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ScienceDirect

Combustion and Flame 153 (2008) 288–315

Combustion and Flame

www.elsevier.com/locate/combustflame

Experimental and numerical analysis of stratified turbulent V-shaped flames

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Received 10 May 2007; received in revised form 16 September 2007; accepted 23 October 2007

Available online 26 December 2007

Abstract

The present paper is devoted to (i) the experimental study of partially premixed combustion with strong equivalence ratio gradients, i.e., stratification of the reactive mixture and (ii) the numerical modeling of turbulent reactive flows in such situations where reactants are far from being ideally premixed. From a practical point of view, at least two variables are necessary to describe the local thermochemistry in this case: the mixture fraction ξ and the fuel mass fraction Y_f are considered to represent respectively the local composition of the fresh mixture and the progress of chemical reactions. From the experimental point of view, the use of simultaneous imaging techniques allows the evaluation of both variables in terms of fuel mole fraction and temperature. In the present study, a combined acetone PLIF measurement and Rayleigh scattering technique is used. The influence of temperature on the fluorescence signal is corrected thanks to the knowledge of the local temperature through Rayleigh scattering measurements. Conversely, the influence of the acetone Rayleigh cross section can be evaluated with the local value of acetone mole fraction. Using the iterative procedure already described by Degardin et al. [Exp. Fluids 40 (2006) 452–463], the corrected fuel mole fraction and temperature fields can be obtained. Here the particular flow configuration under study is a stratified turbulent V-shaped flame of methane and air. In a first step of the analysis, the optical diagnostics are used to perform a detailed investigation of the flame thickness with a special emphasis on the influence of partially premixed conditions. In a second step, experimental data are used to evaluate the LW-P model as defined by Robin et al. [Combust. Sci. Technol. 178 (10–11) (2006) 1843–1870] to calculate turbulent reactive flows with partially premixed conditions based on an earlier analysis by Libby and Williams [Combust. Sci. Technol. 161 (2000) 351–390]. The closure problem raised by the mean scalar dissipation terms is also discussed in the light of experimental results. Since the usual closures for nonreactive flows are expected to be unsuitable to describe reactive scalar fluctuations decay a new modeling proposal based on the recent developments of Mura et al. [Combust. Flame 149 (2007) 217–224] is used. After a preliminary validation step where numerical predictions of the flame mean quantities are compared successfully with the experimental database, numerical simulations are used to describe the mean structure of stratified flames and in particular the evolution of the mean chemical reaction rate for different partially premixed conditions.

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0010-2180/$ – see front matter
doi:10.1016/j.combustflame.2007.10.008

Keywords: Turbulent combustion; Partially premixed combustion; Stratified flames; Flame thickness; Mean scalar dissipation

1. Introduction

In many practical situations relevant to working conditions in energy conversion devices, from internal combustion engines to industrial furnaces, turbulent mixing of fuel and air prior to combustion leads to a reactive mixture that is not homogeneous. Accordingly the equivalence ratio of the mixture is variable in space and time and combustion occurs under partially premixed conditions. Depending on the fuel–air distribution or on the corresponding shape of the probability density function (PDF) of the equivalence ratio with respect to stoichiometric conditions, two different situations are expected:
(i) The first situation concerns the case where the fuel–air mixtures remain either lean or rich everywhere in such a manner that no diffusion flame can exist. This particular situation is commonly referred to as stratified combustion.
(ii) The second situation is a more general and complex situation, where the spatial distribution of equivalence ratio leads to the coexistence of fuel-rich and -lean heterogeneities, giving rise to a combination of premixed and diffusion modes. In some circumstances, the resulting reaction zone can be described as a staggered combustion with a *primary stage* corresponding to a premixed combustion zone (but with different local equivalence ratio depending on the location considered along the flame front), followed by a *secondary stage* corresponding to various multiple diffusion flames.

Various experimental and numerical studies have been carried out to evaluate the influence of spatial or temporal variations of the equivalence ratio and these for different geometrical and initial conditions. The most noticeable effects that have been evidenced can be summarized as follows: (i) extension of the flammability limits, (ii) modification of the inner structure of the flame, and (iii) strong dependence of the combustion efficiency on both turbulence and scalar length scales.

The concept of flammability limit is directly related to the propagative nature of a premixed flame front and especially to the value of the laminar flame speed. The chemical and physical mechanisms that drive the flame propagation into a medium with large and small scales fuel–air heterogeneities are rather different from those observed for homogeneous flames, as evidenced by previous experimental [1–3] and numerical studies [4,5].

For instance, if we first consider large-scale stratification of the equivalence ratio, flame fronts have been found to be able to propagate from stoichiometric conditions to extremely lean mixtures with a flame speed that can be 20% and up to 30% higher than the propagation velocity in the corresponding homogeneous mixture at the same mean equivalence ratio. This behavior is related to the history of the combustion process: flame propagation is back-supported by heat and radicals flux resulting from combustion that has occurred at a higher equivalence ratio. Accordingly, the knowledge of the local value of the equivalence ratio is clearly not sufficient to explain the differences between stratified and homogeneous combustion since all the previous events in the combustion process must be taken into account: those phenomena are related to some kind of memory effects of the flame. Of course, since these are nonlocal effects, they are extremely difficult to incorporate into turbulent combustion models.

The instantaneous structure of partially premixed flame fronts in terms of flame wrinkling, curvature, and rate of strain is also influenced by local fuel heterogeneities. These effects have been already studied and sometimes opposite trends have been found [6–9]. Nevertheless, fuel–air heterogeneities are expected to enhance flame wrinkling, at least when the turbulent intensity is not too large with respect to typical values of the laminar flamelet propagation velocity [10] and when the typical length scale attached to the equivalence ratio is smaller than the integral turbulent length scale.

Indeed, flame wrinkling is the result of both turbulence and fuel–air heterogeneities. In the case of freely propagating homogeneous flames, the experiments performed by Renou et al. [11] have shown that flame curvature statistics are strongly influenced by the integral turbulent length scale. For stratified flames, equivalence ratio fluctuations are other sources of local variations for the reaction rate since local flame fronts propagate with different displacement speeds. This effect that leads to additional deformation of the flame front can play a substantial role when the scale of fuel–air heterogeneities is smaller than the scale of turbulence as long as the ratio u'/S_L^0 is not too large. If this latter situation does not hold, turbulence is expected to prevail against laminar propagation.

This strong coupling between turbulence and stratification can be also studied in terms of combustion efficiency by considering some kind of global mean reaction rate. The evaluation and understanding of this coupling, for different conditions, have been the objective of previous experimental and numeri-