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A 0-D flame wrinkling equation to describe the turbulent flame surface evolution in SI engines

Stéphane Richard [a,*], Denis Veynante [b]

[a] IFP Énergies nouvelles, 1–4, avenue du Bois-Préau, 92852 Rueil-Malmaison cedex, France
[b] Laboratoire EM2C, CNRS École centrale Paris, Grande Voie des Vignes, 92295 Châtenay-Malabry cedex, France

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ABSTRACT

The current development of reciprocating engines relies increasingly on system simulation for both design activities and conception of algorithms for engine control. These numerical simulation tools require high computational efficiencies, as calculations have to be performed in times close to real-time. Then, they are today mainly based on simple empirical laws to describe the combustion processes in the cylinders. However, with the rapid evolution of emission regulations and fuel formulation, more and more physics is expected in combustion models. A solution consists in reducing 3-D combustion models to build 0-dimensional models that are both CPU-efficient and based on physical quantities. This approach has been used in a previous work to reduce the 3-D ECFM (Extended Coherent Flame Model), leading to the so-called CFM1D. A key feature of the latter is to be based on a 0-D equation for the flame wrinkling derived from the 3-D equation for the flame surface density. The objective of this paper is to present in details the theoretical derivation of the wrinkling equation and the underlying modeling assumptions as well. Academic validations are performed against experimental data for several turbulence intensities and fuels. Finally, the proposed model is applied to engine simulations for a wide range of operating conditions. Comparisons are successfully conducted between in-cylinder measurements and the model predictions, highlighting the interest of reducing 3-D CFD models for calculations performed in the context of system simulation.

1. Introduction

System simulation is today increasingly exploited in the design process of internal combustion engines. Few years ago, its use was restricted to the evaluation of air-path configurations, but it has been recently extended to the development of engine control strategies thanks to the new real-time capabilities of 0-D engine simulators [1–3], which can now partially replace engine benches. In a near future, system simulation could also be used more intensively in the design process of combustion systems to recommend optimal engine settings (ignition and injection timings, fuel, air–ratios...), geometrical dimensions (compression ratio, bore and stroke...), or to evaluate the effect of new fuels on the engine behavior, as illustrated in recent works [4,5]. In the past, models used to compute the in-cylinder heat release were mainly based on simple 0-dimensional empirical laws [6,7] characterized by a high CPU efficiency. However, considering the stringency of pollutants and greenhouse gas emission standards, these approaches today suffer from a lack of predictivity to correctly describe all

* Corresponding author. Present address: Turbomeca, 64511 Bordes Cedex, France.
E-mail address: stephane.richard@graduates.centraliens.net (S. Richard).

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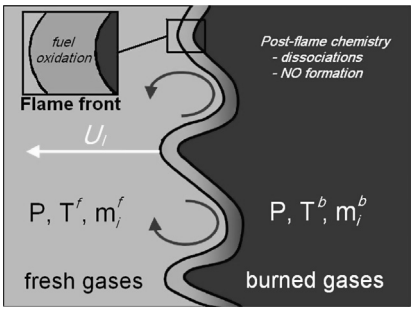

Fig. 1. The coherent flame approach (subscripts f and b respectively refer to fresh and burned gases).

the processes occurring in combustion chambers. To this purpose, 3-D CFD simulation tools could be coupled with 0-D or 1-D models for the air-path, but the required computational resources are still too important to make it an industrial tool for engineers in a near future. An interesting alternative to this coupling is to perform 3-D models reduction [8–10] in order to build 0-D models, whose behavior remains based on physical quantities while being very CPU-efficient. This approach has been used in a previous work [10] to derive the CFM1D model from the 3-D ECFM (Extended Coherent Flame Model), widely exploited in RANS [11] and LES [12] applications. A key point of CFM1D is that the flame wrinkling evolution is described by a new 0-D equation derived from the flame surface density (FSD) transport equation of ECFM. CFM1D was successfully applied to the combustion of gasoline [10], methane [13] or ethanol blends [14] in SI engines but no academic validation was conducted to check the intrinsic quality of the reduction methodology. The objective of this paper is thus to present in details the theoretical bases of the flame wrinkling equation as well as the underlying assumptions. Detailed validations are performed simulating an experiment relative to the ignition and flame propagation in an open vessel [15]. Finally, several operating conditions of a 4-cylinder engine are simulated and in-cylinder pressure and turbulent flame surface results are compared with experimental data.

2. The CFM1D combustion model

In a previous work, the CFM1D combustion model was proposed, based on several assumptions [10]:

- the mixture is an ideal gas;
- the domain in decomposed into two zones, fresh and burned gases, in which the mixture composition is assumed to be homogeneous;
- the pressure is identical in each zone;
- each zone is described by its mass, volume, composition and temperature;
- the turbulent kinetic energy is assumed to be uniform in the cylinder;
- fuel can be found either in a gas or liquid phase. This latter is then regarded as an isolated thermodynamic system exchanging mass and enthalpy with fresh gases.

In CFM1D, the heat released by combustion processes, $\mathrm{d}Q_{\mathrm{comb}}$, is expressed as:

$$\frac{\mathrm{d}Q_{\mathrm{comb}}}{\mathrm{d}t} = \sum_i h_{\mathrm{f},i} \left(\left.\frac{\mathrm{d}m_i}{\mathrm{d}t}\right|_{\mathrm{ff}} + \left.\frac{\mathrm{d}m_i}{\mathrm{d}t}\right|_{\mathrm{pf}} \right) \tag{1}$$

where $h_{\mathrm{f},i}$ is the formation enthalpy of species i, $\mathrm{d}m_i|_{\mathrm{ff}}$ and $\mathrm{d}m_i|_{\mathrm{pf}}$ are the mass variations of this species, respectively in the flame front due to reactions of fuel oxidation and in the burned gases due to post-flame chemistry reactions (Fig. 1). Post-flame chemistry contains two contributions [16]: the first one corresponds to dissociation processes (typically, $\mathrm{CO} \leftrightarrow \mathrm{CO_2}$), which are computed considering a tabulated time scale required to reach the chemical equilibrium, while the second one concerns NO formation, which is described following a similar approach. The species consumption rate through the flame writes:

$$\left.\frac{\mathrm{d}m_i}{\mathrm{d}t}\right|_{\mathrm{ff}} = -\nu_i \frac{W_i}{W_{\mathrm{fuel}}} \rho^{\mathrm{f}} Y^{\mathrm{f}}_{\mathrm{fuel}} U_{\mathrm{l}} S_{\mathrm{tot}} \tag{2}$$

where ρ^{f} is the fresh gases density, $Y^{\mathrm{f}}_{\mathrm{fuel}}$ is the fuel mass fraction in the fresh gases and U_{l} is the laminar flame speed estimated from a correlation depending on the nature of the fuel [10,14,17]. W_i denotes the molecular weight of the species i and ν_i is the stoichiometric coefficient corresponding to the reaction of fuel oxidation. Finally, S_{tot} is the total flame surface, which is estimated in the following section.