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Bistable swirled flames and influence on flame transfer functions

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ABSTRACT

Large Eddy Simulations (LES) are used to study a lean swirl-stabilized gas turbine burner where the flow exhibits two stable states. In the first one, the flame is attached to the central bluff body upstream of the central recirculation zone which contains burnt gases. In the second one the flame is detached from the central bluff body downecirculation zone which is filled by cold unburnt gases and dominated by a strong Precessing Vortex Core (PVC). The existence of these two states has an important effect on the dynamic response of the flame (FTF): both gain and phase of the FTF change significantly in the detached case compared to the attached one, suggesting that the stability of the machine to thermoacoustic oscillations will differ, depending on the flame state. Bifurcation diagrams show that the detached flame cannot be brought back to an attached position with an increased fuel flow rate, but it can be re-attached by forcing it at high amplitudes. The attached flame however, behaves inversely: it can be brought back to the detached position by both decreasing or increasing the pilot mass flow rate, but it remains attached at all forcing amplitudes.

1. Introduction

Swirling flows are commonly used to help flame stabilization in gas turbine combustion chambers. They feature several types of vortex breakdown and can exhibit bifurcation phenomena where different states can co-exist and the flow can jump spontaneously from one to another [1,2]. Bifurcations of flames in configurations which are close to real gas turbine chambers have not been investigated so far even though engineers report that they observe these mechanisms and that there is a link between flame states and thermoacoustic instabilities: when the flame changes from one state to another, its acoustic stability characteristics also change.

Two dynamic phenomena are usually observed in swirled combustion chambers: (1) a helical flow instability, the so-called precessing vortex core (PVC) and (2) thermo-acoustic instabilites.

The PVC is an hydrodynamic instability in swirling flows [3]. It is a large scale structure characterized by a regular rotation of a spiral structure around the geometrical axis of the combustion chamber. It can occur at high Reynolds and swirl number flows [4–10] and its precession frequency is controlled by the rotation rate of the swirled flow [3]. Several studies show that combustion can suppress the PVC [6,7,11], but other cases also show PVCs which are present in reacting flows [12–15]. The interaction of PVC with flames has been analyzed for example by Stöhr et al. [16]: they found the PVC to enhance mixing and to increase the flame surface. This was associated to structures in the inner shear layer, whereas Moeck et al. [15] observed the outer shear layer to create most of the flame perturbations. Both researchers as well as Staffelbach [13] using LES evidenced a "finger-like" rotating structure at the flame foot around which the PVC is turning. Furthermore, asymmetric fluctuations of the heat release rate are usually associated to the rotating PVC [12,15].

A second phenomenon present in todays low-emission gas turbines is thermo-acoustic instabilities [17]. They are due to a resonant coupling of the unsteady heat release and the acoustics propagating in the system and their prediction has become an important task to prevent their appearance at an early design stage [18–20]. For acoustically compact flames the linear analysis of combustion instabilities is generally performed with the Flame Transfer Function (FTF) introduced by Crocco [21,22] and more recently with the Flame Describing Function (FDF) [23,24]. In these approaches the FTF is defined as the relative heat release fluctuation $(\hat{q}/\bar{q})$ to the relative inlet velocity perturbation $(\hat{u}/\bar{u})$ induced by the acoustic field:

$$F(\omega) = \frac{\hat{q}/\bar{q}}{\hat{u}/\bar{u}} = ne^{-i\phi(\omega)} \quad (1)$$

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The $F(\omega)$ function is generally expressed in the frequency domain as amplitude n and phase $\phi(\omega)$ which are functions of the forcing frequency ω (and forcing amplitude for FDFs). It is affected by different mechanisms acting simultaneously on the heat release rate fluctuation and therefore difficult to separate [25]: the axial velocity perturbation [26–29], the perturbation of swirl [30–34] and the perturbation of mixing [35–38]. The gain of FTFs for swirled flames exhibits a typical shape: it starts at 1, then increases towards a maximum, decreases to a local minimum at low frequencies, often reaches a second maximum at higher frequencies and decreases finally to low values at high frequencies. The FTF phase evolves in a quasi-linear way [29,33,34,39].

Both phenomena, the PVC and combustion instabilities, can be simultaneously present in swirled flames and interact with each other but the link between PVC and thermoacoustics remains a controversial issue. Several studies [40,11,10] have shown that the PVC can provoke thermo-acoustic instabilities because the flame position and the recirculation zones change when the PVC is active [10,14]. Forced acoustic oscillations can also lead to a stretching and contracting of the PVC [41]. Moreover, Paschereit et al. [12] observed that low amplitude forcing can suppress the PVC, and Moeck et al. [15] found the same effect but at high oscillation amplitudes.

The aim of this paper is to show that the link between PVC and thermoacoustics can take a different form: the swirled flow leading to the existence of a PVC can be bistable, leading to the existence of two states for the same regime. These two states have very different mean flows but also different FTFs so that one of them may lead to a thermoacoustic oscillation and not the other. This is shown by Tay and Polifke [42]: dependent on the thermal wall boundary conditions used, two different flames with different FTFs are present in the same configuration. In this paper however, it is shown that two different flames and FTFs can exist for exactly the same operating conditions. Moreover, the bistable nature of the swirled flow makes even FTF studies complicated: the flame can switch from a state to another when the mean fuel flow rate injected in the pilot flame is varied but also when the flame is forced acoustically to measure FTFs because these forced oscillations can be strong enough to trigger bifurcations. These phenomena are studied here in one specific example of gas turbine chamber using LES. For this chamber, the existence of two states for the same regime was revealed by LES. In the first state, the flame is attached to the burner and the PVC is suppressed, whereas in the second one, the flame is detached from the burner and separated from the burner outlet by a strong PVC.

The target configuration is first described (Section 2) and the LES-solver, mesh and boundary conditions are presented (Section 3). The LES is validated against experiments in Section 4 in terms of flow fields and pressure drop for the cold flow on an atmospheric test rig. Section 5 shows how the LES is initialized in order to obtain two different flames at the same operating point and Section 6 compares the LES results for mean and instantaneous flow fields. The dynamic response of both flames to an acoustic perturbation is analyzed for different forcing frequencies in Section 7. Bifurcation diagrams are constructed in Section 8 to study the effect of the mean fuel flow rate on re-attachment and detachment process of both flames. Finally, different forcing amplitudes at one frequency are studied and hysteresis and an eventual suppression of the PVC are discussed (Section 9).

2. Target configuration

The burner considered here is a hybrid burner operated at high pressure possessing multiple air and fuel inlets (Fig. 1). Air is injected through two coaxial swirlers (diagonal and axial) with the main air mass flow passing through the diagonal passage. Methane is injected through small holes in the vanes of the diagonal passage and mixes with air before reaching the combustion chamber where the flame stabilizes due to vortex breakdown [2,43]. To help flame stabilization in this lean combustor a pilot methane injection is added in the axial part of the injection system. Cooling air inlets are also present to shield the Cylindrical Burner Outlet (CBO) and the center bluff body, seen on Fig. 1.

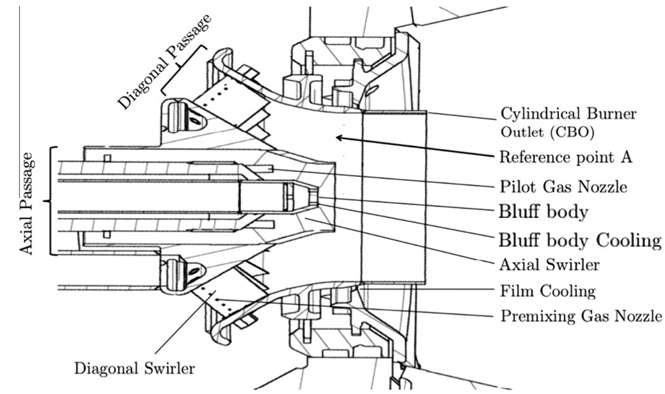

Fig. 1. Burner details and reference point A (proportions changed).

Two configurations were used here:

- Experimental test rig for cold flow validation
  Large-Eddy Simulation was first validated against experiments performed on a test rig at atmospheric pressure. In this specific laboratory experiment installed in Ansaldo Energia S.p.A, a single burner is mounted on a octagonal combustion chamber as shown in Fig. 2. Only air is injected through the diagonal and axial swirler and the results are used to validate LES prediction for pressure losses through the burner as well as velocity profiles.
- Real gas turbine
  In the real gas turbine, the burner is mounted on a section of an annular combustion chamber. This section is used as the computational domain retained for LES (Fig. 3). The use of a single sector LES instead of a full annular LES is justified by the ISAAC assumption assuming that azimuthal modes mainly induce longitudinal fluctuations in each burner and can thus be studied on a single sector [44,45].

3. Large eddy simulation

LES is well suited to unsteady combustion and is a useful tool to predict thermoacoustic limit cycles or FTFs [17,32,20]. The LES solver is described in Section 3.1, and the mesh and boundary conditions are given in Sections 3.2 and 3.3, respectively.

3.1. LES solver

The LES code is a fully compressible explicit solver using a cell-vertex approximation for the reactive multi-species Navier–Stokes equations on unstructured grids [46]. The viscous stress tensor, the heat diffusion vector and the species molecular transport use classical gradient approaches. The fluid viscosity follows the Sutherland law and the species diffusion coefficients are obtained using a constant species Schmidt number and diffusion velocity corrections for mass conservation. A second-order finite element scheme is used for both time and space advancement [47,48]. The Sub-grid stress tensor is modeled by the classical Smagorinsky model [49]. Chemistry is computed using a two-step mechanism for methane/air flames [50] which includes two reactions and six species (CH_4, O_2, CO_2, CO, H_2O and N_2). The first reaction is irreversible