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ScienceDirect
Combustion and Flame 155 (2008) 196–214
Combustion and Flame
www.elsevier.com/locate/combustflame

Effects of mesh resolution on large eddy simulation of reacting flows in complex geometry combustors

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Received 8 November 2007; received in revised form 29 February 2008; accepted 17 April 2008

Available online 29 May 2008

Abstract

The power of current parallel computers is becoming sufficient to apply large eddy simulation (LES) tools to reacting flows not only in academic configurations but also in real gas turbine chambers. The most limiting factor in performing LES of real systems is the mesh size, which directly controls the overall cost of the simulation, so that the effects of mesh resolution on LES results become a key issue. In the present work, an unstructured compressible LES solver is used to compute the reacting flow in a domain corresponding to a sector of a realistic helicopter chamber. Three grids ranging from 1.2 to 44 million elements are used for LES and results are compared in terms of mean and fluctuating fields as well as of pressure spectra. Results show that the mean temperature, reaction rate, and velocity fields are almost insensitive to the grid size. The RMS field of the resolved velocity is also reasonably independent of the mesh, while the RMS fields of temperature exhibit more sensitivity to the grid, as expected from the fact that most of the combustion process proceeds at small scales. The acoustic field exhibits a limited sensitivity to the mesh, suggesting that LES is adapted to the computation of combustion instabilities in complex systems.

Keywords: Mesh resolution; Industrial GT; Large eddy simulations

1. Introduction

Ongoing developments for the next generation of gas turbines focus on lean premixed operating regimes to satisfy emission regulations. The design of these combustion chambers is complex because combustion concepts leading to minimum emissions are also sensitive to combustion instabilities [1–3]. These instabilities are due to a combination of the natural unstable modes of swirling flows (precessing vortex cores or PVCs [4–8]) with acoustics and unsteady heat release [9–12].

To study combustion instabilities but also to provide more accurate results for stable reacting flows, the best numerical technique developed today is large eddy simulation (LES) [13–15]. LES has been used successfully for many academic flames in simple geometries [16–22], but still very rarely for complex realistic combustion chambers. Multiple issues remain to be investigated before LES can be used efficiently for design of combustion chambers: high-order schemes, subgrid scale (SGS) tensors, and flux vectors, flame/turbulence interaction, chemical

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0010-2180/$ – see front matter
doi:10.1016/j.combustflame.2008.04.013

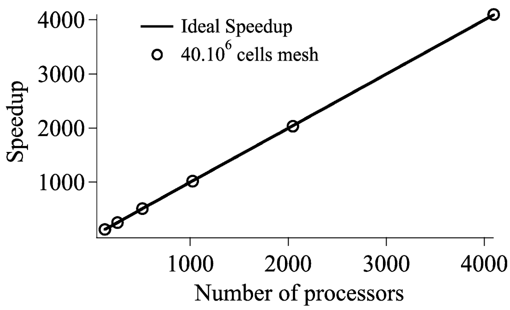

Fig. 1. Typical speed-up curve as obtained for the configuration studied in this work.

schemes, boundary conditions, parallel efficiency, etc.

In this framework, a fundamental and unresolved question is often neglected: the effects of mesh resolution on LES results. Multiple authors have emphasized the importance of this point for LES [23,24]. Although LES results depend on mesh resolution (unlike Reynolds-averaged Navier–Stokes simulation (RANS), which must produce grid-independent results as soon as the mesh is sufficiently refined), they must satisfy multiple properties: in the context of stationary flows, time-averaged values must converge, root-mean-square (RMS) resolved values must increase when the mesh cell size decreases and the SGS turbulence level diminishes, finally the resolved velocity spectra must fill toward larger wave-numbers. In practice, these behaviors are expected to be controlled by the LES models, the flow Reynolds number, and the grid resolution as well as the accuracy of the numerical solver (in the context of implicit filtering [23,25,26]). Mesh dependency analysis of non-reacting LES predictions has recently been addressed [27–29] and quality criteria have been proposed for a posteriori evaluation of the LES flow predictions [24,30–33].

For reacting flows, the computer power needed to simulate realistic geometries is so large that the grids used for LES are usually as large as possible while still being too coarse to resolve all flow zones. In these circumstances, multiplying the number of grid points by a significant factor to verify the effects of grid resolution on the LES results was impossible until very recent times. Very few LESs of reacting flows have been devoted to mesh dependency in simple configurations [27–29], and none of them has addressed this issue in complex geometry combustors. The situation has changed in the last two years: porting LES codes to massively parallel machines in the Top 20 list has allowed a sudden increase of power for combustion computations. For example, Fig. 1 shows the speed-up obtained on such a parallel architecture for a 40-million-cell configuration corresponding to a full gas turbine combustion chamber with the parallel solver used in the present paper [34]. Speed-ups of nearly 95%, as obtained here on 4096 processors, make it possible to address the problem of mesh dependency by performing one "coarse grid" simulation with a reasonable mesh (typically 1.2 million cells) and then comparing it with an "intermediate grid" simulation (8 times more cells) and finally with a "fine grid" simulation (32 times more cells). In the present work, the mesh dependency of the LES predictions is studied for a helicopter combustion chamber [35]. Results on the coarse, intermediate, and fine grids for the same regime allow a direct investigation in terms of mean flow, RMS values, unsteady activity, and acoustic mode excitation.

Although this grid dependency exercise must also be performed on simple academic geometries, using a "real" rich-burn, quick-mix, lean-burn (RQL) combustor case is an interesting test because this configuration puts constraints on meshes that are not found in most academic chambers, where simple structured meshes can be used. Using a real helicopter chamber guarantees that issues relevant to industrial cases will be taken into account. However, a drawback of this choice is that very limited experimental information is available. Therefore, the present paper must be viewed as only a partial response to the problem of LES resolution in combustion, since no experimental result will be used for validation. For extensive comparisons of the present solver with experimental data, readers are referred to previous studies [8,36–38] where velocity and/or temperature fields have been compared in various configurations.

The LES solver used for this study and the SGS models required for such a comparison are described in Section 2. Details on the combustion model are given in Section 3, while the target configuration (a sector of a helicopter combustion chamber) is presented in Section 4. Section 5 then discusses results obtained on the three grids.

2. Massively parallel large eddy simulations of reacting flows

LES for reactive multispecies mixtures involves the spatial filtering operation, which reduces for spatially, and temporally invariant and localized filter functions [39,40] to

$$\widetilde{f(\mathbf{x},t)} = \frac{1}{\overline{\rho(\mathbf{x},t)}} \int_{-\infty}^{+\infty} \rho(\mathbf{x}',t) f(\mathbf{x}',t) G(\mathbf{x}'-\mathbf{x})\, d\mathbf{x}', \tag{1}$$

where G denotes the filter function and $\widetilde{f(\mathbf{x},t)}$ is the Favre-filtered value of the variable $f(\mathbf{x},t)$ [41].