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Scale Adaptive Simulation of a thermoacoustic instability in a partially premixed lean swirl combustor

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ABSTRACT

The thermoacoustic oscillation of a turbulent, swirl-stabilized, partially premixed flame in the PRECCINSTA gas turbine model combustor is analyzed by means of a Scale Adaptive Simulation (SAS) method. In the critical regions of the combustor, the SAS features a fine spatial resolution and thus corresponds to a Large Eddy Simulation (LES). Two combustion models are applied, a simple eddy dissipation model and a detailed finite rate chemistry (FRC) model. A previous LES for the same combustor by Franzelli et al. (2012) indicated that the acoustic impedance of the fuel supply plays a critical role. Therefore in the present work, the fuel channels and fuel plenum are included in the computational domain and thereby the fuel inlet impedance is inherently taken into account. The resulting fields of velocity, temperature and mixture fraction fit well to experimental data with a slightly better agreement for the detailed FRC model. For both combustion models the computed frequency of the thermoacoustic oscillation is close to the experimental value, whereas its amplitude is significantly overestimated by about 15 dB in comparison to measurements. The reason for this overestimation is analyzed using an additional measurement where acoustic damping due to vibrating side walls is suppressed. For the latter experiment both frequency and amplitude agree well with CFD results, which indicates that acoustic damping effects must be carefully taken into account for validation of CFD. The 3D time-resolved simulations further provide detailed insights into the interaction of flow and mixing in the swirler, which leads to a convective time-lag between oscillations of velocity and equivalence ratio in the flow of unburned gas that largely affects the heat release response of the flame. Taken together, the results show that SAS computations can accurately reproduce frequency and amplitude of thermoacoustic oscillations of turbulent partially premixed flames in a gas turbine combustor provided that proper modeling of fuel supply and acoustic boundary conditions is applied.

1. Introduction

Modern gas turbines employ lean premixed combustion since this results in a lower flame temperature, and hence in less thermal nitrogen oxide [1]. However, lean premixed combustion increases the susceptibility to thermoacoustic instabilities, which occur if the combustion dynamics couples with an acoustic eigenmode of the combustor [2]. Since these instabilities can cause severe operational difficulties, their prediction is of great importance in the design process of combustion chambers. Within the last decade Large Eddy Simulation (LES) has been established as a tool that can support this design process as it resolves the energy containing turbulent scales of a flow, which often increases significantly the accuracy of a turbulent flame calculation in combustors with complex geometry [3,4]. LES of thermoacoustic instabilities, in particular, is especially sensitive to acoustic boundary conditions [5–7] and to the dynamics of fuel-air mixing [8,9] and turbulence-chemistry interaction [10]. The application of appropriate boundary conditions and model closures for flow, mixing and reaction is therefore a most critical, yet generally unresolved issue for an accurate and at the same time computationally affordable modeling of these instabilities.

The present work describes a detailed numerical simulation of a thermoacoustic instability focusing on the proper choice and evaluation of acoustic boundary conditions and model closures. The simulation is applied to a turbulent swirl-stabilized flame in a partially premixed swirl combustor that is typical for gas turbines, namely the so-called PRECCINSTA combustor [11]. For the chosen operating condition, detailed measurements of velocity field and thermochemical states by Meier et al. [12] are used for validation.

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Compared to fully premixed operation, thermoacoustic oscillations in partially premixed combustors exhibit an additional complexity as they are driven not only by fluctuations of velocity but also by fluctuations of equivalence ratio in the unburned gas entering the flame zone [8,13–16]. Therefore, the mixing of fuel and air by the turbulent flow in the premixing zone of the combustor has to be well resolved in order to predict the thermoacoustic instability properly. In this work, turbulent fluctuations are modeled using the Scale Adaptive Simulation (SAS) technique, which allows wide variations of the grid resolution within the computational domain. In regions with appropriately high grid resolution, an LES solution is obtained that resolves most of the energy containing turbulent scales of the reacting flow. In case of low grid resolution, an Unsteady Reynolds Averaged Navier–Stokes (URANS) solution is obtained. A grid resolution that is sufficiently high for an LES solution is chosen in the combusting and premixing regions of the flow.

The PRECCINSTA combustor has been analyzed numerically in several previous studies [6,11,17–22]. Most of these works [11,17–20,22], however, investigated either stable operating conditions or assumed a perfectly premixed flame. For the same combustor and operating condition as in this work, the frequency of the thermoacoustic oscillation was computed in an LES by Franzelli et al. with a discrepancy of 100 Hz to the measured data [6]. According to the authors, this deviation might result from inaccurate modeling of the acoustic impedance at the fuel inlet boundaries in the swirler. Therefore in the present work the fuel injection holes and the fuel plenum are included in the computational domain and hence the fuel inlet impedance is inherently taken into account.

An accurate prediction of a thermoacoustic instability also requires precise modeling of the combustor acoustics, which depends strongly on the acoustic boundary conditions [6,7,23–25]. Time Domain Impedance Boundary Conditions (TDIBC) allow to apply acoustic filters of arbitrary order at domain boundaries, and hence to precisely control acoustic wave reflections [26–28]. TDIBC are therefore used in the present work to model the acoustic outlet boundary condition. The computations are carried out with two combustion models, namely a simple yet computationally efficient Eddy Dissipation Model (EDM) and a detailed direct finite-rate chemistry model (FRC). The results from both models are evaluated by a comparison to detailed experimental data including velocity, mixture fraction, temperature and acoustic spectra, and to the previous LES by Franzelli et al.

While the oscillation frequencies of the present SAS computations agree well with the measured values, the corresponding amplitudes of the oscillation are markedly higher than in the experiment. It is suspected that this difference is caused by acoustic damping due to loosely mounted quartz glass windows that were used as combustion chamber side walls in the experiments with optical diagnostics [12]. To test this hypothesis, additional acoustic measurements are performed where the combustor is equipped with rigid metal walls, and compared to the numerical results. Finally, the CFD results are used to examine the mechanism of fuel-air mixing in the swirler nozzle, which leads to the formation of equivalence ratio oscillations and thus significantly affects the dynamics of the thermoacoustic instability.

2. Experimental setup

2.1. Gas turbine model combustor

The combustor shown in Fig. 1 was designed within the EU project PRECCINSTA [11,29] and is derived from an industrial gas turbine by Turbomeca (now Safran Helicopter Engines). Air first enters a cylindrical plenum ($d = 78$ mm) and then passes through a swirl generator with 12 radial vanes and a converging nozzle ($d = 27.85$ mm) with a central conical bluff body into the combustion chamber. The chamber has a square cross section of 85×85 mm and a height of 114 mm, and the exit is cone shaped leading to a short central exhaust pipe ($d = 40$ mm). The combustor is operated at atmospheric pressure and in partially premixed mode, i.e., the gaseous fuel CH_4 is injected through 12 holes into the swirler vanes as shown in Fig. 1.

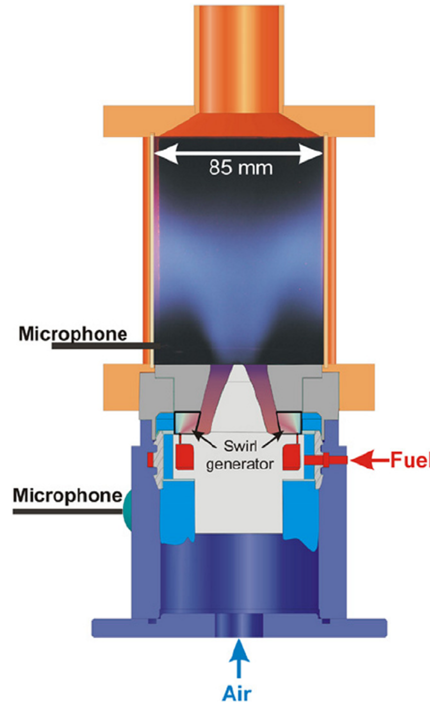

Fig. 1. Sketch of the PRECCINSTA combustor.

Table 1
Operating condition.

Thermal power	$P_{th} = 25.1$ kW
Equivalence ratio	$\phi = 0.70$
Air mass flow	$\dot{m}_{air} = 734.2$ g/min
Fuel mass flow	$\dot{m}_{CH4} = 30$ g/min
Inlet temperature	$T = 320$ K
Pressure	Atmospheric

2.2. Operating condition and validation data

For the present combustor, flames at different operating conditions have been characterized experimentally by the Institute of Propulsion Technology and the Institute of Combustion Technology of the German Aerospace Center (DLR) [11,12]. The three-dimensional velocity field was measured by laser Doppler velocimetry (LDV), and the flame structure by OH* chemiluminescence and planar laser induced fluorescence (PLIF) of OH. Major species concentrations, mixture fraction and temperature were obtained by laser Raman scattering. The present work focuses on the operating condition detailed in Table 1 with an equivalence ratio of $\phi = 0.7$ and a thermal power of $P_{th} = 25$ kW where a pronounced thermoacoustic instability with a frequency of about 280 Hz occurs.

Pressure measurements were carried out as part of this work using acoustic sensors at two locations, one in the air plenum and one in the combustion chamber as shown in Fig. 1. Depending on the pressure amplitude, either microphones (Brüel & Kjær type 4939) or piezo-resistive sensors (Kistler 4043A) are used. In the plenum the sensor is flush mounted to the wall, whereas for the chamber an acoustic probe is used where the sensor is located ≈