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Large eddy simulation of unsteady lean stratified premixed combustion

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Abstract

Premixed turbulent flame-based technologies are rapidly growing in importance, with applications to modern clean combustion devices for both power generation and aeropropulsion. However, the gain in decreasing harmful emissions might be canceled by rising combustion instabilities. Unwanted unsteady flame phenomena that might even destroy the whole device have been widely reported and are subject to intensive studies. In the present paper, we use unsteady numerical tools for simulating an unsteady and well-documented flame. Computations were performed for nonreacting, perfectly premixed and stratified premixed cases using two different numerical codes and different large-eddy-simulation-based flamelet models. Nonreacting simulations are shown to agree well with experimental data, with the LES results capturing the mean features (symmetry breaking) as well as the fluctuation level of the turbulent flow. For reacting cases, the uncertainty induced by the time-averaging technique limited the comparisons. Given an estimate of the uncertainty, the numerical results were found to reproduce well the experimental data in terms both of mean flow field and of fluctuation levels. In addition, it was found that despite relying on different assumptions/simplifications, both numerical tools lead to similar predictions, giving confidence in the results. Moreover, we studied the flame dynamics and particularly the response to a periodic pulsation. We found that above a certain excitation level, the flame dynamic changes and becomes rather insensitive to the excitation/instability amplitude. Conclusions regarding the self-growth of thermoacoustic waves were drawn.

Keywords: Large eddy simulation; Premixed combustion; Stratified combustion; Flame response; Thermo-acoustic instability

1. Introduction

In order to reduce harmful emissions, the current trend in the design of industrial combustors is to operate under fuel-lean and premixed conditions near the blow-out limit. Under such conditions low emissions and improved combustor performance can be achieved, but the reliability of such systems is chal-

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lenging, as they operate close to the lean stability limit and are more susceptible to combustion instabilities. A vital element is the flame response to acoustic excitations. For example, if the heat release fluctuation enters into resonance with the acoustic perturbation, the instability is self-sustained and might grow to unacceptable levels. Experimental evidence of this has been reported in the literature. Sjunnesson et al. [1] studied a V-flame stabilized behind a flame holder and observed that under some conditions, the flame exhibits large-scale and symmetric wrinkling that induces large and periodic heat release fluctuations. In a similar set-up, Sanquer et al. [2] observed that this type of instability induces a strong velocity modulation at a defined frequency. Ganji and Sawyer [3], Pitz and Daily [4], and Keller et al. [5] studied experimentally a lean premixed propane–air flame stabilized in a turbulent free shear layer formed at a rearward-facing step. They reported self-induced instabilities and large-scale flame wrinkling as a result of the shear layer instabilities transitioning into large-scale structures. In addition, Keller et al. [5] managed to reproduce, qualitatively, the periodic wrinkled flame pattern using an external acoustic forcing and found that only a narrow range of frequencies triggers this kind of structures and that the amplitude of the forcing affects the size and behavior of the large-scale structures. Weller et al. [6] used this case to develop and validate a novel flame-wrinkling LES model and observed that the large strain rates in the shear layer delayed the ignition of the flame, allowing the development of Kelvin–Helmholtz vortices. Exothermicity occurs primarily in the large-scale structures that form early in the shear layer as they entrain cold reactants and hot products. In a similar setup, Ghoniem et al. [7] examined a large amplitude instability and showed that the flame convolution around the Kelvin–Helmholtz vortices drives the heat-release fluctuations.

Recently, another experiment was built for studying flame dynamics; the ORACLES rig consists of a sudden expansion where the flame is stabilized behind two symmetric steps. Besson et al. [8] and Nguyen and Bruel [9] reported the expected unsteady flame behavior. They observed that reacting cases exhibits a slow but large periodic flapping of the flame and that the incoming mass flow into the combustion chamber fluctuates strongly in time, with an amplitude of $\sim$20% of the mean mass flow. Results from the ORACLES study have been used by Fureby [10] to examine and validate the fractal flame wrinkling (FFW) model, and by Domingo et al. [11] to examine a recently proposed flame surface density–probability density function (FSD-PDF) subgrid model.

It is worth noting that these instability phenomena occurred within a wide range of frequencies. An important characteristic of the instability is that it enters into resonance with some acoustic mode of the rig, and hence the characteristic frequencies will be rig-dependent. For example, the characteristic instability frequency in the ORACLES rig is $\sim$50 Hz, indicating that the wavelength of the associated thermoacoustic wave is $\sim$2 m, originating far upstream of the combustion chamber. However, the underlying mechanisms and the resulting flame pattern are similar in most of the cases. In order to understand the flame–acoustic coupling, a detailed knowledge of the turbulent flame and the flame response to forcing is needed. This task would benefit considerably from accurate, reliable, and affordable simulations, in that interactions between different physical and chemical processes can be studied and optimized and related to the design of the combustor.

Simulation of combustion instabilities implies solving concurrently a fluid dynamics problem (stirring and mixing), a chemical problem (fuel oxidation), and an acoustic problem (pressure and heat-release fluctuation interactions). As these problems are coupled, unsteady, and often turbulent, they pose a grand challenge to computational fluid dynamics (CFD) in requiring spatial and temporal resolution of both the physical and the chemical processes. Traditional CFD models, usually built around Reynolds-averaged Navier–Stokes (RANS) models and simple combustion models [12,13], predict only the time-averaged flow, and hence are unable to simulate the coupled unsteady processes responsible for combustion or its control. More advanced CFD models, drawing on simultaneously improved predictions of the flow, chemistry, and acoustics, are thus required. The recent increase of computer power brought the hope of being able to use large eddy simulation (LES) [12, 14–17] to study engineering combustion problems. The idea behind LES is to explicitly simulate the large energetic scales of the flow and the thermochemistry directly affected by boundary conditions, while modeling the small subgrid scales. This includes modeling also the chemistry and its interactions with the usually turbulent flow, since the laminar flame thickness, δ_{L}, is often smaller than the affordable grid size, Δ [12]. However, despite promising results, LES of turbulent combustion is difficult. In addition, there is no definitive answer to which numerical approach should be used and which models are appropriate for combustion. We feel that there is a need for confronting LES with the influence of the sum of underlying hypotheses upon the results. Under these conditions, the results should benefit from different computations. We see these so-called numerical experiments as the only current option for addressing the accuracy of flame dynamics predictions.