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Sensitivity of LES-based harmonic flame response model for turbulent swirled flames and impact on the stability of azimuthal modes

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Abstract

This paper describes a numerical study of azimuthal unstable modes in the annular combustor of Cambridge. LES is used to compute a Harmonic Flame Response Model (HFRM) and a Helmholtz solver to predict the overall stability of the combustor. HFRM quantifies the interaction between acoustics and the turbulent swirled flames. They must be known with precision because instabilities are very sensitive to subtle changes. The effects of azimuthal confinement (corresponding to the annular combustor equipped with 12 or 18 burners), thermal boundary conditions and fuel type (methane or ethylene) on HFRMs are simulated here using LES of a single 20 degree ($N = 18$) or 30 degree ($N = 12$) sector. A double-sector LES is also computed to investigate flame/flame interactions. These LES-based HFRMs are then used as inputs for a Helmholtz solver and results show that (1) subgrid-scale LES models lead to marginal effects on the harmonic flame response while (2) azimuthal confinement, thermal conditions and fuel type strongly affect the flame response to acoustics and therefore control the stability of the azimuthal mode. Computations show that the annular experiment performed with methane should be stable while ethylene should lead to azimuthal unstable modes as observed experimentally.

Keywords: Sensitivity; HFRM; Instabilities; Azimuthal mode; LES

1. Introduction

Thermo acoustic instabilities often prevent easy and fast commissioning of new designs of power generation as well as aeronautical gas turbine engines [1,2]. Operating conditions leading to instabilities are currently impossible to predict *a priori* and are usually only discovered during full

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engine testing. Thermo-acoustic instabilities result from the coupling of unsteady combustion and acoustic eigenmodes of the geometry. In the annular chambers of gas turbines, azimuthal modes are the most common and difficult to control [3]. Three tools are available today to simulate azimuthal modes and complement full annular laboratory scale rigs [4–7]: unsteady CFD [8], thermo-acoustic solvers [9] and reduced order models [10,11]. Although the three approaches are clearly essential for our understanding, the combination of full annular rig test facilities and Large Eddy Simulations is the best method to address the underlying mechanisms [12].

Because of their extreme costs, computations of full 360° configurations are still out of reach today and not designed to study underlying phenomena leading to combustion instabilities. To develop predictive tools and determine the stability of a given design point, a reduced strategy is used: (1) A Harmonic Flame Response Model (HFRM), Flame Transfer Function (FTF, [13]) or Flame Describing Functions (FDF, [14]) can be evaluated numerically to link the flame response to acoustics. To do so, only one sector with periodic and non-reflecting boundary conditions is computed using LES since the capture of a self-excited azimuthal mode is not required [15,16]. (2) The acoustic/flame model (HFRM) is then introduced as a source term in a full annular acoustic solver, much cheaper than LES, to study the azimuthal acoustic mode in the complete 360° configuration. Although successful in determining the stability of real burners [9] such coupled approaches are known to be sensitive to multiple parameters [17].

This paper intends to evaluate the robustness of this LES-Helmholtz strategy to determine HFRM using LES and inject them as inputs of a Helmholtz solver to predict the stability of the annular test rig of Cambridge [4,5]. Section 2 describes the annular rig of Cambridge. In Section 3, the numerical strategy and the various cases used to evaluate the HFRM (Section 3.1) and stability (Section 3.2) are defined. Results on mean and phase-averaged flow fields for unforced and forced cases are discussed and compared to experiment in Sections 4.1 and 4.2. Section 4.4 focuses on the HFRM sensitivity to various LES sub models as well as key phenomena (azimuthal confinement, thermal conditions and fuel type) affecting the flow dynamics and flame shape as observed in previous sections. Finally, Section 4.5 gives the stability map of the 360° configuration. The impact of azimuthal confinement, thermal conditions and fuels on the stability is assessed: the annular rig is found to be stable when using methane while ethylene leads to azimuthal instabilities as observed in the annular experiment [4,5].

2. Target configuration: the full annular combustor of [4]

The target experiment is the annular combustor of Cambridge studied by [4] (Fig. 1: for detailed descriptions of the apparatus and experimental methods see [4,5]). The stainless steel rig can include $N = 12, 15$, or 18 equally spaced flames around a circumferential diameter of 170 mm. Premixed reactants are supplied by a common plenum which includes grids and flow straighteners for flow conditioning and acoustic damping. For all configurations, mass flow controllers are used to maintain a constant bulk velocity of $U = 18\ \mathrm{m\ s^{-1}}$ at the exit of each bluff body. This ensures that any changes in the flame structure and dynamics are a result of azimuthal confinement (flame spacing). The rig is instrumented with microphones to characterize the instability modes and a high-speed intensified camera is used to measure the OH^* chemiluminescence of the whole annulus.

To find a set of conditions that give rise to self-excited azimuthal modes, the inner (L_i) and outer (L_o) lengths of the combustor walls, azimuthal confinement, and two fuel types (CH_4 and C_2H_4) were varied in the experiment [4,5]: strong self-excited azimuthal modes only occurred for C_2H_4–air mixtures and when different inner and outer tube lengths $L_i = 130$ mm and $L_o = 300$ mm were used. [6] also found that L_i and L_o must be different to excite azimuthal modes. The occurrence of self-excited azimuthal modes did not depend on azimuthal confinement but the limit-cycle amplitude and the flame structure did. Only longitudinal modes were observed for CH_4-air mixtures.

3. Numerical models

3.1. Large eddy simulations

Large Eddy Simulation (LES) of compressible flow is widely recognized as an accurate method [1] to study combustion instabilities in complex configurations [8,18–20] but the impact of subgrid scale models on LES results for instabilities is rarely discussed. To study the impact of these models on HFRM computations, a fully compressible explicit code (called AVBP) is used to solve the filtered multi-species 3D Navier–Stokes equations with realistic thermochemistry on unstructured meshes [21,22]. Numerics is based on a two-step Taylor–Galerkin finite element scheme of third-order in space and time (TTGC, [23]) to accurately propagate acoustic waves. Boundary conditions use the NSCBC approach [24] and ensure non-reflecting conditions [25] as well as the proper introduction of acoustic waves in the LES domain for HFRM computations.

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