Experimental and Modelling Study of Stratified Premixed Turbulent Combustion[1]

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Abstract

The present study is a new step towards the comprehension and the modelling of complex situations where turbulent premixed flames propagate into reactants that are not homogeneously premixed. Compared to the limiting case of turbulent flame propagation in perfectly premixed reactants, modifications are likely to occur due to the large scale inhomogeneity (stratification) but also because of small scales heterogeneities. That will be discussed in the first introductory section. Those effects need to be experimentally investigated and herein recent experimental results obtained at LMFA are briefly reported. The studied configuration consists in a turbulent V-shaped flame embedded in a stratified premixed medium of CH4 and air (see last section). An unified PDF-flamelet model is introduced in the second section, it is used to perform a tentative comparison with the available experimental data of the V-shaped flame. The proposed modelling requires the calculation of the scalar PDF and it is done using the partial PDFs approach [1].

1 Introduction

There are many problems of practical interest where a flame propagates into a non homogeneous premixed medium ; direct fuel injection engine is a typical example. In that case, the determination of the mean reaction rate is not anymore simply related to the estimation of the flame surface density Σ or to the reactive scalar dissipation rate $\widetilde{\epsilon_Y}$. The problem is to evaluate the mean reaction rate distributed along the surface of flamelet but in this case the equivalence ratio of a portion of flamelet can differ from the neighboring portions. As a consequence, each portion of flamelet has different speed of propagation and the propagation speed of a given portion will depend on the local equivalence ratio but also on that of its neighbors. This can induce an additional stretch specifically due to partial premixing. The effects are expected to depend on the level of fluctuations in

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equivalence ratio but also on the characteristic length scale L_Z of the heterogeneities, see Jimenez *et al.* [2]. For example, an additional wrinkling of the flame surface is clearly visible on the direct visualizations of Zhou *et al.* [3]. To represent the chemical evolution of the reacting mixture, under the assumption of equal diffusivities, of single reaction (or at least supposing that the whole kinetic description can be represented with a single progress variable) and neglecting heat losses or mechanical exchange, two variables are necessary. The first one represents the mixing of reactants at the largest scales ; it is the mixture fraction Z, the second one is used to characterize the progress of the reaction ; here the oxidizer mass fraction Y is chosen.

2 Modelling Proposal

Considering the discussion of the first section, a turbulent combustion model is proposed. The essential ingredients of the modelling are as follows :

- an equation is used for the scalar PDF $P(Y, Z, \boldsymbol{x}, t)$
- mixing frequencies are calculated through transport equations for $\widetilde{\epsilon_Y}/\widetilde{Y''^2}$ and $\widetilde{\epsilon_Z}/\widetilde{Z''^2}$, then the model has the potentiality to take the dependence on L_Z into account
- intermediate regimes of turbulent combustion and flamelet effects are considered with an appropriate modelling of micromixing term following the pioneering work of Pope and Anand [5]

By considering the joint scalar PDF $P(Y, Z, \boldsymbol{x}, t)$, the influence of equivalence ratio fluctuations will be incorporated. The closure of micro-mixing terms that appear in the PDF equation require the estimation of mixing time scales. As indicated, $\tau_Z = \widetilde{Z''^2}/\widetilde{\epsilon_Z}$ is obtained without invoking a similarity hypothesis of the form $\tau_Z = C_Z \tau_t$ (C_Z being a «tuning coefficient») and following [4], an equation for $\widetilde{\epsilon_Z}$ is derived :

$$\frac{\partial \overline{\rho}\widetilde{\epsilon_Z}}{\partial t} + \frac{\partial}{\partial x_i}\left(\overline{\rho}\widetilde{u}_i\widetilde{\epsilon_Z}\right) = \frac{\partial}{\partial x_i}\left(\overline{\rho}D_t\frac{\partial \widetilde{\epsilon_Z}}{\partial x_i}\right) + c_{pz}\overline{\rho}\nu_t\frac{\epsilon}{k}\frac{\partial \widetilde{Z}}{\partial x_i}\frac{\partial \widetilde{Z}}{\partial x_i} + c_{pu}\overline{\rho}\frac{\widetilde{\epsilon_Y}}{k}\frac{\partial \widetilde{u}_i}{\partial x_i}\frac{\partial \widetilde{u}_i}{\partial x_i} + \alpha\overline{\rho}\frac{\epsilon}{k}\widetilde{\epsilon_Z} - \beta\overline{\rho}\frac{\widetilde{\epsilon_Z}^2}{\widetilde{Z''^2}}$$

This is also done for $\widetilde{\epsilon_Y}$ in such a way that when $\widetilde{Z''^2} = 0$ and when $\tau_c \to 0$ the flamelet limit is recovered. Moreover, as pointed out by Pope and Anand [5], the micro-mixing processing itself requires a particular attention in the flamelet regime of turbulent premixed combustion because micro-mixing and reaction are strongly coupled in flamelets. This point is taken into account following [6]. The model is then used to simulate the following experiment.

3 Experimental Study of the Stratified V-Shaped Flame

A new experimental arrangement has been designed to study the propagation of a turbulent stratified V-shaped flame. The stratified flow is provided by an injection rail, set within the settling chamber. Pure fuel is injected by means of several small injection pipes in an homogeneous lean premixed methane-air flow (equivalence ratio $\phi = 0.6$). The flame is then stabilized at the exit of the wind tunnel on a 2 mm diameter rod, and V-expanding in a free flow which mean velocity is $5\,m.s^{-1}$. A grid is set upstream in the flow in order to generate turbulence, whose characteristics are $L_t = 5\,mm$ for the integral length scale and $It = 4\%$ for the turbulence intensity. The stratified flow has been characterized first. At the initial station, the mean value of the equivalence ratio in the premixed turbulent flow is $\phi_0 = 0.6$ and the maximum values of the stratification slice and thickness are $\phi_{max} = 1.15$ and $\delta_S = 16\,mm$, respectively.

Fig. 1: *Experimental and numerical tomographies for homogeneous and stratified V-shaped flames*

A first description of the flame expanding in the stratified flow is obtained by using a tomography technique, that provides qualitative information on the topology of the flame front. Temperature and concentration measurements, as well as CH* chemiluminescence, are also used to improve a quantitative analysis. Results show two averages on 500 threshold photographs, Fig.1, and allow the definition of a flame brush, which angle and thickness appear to increase in the stratified turbulent case. The CH* emission field, Fig.2, also points out high levels located in the stratified front. A comparison of profiles of temperature and CH* emission Fig.2 shows that a mean position of the turbulent flame front can be obtained. On the Fig.1 are also reported the numerical tomographies obtained for homogeneous and stratified V shaped flames, using partial PDFs with the classical IEM model that does not take flamelet characteristics into account. We now have to turn to a more detailed comparison with experimental results with the full modelling that can take flamelets into account within PDF approach and this is in progress.

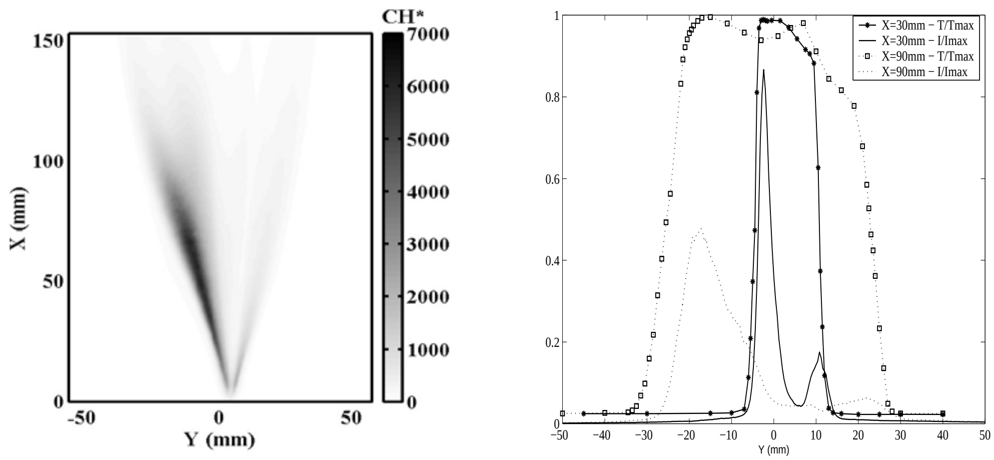

Fig. 2: *CH* emission field of the turbulent stratified flame (left). Normalized temperature and CH* emission profiles (right).*

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