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A ghost-fluid method for large-eddy simulations of premixed combustion in complex geometries

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Abstract

In this paper, a new ghost-fluid method for interfaces of finite thickness is described. It allows to compute efficiently turbulent premixed flames with a finite thickness in low-Mach flows. A level set algorithm is used to track accurately the flame and to define the overlapping region where the burned and unburned gases satisfy the jump conditions. These algorithms are combined with a fractional-step method to alleviate the acoustic CFL constraint. The full algorithm is verified for simple flame–vortex interactions and it is validated by computing a turbulent flame anchored by a triangular flame-holder. Finally, the algorithm is applied in the LES of an industrial lean-premixed swirl-burner.

Keywords: LES; Ghost-fluid method; Premixed combustion; Fractional-step method

1. Motivation and objectives

Large-eddy simulation of premixed combustion is a computational challenge, because complex diffusion and reaction processes often occur in very thin layers. The interaction of these processes with turbulence determines the main properties of the flame brush, such as its burning velocity or its thickness. In turbulent flows, the large vortices wrinkle the flame brush and increase the flame surface, while the small scales may penetrate into the flame and increase the flame thickness. In both cases, the turbulence leads to an increase in the burning velocity. This feature has to be captured by a combustion model. Even if the turbulent scales increase the flame thickness, the flame brush remains difficult to resolve on LES meshes. Numerically, the premixed flame brush is very close to an interface, but its non-zero thickness must be taken into account to represent the flame–turbulence interactions properly.

In state-of-the-art combustion models, the issue of thin flames is overcome in very different ways. The thickened-flame model (TFLES) [1] artificially thickens the flame brush, and the source terms in the species and energy equations are corrected to recover the correct burning velocity. The thickening factor to resolve the flame on a usual unstructured mesh is on the order of 20. This factor can be decreased slightly if naturally

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thicker quantities are used to represent the flame. This is the case in flame surface density approaches [2], but the thickening factor remains large. Instead of transporting reacting scalars, the flame can also be described using a flamelet hypothesis. That is, the reaction zone in the flame is considered to retain a laminar structure. The problem is then reduced to finding the position of the thin reaction layer. This is the principle of the *G*-equation model [3,4] in which a level set technique is used to track accurately the flame front. The displacement velocity of the level set is usually given by a model based on asymptotic analysis or experimental correlations [4,5]. Then, the level set has to be coupled with the Navier–Stokes solver by imposing the temperature profile in the flame brush. Often, Navier–Stokes solvers are not able to deal with large density and momentum gradients, and the imposed temperature profile has to be resolved on more than one cell, typically on the order of five cells.

In all the described models, the flame brush is more or less thickened, and the interactions with the smallest resolved scales are modified. The proposed method overcomes this artificial thickening using a numerical method that better couples the level set technique and the Navier–Stokes solver. This method is based on the ghost-fluid method (GFM) [6], which tracks discontinuities without introducing any smearing or numerical instabilities. While the original GFM has been developed to track infinitely thin discontinuities, the present method extends the GFM formalism to deal with interfaces of finite thickness.

2. A ghost-fluid method for thin flame brushes

2.1. The classical variable-density method for low-Mach number flows

In reacting flows, the density is not constant, and incompressible methods cannot be used. Taking the low-Mach limit without the constant-density assumption, the filtered Navier–Stokes equations reduce to the continuity and momentum equations:

$$\frac{\partial\bar{\rho}}{\partial t}+\nabla\cdot(\bar{\rho}\tilde{\mathbf{u}})=0, \tag{1}$$

$$\frac{\partial\bar{\rho}\tilde{\mathbf{u}}}{\partial t}+\nabla\cdot(\bar{\rho}\tilde{\mathbf{u}}\tilde{\mathbf{u}})=-\nabla\overline{P}+\nabla\cdot\mathbf{t}, \tag{2}$$

where $\bar{}$ and $\tilde{}$ denote the LES filtering and the mass weighted filtering, respectively. ρ is the density, $\mathbf{u}$ is the velocity, P is the pressure and $\mathbf{t}$ is the total stress tensor. In (1) and (2), the density is usually given from the combustion model. The pressure in (2) is not the thermodynamic pressure but rather a Lagrange multiplier called dynamic pressure. Similar to incompressible flows, these equations can be solved using a fractional-step method. A time-staggered discretization of (1) is given as:

$$\frac{\bar{\rho}^{n+3/2}-\bar{\rho}^{n+1/2}}{\Delta t}+\nabla\cdot(\bar{\rho}\tilde{\mathbf{u}}^{n+1})=0. \tag{3}$$

If the density is known at $t^{n+1/2}$ and $t^{n+3/2}$, this equation provides a constraint on the velocity divergence. The first step of the fractional-step method is to advance the momentum equation to:

$$\frac{\bar{\rho}\tilde{\mathbf{u}}^{\star}-\bar{\rho}\tilde{\mathbf{u}}^{n}}{\Delta t}+\nabla\cdot(\bar{\rho}\tilde{\mathbf{u}}^{n+1/2}\tilde{\mathbf{u}}^{n+1/2})=\nabla\cdot\mathbf{t}. \tag{4}$$

In the second step, the momentum is corrected with the dynamic pressure gradient:

$$\frac{\bar{\rho}\tilde{\mathbf{u}}^{n+1}-\bar{\rho}\tilde{\mathbf{u}}^{\star}}{\Delta t}=-\nabla\overline{P}^{n+1/2}. \tag{5}$$

The dynamic pressure $\overline{P}$ is found solving the variable-density Poisson equation:

$$\nabla\cdot\nabla\overline{P}^{n+1/2}=\frac{\bar{\rho}^{n+3/2}-\bar{\rho}^{n+1/2}}{\Delta t^{2}}+\frac{1}{\Delta t}\nabla\cdot(\bar{\rho}\tilde{\mathbf{u}}^{\star}). \tag{6}$$

Solving (4)–(6) for a propagating premixed flame may present several challenges. First, since the flame essentially occurs on the sub-filter scale, the filtered velocity and momentum flux may have steep gradients, which are difficult to integrate in the momentum equation. This may lead to spurious numerical instabilities. Second,