Chapter 1

USING LARGE EDDY SIMULATIONS TO UNDERSTAND COMBUSTION INSTABILITIES IN GAS TURBINES

Thierry Poinsot*
IMF Toulouse
Av.C. Soula, 31400 Toulouse Cedex
France

Jorg Schluter, Ghislain Lartigue, Laurent Selle
CERFACS
42 Av. Coriolis
31057 Toulouse Cedex
France

Werner Krebs and Stefan Hoffmann
Siemens AG KWU
45466 Mulheim
Germany

Abstract

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*Corresponding author, email: poinsot@cerfacs.fr

Introduction

Unsteady reacting flows can not always be computed using classical Reynolds Averaged Navier Stokes (RANS) approaches. Turbulent combustion phenomena such as flame flashback, blowoff or combustion instabilities (McManus et al., 1993; Colin et al., 2000) are not well defined in a RANS framework where only time- averaged quantities are solved for. Moreover, such flows are strongly coupled with acoustic waves and their computation often requires high-order schemes and low turbulent viscosity. For such problems, large eddy simulation (LES) techniques are viewed today as a promising tool. More specifically, LES is the best tool to address a question of interest for modern lean combustors: to satisfy emission regulations, modern gas turbines operate in very lean combustion regimes. These flames are extremely sensitive to combustion oscillations but the exact phenomena leading to instabilities are still discussed. A central question for modeling approaches is to determine the phenomena inducing unsteady reaction rates, required to sustain oscillations, when an acoustic wave enters the combustion chamber. For most gas turbines, this question is linked to the development of large scale vortices at the turbine inlet. These large-scale structures may be due to different causes:

- An amplification of the natural hydrodynamic modes of the flow, especially the precessing vortex core (PVC) phenomenon well known in swirling flows

- A purely acoustically forced mechanism similar to vortices formed in impulsively started jets in which a velocity excursion at the chamber inlet creates a mushroom-shaped vortex.

In the present work, LES was used to study the instabilities appearing in a swirled configuration, close to an industrial gas turbine. Both non-reacting and reacting cases (in premixed mode) were studied and compared. For non-reacting cases, comparisons with experiments performed at University of Karlsruhe are presented in terms of velocity field. For non-reacting flows, no experimental data were available and a simple comparison between non-reacting and reacting cases is proposed in terms of instabilities observed in the two LES.

1. Configuration

A sketch of the configuration is given in Fig. 1.1. The premixed gases are injected into the chamber through a diagonal swirler where vanes are used to swirl the flow. For the present LES, the computation starts

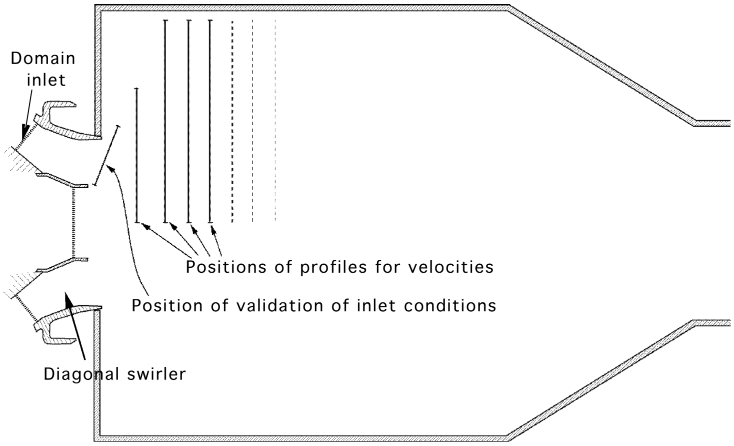

Figure 1.1. Mean reaction rate as predicted using the Magnussen eddy dissipation model (Mean flow simulations).

after these vanes and swirl is introduced as a boundary condition at the domain inlet to minimize the computational load.

2. Models and numerical tool

For this work, the AVBP solver (www.cerfacs.fr/cfd) was used. This solver includes the following features:

- An LES model for combustion based on the Thickened Flame model proposed by Angelberger et al., 1998, Colin et al., 2000 and Légier et al., 2000. This model thickens reaction zones but reduces to normal LES mixing models away from flame fronts. It has the capability of handling pure mixing, premixed flames as well as diffusion flames with fast chemistry.

- Acoustic boundary conditions which allow the control of waves entering and exiting the combustion chamber (Poinsot and Veynante, 2001) and therefore the amount of acoustic power left in the chamber.

- An hybrid mesh solver in which these models are implemented (Schönfeld and Rudgyard 1999). This solver uses high-order schemes on unstructured grids (Colin and Rudgyard, 2000) which are an essential feature of adequate LES simulations.

- A filtered Smagorinski model to evaluate subgrid scale stresses. This model has a sufficient accuracy for such applications and is much simpler to implement than dynamic models on this kind of meshes (Ducros et al., 1997).

3. Inlet boundary conditions

Fixing boundary conditions in complex geometries is one of the difficult tasks of LES. For the present case, profiles of velocities were measured at the entrance of the chamber (ie at the end of the diagonal inlet, see Fig. 1.1) and boundary conditions at the inlet of the computational domain were tuned (in terms of axial and swirling velocities) until a reasonable agreement was found at this first station between measured mean velocities and LES data (Schlüter 2000, Schlüter et al., 2001). This set of conditions were then conserved for all computations.

4. Non-reacting mean flow results

The results obtained at University of Karlsruhe include measurements (using LDA) of the axial velocity u_x, of the circumferential velocity u_θ and of their RMS values. A full discussion of these results compared to LES data is given in Schlüter et al., 2001. Only the main results are summarized here. Fig. 1.2 shows profiles of the mean velocity $\bar{u}_x$ obtained by LES and experiment. Fig. 1.3 shows profiles of the mean circumferential velocity $\bar{u}_\theta$. All velocities have been normalized by the bulk viscosity U_b determined by the total volume flux and the surface of the burner nozzle.

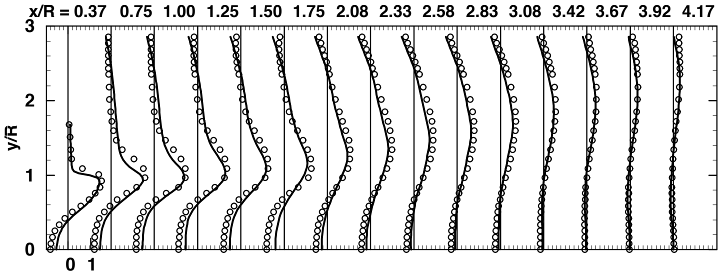

Figure 1.2. Transverse profiles of mean axial velocity $\bar{u}_x$ on various stations along the burner axis. Lines: LES results. Circles: experiments

A very good agreement is obtained between LES and experimental results. Similar agreements are obtained for RMS values, confirming the capacity of LES to predict such swirling flows correctly.

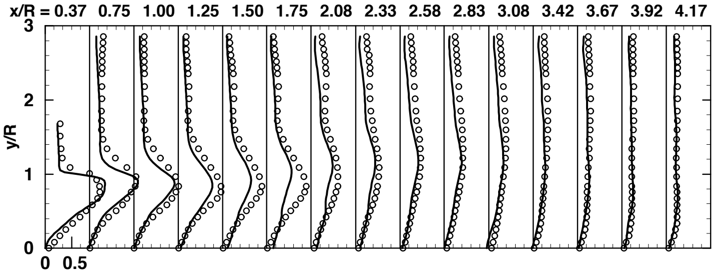

Figure 1.3. Transverse profiles of mean circumferential velocity $\bar{u}_\theta$ on various stations along the burner axis. Lines: LES results. Circles: experiments

5. Non-reacting flow instabilities

In addition to mean flow fields, LES also provides insight into the unsteady structure of the flow. In the present case, the non reacting flow is highly unsteady. Oscillation frequencies are in the range $St = fD/U_b = 0.6$ where D is the burner diameter. Instantaneous snapshots of the magnitude of the circumferential velocity are given in Fig. 1.4 to 1.6 for three instants separated by 0.8 ms.

Fig. 1.4 to 1.6 reveal that vortex shedding takes place at the chamber inlet. This shedding takes place on the inner cone of the swirler, aternatively between opposite sides of the chamber inlet and lead to the formation of a single vortex spiral oscillating inside the burner, a configuration very similar to classical PVC. Note that vortices are also formed on the outer side of the cone but with smaller intensity.

6. Reacting flow simulations

The existence of a strong PVC instability with cold flow leads to the question of its existence for reacting flows. This was investigated using LES of a premixed case with reaction activated. The main result is that combustion seems to inhibit the PVC mode observed in the cold flow. Fig. 1.7 shows a snapshot of temperature isosurfaces in two planes passing through the axis of the burner. Very limited vortex shedding is observed in this case and no PVC seems to appear in the flow, indicating that the strong unstable mode observed without combustion may be damped when reaction is turned on. This results has probably no generic character and it is well known that combustion can also destabilize flows. However, in the present burner, and for this regime, these results suggest that hydrodynamic instabilities (and especially PVC) cannot explain reacting flow instabilities. Such instabilities must involve a strong acoustic forcing at the inlet and cannot appear only by

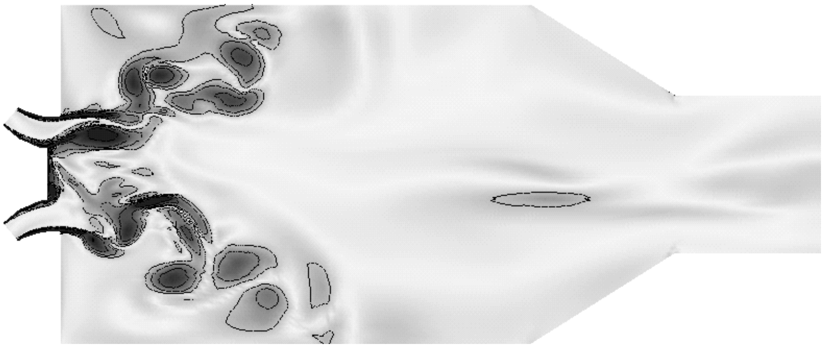

Figure 1.4. Magnitude of the circumferential velocity in the central plane of the burner. Instant t_0.

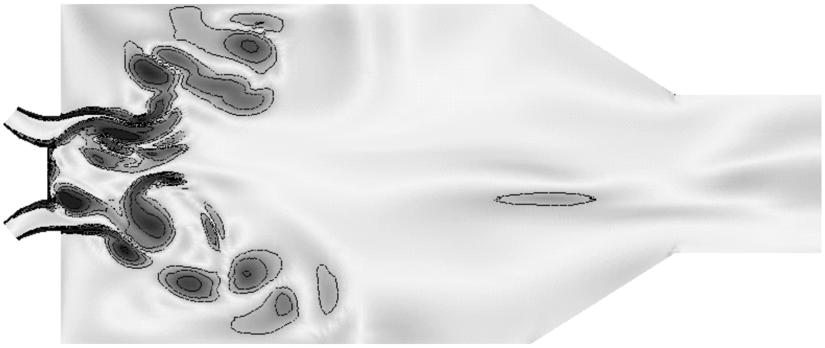

Figure 1.5. Magnitude of the circumferential velocity in the central plane of the burner. Instant t_0+0.8 ms.

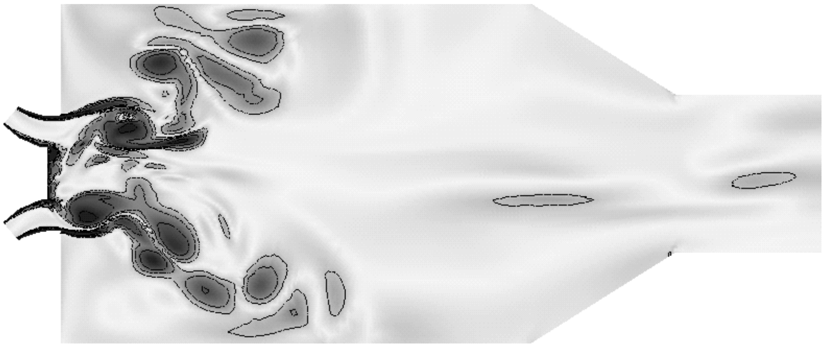

Figure 1.6. Magnitude of the circumferential velocity in the central plane of the burner. Instant t_0+1.6 ms.

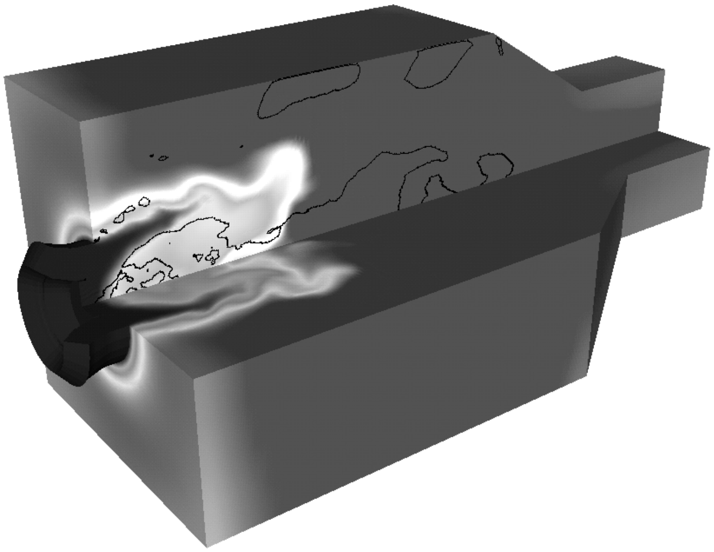

Figure 1.7. Temperature field in two planes for the reacting flow case.

hydrodynamic instabilities. Of course, both phenomena (acoustic and hydrodynamic) are probably coupled in real devices.

7. Conclusions

LES has been performed in a complex gas turbine configuration, both with and without combustion. This shows first the feasibility of such studies using available tools and computers. In the present application case, LES was first used to compute the mean flow field without combustion: comparison with experimental data of Karlsruhe showed very good agreement. LES also revealed the existence of a strong precessing vortex core in the absence of flame, which disappears when combustion is activated.

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