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Large eddy simulation of a partially-premixed gas turbine model combustor

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Abstract

Large-eddy simulations of a dual-swirl gas turbine model combustor (GTMC) are performed. This burner was experimentally studied by Meier et al. (2006), and is operated in the partially-premixed combustion regime. Two different LES-combustion formulations are employed to separately investigate modeling strategies for representing the combustion regime and the turbulence/chemistry interaction. A prior model analysis is conducted to examine the accuracy of describing the turbulent combustion regime inside this burner in terms of premixed or non-premixed flamelet solutions. Modeling results from three different LES computations are compared with measurements for velocity, temperature, and species-mass fractions of CO_2, CO, and H_2. Overall, the simulation results, obtained with a flamelet/progress-variable (FPV) model and a premixed-based filtered tabulated chemistry LES (F-TACLES) formulation, are in good agreement with experimental data. It is shown that the flow-field structure exhibits sensitivity to the representation of the turbulence/chemistry interaction. This is a result of the flame wrinkling at the lifted flame base in the nozzle-near region.

Keywords: Large-eddy simulation; Gas turbine combustor; Turbulence/chemistry interaction; Flamelet modeling; Turbulent combustion

1. Introduction

The current design of gas turbine (GT) combustor systems is driven by the need for increased power-densities, improved fuel-efficiencies, reduced emissions, and lower maintenance cost. Computational techniques have the potential for providing valuable information for the design of GT combustion systems [1]. Over recent years, remarkable progress has been made in the development of numerical techniques for turbulent reacting flows. In particular, the large-eddy simulation (LES) technique has been demonstrated to provide considerably improved predictions of turbulent reacting flows compared to single-point closure models.

Different LES-combustion models have been developed for application to turbulent reacting flows. However, many of these models have been validated in the context of canonical and unconfined flame configurations, such as jet-flames or simple dump combustors. Furthermore, LES-calculations in complex burner configurations, relevant to realistic GT combustors and

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operating conditions, introduce challenges that can be attributed to the lack of experimental data to enable comprehensive model validation, and the geometric complexity and resulting time-consuming mesh-generation. By addressing these issues, several experimental and computational studies have been conducted to establish validation data in GT-relevant combustor configurations. These model combustors are laboratory-scale burners, exhibiting relevant attributes of realistic combustors (such as diffusor, plenum, swirler, and injector assembly). Often, the combustor chamber is modified to provide optical access for non-intrusive diagnostics.

Recent efforts have focused on GT-combustors that operate under premixed conditions. Notable works are LES-computations of the PRECCINSTA swirl burner [2–6]. These simulations utilized premixed combustion models to describe the turbulent reacting flow field. Overall, these validation efforts showed that LES results are in good agreement with experimental measurements. Experiments in this burner [7] showed that the incomplete mixing between fuel and oxidizer represents a mechanism for thermo-acoustic instabilities at certain operating conditions. With the exception of one study [6], most computations focused on the stable operating point without considerating partial premixing.

Another premixed burner configuration is the TECFLAM [8], which has been developed with the objective to provide validation data for model evaluations. This unconfined burner consists of a movable swirl nozzle with a central bluff body, and the burner assembly is placed inside a co-flowing air stream. Comparisons of simulation results [9–11] with recent measurements [8] showed good agreement for velocities, temperature and major species.

To investigate non-premixed combustion regimes with relevance to aircraft engines, Janus et al. [12] experimentally characterized a model combustor (MOLECULES), consisting of a generic nozzle design with a single swirler assembly. The burner was operated at elevated pressure conditions and with preheated air. LES-computations of this configuration have been performed [13,14]. Although these model assessments were limited to comparisons of the velocity field for reacting operating conditions, these simulations provided valuable information about the flow-field structure and the assessment of modeling strategies.

While considerable efforts have been directed towards burner systems operating in premixed and non-premixed combustion regimes, LES-model validation for partially-premixed operating conditions are not available. In particular, partial premixing can introduce additional challenges for turbulent combustion models, since many formulations rely on a flame-topology-dependent representation to model combustion processes and the turbulence/chemistry interaction.

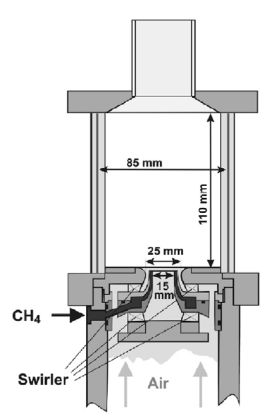
The objective of this work is to extend previous efforts on the LES-model validation in complex GT combustor configurations. To this end, the DLR gas turbine model combustor (GTMC) is considered, which is operated at partially premixed combustion conditions [15,16]. Moreover, this combustor consists of a dual swirler, representing a more complex configuration than previously considered.

2. Methodology

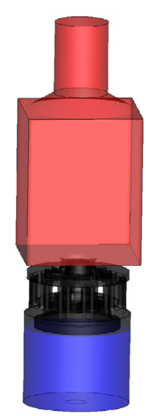
2.1. Experiment configuration

A schematic of the burner and the computational domain is illustrated in Fig. 1. The injector assembly consists of a central air nozzle, an annular fuel nozzle, and a co-annular outer air nozzle. Both inner and outer air nozzles supply swirling air at ambient temperature from a common plenum. The inner air nozzle has a diameter of 15 mm; the annular nozzle has an inner and outer diameter of 17 and 25 mm, respectively. Non-swirling fuel is provided through three exterior ports. The fuel nozzle is recessed by 4.5 mm below the burner face. The combustion chamber has a square cross section of $L_x = 85$ mm in width and $L_z = 110$ mm in height. The exit of the combustion chamber is connected to an exhaust tube with a diameter of 40 mm and a height of 50 mm. In the following, h denotes the axial distance from the bottom of the combustion chamber.

The investigated operating point is “Flame A,” which is characterized by a thermal power of 34.9 kW and a global equivalence ratio of $\Phi_{glob} = 0.65$. The corresponding mass flow rates for air and fuel were 1095 and 41.8 g/min, respectively. The burner was operated at ambient



(a) Combustor schematic [15].



(b) Computational domain.

Fig. 1. Gas turbine model combustor, showing (a) schematic of the burner [15], and (b) rendering of the computational domain.

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