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Coupling heat transfer and large eddy simulation for combustion instability prediction in a swirl burner

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ABSTRACT

Large eddy simulations (LES) of combustion instabilities are often performed with simplified thermal wall boundary conditions, typically adiabatic walls. However, wall temperatures directly affect the gas temperatures and therefore the sound speed field. They also control the flame itself, its stabilization characteristics and its response to acoustic waves, changing the flame transfer functions (FTFs) of many combustion chambers. This paper presents an example of LES of turbulent flames fully coupled to a heat conduction solver providing the temperature in the combustor walls. LES results obtained with the fully coupled approach are compared to experimental data and to LES performed with adiabatic walls for a swirled turbulent methane/air burner installed at Engler-Bunte-Institute, Karlsruhe Institute of Technology and German Aerospace Center (DLR) in Stuttgart. Results show that the fully coupled approach provides reasonable wall temperature estimations and that heat conduction in the combustor walls strongly affects both the mean state and the unstable modes of the combustor. The unstable thermoacoustic mode observed experimentally at 750 Hz is captured accurately by the coupled simulation but not by the adiabatic one, suggesting that coupling LES with heat conduction solvers within combustor walls may be necessary in other configurations in order to capture flame dynamics.

1. Introduction

Heat transfer plays an important role in most power-generating systems using combustion, e.g., in gas turbines, aero engines and rocket engines. The presence of one or multiple flames leads to high temperature gradients in the system. Depending on the application, heat transfer is considered as a desired or an undesired effect. In heating units it is obviously necessary to fulfill the purpose of the machine. On the contrary, it leads to several design challenges in combustion chambers of gas turbines. Turbine blades and combustion chamber walls need to be cooled in order to withstand hot gases. This does not only raise challenges for the design of the solid parts inside the gas turbine, but also for computational fluid dynamics (CFD) when simulating the reactive flow in the combustion chambers. Boundary conditions have to be defined in a way that heat transfer processes between flow and solid parts and their impact on the temperature field inside the combustor are adequately modeled, since the temperature directly affects the flow conditions and the chemical reactions inside the combustion chamber. Advanced CFD methods like large eddy simulation (LES) combined with sophisticated flame models or direct numerical simulation (DNS) with detailed chemical mechanisms only produce accurate results when the wall temperatures in the combustion chamber are known with reasonable precision, which is rarely the case. The problem also applies to the prediction of combustion instabilities, as the acoustic behavior of combustor components is determined by the sound speed field and the geometry; flame dynamics are usually heavily influenced by changes in temperature.

There are numerous experimental and numerical studies illustrating the significant influence of heat transfer on flame dynamics and combustion instabilities. Duchaine et al. [1]demonstrated in their sensitivity study of the flame transfer function (FTF) of a laminar premixed flame that the duct wall temperature has a strong impact on the velocity field and the local flame speed, which leads to uncertainties in the prediction of the phase of the FTF. Kaess et al. [2] investigated the influence of the thermal wall boundary condition on the FTF of a laminar premixed flame with DNS. Their results showed that the flame anchoring position as well as the FTF were significantly altered when changing the adiabatic boundary condition to an isothermal boundary condition. The FTF of the case with the isothermal wall shows a better agreement with the experimentally obtained FTF. Mejia et al. [3] observed a strong influence of the burner rim temperature on the combustion dynamics of a laminar premixed flame: an unstable mode could be triggered by switching on the cooling system of the burner rim. They

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explained this behavior with altered flame foot dynamics [4,5], which lead in turn to changes in the FTF. The study of Hong et al. [6] showed that heat transfer is not only controlled by temperature gradients, but also by the physical properties of the solid combustor parts. Replacing the stainless steel flame holder with one made of ceramics inhibited or delayed the onset of a combustion stability. The authors conclude that the wall thermal conductivity influences the flame speed near the flame holder, which leads to a distinct dynamic behavior of the flame for each flame holder material. Lohrmann and Büchner [7] investigated the influence of the preheat temperature on the FTF of a turbulent swirl-stabilized premixed flame. The delay of the flame response decreased with increasing preheat temperature, which they explained by an increase in the turbulent flame speed that shifts the main reaction zone to an upstream location.

Despite the fact that the influence of wall temperatures on flame dynamics has been observed in many studies, a major hurdle remains: wall temperatures are very difficult to determine in most combustors. As a consequence, heat transfer is neglected in many CFD simulations. Walls are often treated as adiabatic, or at best isothermal but with a guessed temperature. Nevertheless, numerical simulations are often able to capture the right thermoacoustic mode in an unstable laboratory-scale combustor, even when heat transfer is neglected. Differences in frequency or amplitude may occur when the temperature field and the FTF in the simulation only partially match those in the experiment, but the simulation can usually be used for further investigation of the thermoacoustic mode. There are numerous studies of combustion instabilities that illustrate that LES with adiabatic walls can show a reasonable agreement with experiments: the study on a lean-premixed swirl combustor by Huang et al. [8], the LES-studies on the PRECCINSTA configuration [9–11], the massively parallel LES of a realistic helicopter combustion chamber by Wolf et al. [12], LESs of model rocket combustors (Garby et al. [13], Urbano et al. [14]) or the LES-studies of bluff-body stabilized flames by Li et al. [15] and Ghani et al. [16].

However, as illustrated by the simulation of the LIMOUSINE burner performed by Shahi et al. [17], taking into account the heat transfer between the flow and the solid parts of the combustion chamber can significantly increase the accuracy of the results. Another example is the study by Kraus et al. [18], who compared an adiabatic LES and an LES with basic modeling of heat transfer between fluid and solid material. Both LESs show the same mode structure, but taking into account heat transfer effects leads to a higher accuracy in terms of frequency.

To summarize the state of the art in this field, LES of combustors can be classified into four categories, depending on their thermal boundary conditions on walls:

- Type 1: Adiabatic walls: the majority of recent LESs simply consider the walls to be adiabatic [8–16,19–22].
- Type 2: Imposed wall temperatures [23–27]: when experimental data on wall temperatures is available, imposing them as boundary conditions for LES may be a solution. Note that this can be a dangerous methodology: imposing a high local wall temperature may for example, force the flame to anchor at this point, diminishing the predictive quality of the method by forcing the solution artificially. Moreover, limited experimental information is usually available on wall temperatures, which are measured only at a few points. The introduction of diagnostics such as laser induced phosphorescence [27,28] in laboratory-scale experiments may help in certain cases as it can provide a full temperature field on combustor walls. However, in most real engines, detailed wall temperature information is simply not available, making type 2 LES unpractical in industrial cases.
- Type 3: A simple method to account for wall heat transfer is to write a Robin condition [29] on walls linking the wall temperature T_w to the local heat flux Φ through a heat resistance R and a cooling temperature T_∞: $\Phi = (T_w - T_\infty)/R$ where R is roughly evaluated from the combustor wall characteristics [18,30–32]. This is a cheap method to account for dual heat transfer between reacting flow and conduction through walls.
- Type 4: Fully coupled LES/heat conduction solver in the combustor walls: the whole combustor solid structure is also meshed and the temperature within the solid structure is computed by a solver coupled with the LES flow solver [17,33–35].

Most LES are of type 1 because the combustion community does not consider the problem of heat conduction through walls as an interesting one compared to the other challenges found in turbulent flames. However, the benefits of going to a type 4 simulation are obvious as shown by Berger et al. [35]: the LES becomes fully predictive and does not rely on any ad hoc evaluation of wall temperatures in the solid. For a cooled chamber, the only input data is the cooling water temperature and the convection coefficient in the cooling passages between water and combustor walls. On the long term, it is clear that the high precision of LES will require a corresponding high precision for wall temperatures and therefore type 4 simulations. This is true not only for the mean flow characteristics but also for pollutants and for flame dynamics or flame stabilization: Miguel-Brebion et al. [33], e.g., show that flames stabilized behind uncooled or cooled cylinders exhibit totally different shapes, which are well captured when a type 4 simulation is performed. The results of these studies show that not only heat losses have to be considered, but also heat transfer inside the solid parts of combustors, as it can have a strong impact on the temperature field inside the combustion chamber and therefore on combustion. Especially the adequate modeling of internal heat transfer inside the combustor is almost impossible without applying fully coupled simulations of type 4, since temperatures on internal walls in combustors are in most cases unknown.

The present paper shows that a type 4 LES for a full combustion chamber is possible today even in a complex swirl burner and that it allows significant improvements in the description of the flame dynamics, especially to capture self-excited modes: taking into account internal heat transfer from the combustion chamber to other combustor parts can strongly affect thermoacoustics and flame dynamics.

The coupled LES is performed with a fully compressible solver for reacting flows [30,36–38] and a heat conduction solver in the combustor walls coupled to the LES solver with the OpenPalm tool [39] (www.cerfacs.fr/globc/PALM-WEB/). The results of the coupled LES are compared to the results of an adiabatic LES, which is performed with the same numerical setup but with adiabatic walls.

The experiment is briefly presented in Section 2, followed by the description of the numerical setup in Section 3. The impact of accounting for heat transfer in the coupled simulation on the temperature field is depicted in Section 4. Mean velocities and acoustic spectra obtained in the experiment are compared to the LES data. Possible reasons for the differences in combustion dynamics observed between adiabatic and coupled LES are discussed. The paper is concluded by a summary of the main observations and results.

2. Experimental setup

The KIT-Burner is described in detail in [40] and [41], therefore only a brief presentation of its main features is given here.

Identical versions of the burner are installed at two locations: one at Engler-Bunte-Institute, Combustion Technology at Karlsruhe Institute of Technology and the other at DLR (German Aerospace Center) in Stuttgart. It is operated under atmospheric conditions