Large Eddy Simulation of oscillating flow in combustion chambers

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1 Motivation

The development of combustion systems to minimize the emission of pollutants and to increase the system's efficiency involves modifications of the combustion process using premixed systems and highly turbulent swirl stabilized flames. However, these modifications of the combustion process usually lead to stability problems caused by the appearance of combustion-driven oscillations. Therefore, it is very important to understand the relevant feedback mechanisms responsible for the sustainment of the pressure oscillations in the combustion chamber.

Among the possible feedback mechanisms, the in-phase formation of large-scale coherent vortical structures is the object of our study. In the first period of the project only the cold flow will be considered (no combustion).

In order to study the formation of coherent vortical structures, we employ the Large Eddy Simulation technique (LES). This is an approach to compute turbulent flows by explicitly resolving the large-scale part of the turbulent motion. Only the contribution of vortices smaller than the employed mesh is accounted for by a so-called subgrid-scale model in the equations describing the large-scale turbulent motion.

2 Validation

The code employed is LESOCC2 developed at the Institute for Hydromechanics over several years. Its most recent status is described in Hinterberger (2004). This code has been validated for a large number of non-swirling flows. Hence, in the first part of the project we aimed at validating the method for swirling flows. Two experimental test cases have been chosen from the literature, a configuration investigated by Roback and Johnson (1983) and one by Sommerfeld and Qiu (1991). In both cases the configuration consists of two coaxial jets which enter into an expansion duct, Fig. 1, with the annular jet being swirled, the inner jet unswirled.

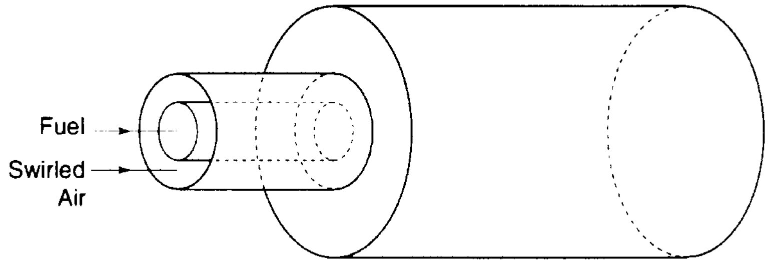


Figure 1: Geometry of a coaxial jet combustor (figure taken from Pierce and Moin (1998))

2.1 The configuration of Roback and Johnson

The Reynolds numbers of the flow are 15900 and 47500 for the inner and annular streams, respectively. The swirl number defined as

$$S = \frac{\int r^2 u_x u_\theta dr}{R\int r u_x^2 dr}$$

is S = 0.41, where u_x and u_θ are the axial and circumferential velocity component, respectively. For this degree of swirl, a central recirculation zone is formed. In addition a second recirculation zone appears in the corner of the expansion. Fig. 2 shows the streamlines of the mean flow, the color representing the axial velocity component. The averaging times required to collect a sufficient amount of samples for statistical evaluation is very large in this type of flow. In particular close to the axis this may yield a slight asymmetry of the picture, but in other parts of the flow the convergence is more rapid. Fig. 3 shows a comparison between experiment and simulation. It includes the LES results of Pierce and Moin (1998). The agreement is reasonably good. However there are some discrepancies which, in our opinion, make the validation not as satisfactory as desired. We have some doubts concerning the experimental conditions at the inlet. In particular, there is an uncertainty about the actual swirl number as different values are quoted in different documents. This is the reason why we extended the validation by computing a second case.

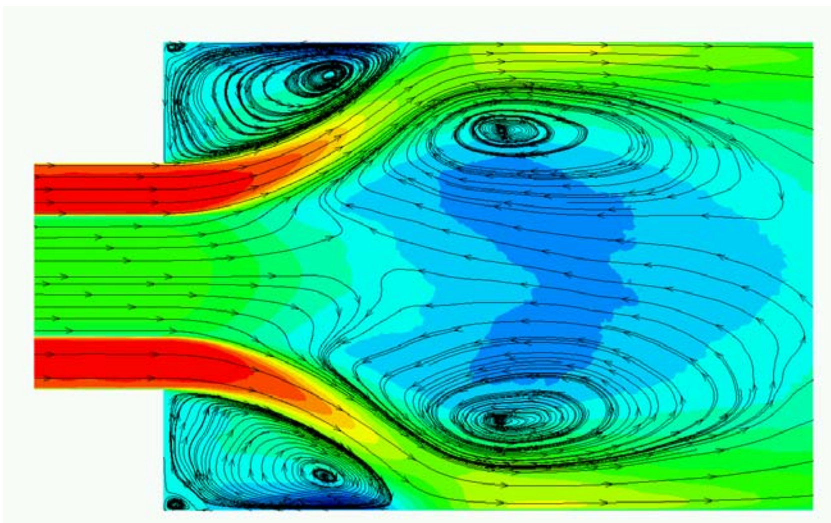


Figure 2: Streamlines. Color:axial velocity.

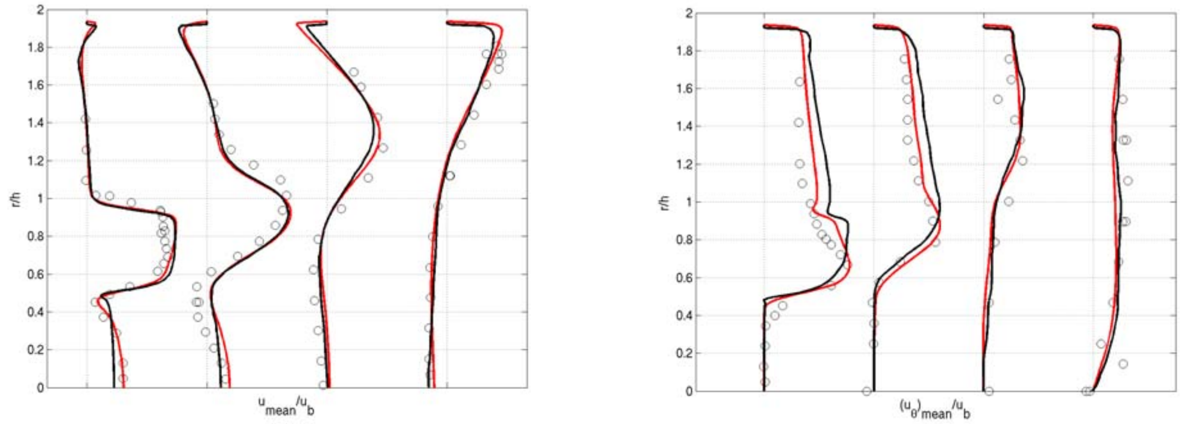


Figure 3: Radial distributions of mean axial and tangential velocities at four axial locations. Symbols, experiment.Black line, present simulation.Red line, LES of Pierce and Moin (1998).

2.2 The configuration of Sommerfeld and Qiu

The Reynolds number, based on the total volume flow rate at the inlet and the outer diameter of the annulus D, is 52400. The swirl number in this case is S=0.47. Two main recirculation zones are also present for this case. Fig. 4 shows a comparison between experiment and numerical simulation at an axial location of 0.8 diameters downstream of the expansion. It includes the LES results of Apte *et al* (2003). The agreement with the experimental data is excellent both for the mean and the rms values of the velocities.

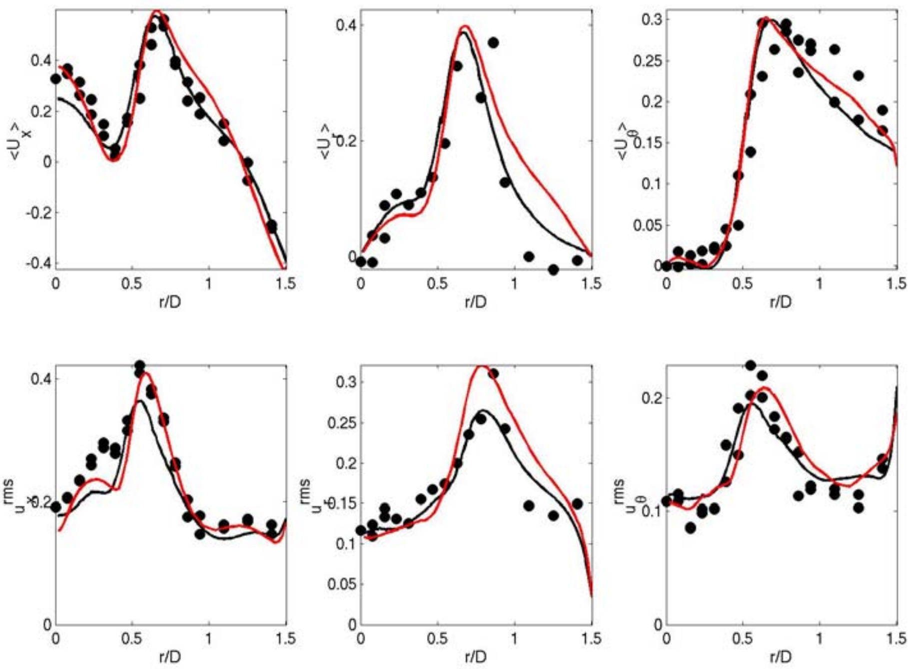
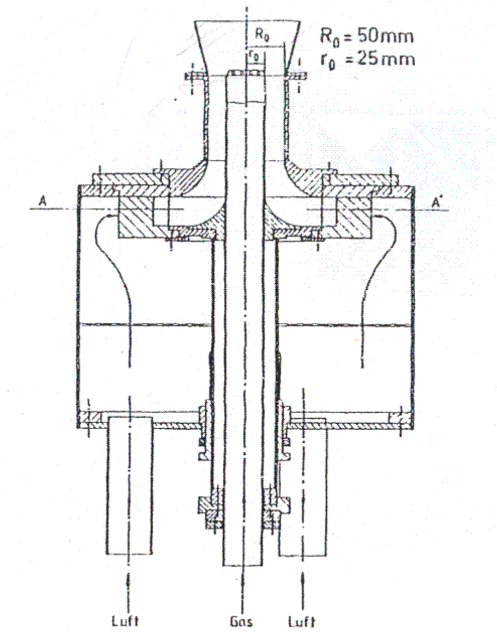


Figure 4: From left to right, radial distribution of axial, radial and tangential velocity components respectively at x = 0.8 D. Upper part, mean values. Lower part, rms values. Symbols, experiment. Black line, present simulation. Red line, LES of Apte *et al* (2003).

3 LES of the configuration investigated in companion project C1

3.1 Experimental configuration and computational model

In the companion project C1 of SFB 606, an experimental study of swirling jets is carried out. The simulation of the configurations studied in C1 is the main subject of our investigations. The experiments are currently underway, but a similar configuration was studied earlier by Hillemanns (1988) so that in a first step we computed the flow investigated by him. It consists of a single annular swirling jet with no inner jet. Compared to the previous cases this configuration features a jet into an open domain. Fig. 5 shows the experimental setup. The Reynolds number of the flow is 163000. The theoretical swirl number is $S_{0th} = 1.5$. With the definition of the swirl number given above, this corresponds to $S = 0.9$. Fig. 5 also shows a sketch of the computational domain employed in the simulations. The simulations were performed using a block-structured mesh consisting of 2.5 million cells. No-slip boundary conditions were applied at the walls. The entrainment was simulated using a mild co-flow. Free-slip conditions were applied at the open boundary placed far away from the region of interest. A convective outflow condition was used at the exit boundary. At the inflow, top-hat profiles were imposed. The inlet swirl was designed to match the swirl at the jet exit. The dynamic subgrid-scale model has been employed, with smoothing by temporal relaxation .



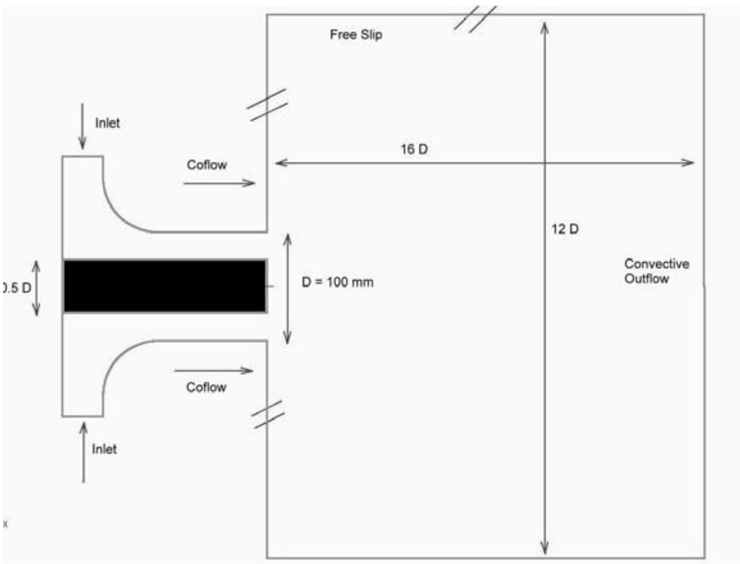


Figure 5: Left, experimental configuration of Hillemanns (1988). Right, sketch of the computational domain.

3.2 Results

As a validation of the present calculation, Fig. 6 compares the calculated mean tangential velocity profiles with measurements for several axial stations downstream of the jet exit. The agreement is excellent.

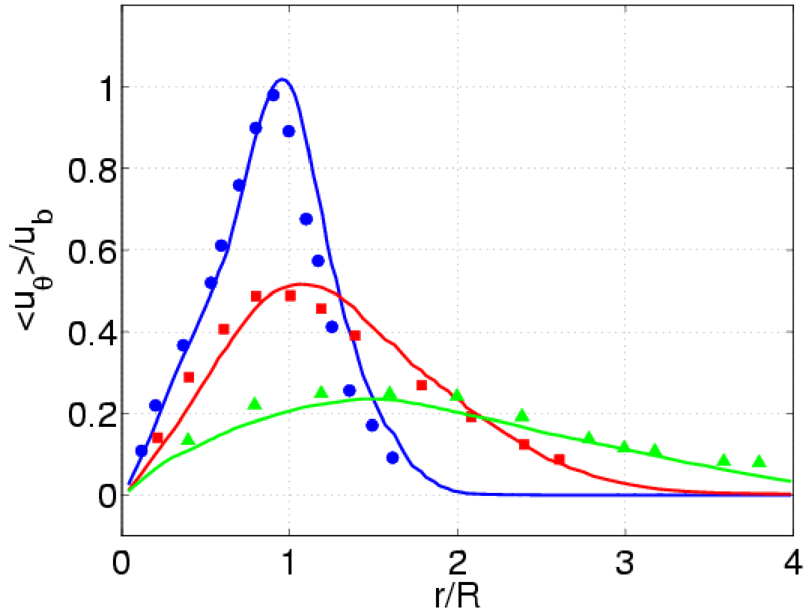


Figure 6: Radial distribution of mean tangential velocity at different axial positions: x=0.5 D (blue), x=1.5 D (red), x=3 D (green). Symbols represent corresponding experimental data.

In the instantaneous flow, large-scale structures are observed, which precess around the jet axis. A characteristic picture is shown in Fig. 7. In the literature on the subject this phenomenon is called precessing vortex core. Actually, two spiral structures can be seen in this picture which corresponds to a particular instant in time. In visualizations of the flow it has been observed that eventually one of them may disappear for a short period of time, until it is formed again. Fig. 8 shows a typical temporal spectrum of tangential velocity fluctuations. It exhibits a pronounced peak at twice the precessing frequency (because most of the time there are two structures) and some activity at the precessing frequency (corresponding to the short periods of time in which there is only one structure present). More details will be given in García-Villalba *et al* (2004).

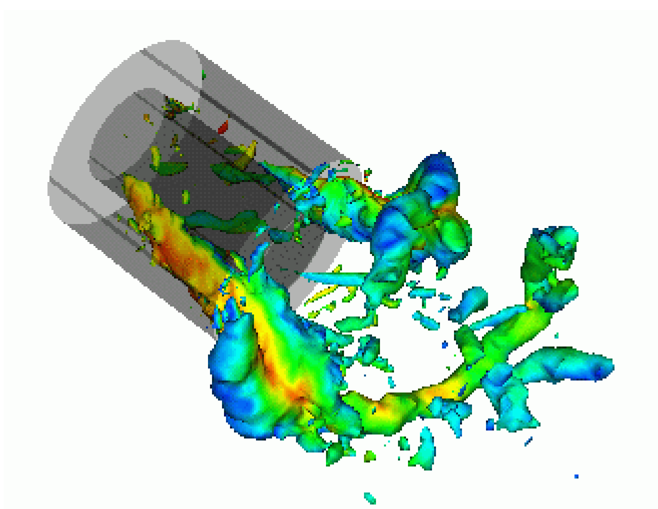


Figure 7: Isosurface of pressure fluctuations p - <p> = -0.4. Color represents the modulus of the velocity vector.

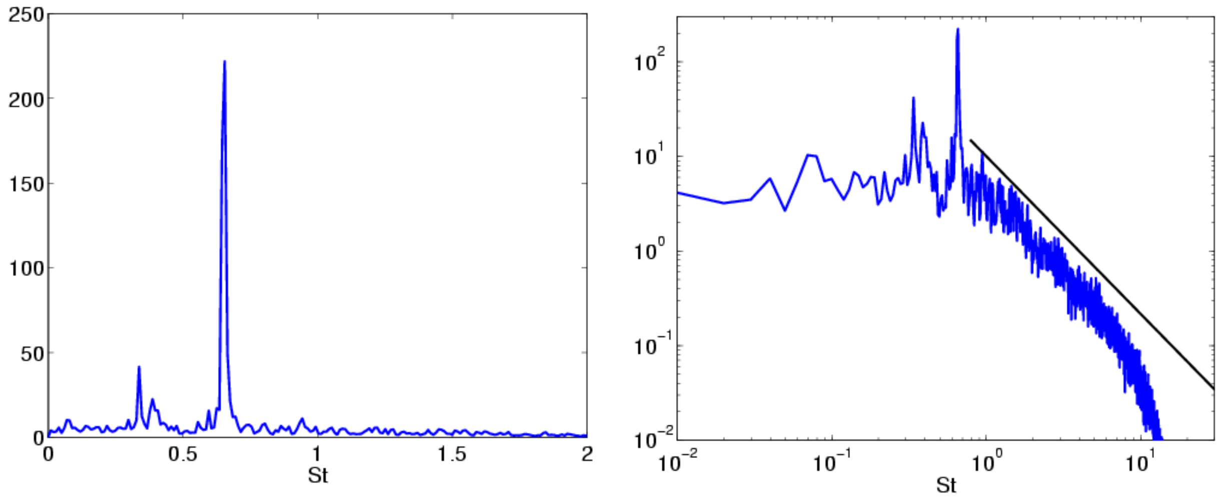


Figure 8: Typical velocity spectrum. Left, diagramme with linear axes. Right, the same diagramme with logarithmic axes. The black line has a slope of –5/3.

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