LES of Chemical and Acoustic Forcing of a Premixed Dump Combustor

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Abstract.
This paper describes first steps towards the development of a Large Eddy Simulation (LES) code able to compute combustion instabilities in gas turbines. This code was used to compute the forcing of an experimentally investigated premixed dump combustor. It is shown that the main effect of acoustic waves entering the combustion chamber is to create large vortices and unsteady heat release when these vortices burn. Another effect of waves entering the combustor is to modulate the fuel and air flow rates produced by the feeding lines. In this case the equivalence ratio of the mixture entering the combustor may also vary. This was investigated in a "chemical effect" simulation where the inlet equivalence ratio fluctuates but the total flow rate remains constant. For perturbations from stoichiometric burning, this mechanism was shown to induce less destabilizing effects than the purely aerodynamical mechanism due to vortex formation and combustion. It is shown that the LES methodology developed is able to reproduce the experimentally observed phase shift between acoustic excitation and total reaction rate in the chamber.

Keywords: LES, combustion, instabilities

1. Motivations and objectives

Computing unsteady reacting flows accurately can not always be achieved using classical Reynolds Averaged Navier Stokes (RANS) approaches. Turbulent combustion phenomena such as flame flashback, blowoff or combustion instabilities (McManus et al 1993, Poinsot and Candel 1988, Candel et al 1996) are not well defined in a RANS framework where only time- averaged quantities are solved for. For such problems, where the intrinsically unsteady nature of the flow makes RANS clearly inadequate. large eddy simulation (LES) techniques are viewed today as a promising tool.

Interestingly, LES may be easier to perform in unsteady flames than in steady turbulent flames: flows submitted to instabilities are dominated and controlled by very large eddies and, accordingly, it is

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likely that a limited range of eddies has to be incorporated to describe the interaction between turbulence and chemistry in such flows (Bray et al 1989, Baum et al 1994).

This paper describes a LES study of phenomena related to the occurence of combustion instabilities in a laboratory burner. More specifically, we use LES 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. This may be due (at least) to two main effects:

- the formation of vortices in the combustion chamber. These vortices capture a large pocket of fresh gases which burns only at later times in a violent process leading to small scale turbulence and high reaction rates.
- a modification of the fuel and oxidizer flow rates when the acoustic wave propagates into the fuel and air feeding lines (Lieuwen & Zinn 1998). This will lead to a change of the equivalence ratio and therefore to a modification of the burning rate when these pockets enter the chamber. If the burner operates in a very lean mode, this effect may be important since a non-flamable mixture may enter the combustion zone.

The objective of the present work is to examine, using LES, which mechanism is predominant in the case of a backward facing step premixed burner developed at Ecole Centrale Paris (ECP). An extensive set of experimental results is available for this burner (Poinsot et al 1986, 1987, 1988) and this configuration is also similar to many classical combustion instabilities experiments (see for example Keller et al 1981) and multiple industrial devices. To achieve this objective, multiple tools were integrated:

- A LES solver able to handle complex geometries. Multiple techniques have been proposed in the past to perform LES of turbulent premixed combustion (Menon and Kerstein 1992, Bourlioux et al 1996, Smith and Menon 1996, 1997, Im et al 1996, Piana et al 1996, 1997, Veynante and Poinsot 1997a,b, Menon & Chakravarthy, 1999). Few of them have been used in a realistic configuration (see for example Kailasanath et al 1985, 1991 or Veynante and Poinsot 1997b). Real combustion chambers will require meshes able to deal with highly complex geometries. For the present work, we used an hybrid mesh code called AVBP.

- The choice of a proper chemical description remains a critical issue in all reacting flows. In the present study, a new technique called ICC (Integrated Complex Chemistry) is used to construct reduced chemical schemes able to predict changes in equivalence ratio for methane and propane.
- Thermal boundary conditions at the walls of the combustion chamber control flame stabilization and quenching (Veynante and Poinsot 1997b). These conditions are sometimes unknown. For the present study, where the configuration corresponds to a burner developed at Ecole Centrale Paris (ECP) and built with ceramic plates, walls are assumed to be adiabatic (Poinsot et al 1987).
- to describe flame - turbulence interactions we used the TFLES model originally presented in (Angelberger et al 1998). It is based on the Thickened Flame (TF) approach initially proposed by O'Rourke and Bracco (1979).

Section 2 describes the single-step chemical scheme used for this work. Section 3 presents the base of the TFLES model. The AVBP code used for our computations is presented in section 4. Section 5 describes the configuration of the ECP burner, along with boundary conditions and the mesh used. Section 6 shows the results of the unforced flow in the ECP burner. In section 7 the relative importance of acoustic and chemical forcing are evaluated. Finally section 8 presents a more detailed investigation of the acoustic forcing.

2. Reduced chemistry for LES

Our objectives require to compute flames with variable equivalence ratio and an important task is to derive a simplified kinetic scheme which can closely predict several global flame properties. This was done for lean propane / air mixtures for pressure $P = 1$ atm and fresh gases temperature $T_0 = 300$ K, corresponding to the operating conditions of the Ecole Centrale experiment.

The development of a simplified scheme was obtained through the ICC technique (Mantel et al 1996; Bedat et al 1997, 1999). Traditionally simplified schemes, such as one-step chemistry, have been derived by simply matching laminar flame speeds and such schemes have been extensively used in simulations of turbulent reacting flows (Westbrook and Dryer 1981). The ICC technique adds to laminar flame speeds the prediction of strain rate effects and the description of flame structure using simple chemical schemes. This is an important advantage because reacting fronts can be subjected to a large range of strain

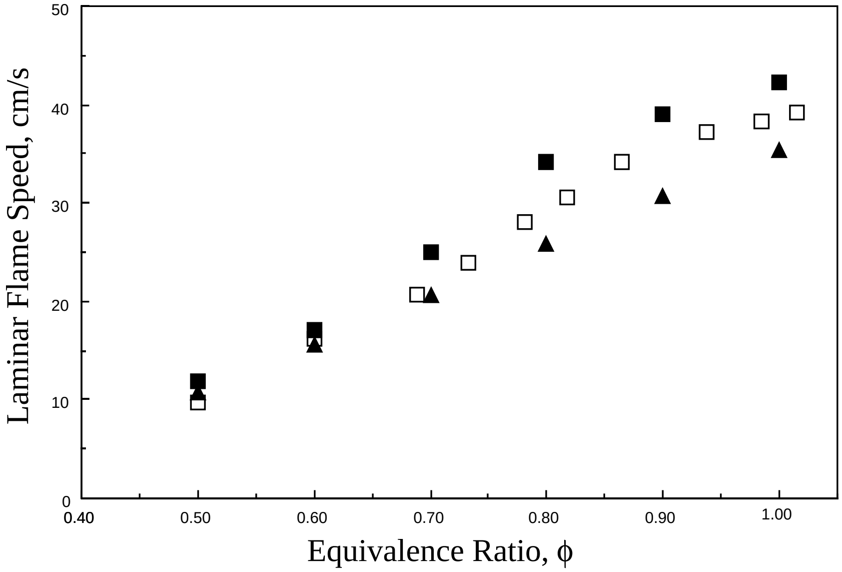

Figure 1. Variation of laminar flame speed s_l^0 with equivalence ratio for atmospheric C_3H_8/air mixtures with reactants at initial temperature $T_0 = 300$ K. squares: experiments; filled squares: detailed chemistry computations; triangles: ICC computations.

rates in multi-dimensional, high-Reynolds-number simulations. In the previous ICC studies (Mantel et al 1996; Bedat et al , 1997) simplified chemical mechanisms were derived for a fixed equivalence ratio. In the present study the ICC technique was extended in order to account for variable equivalence ratio as well as for flame thickening imposed by the necessity to resolve the flame structure using an LES grid.

A one-step global chemistry model was derived, describing several flame properties of lean propane/air mixtures at $P = 1$ atm and $T_0 = 300$ K. The scheme is:

$$C_3H_8 + 5O_2 \rightarrow 3CO_2 + 4H_2O$$

with the specific reaction rate given by: $\dot{\omega} = [C_3H_8]^a[O_2]^b A exp(-E_a/RT)$ where $[C_3H_8]$ and $[O_2]$ are the molar concentrations of the reactants, a and b the corresponding concentration exponents, A the pre-exponential factor, E_a the activation energy, R the perfect gas constant, and T the absolute local gas temperature. After comparison with the full chemistry results, the following parameters were kept for propane: $a = 1.0$, $b = 0.5$, $A = 1.60E09$ (cgs units), $E_a = 14,000$ (cal/mole).

Fig. 1 depicts the experimental (Vagelopoulos and Egolfopoulos, 1998) laminar flame speeds, s_l^0, for atmospheric, lean C_3H_8/air mixtures as well as the predictions obtained by using detailed chemical kinetics and transport and the proposed simplified scheme. The agreement is satisfactory. The detailed chemistry for C_3H_8 was compiled by combining a C3 submechanism (Pitz and Westbrook, 1986) with the well-established C1-C2 GRI 2.1 mechanism (Bowman et al , 1996).

3. The TFLES model

One of the main difficulties when simulating premixed flames in an LES context arises from the fact that typical flame thicknesses are of the order of 0.1 mm, i.e. of the order or smaller than the usual LES mesh sizes. This implies that the reaction progress variable is a stiff variable and the flame front can not be resolved on the LES mesh. For the present computations we chose to use the Thickened Flame LES (TFLES) approach (Angelberger et al 1998).

The basic idea is to artificially thicken the flame front by a factor F so that the progress variable can be resolved on the LES mesh, while maintaining the laminar flame speed at its original value s_l^0. Premixed flame theory shows that this is easely achieved by multiplying the species and temperature diffusivities by F while dividing the preexponential factor by the same factor. The value of F is typically chosen such that the thickened flame is resolved on 10 grid points, i.e. $F\,\delta_l^0 \approx 10\,\bar{\Delta}$ where $\bar{\Delta}$ is the mesh size.

As discussed in (Angelberger et al 1998) and (Colin et al 1999) the thickening of the flame implies that flame-turbulence interaction is modified as the Damköhler number Da comparing turbulent and chemical time scales:

$$Da = \frac{\tau_t}{\tau_c} = \frac{l_t}{u'}\frac{s_l^0}{\delta_l^0}$$

is decreased by the factor F when thickening the flame. Thus the response of the thickened flame to the spectrum of eddies found in turbulent flows will not be the same as that of the unthickened flame. To account for this a so called efficiency function E is introduced that can be seen as a sub-grid scale model for turbulence-flame interaction. This efficiency function is the core of the TFLES model and it has been derived using DNS studies of flame-vortex interactions and spectral analysis (Angelberger et al 1999).

The resulting evolution equation for the fuel mass fraction takes the form:

$$\frac{\partial \rho Y_F}{\partial t} + \nabla \cdot (\rho\,\tilde{\mathbf{u}}\,Y_F) =$$
$$\nabla \cdot (\rho\, D\, F\, E\, \nabla Y_F) + \frac{A}{F}\, E \frac{\rho Y_F}{W_F}\frac{\rho Y_O}{W_O} \exp\left(-\frac{E_a}{RT}\right)$$

The equations for oxidizer mass fraction and temperature are equivalently expressed. This approach is not based on a filtering of the fuel mass fraction equation (although it may be derived using such techniques). It achieves the goal of propagating the flame front at a speed of $E\,s_l^0$ while maintaining a constant flame front thickness (and thus the resolution of flame gradients).
The efficiency function is modelled as:

$$E = \frac{1 + \alpha \Gamma\left(\frac{\Delta_e}{\delta_l^0}, \frac{u'_{\Delta_e}}{s_l^0}\right)\frac{u'_{\Delta_e}}{s_l^0}}{1 + \alpha \Gamma\left(\frac{\Delta_e}{\delta_l^1}, \frac{u'_{\Delta_e}}{s_l^0}\right)\frac{u'_{\Delta_e}}{s_l^0}}$$

with

$$\Gamma\left(\frac{\Delta_e}{\delta_l^1}, \frac{u'_{\Delta_e}}{s_l^0}\right) = 0.75 \exp\left[-\frac{1.2}{\left(u'_{\Delta_e}/s_l^0\right)^{0.3}}\right]\left(\frac{\Delta_e}{\delta_l^1}\right)^{\frac{2}{3}}$$

$\alpha$is a model constant and δ_l^1 the thickened flame thickness $\delta_l^1 = F\delta_l^0$. The subgrid-scale turbulent velocity u'_{Δ_e} at the filter size Δ_e is estimated as:

$$u'_{\Delta_e} = c_2\,\bar{\Delta}\,\nabla \times (\nabla^2(\tilde{u}))$$

where $\tilde{u}$ is the resolved velocity corresponding to the mesh size $\bar{\Delta}$ and $c = 2.0$ is a model constant. Justifying the expression for u'_{Δ_e} is not the aim of this paper and the reader is referred to (Colin et al 1999) for a complete description. We just want to emphasize the main advantage of this estimation:

- The operator used to estimate u'_{Δ_e} is local and easely computed using finite volume techniques.
- The filter size Δ_e of this operator has been shown to be sufficient to account for the response of the thickened flame to the turbulent eddies in the flow. Note that thus the efficiency function does not only take into account eddies smaller than $\bar{\Delta}$ but also eddies of sizes up to $\Delta_e = 10\bar{\Delta}$ (that are resolved on the LES mesh, but to which the thickened flame does not respond like the real one).
- It is constructed to eliminate the dilatational part of the velocity field for the evaluation of u'_{Δ_e}. Only the rotational part of the resolved velocity field – which is directly related to eddies – is considered. This ensures that u'_{Δ_e} is zero in a laminar flame (as expected intuitively) and

that the TFLES model will propagate an unstrained lamianr flame at the speed s_l^0.

4. Implementation into the AVBP code

The TFLES model has been implemented into the AVBP hybrid flow solver. This code solves the compressible and reactive Navier-Stokes equations on hybrid meshes. Space and time discretisation is done using the 3rd order, explicit, finite volume scheme TTGC (Colin & Rudgyard 1999). AVBP has been built on top of the parallel library COUPL produced jointly by CERFACS and Oxford University. It has been used for a variety of unsteady flows using DNS and LES (Nicoud et al 1996, Nicoud 1997, Ducros et al 1997).

The complete LES model consists of two parts:

- A filtered Smagorinsky LES model is used to estimate the subgrid-scale transport terms for the momentum equation in a classical way. The LES filter size is the mesh size $\bar{\Delta}$.
- The TFLES model is used to compute the transport terms for species mass fractions and temperature as well as the reaction rates as shown above on the fuel mass fraction. The TFLES model should hereby be viewed as a mean of propagating a premixed flame on a coarse grid, much like e.g. G-equation techniques. The Arrhenius expression for the reaction rate makes use of the C_3H_8 chemistry for variable equivalence ratio described above.

The NSCBC characteristic method is used to impose flow conditions on the boundaries of the domain (Poinsot & Lele 1992).

5. Configuration and numerical setup

The configuration studied here is displayed on Fig. 2. An acoustic wave traveling along the air feeding line of a backward facing step combustor introduces an air flow rate perturbation $\dot{m}_a'$ of the mean air flow rate $\dot{m}_a$. The mean equivalence ratio is ϕ. When the acoustic wave passes near the gas injection system, a fluctuation of the fuel flow rate $\dot{m}_f'$ is created. The perturbation of the equivalence ratio ϕ' due to the acoustic wave is given by: $\frac{\phi'}{\phi} = \frac{\dot{m}_f'}{\dot{m}_f} - \frac{\dot{m}_a'}{\dot{m}_a}$

This perturbation of the equivalence ratio will influence the burning rate. But the hydrodynamic effect of $\dot{m}_a'$ is also to induce the formation of a vortex near the chamber dump. These two effects may be isolated by performing the following simulations:

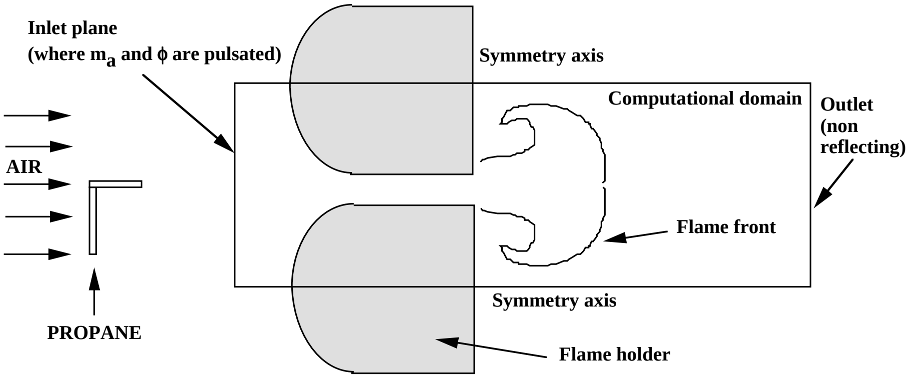

Figure 2. Configuration for simulations of combustion instabilities: the propane - air burner used by Poinsot et al (1987). Only one of the injection slots is computed (the real system had five slots). The computational domain is 22.4 cm long and 2 cm high.

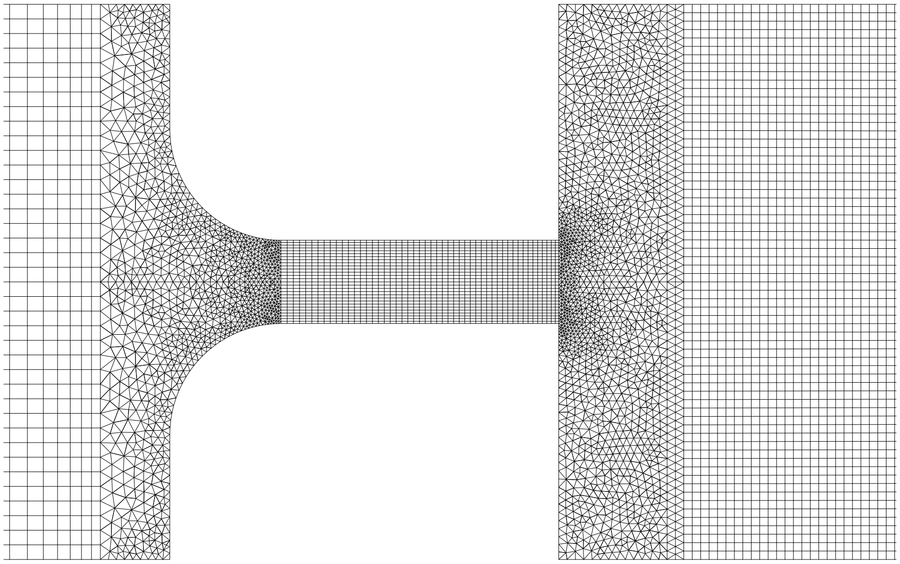

Figure 3. Hybrid 2D mesh of the ECP burner. Close-up view of the backward facing step.

- Case A: Pure aerodynamical (or acoustic) forcing of the chamber with $\phi' = 0$. In this case the inlet flow rate fluctuates but the equivalence ratio remains constant. This may be achieved for example by assuming that the distance between the fuel injector and the chamber is very long or assuming that both fuel and air lines react in the same way to acoustic perturbations (i.e. $\dot{m}'_f/\dot{m}_f = \dot{m}'_a/\dot{m}_a$).
- Case C: Pure chemical forcing of the chamber with $\dot{m}'_a = 0$ and $\dot{m}'_f \neq 0$ but remaining small so that only the inlet equivalence ratio is modulated and the total inflow rate $\dot{m}_a + \dot{m}_f$ is kept constant. This is an idealized case where only changes in equivalence ratio at the inlet perturb the burner. In reality these equivalence ratio modulation will always be associated with non-negligible flow rate modulations. The aim is to isolate the effect of chemical forcing from the acoustic. In the computation the equivalence ratio is modulated by pulsating the fuel mass fraction at the inlet while keeping the total inflow rate constant.

Obviously real situations correspond to cases where chemical and acoustic forcing are combined. In the ECP burner mixing of fuel and air was achieved far upstream of the combustion chamber so that it is expected that only acoustic forcing is significant in the experiment.

The combustion chamber is computed as an amplifier system (and not as a resonator): inlet and outlet boundary conditions are non reflecting and all acoustic waves produced in the combustor are allowed to leave the chamber so that no self-induced low-frequency mode can occur. The combustor can then be forced to study its response. Forcing is introduced at the inlet of the combustor by modulating the incoming acoustic wave or the incoming gas equivalence ratio following the NSCBC technique (Poinsot and Lele 1992).

All computations were performed in two dimensions since flow visualizations have indicated that large scale structures were 2D in this chamber. The hybrid mesh used in our computations is shown in fig. 3. It consists of 5000 tetrahedral cells in the vicinity of the backward facing step and 45000 hexahedral cells elsewhere. Typical simulations run during 500000 iterations, corresponding to 100 acoustic travel times in the chamber and more than 4 convective times. Initialization of computations in such cases is not simple since the LES code has low levels of dissipation: the computation starts from an initial state where a strip of fresh gas is located in the combustion chamber and surrounded by two strips of burnt gas on each side. To allow stabilization during this first phase, artificial viscosity (fourth-order) is used. After a few transit times in the burner, artificial viscosity is suppressed.

The next sections will first describe the flow without forcing and then the results on the relative effect of aerodynamic and chemical forcing.

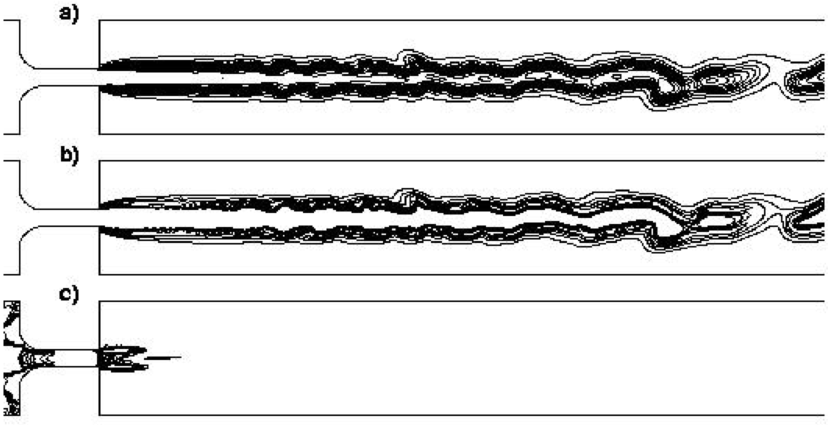

Figure 4. Instantaneous fields of temperature (a), reaction rate (b) and subgrid scale turbulent velocity (c) for an unforced regime.

In a last step aerodynamic forcing results are compared to experimental results.

6. Flow without forcing

Simulations were first performed for the unforced flow in the ECP burner. The operating point corresponds to an inlet temperature of 300 K, an equivalence ratio of 1, an inlet velocity of 6.4 m/s. The flame speed is 0.36 m/s and the adiabatic flame temperature 2190 K.

A typical snapshot of the unperturbated flow for this regime is given in Fig. 4. The flame is only slightly corrugated and corresponds to the state observed in the experimental set-up in the absence of instabilities (Fig. 6 in Poinsot et al 1987).

7. Comparison between different forcings

The first excitation case corresponds directly to the experiment of Poinsot et al (1987): the objective is to reproduce the combustor response to a 530 Hz excitation of the inlet flow rate corresponding to one of the strongest instability modes observed in the chamber. More precisely, LES is used to measure the time delay between inlet flow rate perturbations and reaction rate oscillations. The wave amplitude is chosen to induce a flow rate change equal to 50 percent of the mean flow rate. The forcing frequency is 530 Hz.

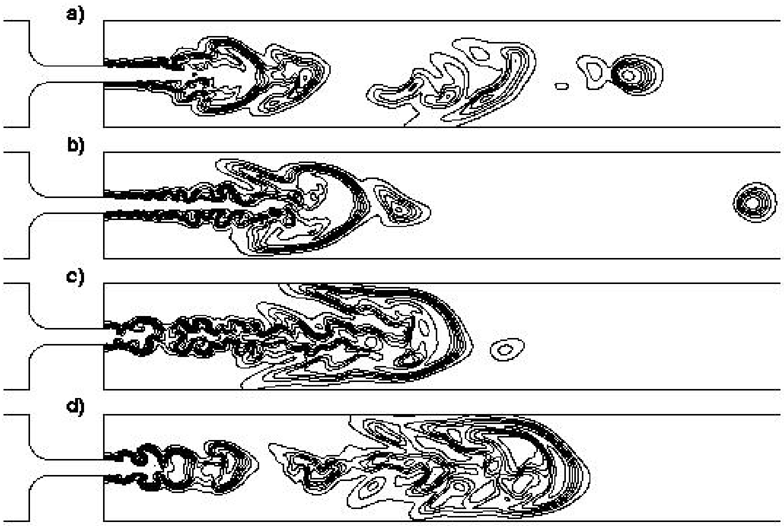

Figure 5. Temperature fields during one forcing cycle at 530 Hz. Time separation between each picture: a quarter period (0.47 ms)

Snapshots of temperature during one cycle of forcing are displayed on Figs. 5. The general features observed in the LES match those observed in the experiment: a large mushroom-shaped structure is produced (similar to vortices observed in impulsively-started jets) and leads to a high increase of flame surface and reaction rate. This mushroom is essentially symmetrical with respect to the central axis of the burner.

In a second stage, the combustor was forced by modulating the inlet equivalence ratio ϕ between 0.3 and 1.7 using a sinusoidal function at the same frequency of 530 Hz. The equivalence ratio modulation amplitude is large to maximize its effects. To achieve such levels, both fuel and air flow rates would have to be affected by the acoustic wave and in opposite directions: the fuel flow rate should decrease when the air flow rate increases. Since this is unlikely to happen in practice, the present simulations provide a maximization of potential effects of unmixedness on combustor response. The overall mass flow rate was kept constant so that no vortices were formed at the inlet and only the chemistry effect was active at least during the initiation of the oscillations. Fig. 6 shows how the lean and rich regions created at the inlet enter the combustor and affect the flame front.

Finally, Fig. 7 compares the effects of acoustic forcing (case A) with those of chemical forcing (Case C) on the total reaction rate in thr burner. The case without forcing is added for reference. Acoustic forcing

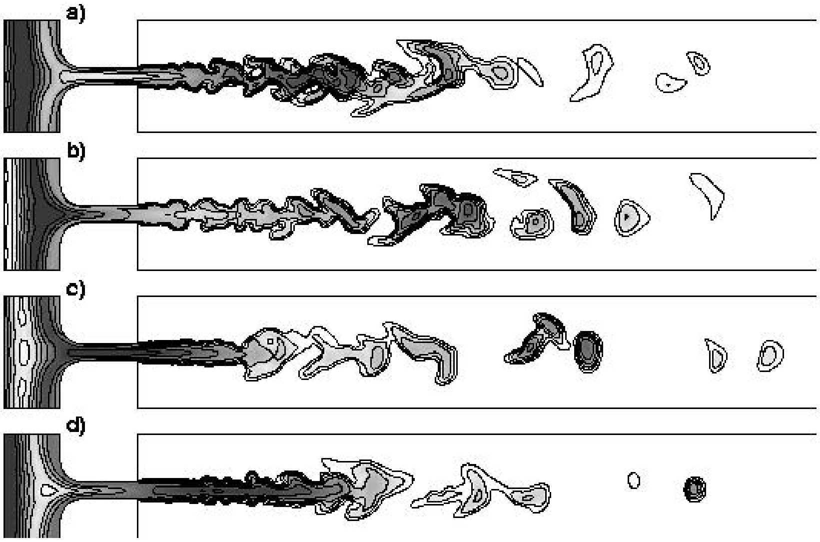

Figure 6. Fuel mass fraction fields during one forcing cycle at 530 Hz (modulation of equivalence ratio ϕ).

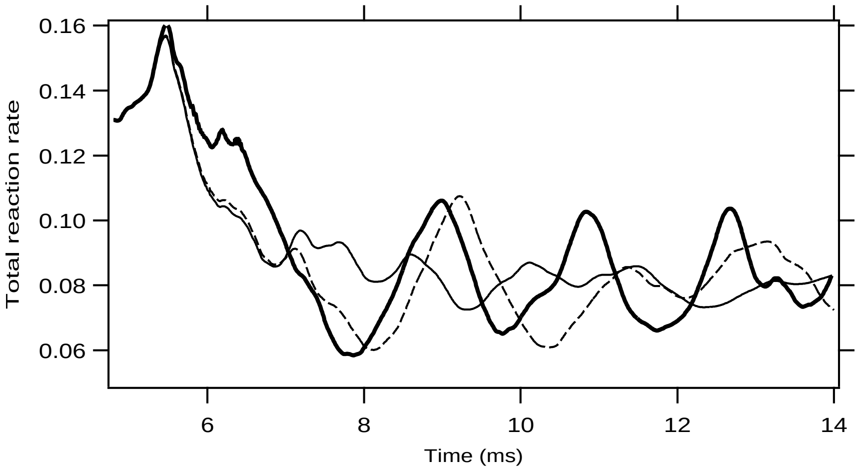

Figure 7. Total reaction rate vs time for unforced flow (solid line), acoustic forcing at 530Hz with an amplitude of 50 percent (thick line) and for amodulation of equivalence ratio between 0.3 and 1.7 (dashedline). The total reaction rate is non-dimensionalized by the reference value $\omega_{ref} = \rho_{fg} c_{fg} / l_{ref}$ where fg refers to the reference state in the fresh gases and l_{ref} is the half channel width.

has a stronger effect on the total reaction rate than chemical forcing. Since we chose a very large range of variations for the chemical forcing, it seems that acoustic forcing is the main phenomenon to consider for combustion instabilities in the present system.

8. The acoustic forcing

Effects of acoustic forcing as computed by LES are now compared to experimental results. The time delay betweeb flow rate oscillation and reaction rate perturbations is the central data in combustion instability models. This delay was of the order of 0.9 ms (corresponding to a phase shift of π) in the experiment.

First simulations indicated that under acoustic forcing the large scale vortical structures are essentially symmetric to the centre-line of the burner – which also correlates experimental evidence in (Poinsot et al 1987). Thus in order to spare computational time only half the burner was computed, imposing a symmetry condition on the centre-line and keeping the mesh resolution unchanged.

Figure 8 compares experimental visualisations of the downstream region of the dump with computational results at four equally spaced instants during one forcing cycle. The experimental pictures are strioscopies taken through a viewing window with a diameter of 40 mm located 21 mm downstream of the backward facing step. They allow to visualize the flame region based on density gradients induced by the combustion process and are compared to calculated temperature fields taken at the same instant in the cycle. A good correspondance between the experiment and the LES sdimulations can be seen. The surge in inlet mass flux creates a mushroom-like vortex that is convected downstream of the backward-facing step while growing in the transverse direction. When the flame brush reaches the top and bottom symmetry axis – i.e. when it starts to interact with neighbouring flames – a region of intense turbulence appears. This region is evidenced by the important small scale motions in the interaction region between nieghbouring jets visible on the strioscopies c) and d). It is also predicted by the computations as can be seen from figure 9 that shows snapshots of the efficiency function during one forcing cycle. In the interaction region the efficiency reaches values of up to 3.5, indicating a strong straining due to turbulent eddies. In this region the local reaction rate reaches maximum values of over 3 times the maximum reaction rate of an unstrained flame in the same thermodynamic conditions, see figure 10. Another region where subgrid-burning is intense is the immediate vicinity of the step, where the eddies associated to flow detachment create a significant

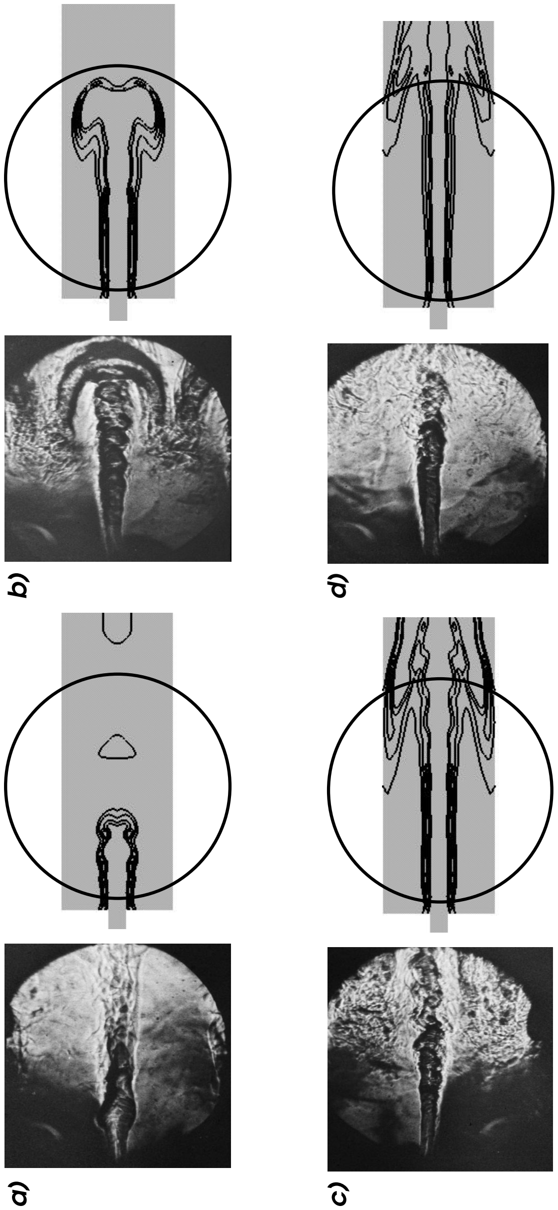

Figure 8. Snapshots of temperature ($300K < T < 2190K$) during one forcing cycle at $530Hz$ on the half mesh. The flow field has been mirrored with respect to the central symmetry axis during postprocessing. Time separation between each picture: a quarter of a period.

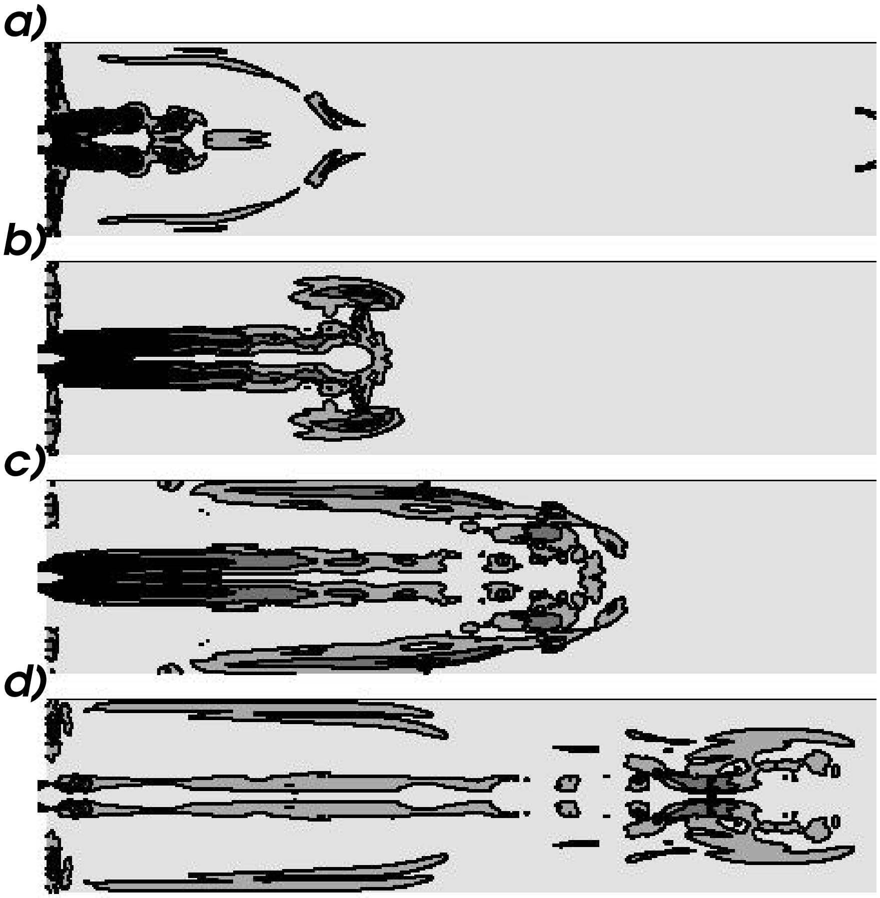

Figure 9. Snapshots of efficiency ($1.0 < E < 3.5$) during one forcing cycle at $530Hz$ on the half mesh. The flow field has been mirrored with respect to the central symmetry axis during postprocessing. Time separation between each picture: a quarter of a period.

increase of flame surface. The associated increased consumption speed that allows the flame not to be blown off as a consequence of the inlet flow pulsation.

The response of the flame to the inlet mass flux is not immediate. The phase shift observed experimentally between the maximum of inlet mass flux and the maximum of reaction rate is around π (see Fig. 12 in Poinsot et al 1987). This phase shift is an important quantity to reproduce if one wants to predict acoustic transfer functions of combustion chambers. Figure 11 shows the phase shift predicted by the LES computations between the non-dimensional inlet mass flux and the non-dimensional reaction rate in the experimental viewing window

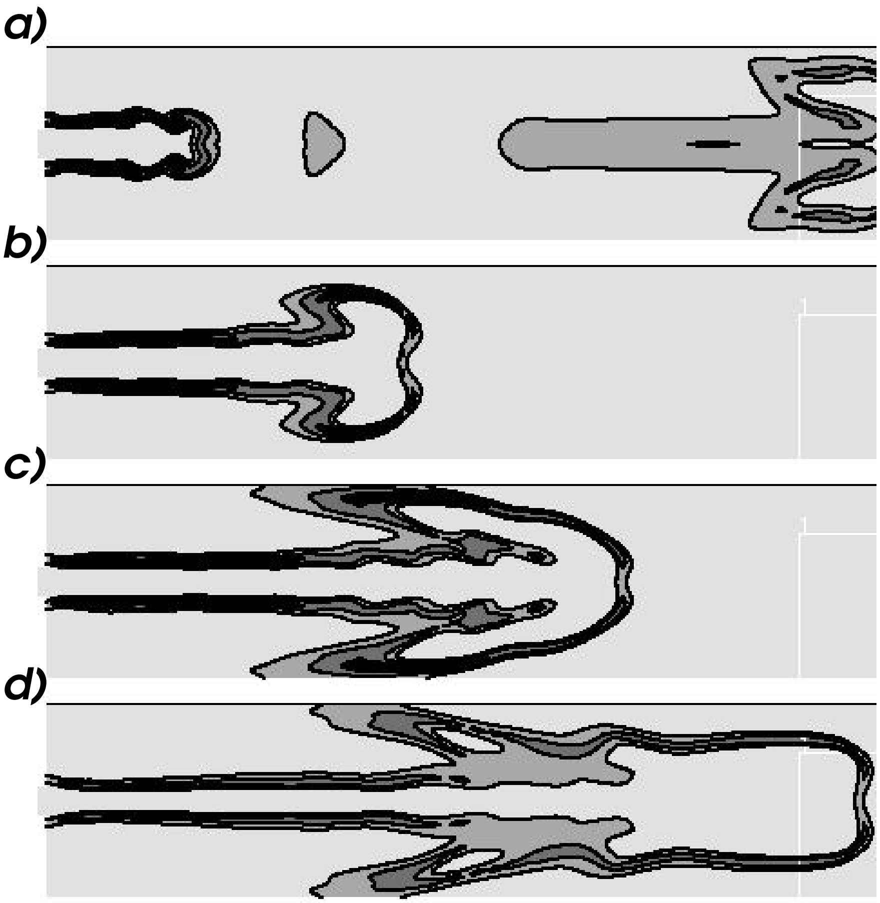

Figure 10. Snapshots of reaction rate ($0.0 < \dot{\omega}/\dot{\omega}_{arrh,max} < 3.25$) during one forcing cycle at $530Hz$ on the half mesh. The flow field has been mirrored with respect to the central symmetry axis during postprocessing. Time separation between each picture: a quarter of a period.

used to observe the reaction zone. The curves are phase averages over 10 periods of pulsation. The phase shift obntained by our computations is around 0.8π i.e. quite close to the experimental findings. It thus seems that the LES tools presented in this paper are able of reproducing satisfactorily the essential physical phenomena associated with combustion instabilities.

Conclusion

Large eddy simulations of the effects of acoustic waves and equivalence ratio variations on flame response have been performed for a premixed

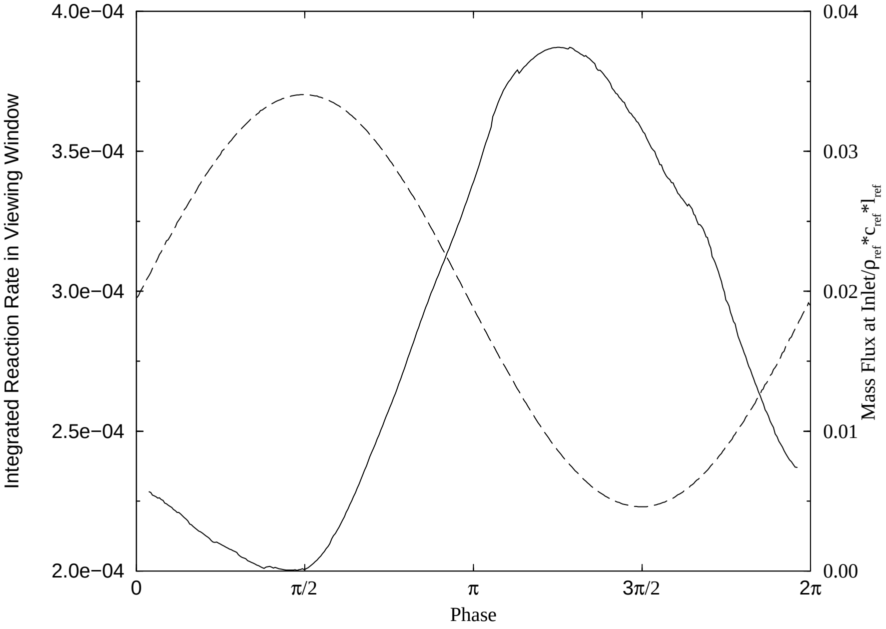

Figure 11. Phase averaged response of the reaction rate in the experimental viewing window to acoustic forcing at the burner inlet. Curves have been obtained over 10 periods of pulsation. Solid line: integrated reaction rate in experimental viewing window – Dashed line: inlet mass flux.

turbulent flame stabilized in a backward-facing step combustor. The developed code includes (1) a chemistry model based on a new reduction technique called ICC for propane (2) a flame thickening methodology to handle flame turbulence interactions and (3) specific boundary conditions to control and measure acoustic wave reflections on inlets and outlets. The chemistry reduction method (called ICC) was derived and validated by comparing its result with full schemes / full transport results obtained with stagnation point flame codes. The code itself is a compressible parallel finite volume solver able to handle hybrid grids (AVBP).

Results indicate that the final tool was able to predict forced combustor response over a certain number of excitation cycles and to reproduce qualitatively the phenomena observed in the experiment of Ecole Centrale Paris. The phase shift between flow rate oscillations and unsteady heat release, for example, was recovered in the case of acoustic forcing. This indicates that predicting combustion instabilities using appropriate LES codes may be close at hand.

Modulating the inlet equivalence ratio around stoichiometry also leads to unsteady heat release but with lower amplitudes than with acoustic forcing.

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