Available online at www.sciencedirect.com
SCIENCE DIRECT®
ELSEVIER
Applied Thermal Engineering 24 (2004) 1583–1592
APPLIED THERMAL ENGINEERING
www.elsevier.com/locate/apthermeng

Experimental and numerical investigation of self-excited combustion oscillations in a scaled gas turbine combustor

G. Lartigue [a], U. Meier [b], C. Bérat [c,*]

[a] CERFACS, 42, Avenue G. Coriolis, 31057 Toulouse, France
[b] DLR, Pfaffenwaldring 38-40, D-70569 Stuttgart, Germany
[c] Turbomeca, 64511 Bordes, France

Received 10 July 2003; accepted 31 October 2003
Available online 12 May 2004

Abstract

The Prediction and Control of Combustion Instabilities in Industrial Gas Turbines (PRECCINSTA) project, financed by the European Commission Fifth Framework, concerns prediction and control of combustion instabilities in tubular and annular gas turbine combustors. One work package within the PRECCINSTA project joins DLR, CERFACS, and Turbomeca to study turbulence chemistry interaction fundamentals as follows.

Turbomeca has a low emissions industrial gas turbine injector that exhibits regimes of unsteady behaviour at engine conditions. A derivation of this injector was designed for the scaled conditions and delivered to DLR for detailed non-intrusive measurements. This injector repeats the unforced unsteady behaviour. The detailed measurements will also serve to validate the latest large eddy simulation (LES) calculations by CERFACS.

The non-intrusive measurements capabilities of DLR include: Spectroscopic techniques using pulsed lasers to provide temporally and spatially resolved measurements of flame structure, temperature and composition, planar laser-induced fluorescence (PLIF) of radical species like OH or CH allows qualitative visualisation of flame structure and location, heat release or mixing regions, and laser Doppler velocimetry (LDV).

CERFACS is at the leading front of LES with their AVBP flow solver. The key feature of this flow solver is that it resolves the unsteady, reacting and compressible equations of the fluid mechanics and thus takes into account the acoustic phenomena. This enables to simulate the coupling between the turbulent flame and the acoustics, which is known to be the fundamental mechanism of combustion instabilities.

* Corresponding author. Fax: +33-5-59-12-51-45.
E-mail address: claude.berat@turbomeca.fr (C. Bérat).

1359-4311/$ - see front matter
doi:10.1016/j.applthermaleng.2003.10.026

Keywords: Gas turbine; Injector; Combustion; Instability; Large eddy simulation; Measurement

1. Introduction and objectives

This study is part of the EC funded Prediction and Control of Combustion Instabilities in Industrial Gas Turbines (PRECCINSTA) project, see Kelsall et al. [1]. This project will finish in 2005. The list of partners of the PRECCINSTA project are shown in Table 1.

The objectives of this project can be summarised as follows:

The first part being the design, manufacture, and test of a scaled industrial low emissions injector in a lab scale burner. Next, the measurements of these tests are used to generate the experimental data to improve the understanding of the fundamental physical and chemical mechanisms leading to combustion instabilities and as final part to provide boundary conditions and experimental data to verify the large eddy simulation (LES) combustion models developed.

The remaining sections of this paper are organised in the above fashion: from the injector, to its installation in the sector rig, measurements, and LES calculations.

Table 1
Co-ordinator and partners of PRECCINSTA

PROJECT CO-ORDINATOR:			
1	ALSTOM Power Sweden AB		
PARTNERS:			
2	ALSTOM Power UK Ltd.	AAP-UK	UK
3	Nuovo Pignone S.p.A	NP	Italy
4	TURBOMECA S.A	TM	France
5	Rolls-Royce plc	Rolls-Royce	UK
6	PowerGen UK plc	PG	UK
7	ENEL Produzione SpA	ENEL	Italy
8	Electricité de France	EDF	France
9	KEMA Nederland B.V	KEMA	Netherlands
10	Deutsches Zentrum für Luft und Raumfahrt e.V	DLR	Germany
11	Centre Européen de Recherche et Formation Avancée en Calcul Scientifique	CERFACS	France
12	Queen Mary and Westfield College	QMW	UK
13	The Chancellor, Masters and Scholars of The University of Cambridge	UCAM	UK
14	Centre National de la Recherche Scientifique	CNRS	France
15	QinetiQ Ltd.	QinetiQ	UK
16	University of Wales, Aberystwyth	UWABER	UK
17	Cranfield University	Cranfield	UK
18	SIEMENS AG Power Generation (KWU)	SIEMENS	Germany
19	ANSALDO Energia SpA	ANSALDO Energia	Italy
20	AEA Technology GmbH	AEA	Germany
21	University of Karlsruhe	UNIKARL	Germany
22	ANSALDO Caldaie SpA	ANSALDO Caldaie	Italy

2. Low emissions industrial gas turbine injector

Turbomeca has developed an injector for low emissions industrial applications. For more details on this injector see publications of Schott et al. [2] and Niass [3]. The combustion system equipped with this injector gives combustion oscillations in certain regimes. Engine and rig tests have shown this injector to be the cause, or one of the main contributors. Extensive CFD has been performed to study the influence of swirl angle, diffuser, and fuel injection. The fuel injection is at the swirler location as shown in Fig. 1. The instabilities pertain to certain regions of equivalence ratio.

Based on above mentioned work the decision was made to supply an injector for detailed tests at DLR with:

- two swirl angles,
- two diffuser geometries (with and without a rounded contour),
- forced oscillations generated with loudspeakers upstream the swirler.

Fig. 2 shows the injector adapted for the DLR test rig.

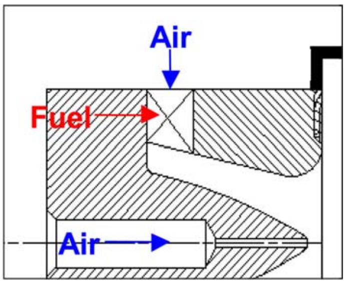

Fig. 1. Turbomeca low emissions injector.

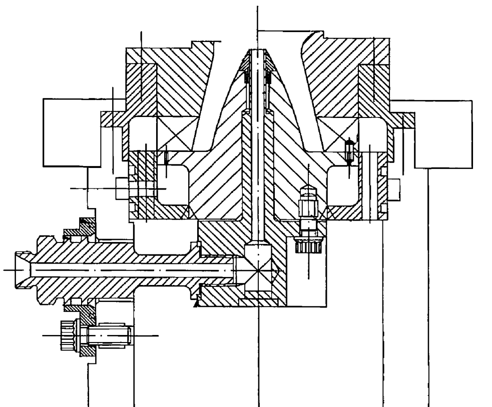

Fig. 2. Adaptation of the TM's single swirler injector to the DLR's gas supply holding the burner on their Stuttgart test rig.

3. Experimental measurements at DLR

The scaled injector was assembled and installed in a combustion chamber/plenum configuration designed for almost unobstructed optical access of the combustion chamber. The experimental arrangement as well as the visual appearance of the flame is shown in Fig. 3.

Structural properties and acoustic characteristics of the lab scale burner were studied in the ''glass box'' square combustion chamber at DLR Stuttgart using video recordings, photography and acoustic measurements. Since this burner allows for a multitude of combinations of nozzle exit shapes and fuel mixing geometries, in addition to variation of power and equivalence ratio, it was necessary to perform a survey characterisation of the burner using simple and fast methods, but for a wide range of operating conditions. These results formed the basis for the decision on a small range of relevant conditions, which are to be investigated in detail by more sophisticated methods, in order to provide validation data sets for LES modelling.

In a next step, further investigations covered the response of the burner/plenum/combustion chamber assembly to adding a forced oscillations driver device—in this case a 300 W loudspeaker attached axially to the plenum—and the response to forced excitation of periodic oscillations. These tests concentrated on a burner configuration with a step function exit contour and fuel mixing through the swirler. The operating point envisaged was at a thermal power of 35 kW with methane as fuel at an equivalence ratio ϕ near 0.7. The flame shows a self-excited oscillation with a dominant frequency of ~300 Hz under these conditions; it was expected that near the onset of a self-excited instability, the relatively small amplitude of air pressure fluctuations in the plenum

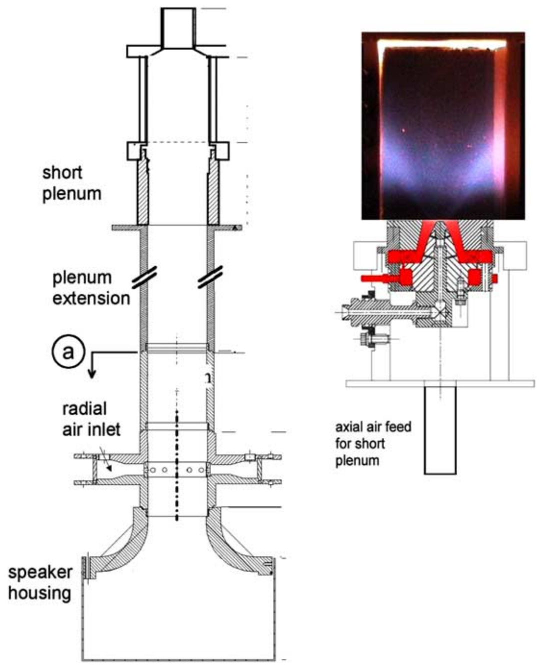

Fig. 3. Burner and Plenum design for different configurations. Section below ''a'' is removed for measurements shown with square symbols in Fig. 4 Top right: Visible flame shape.

induced by a loudspeaker could be sufficient to cause a noticeable response of the flame to external forcing if driven near the resonance frequency.

It was discovered that the presence of the extended plenum with radial air feed and speaker housing induced a strong damping on self-excited oscillations of the burner. This is illustrated in Fig. 4. The left diagram shows the amplitude of the most intense frequency in the Fourier spectrum, the right diagram the corresponding frequency. The blue symbols show measurements with a short plenum, i.e., all components below the position marked "a" in the left part of Fig. 3 removed, and axial air feed as indicated in the right part. The acoustic spectrum is dominated by an intense bimodal distribution with frequencies of 200 and 400 Hz, respectively, in the slightly rich regime, a 500 Hz oscillation near $\Phi = 1$, and a 300 Hz-oscillation for $0.6 < \Phi < 0.7$. The red symbols show measurements for the extended plenum. In the fuel-rich regime, the oscillations at 200 Hz remain, although much less intense. The oscillations on the lean side and at $\Phi \approx 1$ have disappeared completely.

First experiments with forced excitation showed that the 35 kW flame shows little response to acoustic excitation, unless very high amplitudes of the acoustic excitation are applied. This result is based on observation of the visible flame shape. At lower power, however—around 20–25 kW—the flame reacts noticeably to acoustic excitation even with low amplitudes by changing its shape and the position of the stabilisation zone on the nozzle exit.

An indispensable basic requirement for laser-based investigations on periodically oscillating flames is the ability to obtain phase-coupled measurements. Since the lasers used for laser-induced fluorescence (LIF) and Raman experiments are pulsed lasers with fixed low repetition rates, a method had to be developed to synchronise these systems with a variable acoustic frequency in the flame. In the case of laser Doppler anemometry (LDA) used for velocity measurements, measurements are performed at random phase angles; therefore, for each measurement the corresponding pressure trace in the plenum was recorded simultaneously, which allows an a posteriori-assignment of velocity measurements to phase angle intervals.

An example for phase-coupled velocity measurements is given in Fig. 5. The two curves show the axial component of the velocity at 5 mm distance from the burner exit plane as a function of radial position for two different phase angles. The phase difference between the two measurements is 180°; phase angle zero is defined as the positive zero transition of the pressure curve of the acoustic oscillation measured in the plenum. The most striking feature of this measurement is the

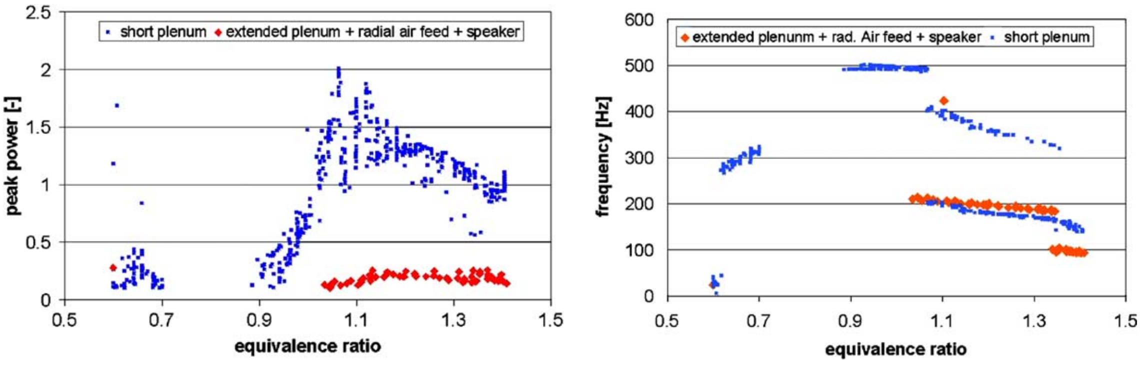

Fig. 4. Amplitude (left) and frequency (right) of the dominant self-excited oscillation as a function of equivalence ratio.

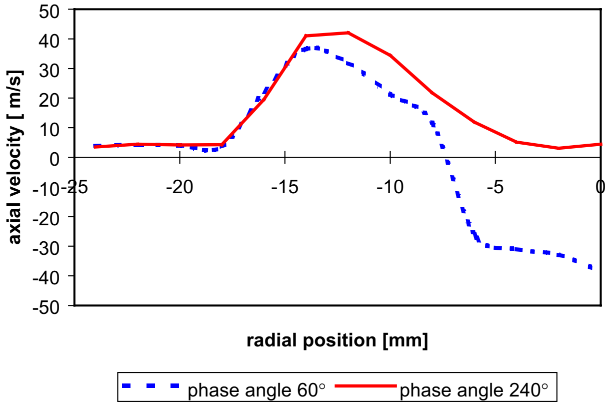

Fig. 5. Phase-coupled axial velocity measurements.

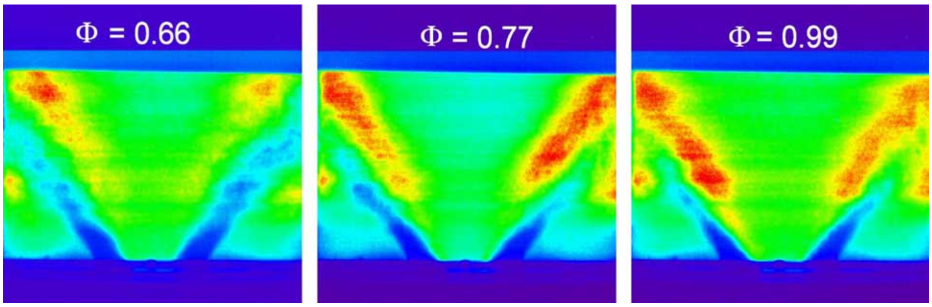

Fig. 6. Time-averaged OH distributions in the 35 kW flame at different equivalence ratios.

occurrence of a strong inner re-circulation zone and the strong fluctuation of the axial velocity with phase angle on the burner axis.

As a first example for results of PLIF measurements, Fig. 6 shows OH-LIF images in the lab scale burner at 35 kW power for three different equivalence ratios. The width of each image corresponds to the full combustion chamber width of 85 mm. Each image is the average of 200 single-pulse measurements at random phase angles. It can be seen that the combustion intensity reaches its maximum several centimetres above the nozzle exit. The flow of cold mixed unburned gases is clearly visible as a V-shaped structure above the nozzle exit. The penetration depth of this flow changes with equivalence ratio. This observation is plausible because the equivalence ratio was changed by varying the air mass flow rate, thereby changing the axial momentum of the unburned gases as well.

4. Calculation setup by CERFACS

LES is a standard tool to study the dynamics of turbulent flames. It is also one of the key tools for predicting and studying the combustion instabilities encountered in many modern combustion devices, such as aero or industrial gas turbines, rocket engines or industrial furnaces.

4.1. LES solver AVBP

The LES solver AVBP (see www.cerfacs.fr/cfd/CFDWeb.html) is used here. The full compressible Navier–Stokes equations are solved on hybrid (structured and unstructured) grids. The combustion model for the LES is based on various techniques. The laminar reaction rate is modelled by a reduced kinetic scheme with an Arrhenius law [4]. The interaction with turbulence is described with the Thickened Flame model, combined with an Efficiency Function [5,6]. For more information on AVBP (version 5.2) used here see Selle et al. [7]. CERFACS is able to produce LESs of turbulent combustion in both fully premixed and diffusion configurations. The intermediate case of partially premixed flames can also be simulated. This enables the code to take into account many phenomena (ignition, extinction and interaction with acoustics, for example).

4.2. The modelling

After obtaining the final geometry configuration several different meshes were tested before finding a suitable compromise between the CAD, the actual set-up, the mesh size and the way Boundary Conditions must be applied. Fig. 7 shows a cross cut of the calculation domain.

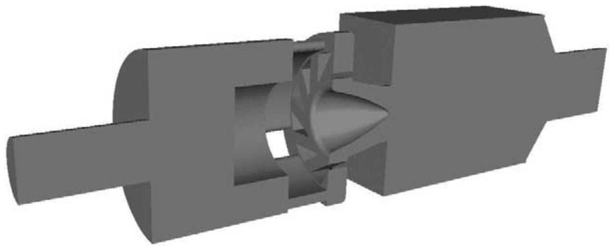

Fig. 7. Cross cut of calculation domain showing radial swirler feed and laboratory combustor.

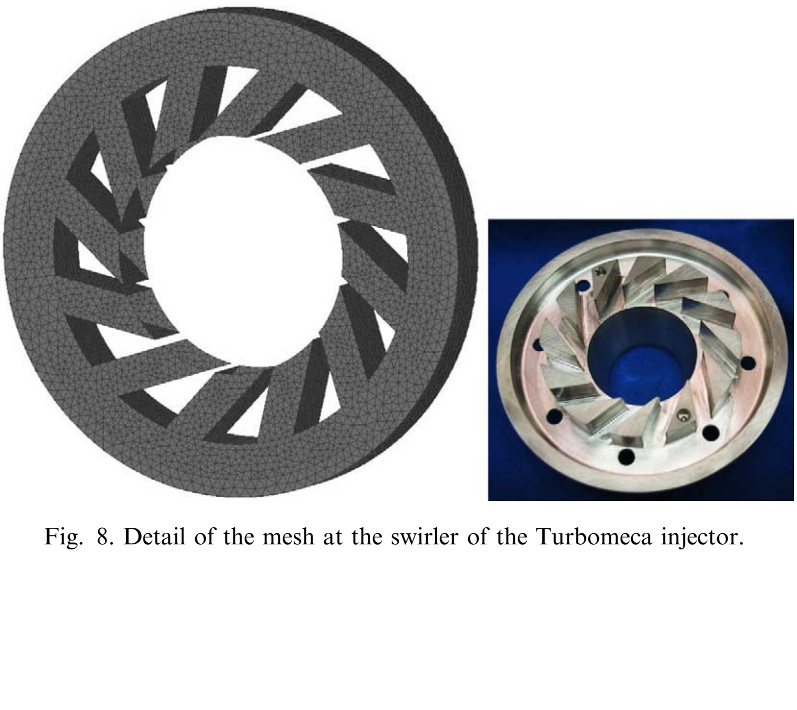

Fig. 8. Detail of the mesh at the swirler of the Turbomeca injector.

The model includes the plenum feeding the Turbomeca injector and the actual exit of the combustor. A part of the mesh is shown in Fig. 8. The operating conditions are at atmospheric pressure and non-pre-heated air.

LESs of any reacting flow are always preceded by the computation of the non-reacting case. It enables to point out the potential problems and to solve them on a much simpler configuration that is also relevant but whose CPU cost is much lower. It also permits to have an established cold flow and this configuration is much easier to ignite, just like it is done in the real set-up. The mesh used for these simulations is fully unstructured (tetrahedrons) and is composed of 500,000 grid points and 3 millions cells. It includes the upstream plenum, the Turbomeca injector with its 12 air slots, the DLR combustion chamber and the exhaust pipe.

The mass flow, the temperature and the composition is imposed in a non-reflecting way at the inlet of the domain. Following the same methodology, the pressure is also imposed in a non-reflecting way [7] at the outlet of the domain. This treatment enables the acoustic waves to leave the computational domain—and thus avoids a non-physical behaviour of the solution—while maintaining a mean pressure of 1 atm.

4.3. Results on the cold flow

The LES was able to point out many phenomena: the existence of a strong axial re-circulation zone due to the swirl component of the velocity, as well as corner re-circulation zones shown in Fig. 9. The LES also indicated the existence of a ‘‘precessing vortex’’ as can be observed in Fig. 10.

In terms of quantitative comparisons the LES duplicates very well the measured velocity profiles for the cold flow, as can be seen in the four comparisons made in Fig. 11.

5. Future work

The experiments will be extended to phase-coupled measurements, in addition to Raman measurements of temperature and mixture fractions.

LES of the hot flow will be done for two cases. The first one is for an equivalence of $\phi = 0.75$ and the second one is for $\phi = 0.70$.

The measurements will be compared to the simulations.

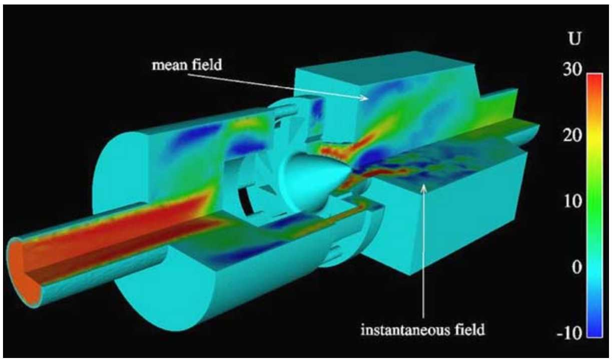

Fig. 9. Mean and instantaneous flow field of the axial velocity component U.

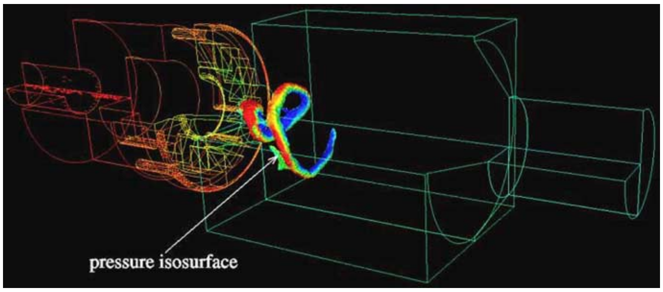

Fig. 10. Visualisation of a ‘‘precessing vortex’’ by pressure iso-surfaces.

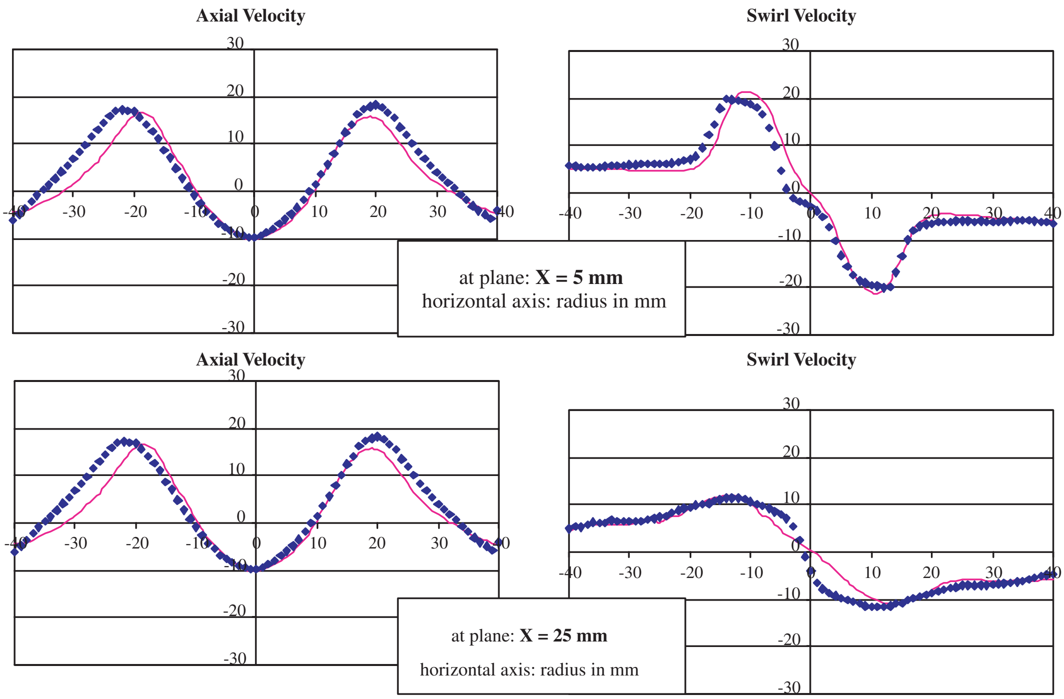

Fig. 11. Cold flow velocity comparisons at 5 and 25 mm between LES (lines) and measurements (dots).

6. Conclusions

Combustion instability related to an industrial injector repeated in lab scale conditions, even without acoustic forcing.

LES calculations of the cold flow demonstrate the existence of a ‘‘precessing vortex’’ that may well be at the heart of the combustion instabilities of this system.

This project will continue to gather measurements and flow simulations to enrich the understanding of unsteady flow phenomena in combustion chambers.

Acknowledgements

This work is funded by the European Commission Fifth Framework whose support is gratefully acknowledged. It is part of the research project PRECCINSTA: PREdiction and Control of Combustion INStabilities in Tubular and Annular gas turbine combustion systems (Contract ENK5-CT-2000-00060).

The authors appreciate the collaboration with Dr. B. Lehmann, DLR-Institute of Propulsion Technology, Dept. Turbulence Research, Berlin, who provided the LDA velocity measurements.

References

[1] G. Kelsall, C. Troger. Prediction and Control of Combustion Instabilities in Industrial Gas Turbines, International Conference on Gas Turbine Technologies, 10/11 July.
[2] G. Schott, G. Grienche, T. Niass, G. Martin, Développement d'une technologie de chambre de combustion à faibles émissions polluantes pour turbomachines de petite et moyenne puissances, NO_x Conference 2001, Paris.
[3] T. Niass, G.H. Martin, F. Ropital, G. Grienche, H. Verdier, Carbon deposits in gas turbine injectors, ASME 2001-GT-0072, 4–7 June 2001, New Orleans.
[4] Westbrook, Dryer, Simplified reaction mechanisms for the oxidation of hydrocarbon fuels in flames, Combustion Science and Technology 27 (1981) 31–43.
[5] O'Rourke, Bracco, Two scaling transformations for the numerical computation of multidimensional unsteady laminar flames, Journal of Numerical Physics 33 (1979) 185–203.
[6] Colin, Ducros, Veynante, Poinsot, A thickened flame model for large eddy simulations of turbulent premixed combustion, Physic of Fluid 12 (2000) 1843–1863.
[7] L. Selle, G. Lartigue T. Poinsot, P. Kaufmann, W. Krebs, D. Veynante, Large-eddy simulation of turbulent combustion for gas turbines with reduced chemistry, Center of Turbulence Research, Proceedings of the Summer Program 2002, pp. 333–344.

Glossary

Acronym Description

LDV	Laser dopler velocimetry
LDA	Laser-Doppler anemometry
LES	Large eddy simulation
LIF	Laser-induced fluorescence
PLIF	Planer laser-induced fluorescence