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Modeling heat loss effects in the large eddy simulation of a model gas turbine combustor with premixed flamelet generated manifolds

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Abstract

Large eddy simulation results are presented for a model gas turbine combustion chamber, which is operated with a premixed and preheated methane/air mixture. The off-center position of the high axial momentum confined jet burner causes a strong outer recirculation, which stabilizes the flame. Turbulent combustion is modeled by the premixed flamelet generated manifolds (PFGM) technique, which is combined with the artificial thickened flame (ATF) approach. The influence of different heat loss modeling strategies on flame propagation and structure is investigated. Besides the established method of using burner-stabilized flames as basis for the non-adiabatic tabulation, an alternative approach based on freely propagating flames with heat loss inclusion by scaling of the energy equation source term is presented. Different grid resolutions are applied to study the impact of cell size and filter width on the results, the effect of subfilter modeling is also examined. The simulation setup and the modeling approach are validated by comparison of computed statistics against measurements. A good overall agreement between simulation and experiment is observed. However, the length of the flame was slightly under-predicted; it is shown that a simple method for consideration of strain effects on the flame has the potential to improve the predictions here. The effect of heat loss on the combustion process is then characterized further based on probability density functions obtained from the simulation results.

Keywords: Large eddy simulation; Confined jet flame; Turbulent premixed combustion; Tabulated chemistry; Heat losses

1. Introduction

Concepts for modern gas turbine combustors often feature regions with (partially) premixed combustion, which are exposed to significant heat loss. Large eddy simulation (LES) has proven in the past to be a very capable approach for the numerical simulation of such devices.

Different methods have been established for the modeling of premixed combustion within LES, for example based on tracking of the flame front by the G-equation model [1–3] or modeling of the flame surface density (FSD) [4,5]. Another

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group of models is based on widening of the flame in normal direction by means of either filtering [6–8] or artificial thickening (ATF) [9,10]; the latter approach is applied here. The combustion progress and flame propagation are described through the premixed flamelet generated manifolds (PFGM) technique [11–13]. These approaches are all derived for adiabatic conditions in their basic formulation, and need to be extended by heat loss effects for the proper computation of confined geometries. Heat loss due to radiation has been considered for example by Marracino and Lentini [14], by Ihme and Pitsch [15], by Franchetti et al. [16] and by Schmitt et al. [17]. Fiorina et al. [18] suggested the computation of burner stabilized one-dimensional flames and to use the tabulated results for correcting the source term and the flame speed. This approach has been applied within the RANS [19] and the LES [20,21] context.

The present work aims to model and investigate the influence of the heat loss on the LES results in the lean premixed combustion regime. Three different models are compared to the adiabatic reference solution: First a very simple model where the heat loss only affects the temperature and the transport coefficients, secondly the model by Fiorina et al. [18], and thirdly an approach with non-constant heat loss inside the flame.

To properly judge the model behavior, a test case with a significant amount of heat loss was required, which was found in a confined laboratory scale burner investigated at DLR Stuttgart by Lammel and coworkers [22]. Its jet-nozzle exit is arranged in an off-center position, resulting in a strong recirculation of the hot combustion products, which stabilizes the flame and causes strong heat loss to the burner walls. We consider a configuration with values of 90 m/s, 0.71 and 573 K for the bulk inflow velocity, the equivalence ratio of the premixed methane/air mixture and the temperature at the inlet, respectively. This burner has also been investigated with RANS by Donini et al. [19], and with hybrid RANS/LES by Di Domenico et al. [23].

2. Modeling approach

In the PFGM approach [11,12], one dimensional freely propagating flames are computed with a detailed chemical mechanism. The results are mapped over a small subset of control variables and subsequently stored in a low dimensional lookup-table, which is accessed by the CFD solver. In the present work, the one dimensional flame computations are carried out with the software library Cantera [24] for the GRI-3.0 [25] mechanism. A unity Lewis number assumption for all species is used, which required the implementation of an additional transport model into Cantera. The reaction progress is described by the species mass fraction sum $Y_C = Y_{CO_2} + Y_{CO} + Y_{H_2O} + Y_{H_2}$. We found that this progress variable definition works well for methane/air over the whole flammability range, although both simpler and more complex formulations exist.

2.1. Inclusion of heat loss in PFGM

To include the heat loss into the PFGM, the sum of sensible and chemical enthalpy $h = h_s + \sum_{k=1}^{N} \Delta h^0_{f,k} Y_k$ is used as second progress variable. As mentioned above, different methods are used to generate the non-adiabatic PFGM table:

For the first method (**M1**) only the adiabatic free flame without heat loss is computed. Afterwards the gas temperature is successively reduced from the adiabatic to the ambient temperature. The gas composition, the laminar flame speed, the laminar flame thickness and the reaction rate are kept constant. The heat loss influences the solution by reducing the temperature which alters the density and the transport coefficients.

The second method (**M2**) relies on the computation of burner stabilized flames [18]. At the inlet of the domain, constant values are prescribed for the mass flow and the temperature. By setting a lower mass flow, a higher level of heat loss over the entire flame is induced. Although the underlying assumption of temperature independence of the heat loss is unlikely to hold entirely in a real flame, this approach has been used with good success for the prediction of the flame behavior as well as the inner flame structure by Fiorina et al. [18], Cecere et al. [20], Ketelheun et al. [21] and Donini et al. [19]. Outside the flammability region, the temperature is reduced corresponding to M1, this time not starting from the adiabatic flame but from the burner-stabilized flamelet with the maximum heat loss. As it was found that the results of the CFD simulations performed within this work were insensitive to the exact value of the flammability limit, it was assumed that it is reached when the flame speed falls below 0.05 m/s.

The third method (**M3**) is based on introducing heat loss into a freely propagating flame. This is achieved by scaling the energy equation source term due to chemical reaction by a constant factor $(1 - f_L)$ over the whole flame. The modified energy equation that was implemented in Cantera reads:

$$\dot{m}\, c_p \frac{\partial T}{\partial z} = \frac{\partial}{\partial z}\left(\lambda \frac{\partial T}{\partial z}\right) - \sum_{k_1}^{K} c_{pk} j_{k,z} \frac{\partial T}{\partial z} - \boxed{(1 - f_L)} \sum_{k_1}^{K} h_k \dot{\omega}_k W_k \tag{1}$$