Studies of mean and unsteady flow in a swirled combustor using experiments, acoustic analysis and Large Eddy Simulations

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Short title : **LES, acoustics, experiments in gas turbines.**

Abstract

The turbulent flow within a complex swirled combustor is studied with compressible LES (Large Eddy Simulation), acoustic analysis and experiments for both cold and reacting flows. Detailed fields of axial, tangential and radial velocities (average and RMS) given by LES are compared to experimental values measured by LDV. The unsteady activity is identified using LES and acoustic tools for the whole geometry from inlet (far upstream of the swirler) to the atmosphere (far downstream of the chamber exhaust). Concerning comparisons between experiments and LES, this nose-to-tail procedure removes all ambiguities related to the effects of boundary conditions. Results for the cold flow show that the second acoustic mode at 360 Hz dominates in the plenum while a hydrodynamic mode at 540 Hz due to a Precessing Vortex Core (PVC) is found in the combustion chamber. With combustion, the PVC mode is damped and the main mode frequency dominating all unsteady activity is 500 Hz. Acoustic analysis shows that this mode is still the second acoustic mode observed in the cold flow: its frequency shifts from 360 Hz to 500 Hz when combustion is activated. More generally, these results illustrate the power of combined numerical tools (LES and acoustic analysis) to predict mean flow as well as instabilities in combustors.

Key words: GAS TURBINES, ACOUSTICS, LARGE EDDY SIMULATION

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1 Introduction

The design of modern combustion chambers for gas turbines relies heavily on RANS (Reynolds Averaged Navier Stokes) which predicts the mean values of all parameters in the chamber (velocity, temperature, density, species mass fractions and turbulent quantities). Even though these mean fields are essential ingredients of a successful design, recent research has shown that they had to be complemented by other tools. In the continuous development of gas turbines burners and chambers, unexpected problems such as flashback, quenching or combustion oscillations appear in many cases. Combustion instabilities are one of the most dangerous phenomena: these oscillations are caused by combustion / acoustics coupling and can lead to the complete destruction of the combustor [$1-6$]. They are difficult to predict at the design level using RANS methods. To understand and predict combustion instabilities, other numerical methods are needed [7, 8]:

- Acoustic analysis: using drastic assumptions on the flow and on combustion, the stability of a combustor can be studied using purely acoustic tools which predict the frequency and the growth rates of all modes. Such tools have been available in research centers but also in industry for a long time with various levels of sophistication: longitudinal low-frequency modes [4, 9, 10], longitudinal/azimuthal modes [11, 12] fully three-dimensional acoustic modes [13, 11], linear or non-linear methods [$14-16$], analytical or numerical techniques. The weakest part of these models is the description of the flame response to acoustic perturbations.
- LES (Large Eddy Simulations): more recently, the development of LES has allowed detailed studies of turbulent combustion. Even though the cost of such LES remains very high, the predictive capacities of these tools for turbulent combustion have been clearly demonstrated [$17-20$]. Extending LES to study flame / acoustics coupling is therefore an obvious research path [21, 8].

Even though they can address the same issue (flame / acoustics coupling), acoustic tools and LES follow different routes: while LES provides a detailed analysis of one reacting case, acoustic tools can be used to explore a wide range of parameters and geometries. Combining these solvers is likely to offer the best solution to understand and control combustion oscillations but very few studies have tried to use both approaches together. The objective of this paper is to explore this path by using simultaneously Large Eddy Simulation and acoustic analysis for a swirled premixed gaseous combustor. These two approaches are compared to detailed measurements performed at DLR Berlin and Stuttgart. First, mean LES profiles are compared for all velocity components (mean and RMS) for cold and reacting flows: this set of data constitutes a very extensive validation data base for LES results since it incorporates profiles of mean and RMS velocitiy components in the axial, tangential and radial directions. Then the unsteady activity in the combustor is characterized using LES, acoustic analysis and experimental results: the natural hydrodynamic instabilities of the swirled flow (especially the Precessing Vortex Core [22]) are identified and their importance in flow / acoustics coupling is studied for cold and reacting cases. Oscillation frequencies revealed by LES and acoustic analysis are compared to experimental measurements using microphones and hot-wire measurements.

An important aspect of the study is the design of a combustor and the use of numerical tools allowing a 'stand-alone' computation. LES and acoustic analysis are run in a nose-to-tail mode in which boundary conditions are extremely simple: the mass flow rate is imposed at the inlet of the whole device while the pressure at infinity is specifed far away from the exhaust for the outlet. No boundary condition (like velocity, species or swirl profiles at the inlet) can be tuned to match results: this allows a more precise evaluation of the two methods capacities and limits.

The experimental configuration is described in Section 2. Section 3 and 4 provide short descriptions of the LES and acoustic tools. Section 5 presents results for the non-reacting flow while Section 6 describes results for the reacting case at equivalence ratio 0.75.

2 Configuration: swirled premixed burner

The burner is a swirled injector (Fig. 1): swirl is produced by tangential injection downstream of a plenum. The chamber has a square cross section (86 mm $\times$ 86 mm) to allow optical diagnostics. The chamber length is 110 mm and ends into an exhaust duct with a 6:1 contraction. The burner operates at atmospheric pressure and the inlet air temperature is 300 K.

In addition to swirl, a central hub is used to stabilize the flame and control its position. In the experiment, methane is injected through holes located in the swirler but mixing is fast so that for the present computations, perfect premixing can be assumed. Experiments include LDV velocity measurements as well as a study of combustion regimes. Velocity profiles are measured for the axial, tangential and radial components at various sections of the combustor for both cold and reacting flows. Microphones are used to charaterize the unsteady activity in the plenum and in the chamber.

To provide a non ambiguous comparison between LES and experiments, it is important to consider a stand-alone configuration, i.e. a situation where the influence of boundary conditions is as small as possible: for example, the possibility of tuning the LES inlet or outlet conditions to match the experimental results (a procedure which is often employed but rarely mentioned for obvious reasons) must be suppressed. For the present study, boundary conditions were pushed as far away as possible from the chamber by extending the computational domain upstream and downstream of the combustion zone (Fig. 2): the swirlers and the plenum are fully meshed and computed and even a part of the outside atmosphere is meshed to avoid having to specify a boundary condition at the chamber exhaust (Section 3 in Fig. 2). At the inlet of the plenum (Section 1), a flat velocity profile is imposed and it was checked that this profile had no influence on results as long as the total mass flow rate was conserved. At the outlet of the combustion chamber (Section 3), a part of the exhaust atmosphere is added to the computation. This is an expensive but necessary step: acoustic waves reaching the chamber exhaust (Section 3) are properly transmitted or reflected without having to specify an acoustic impedance for this section since it is not a boundary condition but a part of the computational domain.

3 Large Eddy Simulations for gas turbines

Large Eddy Simulations (LES) are powerful tools to study the dynamics of turbulent flames $[23-26, 8, 19, 20]$. In this study a parallel LES solver called AVBP (see www.cerfacs.fr/cfd/) is used to solve the full compressible Navier Stokes equations on hybrid (structured and unstructured) grids with third-order spatial and temporal accuracy $[27, 28]$.

No-slip adiabatic conditions are imposed at all walls of the chamber. Sub-grid stresses are described by the WALE model [29]. Even though this model can predict wall turbulence as shown in [29], the mesh size near walls is not sufficient to correctly resolve turbulent boundary layers for all walls of the combustors. This obvious limitation is well known of most LES in combustion chambers but, interestingly, it has limited effects on the results. The comparisons of LES and LDV data (Sections 5 and 6) show that only a limited zone near the walls is affected by the lack of resolution in these regions: most of the turbulent activity is generated by the velocity gradients inside the chamber which are well resolved on the grid so that this approximation is acceptable. Other simulations performed with law-of-the-walls for LES do not exhibit significant differences with the present no-slip condition (not shown in this paper).

The flame / turbulence interaction is modeled by the Thickened Flame / Efficiency Function model $[21, 30]$. The chemical scheme for methane / air combustion takes into account six species (CH_4, O_2, CO_2, CO, H_2O and N_2) and two reactions [20].

$$CH_4 + \frac{3}{2} O_2 \longrightarrow CO + 2H_2O \tag{1}$$

$$CO + \frac{1}{2} O_2 \longleftrightarrow CO_2 \tag{2}$$

The first reaction (1) is irreversible whereas the second one (2) is reversible and leads to an equilibrium between CO and CO_2 in the burnt gases and a correct prediction of product temperatures. The rates of reaction (1) and (2) are respectively given by:

$$q_1 = A_1 \left(\frac{\rho Y_{CH_4}}{W_{CH_4}}\right)^{n_{1F}} \left(\frac{\rho Y_{O_2}}{W_{O_2}}\right)^{n_{1O}} \exp\left(-\frac{E_{a1}}{RT}\right) \tag{3}$$

$$q_2 = A_2 \left[\left(\frac{\rho Y_{CO}}{W_{CO}}\right)^{n_{2CO}} \left(\frac{\rho Y_{O_2}}{W_{O_2}}\right)^{n_{2O}} - \left(\frac{\rho Y_{CO_2}}{W_{CO_2}}\right)^{n_{2CO_2}}\right] \exp\left(-\frac{E_{a2}}{RT}\right) \tag{4}$$

where the parameters are provided in Table 1.

The unstructured mesh used for this study contains 3 millions elements. A specific feature of AVBP is the possibility of using hybrid meshes on massively parallel computers : the combustion chamber, the injection and the exhaust can be computed simultaneously. Since the solver is fully compressible, acoustic waves are also explicitely captured and characteristic methods are used to specify boundary conditions while controlling acoustic waves reflection [31, 28]. For the burner of Fig. 1, the inlet (Section 1 in Fig. 2) is a fixed velocity section while the outlet of the atmosphere part (Section 2) corresponds to a constant pressure surface [8].

4 Three-dimensional acoustic solver

The problem of the coupling between flames and acoustics is old and still unsolved except in certain simple cases. The famous example of the singing flame of Lord Rayleigh [32] demonstrated that this coupling can be very strong: it is sufficient to place a flame in a duct to observe (for certain conditions) that the acoustic modes of the duct can be excited at very high levels. Being able to predict the acoustic eigenmodes of the combustor is therefore a necessary step to understand and avoid combustion instabilities. In the present work, a code called AVSP is used to solve the Helmholtz equation in a non-isothermal flow [7, 8]:

$$\nabla \cdot \left(c^2 \nabla p'\right) - \frac{\partial^2}{\partial t^2} p' = 0 \tag{5}$$

where p' is the pressure perturbation and c is the local sound speed. The sound speed c is obtained by averaging LES results. Eq. (5) integrates the influence of combustion on the local sound speed but not its effect as an active acoustic generator [8]. This is sufficient to identify modes but not to predict whether they will actually be amplified or damped by the combustor. The pressure fluctuations equation (5) is solved in the frequency domain by assuming harmonic pressure variations at frequency $f = \omega/(2\pi)$: $p' = P'(x, y, z) \exp(-i\omega t)$ with $i^2 = -1$.
Eq. (5) then becomes the Helmholtz equation where the unknown quantity is the pressure oscillation amplitude P' at frequency f:

$$\nabla \cdot \left(c^2 \nabla P'\right) + \omega^2 P' = 0 \tag{6}$$

Solving Eq. (6) with proper boundary conditions on walls, inlets and outlets provides the frequencies of the eigenmodes (the real part of ω), their growth rate (the imaginary part of ω) and the mode structure (the distribution of P'). Like the LES solver, the Helmholtz solver uses hybrid meshes and can be applied to the full geometry of the burner. For the burner of the present study (Fig. 1), the acoustic boundary conditions match those used for the LES solver (Section 3): the inlet (Section 1 in Fig. 2) is treated as a velocity node and the boundary of the atmosphere part meshed for the exhaust (Section 2 in Fig. 2) as a pressure node.

5 Non reacting flow

The cold flow was characterized for a mass flow rate of 12 g/s. An example of instantaneous axial velocity field is presented in Fig. 4. As expected from the large swirling motion induced by the vanes, a large recirculation zone is found on the chamber axis. Other recirculated zones exist in the corners of the chamber. All these zones are highly unsteady and their position oscillates rapidly with time. Note the complex flow inside the plenum, upstream of the swirler where other recirculated zones are found. Outside Section 3 (Fig. 2), the large atmosphere zone which is meshed damps perturbations.

5.1 Average profiles

LES and experimental average velocity profiles have been compared at various sections of the combustion chamber (Fig. 3). The averaging time for LES is 100 ms corresponding to 15 flow-through times in the chamber at the bulk velocity. Data compared for LES and experiments are :

- average axial (Fig. 5), azimuthal (Fig. 7) and radial (Fig. 9) velocities,
- RMS axial (Fig. 6), azimuthal (Fig. 8) and radial (Fig. 10) velocities [1] in the same sections

The comparison of all profiles shows an excellent agreement for all velocity components: the mean velocity is correctly predicted as well as the length of the central recirculation zone (Fig. 5). The swirl levels observed in the tangential velocity profiles are also very good (Fig. 7). Considering that this computation has absolutely no inlet boundary condition which can be tuned to fit the velocity profiles, this confirms the capacity of LES in such flows. The RMS profiles obtained experimentally by LDV and numerically by LES, both for axial (Fig. 6) and azimuthal (Fig. 8) velocities are also very close. The small discrepancies observed close to the chamber axis are due to the experimental difficulty of producing a perfectly symmetric flow: at $x = 5$ mm for example, the experimental mean profile of tangential velocity (circles in Fig. 7) is not symmetrical and slightly deviates from the LES profiles. Near walls (for $y = -43$ or $+43$ mm in Fig. 5 to 10), even though the mesh is not sufficient to resolve turbulent near-wall structures, the agreement for all profiles is perfect for all available LDV measurements. As mentioned in Section 3, near-wall turbulence effects have a limited effect on the mean and RMS flow field in the chamber.

5.2 Unsteady and acoustic analysis

The RMS fluctuation levels in both LES and experiments (Fig. 6 and 8) are very intense around the axis, close to the mouth of the burner (of the order of 20 m/s at $x = 1.5$ mm). Even though this activity appears as 'turbulence', it is actually due to a large scale hydrodynamic structure, called Precessing Vortex Core (PVC) which is well known in swirling flows [33, 34, 22] and is visualized in Fig. 11 from LES data. The spiral structure of Fig. 11 rotates around the burner axis at a frequency of 540 Hz in the LES. Measurements performed inside the chamber reveal a dominant frequency around 510 Hz.

The Helmholtz solver confirms the hydrodynamic nature of the 540 Hz frequency by demonstrating that it is not an acoustic mode: the acoustic eigenmodes of the combustor obtained with AVSP are listed in Table 2 and none of them matches the 540 Hz frequency. The first acoustic mode of Table 2 (172 Hz) is observed neither in LES nor in experiments: this mode is stable. However, the second mode (363 Hz) is indeed identified in experiments (around 340 Hz) and in LES (around 360 Hz) but only in the plenum and in the exhaust pipe. This mode is actually present everywhere in the device but

[1] All RMS quantities are computed with the resolved LES signal. Subgrid scale turbulence effects are not included.

it is dominated by the PVC signal inside the first part of the chamber. Fig. 12 shows experimental and numerical pressure spectra measured in the plenum and in the chamber and confirms that these two modes exist simultaneously but not in the same places.

To extend the analysis of these modes and especially to look at their spatial structure, measurements are difficult since they would require multiple simultaneous pressure probes. It is more convenient to use now LES and acoustic solver results: the pressure fluctuations amplitude (measured by $\overline{p'^2}^{1/2}$) computed both with LES and the acoustic solver are presented in Fig. 13. Since the 3/4 wave mode has a long wavelength compared to the chamber, this plot is obtained in the LES and in the Helmholtz solver by displaying local RMS pressure versus x coordinate. In Fig. 13, LES shows RMS of the whole pressure signal whereas the acoustic solver displays only the RMS acoustic structure of the 363Hz mode. The two codes give very similar pressure amplitudes in the plenum ($x < -0.05$ m) and in the exhaust ($x > 0.05$ m), indicating the acoustic nature of the pressure fluctuations in these regions. However, in the swirler and in the first half of the chamber (-0.05 m $< x < 0.05$ m), the pressure fluctuations given by LES are larger than the acoustic predictions of the Helmholtz solver: these fluctuations are due to the PVC at 540 Hz. The PVC acts acoustically like a rotating solid placed in the flow: this dipole radiates weakly outside of the chamber. This explains why the acoustic mode at 360 Hz is visible and unaffected in the plenum and in the exhaust.

High levels of RMS velocity are found also in the swirler (not shown here) confirming the requirement for a nose-to-tail computation: there is no section in the swirler or in the chamber inlet which could possibly be used to specify inlet boundary conditions and reduce the size of the computational domain.

In summary, for cold flow, two modes coexist: a low-amplitude acoustic (3/4 wave) mode at 360 Hz everywhere in the device and a strong hydrodynamic mode at 540 Hz due to the PVC, localised near the burner mouth ($0 < x <$ 5 cm).

6 Reacting flow

The reacting case corresponds to an equivalence ratio of 0.75, an air flow rate of 12 g/s and a thermal power of 27 kW. A snapshot of an instantaneous temperature isosurface (Fig. 14) reveals a very compact flame located close to the burner mouth.

6.1 Average profiles

Mean and RMS temperature profiles are displayed in Fig. 15. As expected from the snapshot of Fig. 14, combustion is nearly finished at $x = 35$ mm and no fresh gases are found (in the mean) beyond this section. RMS temperature levels are quite high close to the burner mouth (300 K) indicating a strong intermittency and flame flapping in this zone. No comparison is possible with experiments here because temperatures have not been measured yet.

The velocity fields, however, have been measured and are presented in Fig. 16 (mean axial), 17 (RMS axial), 18 (mean tangential), 19 (RMS tangential), 20 (mean radial), 21 (RMS radial). The overall agreement between mean LES results and experimental data is very good. The LES captures both the mean values and the fluctuations precisely, except in a zone close to the burner mouth. This lack of precision could be due to an insufficient mesh resolution in this region but a more fundamental issue linked to averaging techniques in non-constant density flows is probably responsible for the discrepancy observed in these zones: LES averages are obtained using time averages of the Favre filtered LES quantities while experimental results come from LDV measurements in which determining whether the averaging process leads to Favre or Reynolds quantities is a difficult question [35, 8]. Most zones where experiments and LES do not match in Fig. 17 or 19 are regions where the RMS temperature (Fig. 15) is large, i.e. zones with strong intermittency. In these zones, Reynolds and Favre averages can be very different [8] and this could be the source of the present errors. In regions with limited RMS temperatures (for example at $x = 35$ mm), the experimental and LES data match very well confirming the possible explanation. Obviously, these results suggest that more studies are required to clarify this issue and this was left for further work.

6.2 Unsteady and acoustic analysis

The first major consequence of combustion is to damp the PVC observed in the cold flow (Section 5.2). Even though this mechanism cannot be expected to exist in all swirled combustors, it has already been observed in other cases [20]. With combustion, dilatation and increased viscosity in the burnt gases seem to damp the PVC: its signature on the unsteady pressure field disappears and is replaced by the acoustic mode traces.

For this reacting flow, two self-excited acoustic modes appear experimentally around 300 Hz and 570 Hz. To identify the nature of these modes, the Helmholtz solver was run using the average temperature field given by LES to obtain the list of acoustic eigenmodes with combustion. Table 2 confirms that the two frequencies observed in experiments are the first two modes (1/4 wave and 3/4 wave) of the combustor. The agreement between measurements and the Helmholtz solver is very good: around 10% for the 1/4 wave and less than 2% for the 3/4 wave mode. The most 'active' mode is still the 3/4 wave mode observed for the cold flow (Section 5.2): its frequency shifted from 360 Hz (cold flow) to 570 Hz (reacting flow). The difference between the measured LES frequency (500 Hz) and the experimental (570 Hz) or Helmholtz solver (588 Hz) values for this mode is probably due to changes in acoustic boundary conditions but there is little doubt that LES, experiments and Helmholtz solver are pointing at the same mode: this can be checked by displaying the field of RMS pressure measured in the LES along the chamber axis together with the modal structure predicted by the Helmholtz solver for the 3/4 wave mode (Fig. 22). Even though the LES signal contains the signature of all modes (and not only of the 3/4 wave mode), its shape neatly matches the structure of the 3/4 wave mode predicted by the Helmholtz solver. Unlike the RMS pressure profile for the cold flow (Fig. 13), the match between the LES and the Helmholtz solver is good everywhere, even in the combustion chamber, indicating that the whole flow is locked on the 3/4 wave mode.

In summary, with combustion (for this regime at an equivalence ratio of 0.75), the hydrodynamic mode (PVC) is damped and the acoustic activity is increased. The most amplified mode is the 3/4 wave mode for the whole device (Fig. 22). The mode structure measured in the LES matches the structure predicted by the Helmholtz code.

7 Conclusions

LES and acoustic analysis were used jointly to analyse a swirled premixed combustor and results were compared to experimental data. Both the mean flow and the unsteady activity were studied for cold and reacting regimes. The full geometry was computed from plenum inlet to atmosphere to avoid any possible bias effect or tuning exercices of boundary conditions during LES / experiments comparison.

The mean values of velocity measured in five sections in the chamber obtained with LES and experiments match perfectly well for both cold flow and for a reacting case at equivalence ratio 0.75. The RMS values are also in very good agreement for the cold flow and limited discrepancies are observed for reacting flows in regions of large intermittency, suggesting that these errors might be due to the definition of the averaging procedure in these regions (Favre vs Reynolds). Generally speaking, these results confirm the remarkable predictive capacity of LES methods and also highlight the need for well-defined boundary conditions: for example, the computation must include the swirler vanes and cannot start at the chamber inlet plane.

Regarding the unsteady behavior of the flow the LES results (confirmed by experimental data) show that, without combustion, the 3/4 wave acoustic longitudinal mode at 360 Hz coexists with a Precessing Vortex Core (PVC) at 540 Hz. With combustion, the pressure fluctuations in the chamber lock onto the 3/4 wave acoustic mode of the device which shifts from 360 Hz (cold flow) to 588 Hz (reacting case): the PVC disappears and the acoustic structure revealed by LES matches exactly the prediction of the acoustic solver for this mode. Future studies will concentrate on the unsteady flame movements using PLIF and Raman measurements but the present results demonstrate that the nature of the acoustic / flow coupling changes when combustion is activated: hydrodynamic structures such as PVC appearing in cold flow can disappear when combustion starts while acoustic modes are reinforced by combustion. More generally, this study confirms the potential of LES for such flows and also highlights the need for Helmholtz solvers and a joint use of both methods.

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Tables

A_1	n_{1F}	n_{1O}	E_{a1}	A_2	n_{2CO}	n_{2O}	n_{2CO_2}	E_{a2}
$2E15$	0.9	1.1	35000	$2E9$	1	0.5	1	12000

Table 1
Rate constants for methane / air two-step scheme. The activation energies are in cal/moles and the preexponential constants in cgs units.

Mode	Mode	Cold flow (Hz)			Reacting flow (Hz)		
number	name	Helm	Exp	LES	Helm	Exp	LES
(1)	1/4 wave	172	damped	damped	265	300	290
(2)	3/4 wave	363	340	360	588	570	500
(3)	5/4 wave	1409	damped	damped	1440	damped	damped

Table 2
Longitudinal modes frequencies predicted by Helmholtz solver (Helm), measured in the experiment (Exp) and in the LES (LES).

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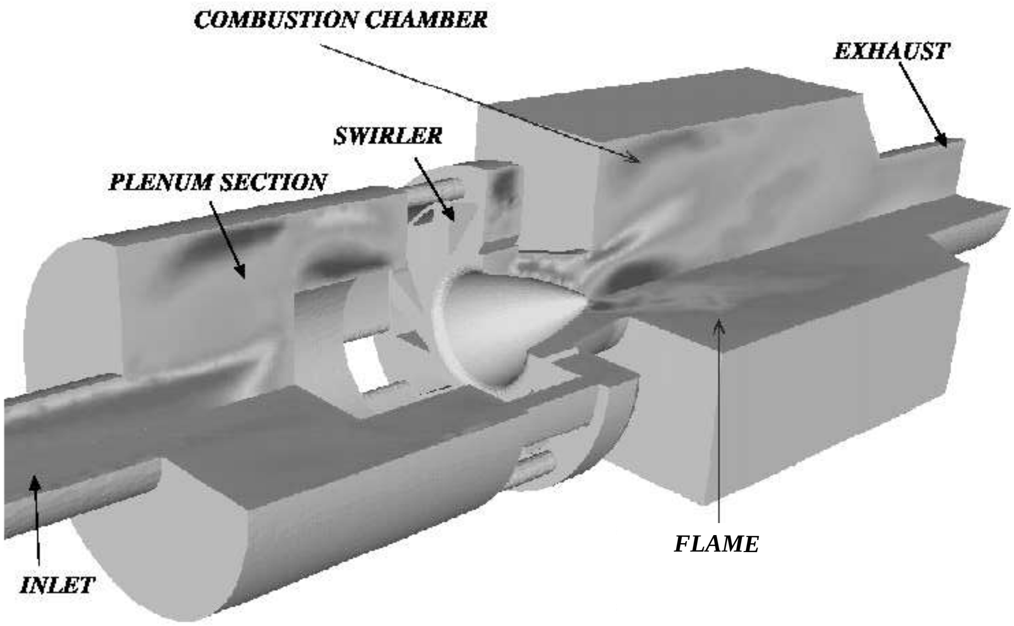

Fig. 1. Global view of the burner and combustion chamber.

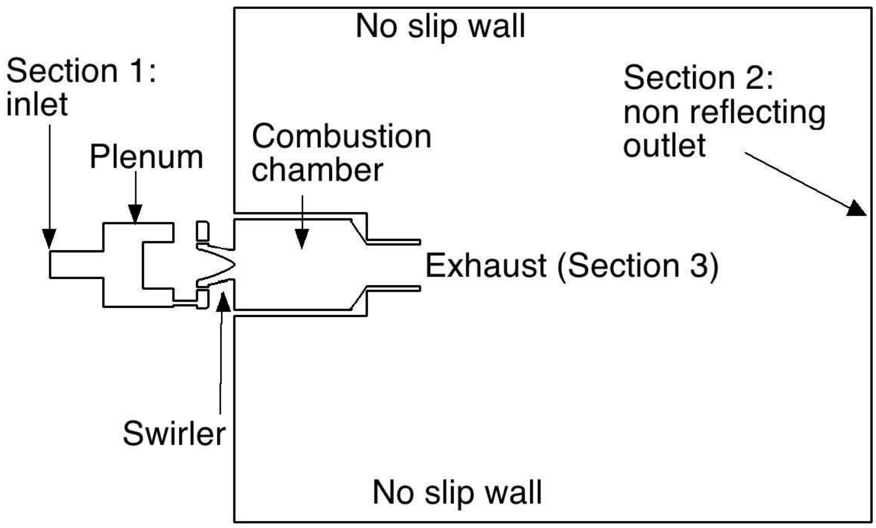

Fig. 2. Boundary conditions: the atmosphere downstream of the exhaust (Section 3) is also meshed to avoid specifying boundary conditions in this section.

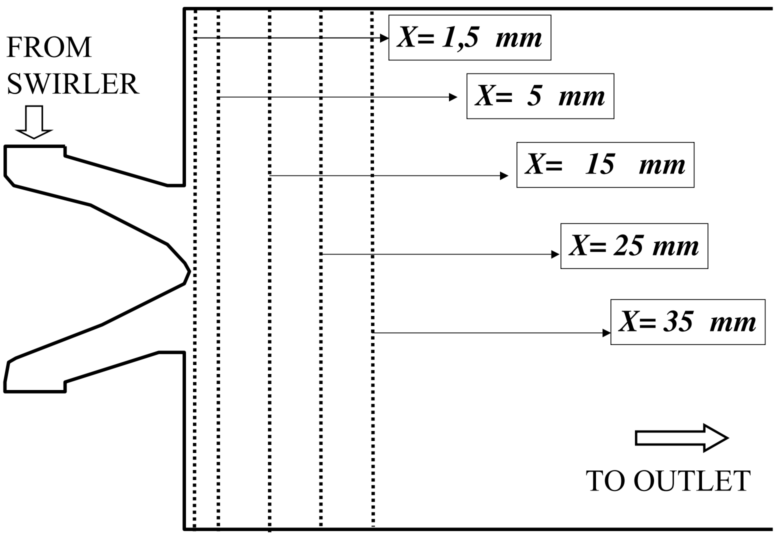

Fig. 3. Location of cuts for velocity profiles comparisons.

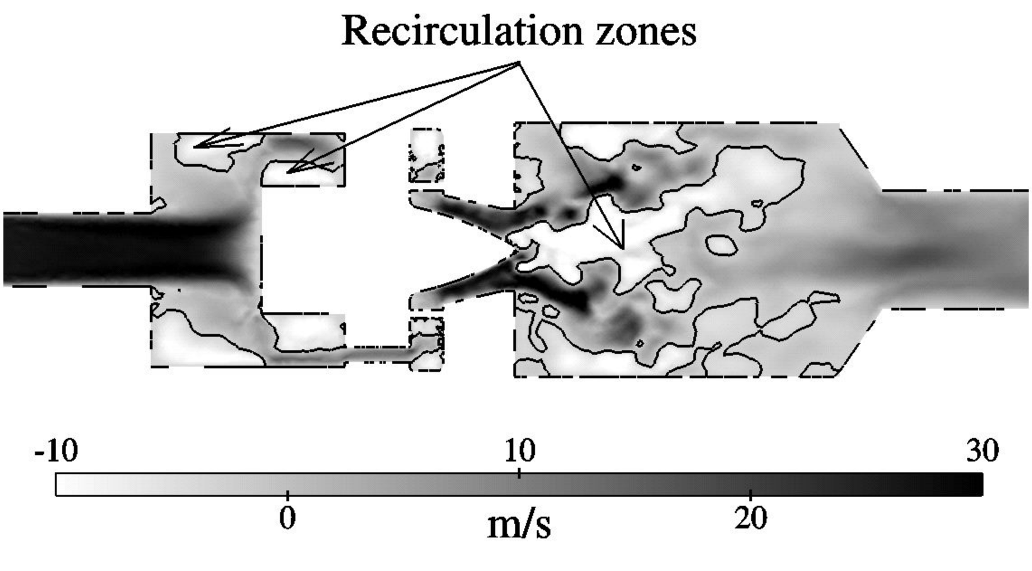

Fig. 4. Instantaneous field of axial velocity for cold flow.

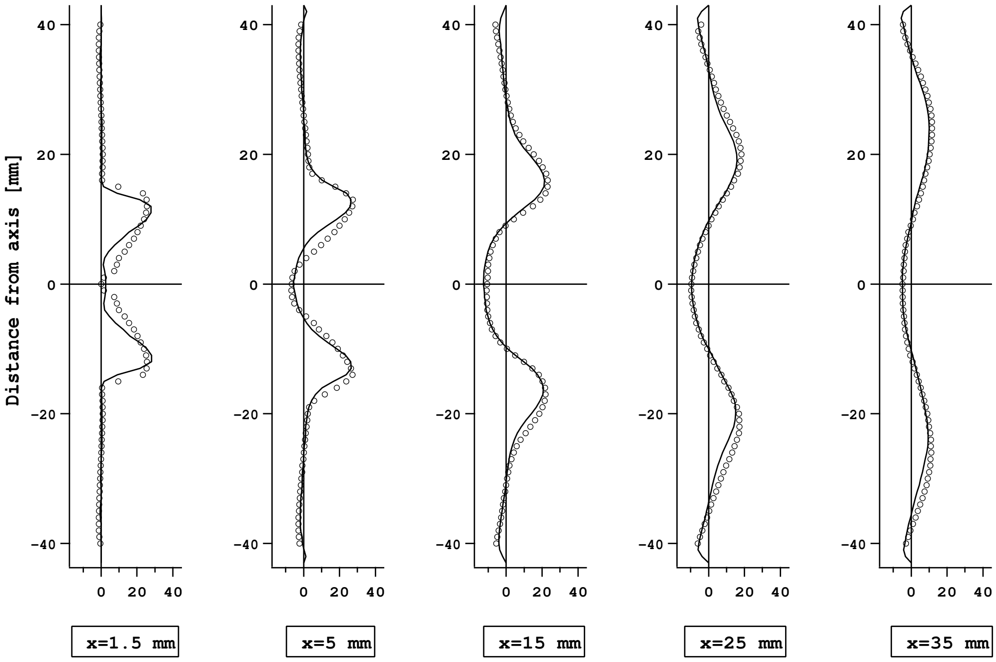

Fig. 5. Average axial velocity profiles for cold flow ○ LDV; —— LES.

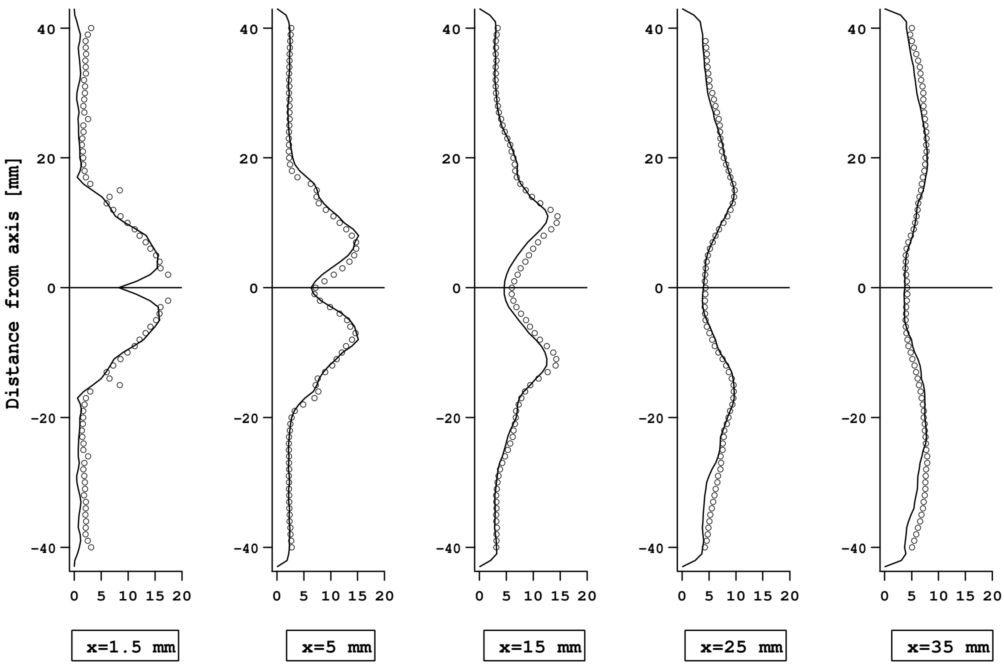

Fig. 6. RMS axial velocity profiles for cold flow. ○ LDV; —— LES.

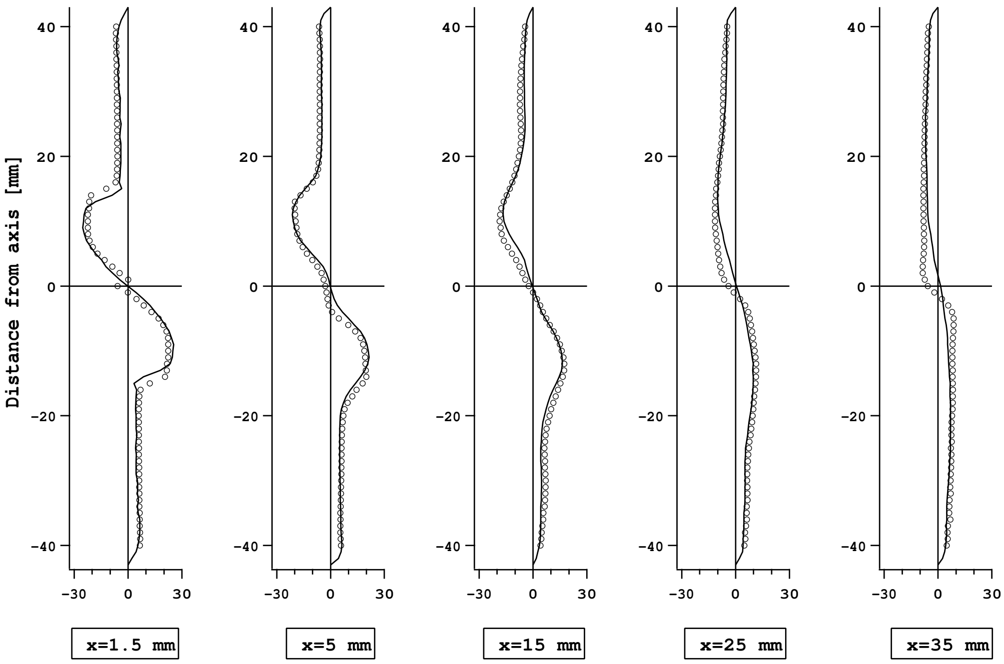

Fig. 7. Average azimuthal velocity profiles for cold flow. ○ LDV; —— LES.

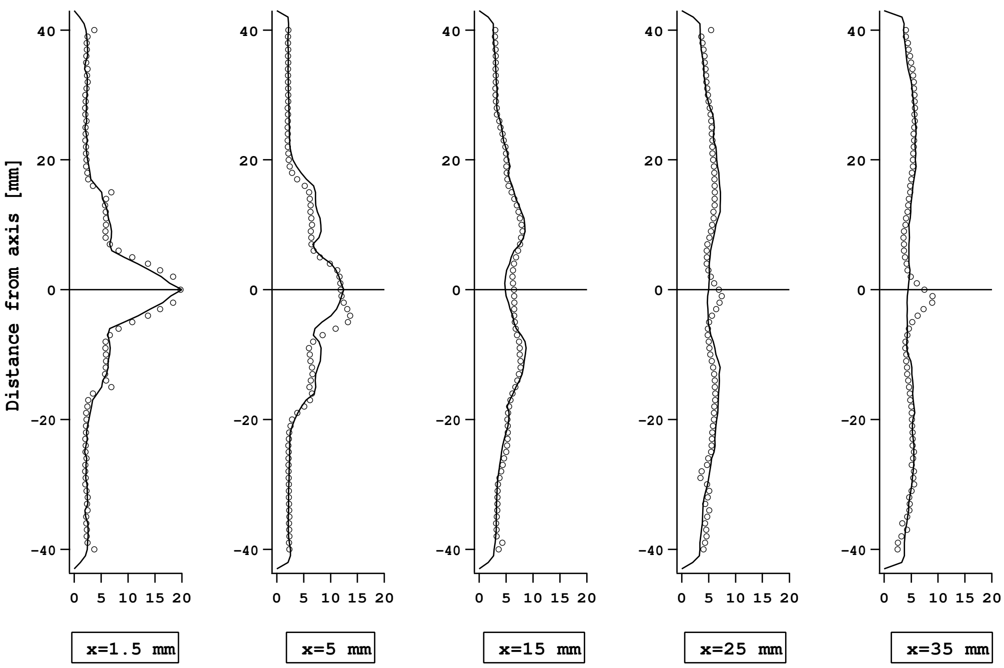

Fig. 8. RMS azimuthal velocity profiles for cold flow ○ LDV; —— LES. .

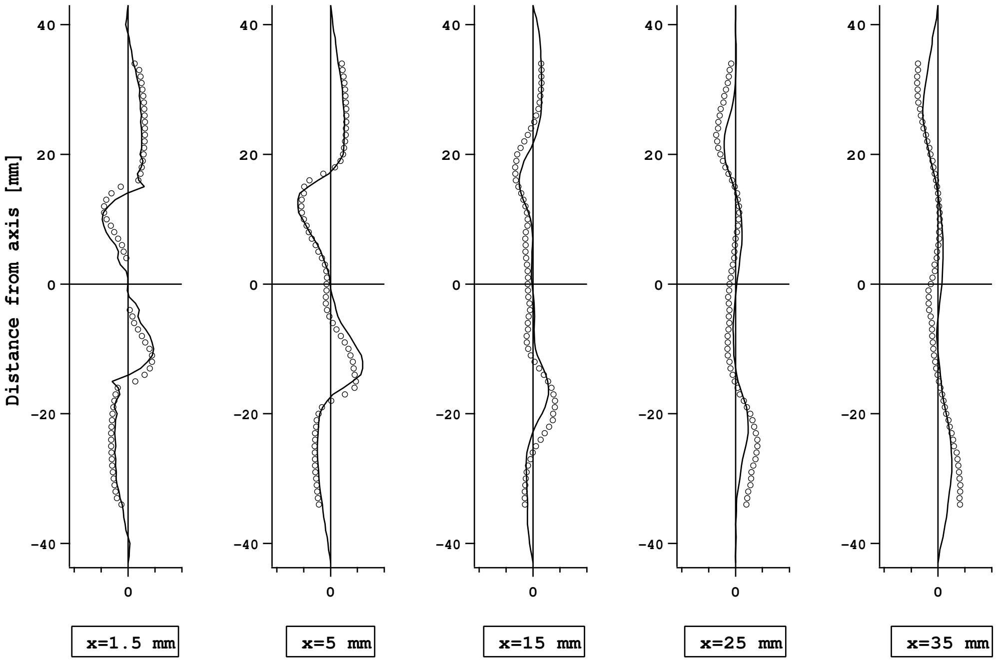

Fig. 9. Average radial velocity profiles for cold flow. ○ LDV; —— LES.

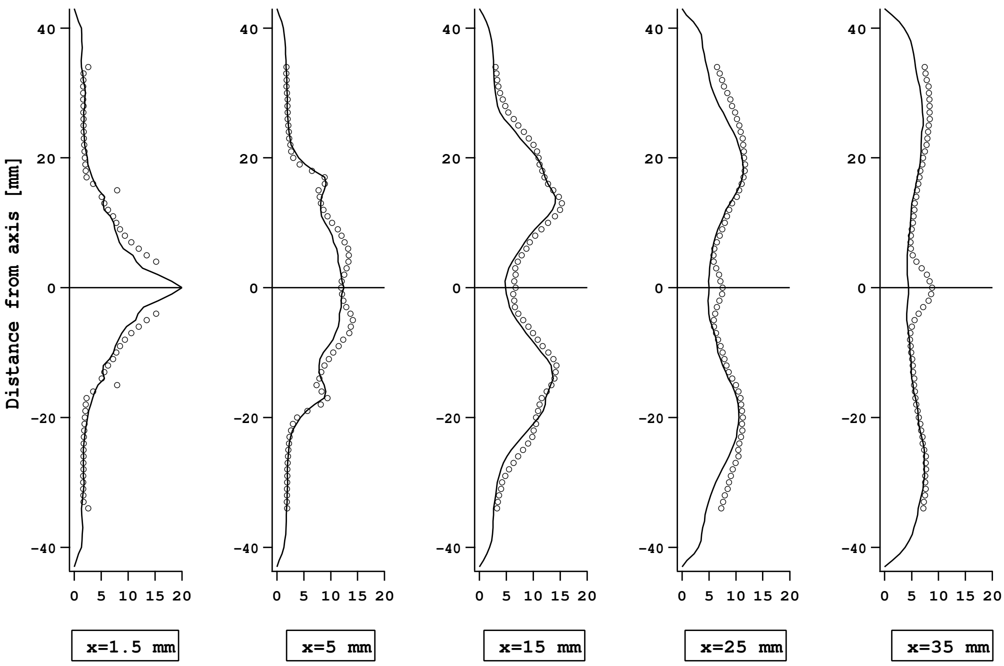

Fig. 10. RMS radial velocity profiles for cold flow ○ LDV; —— LES. .

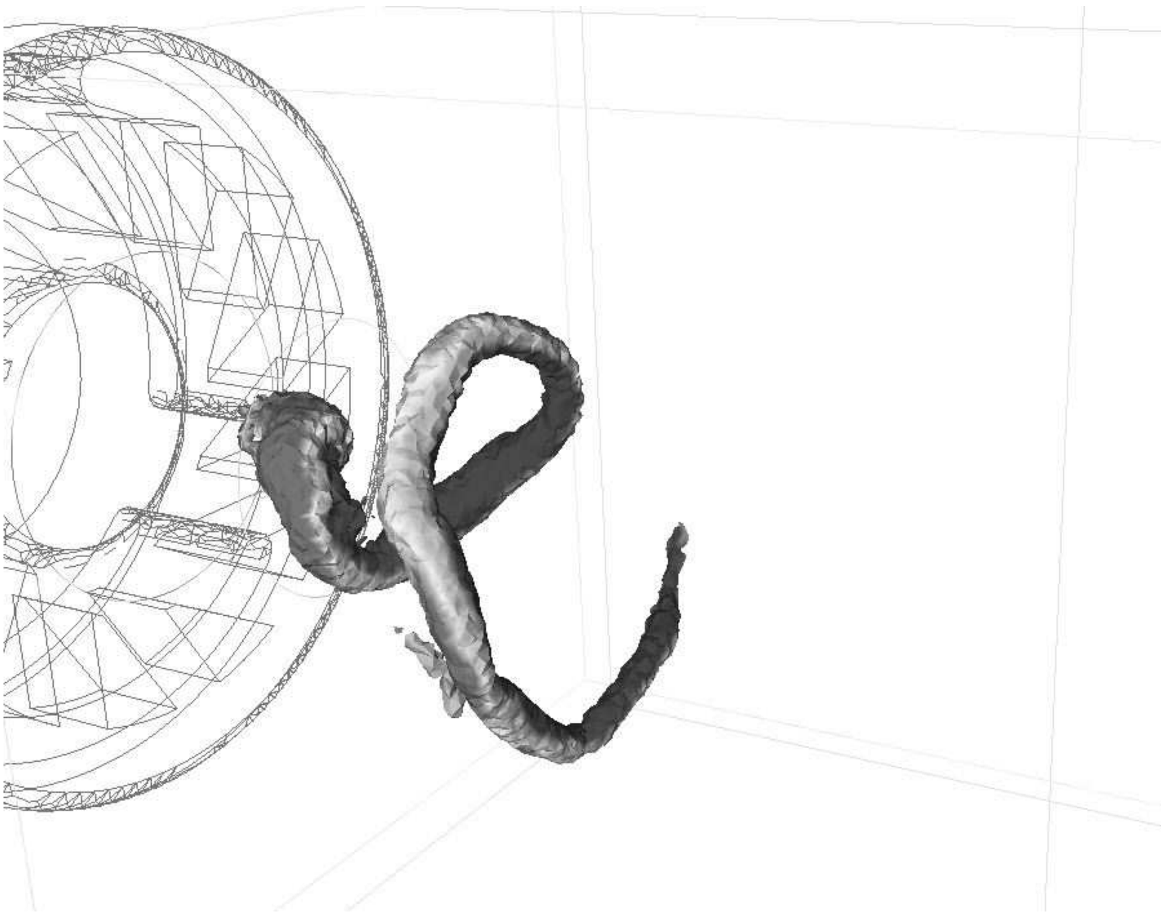

Fig. 11. Visualization of the 540 Hz PVC hydrodynamic instability at the exit of the swirler using an isosurface of low pressure.

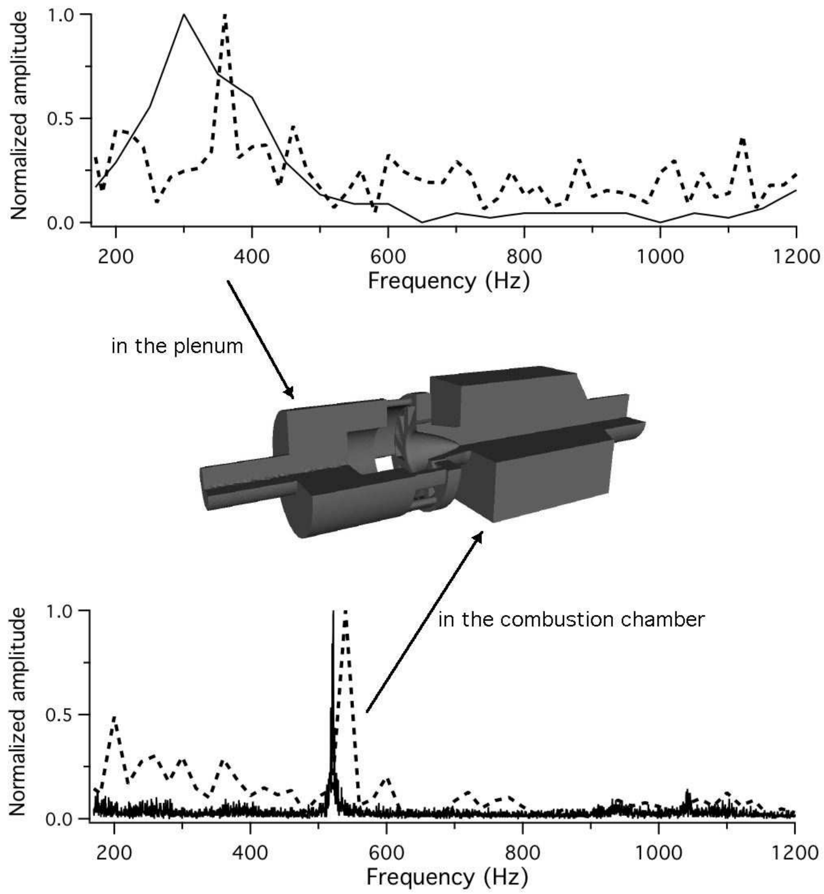

Fig. 12. Pressure fluctuations spectra for cold flow at two locations. Solid line: experiment; Dashed line: LES

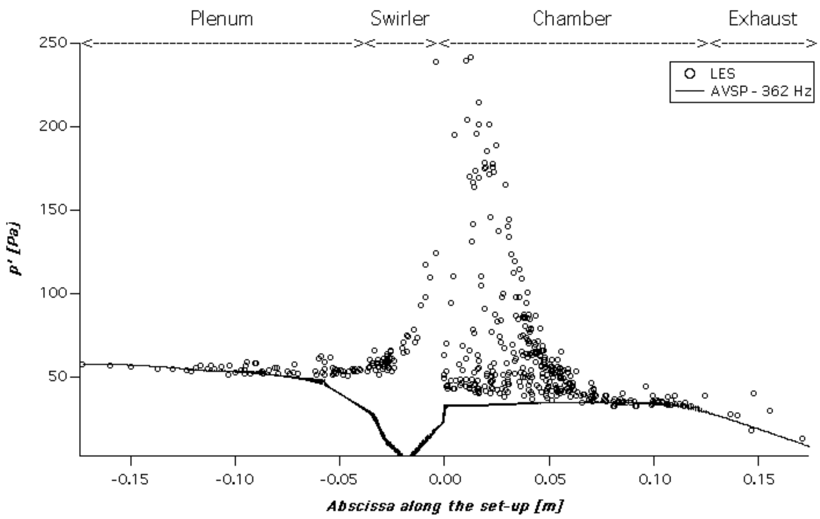

Fig. 13. Pressure fluctuations amplitude obtained by LES (circles) and acoustic (solid line) code for cold flow.

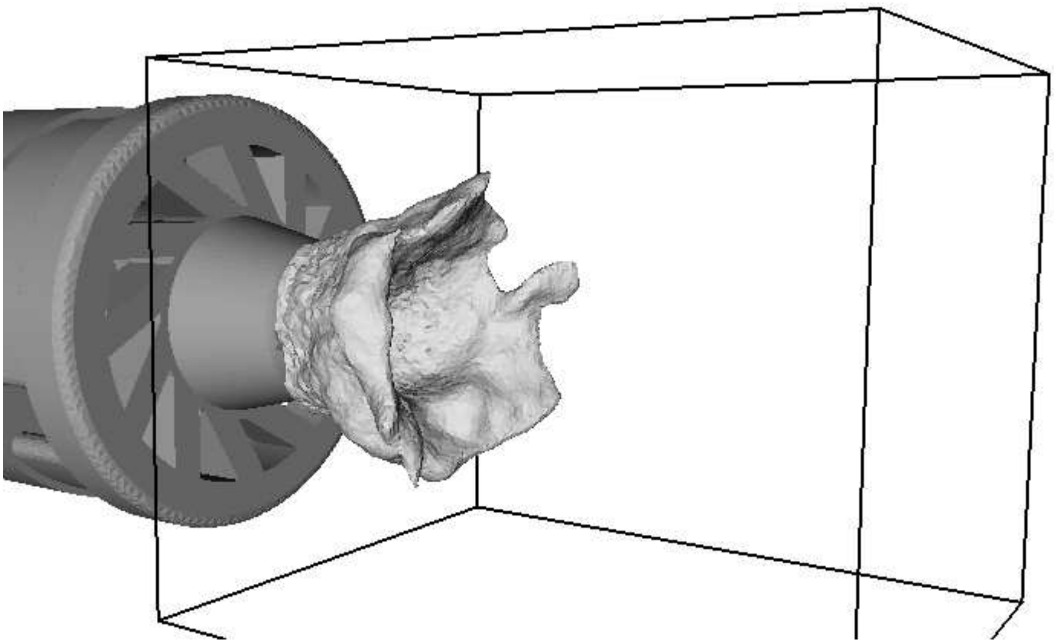

Fig. 14. Instantaneous 1250 K isosurface (LES data).

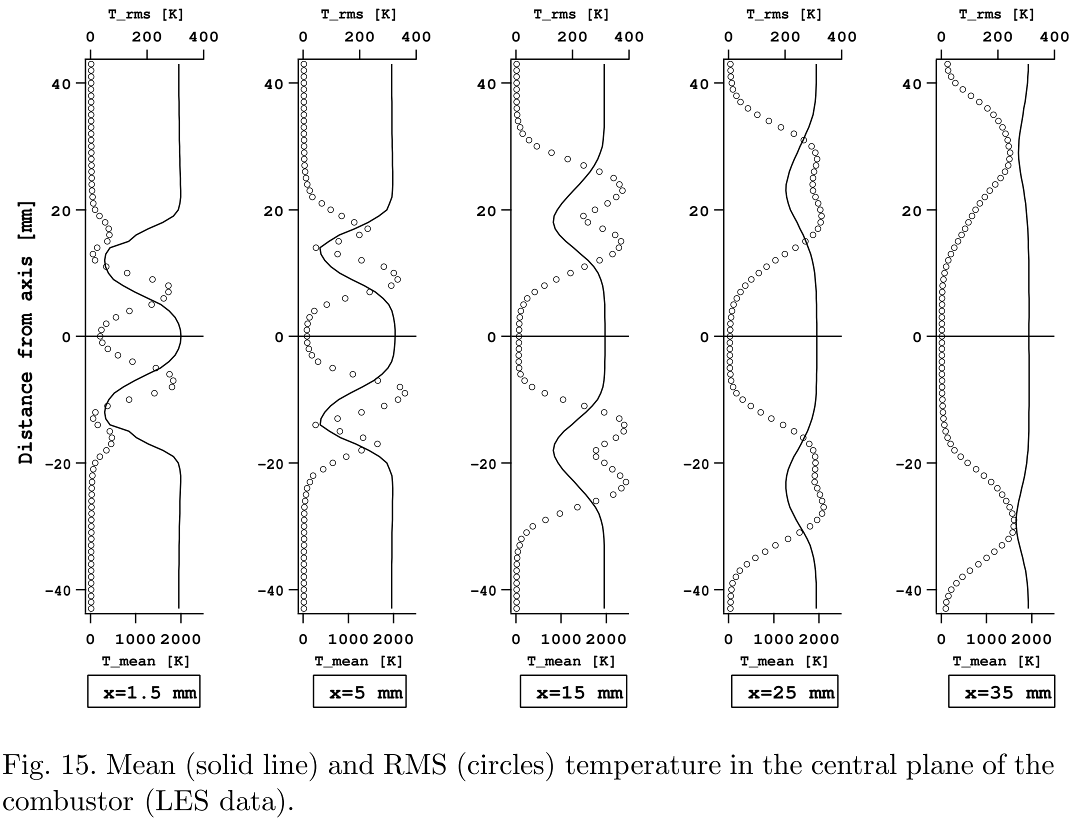

Fig. 15. Mean (solid line) and RMS (circles) temperature in the central plane of the combustor (LES data).

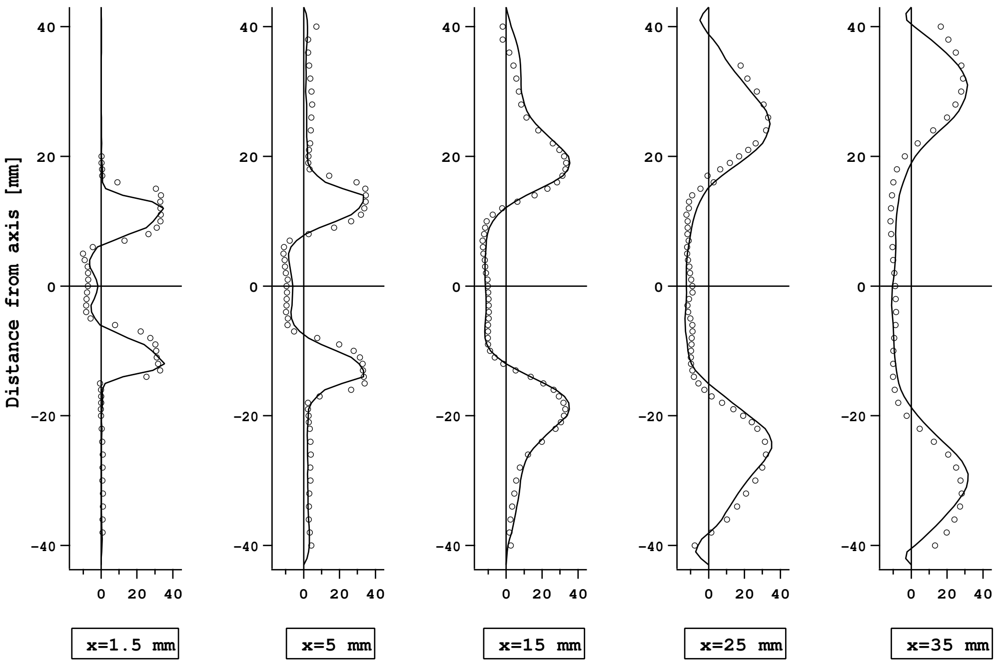

Fig. 16. Mean axial velocity in the central plane for reacting flow. ○ LDV; ——— LES.

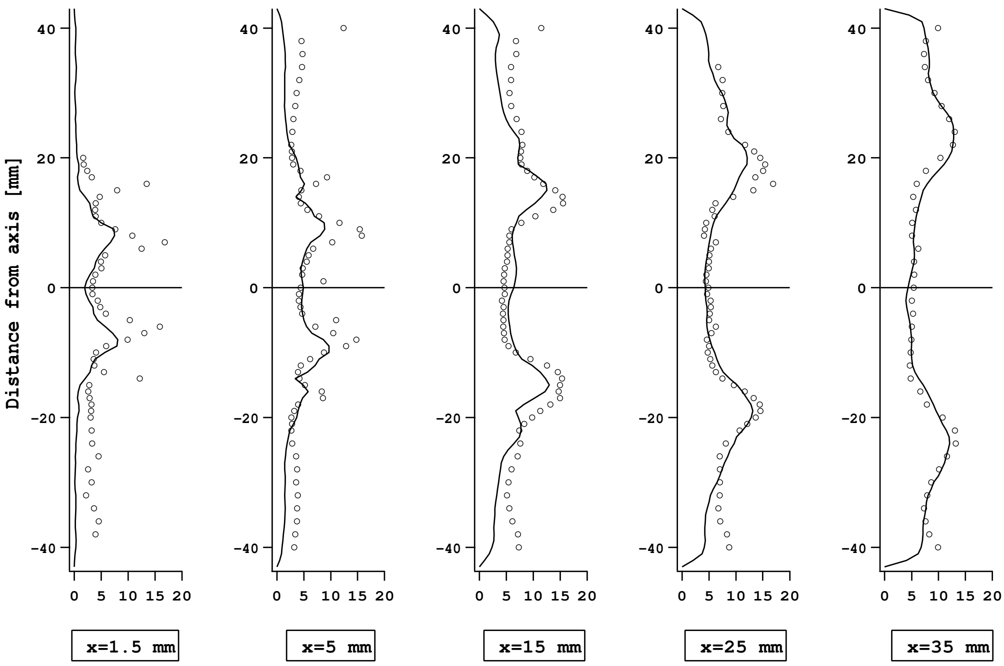

Fig. 17. RMS axial velocity in the central plane for reacting flow ○ LDV; ——— LES.

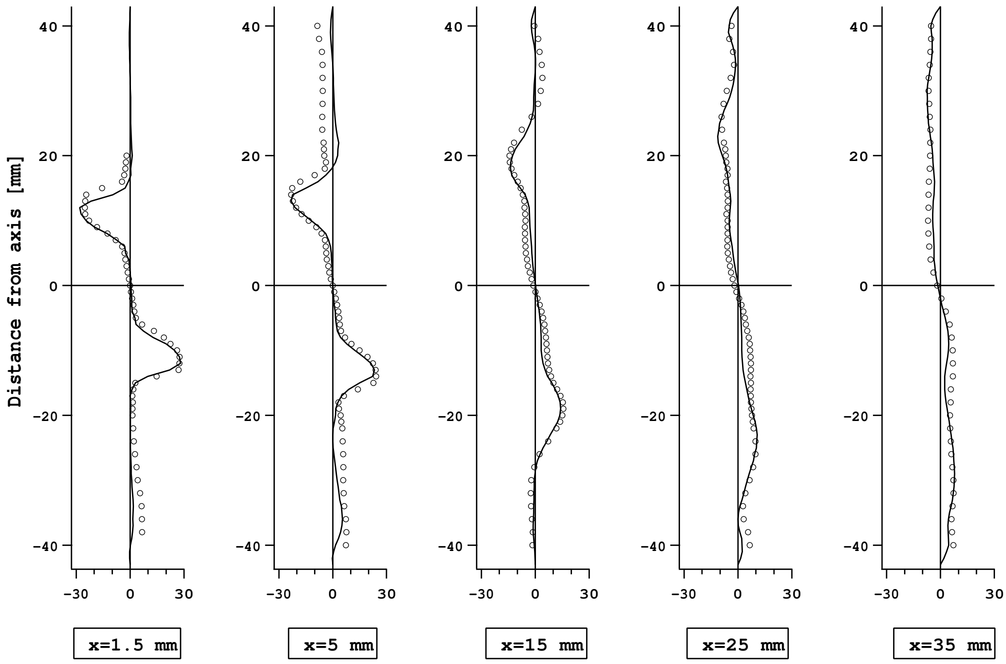

Fig. 18. Mean tangential velocity in central plane for reacting flow.
∘ LDV; —— LES.

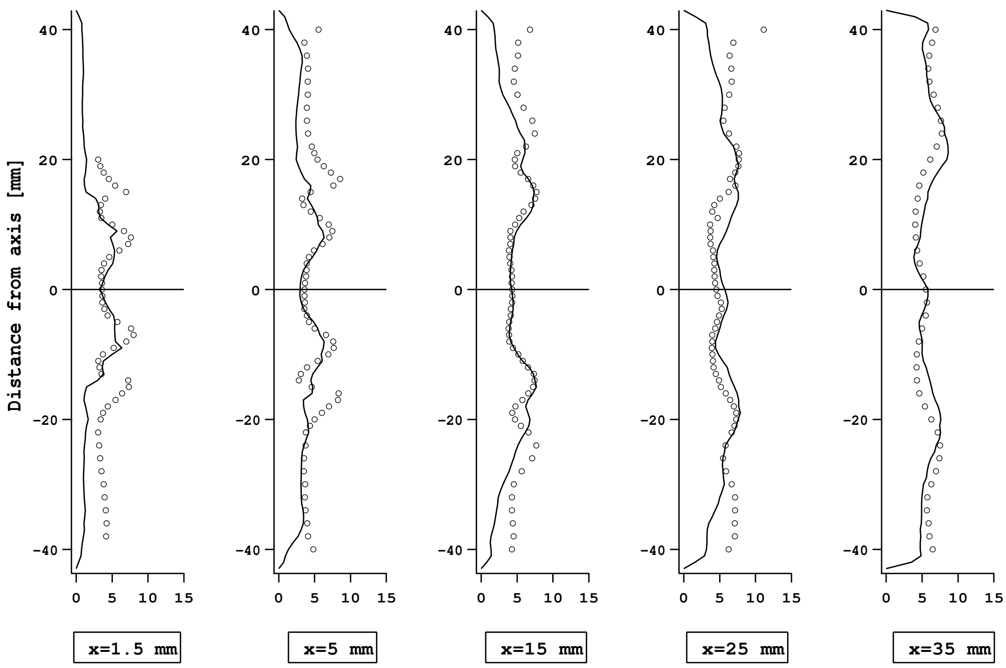

Fig. 19. RMS tangential velocity in central plane for reacting flow.
∘ LDV; —— LES.

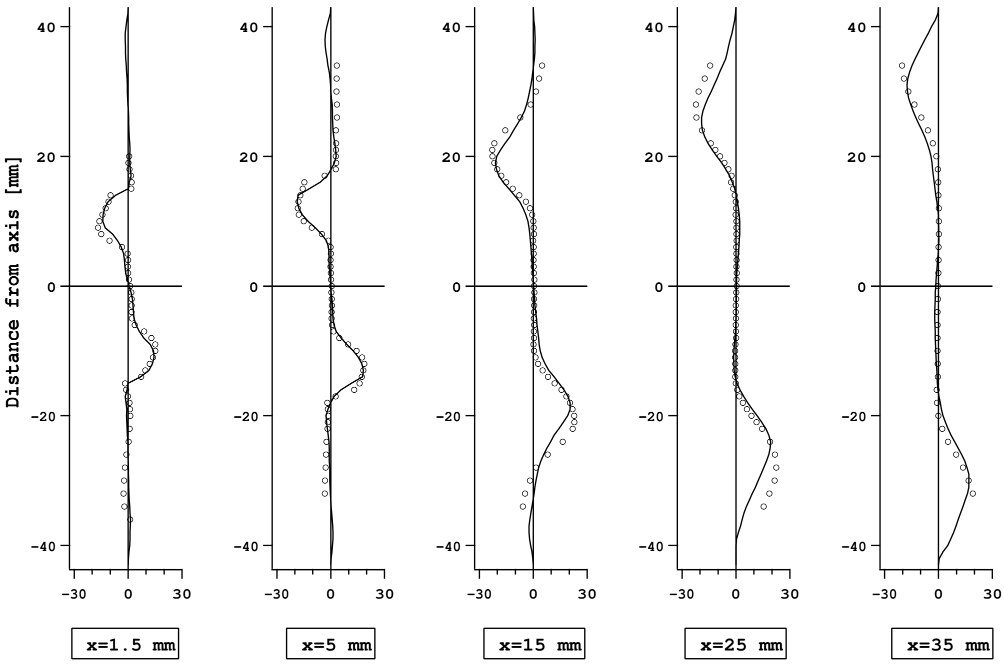

Fig. 20. Mean radial velocity in central plane for reacting flow. ○ LDV; ——— LES.

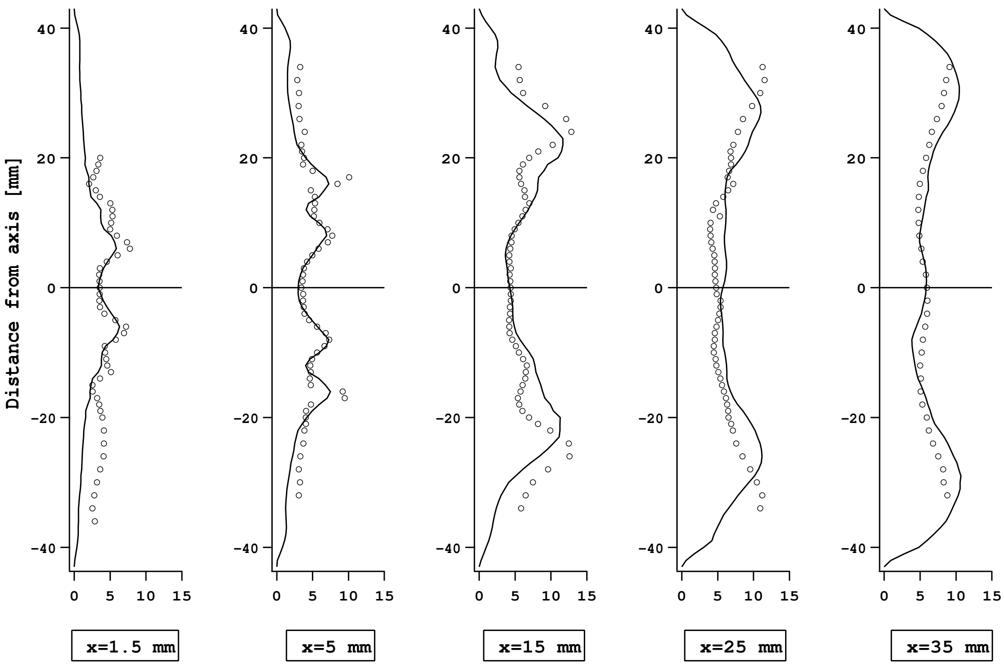

Fig. 21. RMS radial velocity in central plane for reacting flow. ○ LDV; ——— LES.

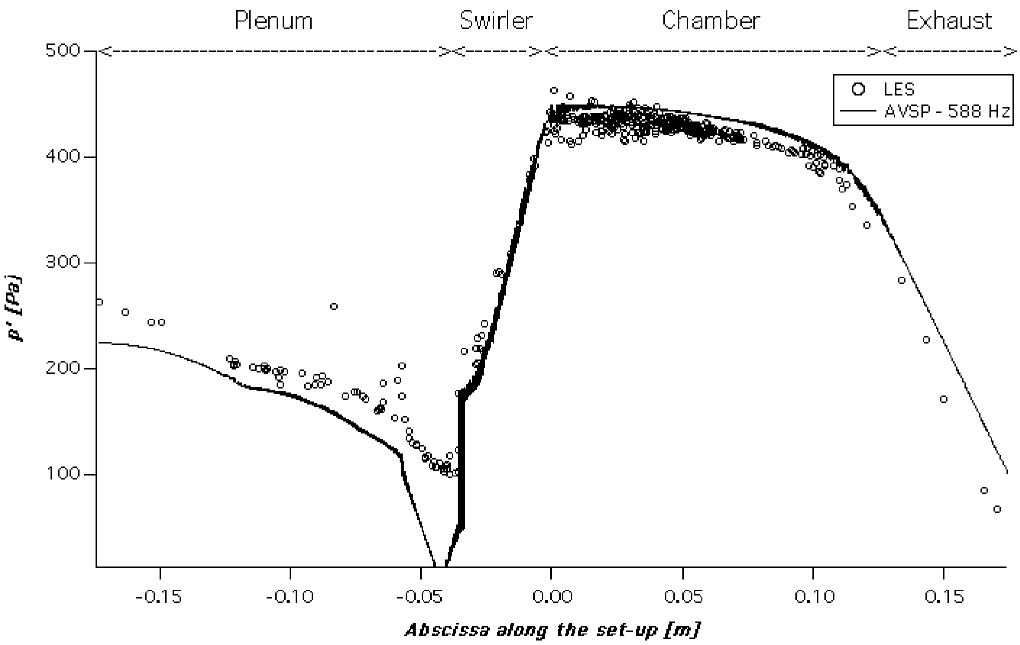

Fig. 22. Pressure fluctuations amplitude predicted by the LES code (circles) and the acoustic solver (line) for reacting flow.