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Adaptation of a dynamic wrinkling model to an engine configuration

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Abstract

The dynamic model proposed by Charlette et al. represents an interesting alternative to the FSD balance equation to predict the transient growth of a flame kernel. The dynamic wrinkling model coupled to the algebraic Flame Surface Density (FSD) model of Boger et al. is here evaluated for the first time in an internal combustion engine configuration. Preliminary tests enable to evidence practical difficulties when applying the model to this type of complex configuration. Improvements are proposed to adapt the model to the engine configuration. Final simulations are performed on a spark ignition engine configuration, using both the adapted dynamic model and an equilibrium wrinkling formulation. The results are compared to the ones obtained by Robert et al. on the same configuration using the ECFM-LES model solving a FSD balance equation. The dynamic model proves to very well predict out-of-equilibrium values and to account for cycle-to-cycle variabilities, as the model parameter is calculated on the fly. On the contrary, the results obtained using the equilibrium formulation clearly demonstrate that the flame-turbulence equilibrium assumption is not adapted to such configurations.

Keywords: LES; Engine; Combustion; Dynamic wrinkling

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1. Introduction

Large Eddy Simulation (LES) is an attractive tool to predict transient phenomena. In internal combustion engines, the description of the flame evolution requires specific modeling, as the flame kernel, initially laminar, is progressively wrinkled by turbulence and then quenched when it reaches the walls of the combustion chamber. This out-of-equilibrium behavior cannot be well-reproduced by algebraic subgrid scale (sgs) closures derived assuming flame-turbulence equilibrium [1,2]. Preference is given to solve a balance equation for the Flame Surface Density (FSD) [3–5], but a model parameter remains in the closure of its sgs strain term. A possible alternative is to use a balance equation for the wrinkling, as proposed by Weller et al. [6], but the practical implementation

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is delicate. To estimate the flame wrinkling factor dynamically from the resolved flame surface appears as a promising solution that can be coupled to any standard combustion model such as the G-equation approach [7,8] and more recently in [9,10] with the algebraic FSD model of Boger et al. [11]. Thus, Wang et al. [10] successfully reproduced the transient growth of a flame kernel in decaying homogeneous isotropic turbulence of various characteristics, the dynamic procedure self-adapting the unique parameter of the wrinkling closure. Their results bring a promising alternative to the FSD balance equation. Following this path, the dynamic model was successfully coupled with the TF-LES combustion model [9,12], the F-TACLES combustion model [13] and evaluated on turbulent premixed flames (Chen et al. flame [14], PRECCINSTA burner [15], Tecflam burner [16]), demonstrating the ability of the dynamic model to adapt to various configurations and operating conditions.

The present work proposes to evaluate this dynamic model coupled to the algebraic FSD model of Boger et al. in a SI (Spark Ignition) engine. We first show that direct application of the formulation of Wang et al. [10] is not possible because of theoretical and numerical issues at walls and when two flame fronts interact. Modifications are then proposed, finally allowing to compare the dynamic model results with those obtained by Robert et al. [17] on a SI engine using the ECFM-LES model (Extended Coherent Flame Model for LES) which solves a FSD transport equation.

2. Combustion models

The Boger et al. model writes the filtered progress variable balance equation as [11]:

$$\frac{\partial \overline{\rho}\tilde{c}}{\partial t} + \nabla.(\overline{\rho}\tilde{u}\tilde{c}) = \nabla.\left(\frac{\rho^u \Xi_\Delta s_L^0 \Delta}{16\sqrt{6/\pi}}\nabla\tilde{c}\right) + 4\rho^u s_L^0 \sqrt{\frac{6}{\pi}}\,\Xi_\Delta \frac{\tilde{c}(1-\tilde{c})}{\Delta} \quad (1)$$

where Δ is the combustion filter [4,11] and ρ^u the unburned gases density. The resolved flame front is propagated at the sub-grid scale turbulent flame speed $s_T = \Xi_\Delta s_L^0$, where s_L^0 is the laminar flame speed and the wrinkling factor Ξ_Δ measures locally the ratio between total and resolved flame surfaces. This factor is modeled as [10,12]:

$$\Xi_\Delta = \left(\frac{\Delta}{\delta_c}\right)^\beta \quad (2)$$

where the inner cutoff scale is estimated as twice the laminar flame thickness, $\delta_c = 2\delta_L^0$ [18]. The model parameter β is related to the fractal dimension of the flame surface $D = \beta + 2$ [19–21] and may be determined dynamically equating flame surfaces when computed at filtered and test-filtered scales (Germano-like identity) [9,12,22]:

$$\left\langle \overbrace{\Xi_\Delta |\nabla\,\tilde{c}\,|} \right\rangle = \left\langle \Xi_{\gamma\Delta} \left|\nabla\,\hat{\tilde{c}}\,\right| \right\rangle \quad (3)$$

where $\overbrace{\cdot}$ denotes a test-filtering operator and $\hat{c} = \overbrace{\rho c} / \overbrace{\rho}$ the corresponding mass-weighted filtering of the progress variable c. The effective filter width when applying consecutively two Gaussian filters is $\widehat{\Delta} = \gamma\Delta = \sqrt{\Delta^2 + \overbrace{\Delta}^2}$. $\langle\cdot\rangle$ denotes an averaging operator that may be the overall computational volume (*global formulation*) or a small local volume (*local formulation*). In the latter case, the averaging operation is replaced by a Gaussian filter of width Δ_{avg}, easier to implement on massively parallel solvers with unstructured meshes [12]. Combining Eqs. (2) and (3) and assuming that β is constant over the averaging domain $\langle\cdot\rangle$ gives:

$$\beta = \frac{\log(\langle \overbrace{|\nabla\tilde{c}|} \rangle / \langle |\nabla\hat{\tilde{c}}| \rangle)}{\log(\gamma)} \quad (4)$$

Note that the dynamic procedure compares test-filtered and resolved flame fronts to infer sub-grid scale wrinkling factors. It will not work when the flame kernel is smaller than the filter width $\widehat{\Delta}$ because the test-filtered flame front is then not fully resolved. A first solution could be to initialize a large enough spherical laminar flame front at some instant after spark timing so that the dynamic model would be immediately applicable. This solution would fail because the dynamic model would then underestimate the sgs wrinkling. An adapted spark ignition model is required to describe the growth of the flame kernel from spark timing up to the instant when the dynamic procedure can be applied. However this aspect is not treated in the present study as focus is on the prediction of the wrinkling using the dynamic model. Accordingly, present calculations were initialized with an already grown and wrinkled flame kernel from the simulations of Robert et al. This solution allows the direct comparison of ECFM-LES and dynamic models.

In the following, global and local dynamic formulations are thus compared to an algebraic expression and to reference simulations of Robert et al. [17] using the ECFM-LES model. The FSD equation reads [4]:

$$\partial\overline{\Sigma}/\partial t = T_{res} + T_{sgs} + S_{sgs} + \alpha C_{sgs} + P + \alpha(C_{res} + S_{res}) + (1-\alpha)S_{ign} + \overline{\dot{\omega}_\Sigma^{ign}} \quad (5)$$

where T_{res}, S_{res}, C_{res} and P are the transport, strain, curvature and propagation terms due to resolved flow motions, respectively; T_{sgs}, S_{sgs} and C_{sgs} the unresolved transport, strain and curvature terms. S_{sgs} is written as $\alpha_{t,CFM}\, a_t\, \overline{\Sigma}$, with $\alpha_{t,\,CFM}$ a model constant for the sgs strain a_t. $\overline{\dot{\omega}}_\Sigma^{ign}$ is a source term

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