LES of the interaction between a premixed flame and complex turbulent swirling flow

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Abstract. In this paper the Triple Annular Research Swirler, a fuel injector characterized by complex design with three concentric air passages, has been studied numerically. A swirl-stabilized lean premixed flame has been simulated by means of Large Eddy Simulation. The computations characterize successfully the dynamics of the flame and their interactions with the complex swirling flow. The flame is stabilized upstream the fuel injector exit, and the dynamics are led by a Precessing Vortex Core which seems to originate in the inner air passage. The results obtained by Proper Orthogonal Decomposition analysis are in agreement with previous findings in the context of swirling flows/flames.

1. Introduction

The dynamics of swirling flows and swirl-stabilized flames are still an open field of research. Swirl stabilization is a desirable choice because of enhanced mixing, flame compactness, no need for (cooled) bluff bodies. On the other hand, especially when dealing with very lean operation for low NOx emissions, see Lefebvre (1995), instability problems arise. Examples are helical instabilities, see the work of Shtork et al. (2008); Precessing Vortex Core (PVC), see the review of Syred (2006) or the work of Martinelli et al. (2007); flashback, we cite here a couple of works: Konle et al. (2008); Sommerer et al. (2004). The main goal of this work is to contribute to the understanding of the dynamics of swirling flames, which is crucial to predict, avoid and overcome stability problems. To do so, we choose a numerical approach and perform Large Eddy Simulations, LES, which guarantee the adequate resolution of turbulence in both space and time, enabling to resolve the dynamics of the flow and the flame. LES underwent enormous progresses in the last years and are nowadays a very promising tool for the study of flame instabilities (Poinsot & Veynante (2000)). Thanks also to the power increase of modern computers, it is nowadays possible to perform LES in cases of interest for real life applications. Therefore, as test case we study a complex geometry fuel injector, the Triple Annular Research Swirler, TARS, see Li & Gutmark (2005). Such device is characterized by a design similar to burners in place in aero-engines, and is therefore of industrial relevance. The stabilization mechanism is not trivial for this burner, for example in the work of Iudiciani et al. (2009) it was shown how flame stabilization could be achieved both with and without the existence of a Central Recirculation Zone (CRZ). Moreover, focusing on the interaction between swirling flames and flows is challenging given the complexity of the geometry. A way to extract the
dominant features of the flow from the LES data (as well as possibly experimental data), is
to post-process them by means of Proper Orthogonal Decomposition, POD, see Berkooz et al.
(1993) for a review. Because of its capability of highlighting coherent structures, such technique
has recently gained interest for the analysis of flame dynamics, we refer here the reader to the
works of Roux et al. (2008); Lacarelle et al. (2009); Steinberg et al. (2010); Iudiciani & Duwig
(2011)

2. Test case: TARS burner

The TARS fuel injector was developed by Delavan Gas Turbine Products, a division of Goodrich
Corporation, in collaboration with General Electric Aircraft Engines. It is meant to be a research
device, but has a complex geometry with a design typical of an aero-engine application. It is
characterized by three concentric air passages: outer, intermediate, and inner swirlers. The inner
and intermediate are axial swirlers, the outer is radial. Planar cuts of the TARS (longitudinal
and transversal cross sections) are shown in Fig. 1(a). The diameter of the nozzle at the outlet
of the TARS is \( D = 0.0508 \) m. The coordinates will be non-dimensionalized in the following
with respect to it. The swirlers are interchangeable with similar ones featuring different vane
angles and/or rotating direction (clockwise, counter-clockwise). In this numerical study, the
TARS featured co-rotating flow and vane angles equal to 50 degrees for all the three swirlers.
The operational conditions are reported in Table 1

![Figure 1. TARS geometry details](image)

**Table 1.** Operational conditions

| Air flow rate | Fuel flow rate | Eq. ratio | Reynolds no. | Inlet gas temp. | Ambient pressure |
|---------------|----------------|-----------|--------------|----------------|-----------------|
| \( \dot{m}_a \) | \( \dot{m}_f \) | \( \phi \) | \( Re \) | \( T_i \) | \( p_0 \) |
| 0.0164 kg/s | 0.00043 kg/s | 0.45 | 14000 | 670 K | 101325 Pa |
3. LES formulation

When dealing with reacting flows, both the turbulence and the chemistry, highly non-linear and coupled processes, should be simulated. Besides the classical Navier-Stokes formulation (continuity, transport of momentum and energy), one has to solve also transport equations for the chemical species involved in the reactions. When performing Large Eddy Simulations, the Navier-Stokes equations are filtered in space. In this way all the turbulent structures above the filter cut-off wavelength are resolved, while the unresolved components are modeled. Denoting the filtered quantities with a bar, and density weighted (Favre) filtering with a tilde, \( \bar{\dot{f}} = \frac{\partial \bar{f}}{\partial \bar{\rho}} \), the equations read, see Poinset & Veynante (2000):

\[
\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_i}(\rho \bar{u}_i) = 0
\]  

(1)

\[
\frac{\partial p \bar{u}_i}{\partial t} + \frac{\partial}{\partial x_j}(p \bar{u}_i \bar{u}_j) = -\frac{\partial \rho}{\partial x_j} \sigma + \frac{\partial}{\partial x_i}(\rho \bar{u}_i \bar{u}_j - \mu \bar{u}_i \bar{u}_j)
\]  

(2)

\[
\frac{\partial \bar{h}}{\partial t} + \frac{\partial}{\partial x_i}(p \bar{u}_i \bar{h}) = \frac{\partial}{\partial x_i} \left( p \bar{u}_i \bar{h} - \bar{\rho} \bar{u}_i \bar{h} + \lambda \frac{\partial \bar{h}}{\partial x_i} \right)
\]  

(3)

\[
\frac{\partial \bar{Y}_k}{\partial t} + \frac{\partial}{\partial x_i}(p \bar{u}_i \bar{Y}_k) = \frac{\partial}{\partial x_i} \left( p \bar{u}_i \bar{Y}_k - \bar{\rho} \bar{u}_i \bar{Y}_k + \rho D_k \frac{\partial \bar{Y}_k}{\partial x_i} \right) + \bar{\omega}_k
\]  

(4)

using Fick’s and Fourier’s laws for diffusion of mass and energy, respectively. The symbols used in equations (1-4) are the conventional ones: \( \rho \) denotes the density, \( u \) represents the velocity vector, \( p \) the pressure, \( Y_k \), \( D_k \) and \( \bar{\omega}_k \) are the mass fraction, the diffusivity, the reaction rate of the k-th species, respectively. \( T \) denotes the temperature, \( h \) is the total entalphy, \( \sigma \) is the viscous stress tensor, \( \lambda \) the thermal conductivity. The subgrid momentum transport term, \( \bar{p} \bar{u}_i \bar{u}_j - \mu \bar{u}_i \bar{u}_j \), is closed using the filtered Smagorinsky model introduced by Sagaut et al. (2000). The analogous terms in equations 3 and 4 are also modeled through a typical gradient assumption. An effective viscosity is introduced yielding effective Schmidt and Prandtl number equal to 1 (Duwig et al. (2011)). The production rate of the k-th species is computed through the typical Arrhenius expression. As a reaction mechanism, a global four-steps chemical scheme tailored for preheated very lean methane flames is chosen, see Kruger et al. (2011) for details. In this work, an implicit LES (ILES) closure is chosen for the filtered reaction rate terms (see Duwig et al. (2011)). It is therefore assumed that each computational cell is a perfectly stirred reactor, i.e. that the subgrid mixing is faster than chemical reactions. This assumption is reasonable given the high Karlovitz number estimated for this flame. Denoting with \( S_l \) and \( \delta_l \) the laminar flame speed and thickness, respectively, and with \( l_t \) and \( u' \) the turbulent length scale and velocity fluctuations, respectively, the Karlovitz number can be computed as \( Ka = \left( \frac{l_t}{S_l} \right)^{-\frac{1}{2}} \left( \frac{u'}{S_l} \right)^{\frac{3}{2}} \) (cfr. Poinset & Veynante (2000)). Performing a 1D analysis of the laminar flame using the GRI mechanism (see Smith et al. (2011)), one obtains \( S_l = 0.377 \, m/s \) and \( \delta_l = 0.00081 \, m \). From temporal statistics \( u' \simeq 12 \, m/s \) in the region of the flame. The turbulent length scale is less trivial to estimate. A reasonable value for \( l_t \), half the diameter of the narrowest vanes inside the TARS, yields \( Ka \simeq 160 \), supporting the perfectly stirred reactor hypothesis.

4. Numerical details

The computational domain is reported in Fig. 1(b). It contains a part of the plenum upstream the TARS, the TARS itself, the mounting plate, and a square confinement. The inlet is placed
at about 3D upstream the mounting plate. The confinement is about 4D x 4D x 5D. The origin of the coordinates is placed at the center of the TARS nozzle outlet, so that x/D=0 corresponds to the mounting plate. A 2.6 million cells unstructured mesh is used, although mostly composed by cubes, ensuring quality. Polyhedral cells are used only close to the boundaries to fit the geometry. Layers of refined cells are added in proximity of the walls, to better capture the gradients. The mesh is refined inside the swirlers and downstream the TARS it is progressively coarsened towards the outlet and the external boundary. At the finest level the dimension of a cubic cell is about D/100. Inlet and outlet boundary conditions are imposed in a classical way. At the inlet, constant top-hat axial velocity profile is imposed, so to fulfill the measured mass flow rate. Zero gradient condition is applied for the pressure, Dirichlet boundary conditions are imposed for the temperature and the species mass fractions, i.e. it is assumed that the mixture is perfectly premixed and homogeneous. At the outlet, the pressure is fixed (reference pressure = 1 atm) and Neumann boundary conditions are applied for the other variables. Concerning the walls, no slip condition is applied for the velocity, zero gradient for the pressure and the species mass fractions. For the temperature, a distinction is made for the confinement walls (denoted as “Wall 2” in Fig. 1(b)). A constant temperature of T=1100 K is imposed at the square confinement to take into account heat losses. The rest of the walls (“Wall 1” in Fig. 1(b)) are instead assumed to be adiabatic (zero gradient condition).

5. Proper Orthogonal Decomposition

The Proper Orthogonal Decomposition (POD) is a procedure to obtain a modal decomposition of a given ensemble of data, for example a certain number of realizations of the flow (instantaneous samples) \( q(x,t) \). Applying the POD procedure an instantaneous realization at time \( t_k \) \( q(x,t_k) \) can be reconstructed in terms of a basis of eigenfunctions \( \psi_j \), which represent typical modes of the ensemble:

\[
q(x,t_k) = a_0 \psi_0 + \sum_{j=1}^{\infty} a_j(t_k) \psi_j(x)
\]  

In eq. (5) \( \psi_0 \), or mode 0, represents the time averaged field while subsequent modes capture the fluctuations and therefore the dynamics. The coefficients \( a_j(t_k) \) are referred as time coefficients. POD can be seen as analogous to the Fourier modal analysis. Whereas in the Fourier decomposition the modes are a-priori chosen to be sinusoidal, in POD the basis is empirical, in the sense that it depends on the data. For details the derivations and the implementation of POD the reader is referred to Berkooz et al. (1993); Smith et al. (2005). The modes are ordered in descending variance content. Thus, if the variable \( q \) to which the decomposition is applied represents the velocity, the first POD modes have the highest turbulent kinetic energy content and typically identify coherent structures.

6. Results

In Fig. 2 an instantaneous snapshot is reported in a two dimensional cut on a plane along the symmetry axis \( (y/D=0) \). The contourplot of the axial velocity is shown, together with a temperature iso-line. It is possible to see the complex flow/flame configuration for this burner. The highest velocities are found in the narrow vanes of the swirlers. The three jets coming out of the three air passages mutually interact with each other and merge in a unique swirling jet at the expansion plane. This jet surrounds a typical central recirculation zone (CRZ) caused by vortex breakdown. The flame is stabilized at the internal shear layer between the swirling jet and the CRZ, and at the external shear layer with the surrounding air. The flame can be seen in better details in Fig. 3, where the contour plot of the temperature is reported. In the bottom part of the figure a perpendicular cross section is also shown (relative to the axial position at
the expansion plane, indicated by the second white solid line in the top part of the figure.) 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, though, that the leading edge of the flame is inside the TARS, and shows a tendency to flashback into the central swirler. Such tendency is highlighted in Fig. 4 where three subsequent 3D visualizations of the flame are reported. More specifically an iso-surface of the temperature is visualized, coloured according to the axial velocity. The time is non-dimensionalised with respect to a reference time \( \tau = D/U_0 = 0.001 \text{s} \). The reference velocity \( U_0 = 50 \text{m/s} \) is a typical velocity in the swirler vanes. It can be seen that the leading edge of the flame is spinning around close to the inner swirler tip. It suggests the existence of a PVC. The wrinkling of the flame is visualized in better details and it can be seen how the flame interact with the external shear layer, where isolated pockets of burnt gases are shed downstream.

The PVC, and in particular the way it interacts with the flame, can be more clearly interpreted from Fig. 5. The graph reports the temperature variations in a \( y-t \) plane at three different axial
locations (Relative to the three solid lines in Fig. 3). Looking at the axial location $x/D=0$ (Expansion plane, middle picture in Fig. 5), the flame moves up and down in the y-direction. One can clearly count 4 periods in a time interval of $5\tau$, corresponding to a Strouhal number of 0.8. Although the signal is not as strong, since the flame does not always cut the y axis, the same frequency can be seen at the axial location close to the inner swirler tip ($x/D=-0.2$). Downstream the TARS (at $x/D=0.3$, right hand side on the picture) the interaction between the shear layer and the flame is more irregular. The PVC seems to originate from helical structures in the central air passage, already observed for the same burner in a previous work in a cold case, see Iudiciani et al. (2011). In Fig. 6 a time sequence of snapshots over about one cycle of the dynamics is reported. The images show a close-up view at the tip of the central inner swirler, in a longitudinal plane ($y/D=0$). The velocity vector map and a temperature isoline are reported. The precessing motion of the 3D flame results in a vertical movement in this plane. Such flapping motion in this plane is due to the alternate passage of counter-rotating vortices in the inner swirler, which are a longitudinal planar cut of the 3D helical structures, see the works of Iudiciani & Duwig (2011) and Steinberg et al. (2010) for a similar behaviour in other swirling burners. The presence of a PVC is confirmed by the POD analysis in the perpendicular
Figure 5. Temperature y-t plane map. Units in Kelvin degrees.

Figure 6. Close-up at the inner swirler tip. Vector map and temperature iso-line (T=800K).

plane at x/D=0 (Expansion plane, middle solid line in Fig. 3). In Fig. 7 the first three modes are reported (Axial velocity). As stated in section 5 Mode 0 represents the mean field. It is not perfectly axial-symmetric, due to the low number of samples available for the POD analysis.
(about 150 samples). The complexity of the flow should be once more remarked. One can see how the influence of the eight vanes of the intermediate and outer swirler is visible. Despite the low number, the samples span over a time of about 35τ and are enough to capture the PVC, which is dominating the dynamics (captured by the subsequent modes, we recall once again). Modes 1 and 2 in Fig. 7 are a pair of modes shifted by π/2 in space. They capture the offset in the dynamics of the CRZ, which otherwise appears centered in the mean field. They are characterized by the typical shape for the PVC modes in a cross section perpendicular to the axis. Similar results were also found in other works applying POD to analyse swirling flows, e.g. see Duwig & Fuchs (2007); Iudiciani & Duwig (2011); Oberleithner et al. (2011).

Figure 7. Pod Modes $\psi_0(x)$, $\psi_1(x)$, $\psi_2(x)$. $x/D=0$. Axial velocity contour plot. Arbitrary scale. The white line denotes the TARS nozzle position.

7. Concluding remarks

This work confirmed that LES of flames of industrial interest are nowadays possible. A burner with a design close to real aero-engine applications, the TARS, has been simulated. The flow coming out of the TARS is reflecting the complex geometry: three swirling jets merge together at the TARS outlet. The recirculation zone extends inside the TARS and subsequently the flame is stabilized upstream the burner exit, showing a tendency to flashback in the inner swirler. The flashback might be prevented by the PVC originating in the same inner swirler. The PVC extends to the whole burner and seems to lock the two outer annular jets despite their higher momentum, at least in the vicinity of the burner nozzle. The dynamics of the flame and their interactions with the flow are characterized. The PVC drives the dynamics of the flame which is dragged into a precessing motion. The alternate passage of the helical structure results in a flapping motion of the flame tip in a 2D planar cut. This was already observed in other works, see for example Iudiciani & Duwig (2011); Steinberg et al. (2010), and is of interest for experimental studies, since diagnostics techniques often provide 2D data. POD analysis was then performed in a transversal cross section. It highlighted a pair of modes with typical shape of two embracing helices. In the context of swirling flows/flames, such modes were reported by POD also in previous works for other burners. They might therefore be set as a benchmark to validate the existence of a PVC when evaluating numerical or experimental data.

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