure double PVC

5 Conclusion

This work discusses an unsteady numerical simulation of the reacting swirling flow in a lean premixed burner, which is solved by ANSYS Fluent software. The combustor is operated with air and propane at atmospheric pressure and a global equivalence ratio $\Phi = 0.5$. Detached Eddy Simulation model and Finite-Rate/Eddy Dissipation model for turbulence-chemistry interaction are used. The applied approach is useful to capture the vortex-flame interaction, and the DES model can predict the unsteady behavior of the flow with all distinctive features. Comparing with experimental data, the performance DES in predicting the high swirling flow properties (axial velocity profiles) is competitive.

The dynamic of the flame and its interactions with the PVC is characterized. The flame front is wrinkled with both small and large scale structures .The IRZ extends inside the converging-diverging nozzle and subsequently the flame is stabilized upstream the combustion chamber inlet, showing a tendency to flashback in the contraction. The flashback might be prevented by the PVC originating in the same location. The PVC found as a double coherent structure and performs a rotational motion around the central axis.

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