Large-eddy simulation of a reacting swirling flow in a model combustion chamber

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Abstract. We perform Large-eddy simulations of a non-premixed swirling flame in a model of a combustion chamber with a swirling air bulk flow at $Re = 15000$ and a central pilot low-velocity jet with methane using the Flamelet-generated manifold model. The unsteady behaviour of this regime is well reproduced based on the flame dynamics. The distribution of turbulent kinetic energy suggests the presence of intensive vortical structures typical of high-swirl flows similar to the precessing vortex core.

1. Introduction

Combustion of fossil fuels represents the main source of energy. The widespread use of gas turbines for these purposes in the energy sector, industry and transport is due to their high energy efficiency. However, the environmental requirements for gas turbine engines and power plants become more severe, forcing the development of new technologies for low-emission combustion. One of these technologies is dry-lean combustion, based on a fuel-air mixture with a significant excess of air. From a practical point of view, the introduction of this technology is largely limited by unsteady dynamics of the flame leading to stability issues in typical combustion chamber configurations.

Combustion chambers represent complex systems with the efficiency depending on hydrodynamic stability of the flow, fuel supply and its mixing, chemical reactions, heat release and pressure fluctuations [1, 2]. The flow in the combustion chamber is typically subjected to swirl to increase the flame stability [2, 3]. Strong fluctuations often limit the conditions for the safe and efficient operation [3]. In particular, hydrodynamic and thermoacoustic instabilities in combustion chambers can damage the device. Flow control techniques are necessary to suppress these harmful instabilities [4–6]. Here we perform Large-eddy simulations of a reacting swirling flow in a model combustion chamber in order to develop a new control strategy as a next step.

2. Problem formulation and computational details

We perform Large-eddy simulations (LES) of a reacting swirling flow in a model combustion chamber with the TURBOMECA swirler. The configuration is shown in Fig. 1 where the swirling air flow is supplied through 12 main channels while the methane is delivered by the pilot jet. The cylindrical coordinates are used below with the origin located at the tip of the nozzle. The uniform velocity profile is set at each inlet (main channels) with the same amplitude to match the target Reynolds number $Re = 15,000$ based on the bulk velocity $U_{air} = 6.4m/s$ and outer diameter $D = 37mm$. The nozzle represents
an annular channel with the inner diameter \( d = 6 \text{mm} \). The bulk velocity of the methane pilot jet corresponds to \( U_{\text{fuel}} = 2 \text{m/s} \).

![Combustion chamber geometry with the swirler and central pilot jet. Pink areas correspond to boundary conditions at a solid wall, green regions represent the inlets, and top circular area is the outlet. The cylindrical coordinate system \( r, x \) has its origin in the center of the pilot jet exit.](image)

**Figure 1.** Combustion chamber geometry with the swirler and central pilot jet. Pink areas correspond to boundary conditions at a solid wall, green regions represent the inlets, and top circular area is the outlet. The cylindrical coordinate system \( r, x \) has its origin in the center of the pilot jet exit.

The flow is governed by the variable-density Navier-Stokes equations in the low-Mach number approximation represented by the mass and momentum equations as well as four transport equations on the progress variable, mixture fraction and its variances using the Favre-averaging and Flamelet-generated manifold (FGM) model [7, 8] with the flamelet tabulation based on GRI-Mech 3.0 mechanism [9]. The equations are discretized within the unstructured finite-volume computational code OpenFOAM [10] which is of the second-order accuracy in time and space on a cell-centered collocated mesh. The mesh consists of \( 4.1 \times 10^6 \) cells with 288 cells along the azimuthal direction, 63 cells in the radial direction inside the nozzle and 62 cells outside the nozzle. The overview of the geometry, flame surface and mesh are presented in Figure 2 with the blow-up around the nozzle demonstrating a sufficient resolution in the region of interest. Let us note a significant mesh refinement in the inner shear layer between the air and methane flows.

3. **Results**

This non-premixed regime has been studied at the Institute of Thermophysics SB RAS using advanced experimental techniques. The direct comparison against our simulations has shown close agreement confirming the adequate choice of the modeling framework and mesh resolution. Previously we reported the isothermal simulations and experiments with excellent agreement [11]. Below we describe preliminary results on flame dynamics and time-averaged characteristics.
Figure 2. The visualization of the computational domain close to the nozzle together with the instantaneous temperature field. Right two figures show the computational mesh and its blow-up near the pilot jet nozzle.

Figure 3 shows visualization of the temperature field at several consecutive time instants. The figure indicates that the flame is attached to the nozzle and the flame isosurface contact angle with the nozzle varies slightly, but its azimuthal position seems to revolve with the main flow in the clockwise direction. The flame configuration has azimuthal inhomogeneity, within x=1-2D from the nozzle it seems to have a confined shape with quite limited oscillation of the isosurface, however, further up we can notice that its shape is modulated by a helical structure with low spatial frequency resembling the precessing vortex core phenomenon for high-swirl flows.

Figure 3. Visualization of the flame dynamics with Δt = 0.0012s shown as constant temperature isosurface.

Figure 4 demonstrates time-averaged distributions of velocities, temperature and their stresses indicate that mainly combustion occurs in both recirculation zone and in the outer mixing layer of the swirled flow. Distribution of mean stresses suggests that the inner recirculation zone is primarily steady which can be also outlined from figure 3 which illustrates spatial oscillations of isosurface of instantaneous temperature in the outer mixing layer. Essentially the high heat area is confined within the distance of one diameter after the tip of the nozzle as it can be seen in the temperature field distribution.
Figure 4. Time-averaged flow characteristics with streamlines. The temperature is shown in °C.

4. Conclusion
We studied a reacting swirling flow of a methane and air mixture in a model of a combustion chamber. We noticed that the flame is attached to the surface of the nozzle with a contact angle moving azimuthally with the main swirled flow. We demonstrated that within one calibur the flow has a rather steady configuration where externally the shape is constrained by the outer mixing layer and internal flow contour is determined by heat expansion which is suggested by high temperature distribution in the recirculation zone from within the vortex core. Further downstream the temperature isosurface features a helical structure, propagating with low-frequency, which was observed earlier in the isothermal lower-swirl case [11].

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