Experimental Thermal and Fluid Science 73 (2016) 109–114

Contents lists available at ScienceDirect

Experimental Thermal and Fluid Science

journal homepage: www.elsevier.com/locate/etfs

Scale analysis of the flame front in premixed combustion using Proper Orthogonal Decomposition

G. Maurice [a,b], F. Thiesset [a], F. Halter [a,*], N. Mazellier [b], C. Chauveau [a], I. Gökalp [a], A. Kourta [b]

[a] CNRS ICARE, Avenue de la Recherche Scientifique, 45072 Orléans Cedex 2, France
[b] University of Orléans, PRISME, EA 4229, 45072 Orléans, France

ARTICLE INFO

Article history:
Received 25 September 2015
Received in revised form 25 September 2015
Accepted 25 September 2015
Available online 3 October 2015

Keywords:
Premixed turbulent combustion
Flame brush
Flame wrinkling

ABSTRACT

The main objective of the present study is to explore the degree of interactions between turbulence and the flame front in the context of lean premixed combustion. Premixed methane Bunsen flames are investigated using Mie scattering at three different pressure magnitudes (0.1, 0.2, and 0.3 MPa) and equivalence ratios (0.6, 0.7, 0.8) through six operating conditions at the same mean bulk velocity (3.6 m/s). Nearly homogeneous and isotropic turbulence is generated by a multi-scale grid consisting of three distinct perforated plates. The multi-scale nature of the flame front is characterized using an original method based on Proper Orthogonal Decomposition (POD). Particular emphasis is shed to the scales responsible for the flame brush and the wrinkling of the flame front. The flame front curvilinear length is analyzed as a function of the mode (or equivalently the scale) and yields the well known Richardson plot that is usually observed using fractal analysis. The inner and outer cut-off length-scales, together with the fractal dimension can thus be evaluated using the present method. An analytical expression for unambiguously assessing the latter three parameters is introduced and compares favorably well with experimental data. Second, the reconstruction of the flame using only the first few modes suggests that, the flame brush is characteristic of a rather large-scale phenomena whilst the smallest scales act in decreasing the total flame brush.

1. Introduction

Turbulence gives rise to a large and continuous range of scales. The largest eddies reflect the way kinetic energy is injected in the system and therefore depend on the type of flow. These large-scales are sometimes referred to as coherent structures whose topology and dynamic are strongly affected by initial and boundary conditions. In contrast, one frequently asserts that the anisotropic and non-universal influence of the largest scales diminishes during the first non-linear local interactions and is thus expected to decline at the smallest scales. Consequently, it is still often postulated that the smallest scales have the best prospect of being universal or quasi-universal [1]. Since, in premixed combustion, the corrugation of the flame front results mainly from the interaction with turbulence, it may be argued that such a statement holds also for the statistics of the flame front wrinkles at a given scale. This intuitive conjecture encourages us in exploring the multi-scale nature of turbulent flames with the far aim of quantifying the degree of dependence of the large-scales wrinkles to initial and boundary conditions and assessing the degree of universality of the flame front at small-scales.

In the past-few years, the multi-scale facets of the flame front have been first analyzed using a fractal approach. More particularly, the scales distribution of the flame front has been generally inferred by means of the box-counting technique (see among others [2] and references therein). This approach led to the identification of the three distinct ranges in the wrinkling scales distribution. At large-scales, the production of wrinkles is almost negligible. As we travel through smaller scales, one may reach the outer length scale where the flame front starts being corrugated. Then, at intermediate scales, a power-law dependence of the wrinkling to the scale is observed with a scaling exponent related to the so-called fractal dimension. Finally, the smallest-scales, i.e. scales smaller than an inner cut-off length-scale are not efficient enough for corrugating the flame front, since viscous, kinematic and/or thermo-diffusive effects are dominant and preclude the creation of smaller wrinkles.

As in the field of turbulence, spectra have also been used for evaluating the distribution of scales of the flame front, leading to very similar deductions [3]. Note however that in practice, the flame front is not described by single valued spatial coordinates

* Corresponding author.
E-mail address: fabien.halter@cnrs-orleans.fr (F. Halter).

http://dx.doi.org/10.1016/j.expthermflusci.2015.09.030
0894-1777/

which makes the calculation of spectra rather tenuous, if not impossible. With this limitation in mind, it was noted however that the spectral exponent in the inertial range was close to previous estimations of the fractal dimension [3].

In the present study, we propose to explore the multi-scale facets of the flame front by means of Proper Orthogonal Decomposition (hereafter abbreviated by POD). POD belongs to a family of modal decomposition methods and is widely used in the field of fluid mechanics. Generally, use is made of POD to educe coherent structures from the randomly fluctuating flow. It has been introduced in fluid mechanics by Lumley [4] and the snapshot method which is more convenient for large data sets has been developed by Sirovich et al. [5]. At this stage, it has to be emphasized that, unlike spectral or fractal approaches, POD has the tremendous advantage of allowing to finely reconstruct the instantaneous flame front mode-by-mode or equivalently scale-by-scale, and the contribution of each scale to the instantaneous flame brush or wrinkling can be inferred. Note that POD is a data driven technique meaning that the decomposition is based on a *a priori* basis. This implies that the relationship between a POD mode and a physical scale is not straightforward.

In the field of combustion, very few studies have focused on modal decompositions. It has been early used by Danby and Echekki [6] to investigate the auto ignition of inhomogeneous hydrogen air mixture. These authors tried several preprocessing techniques on the data-set in order to optimize the number of modes needed to minimize the reconstruction error. Later, using PIV data sets and OH-PLIF together with the extended POD methods [7] introduced by Borée [8], Duwig et al. used POD to study (i) thermo acoustics instabilities [9], (ii) the interaction of precessing vortex core with a swirling flame [10] and (iii) unsteady flames driven by acoustic perturbation. Finally, to characterize the flame shedding process behind a bluff-body [11], Kostka et al. used POD on flame chemiluminescence images to extract the coherent behavior and separate the energy at given mode into symmetric, asymmetric, and uncorrelated components.

Here, POD is applied to the flame front spatial coordinates extracted from Mie scattering tomography measurements. First, particular attention is paid to the scale distribution of wrinkles, by evaluating the curvilinear length of the flame front as a function of the scale. For this purpose, the correspondence between the mode number and a typical scale is successfully inferred. An analytical expression for assessing the inner and outer length-scale together with the scaling exponent is also proposed. Finally, the focus is rather on the large-scales and their contribution to the flame brush.

The paper is organized as follows. First we describe the experimental set-up and measuring technique. Secondly, the POD algorithm as applied to the present configuration is outlined. Then, results for the curvilinear length and flame brush are presented and discussed. Findings are summarized in a final section.

2. Experimental apparatus

The turbulent methane/air premixed flame is generated via an axisymmetric Bunsen burner with $D = 25$ mm in diameter. For all cases reported in this study, the bulk velocity U_d of the fresh gases is 3.6 m/s. A turbulence generator located upstream from the burner exit enables to produce a nearly homogeneous and isotropic turbulence which has been fully detailed in Fragner et al. [12]. A schematic of the experimental set-up is given in Fig. 1. The burner is implemented in a pressure chamber that allows to regulate the pressure P within the range 0.1–1 MPa. Experimental operating conditions are listed in Table 1. The instantaneous flame front is captured by means of laser tomography using a 15 W 532 nm continuous laser light, the fresh gases being seeded with organic oil droplets. The flame front images are recorded with a phantom V1210 Phantom camera, using a 105 mm F2.8 lens, at a frame rate of 10,000 fps on a cropped sensor at 800 $\times$ 384 pixels. The physical field of view is 40.32 mm wide and 84 mm high which leads a spatial resolution of 0.10582 mm/pixel. For each experimental operating condition $N_{im} = 10,000$ images were acquired. The instantaneous 2D flame front is binarised following a threshold algorithm. Firstly, a contrast-limited adaptive histogram equalization (CLAHE) is applied to the original images in order to optimize the contrast in the images. Then, to limit the pixelixation associated with the CLAHE, images are filtered using a gaussian filter of size equal to 4 times the spatial resolution. For the binarizing procedure, we use a standard threshold-based technique. More precisely, the histogram of the gray scale is calculated. The latter reveals two distinct peaks corresponding to the fresh and burned gas respectively. The threshold value for discriminated the flame contour is set as the average value between the gray scale of these two peaks. This binarization procedure leads irremediably to a digitization noise (pixelization) which, in the present case, is smoothed using a low-pass gaussian size equal to 3 times the spatial resolution. It was checked that doubling the size of the filter did not yield observable changes on the properties of interest (namely the flame wrinkling distribution). This indicates that the present measurements are well resolved and that the filter size that is used here is much smaller than that of the smallest flame wrinkling characteristic length scale. Then, the contour of the turbulent flame is extracted by means of an edge detection algorithm.

For the present study, we made the choice of focusing only on the longest contour representing the largest topologically connected object, whereas holes and pockets are not taken into account. The contribution of these missing flame holes and pockets to e.g. the flame surface density was rather limited notwithstanding the relatively low turbulence intensity of our experiments.

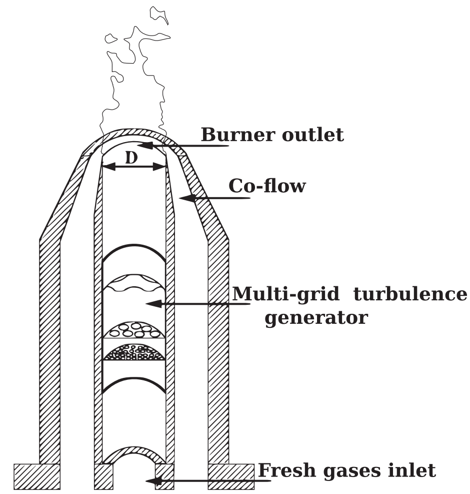

Fig. 1. Sketch of the turbulent Bunsen premixed burner [12].

Table 1
Operating conditions. P is the pressure in the combustion chamber, ϕ is the equivalence ratio, S_l is the laminar flame speed and δ_l is the laminar flame thickness.

Case	P (MPa)	ϕ	S_l (m/s)	δ_l (mm)
1	0.1	0.6	0.113	0.197
2	0.1	0.7	0.191	0.117
3	0.1	0.8	0.226	0.083
4	0.2	0.6	0.076	0.147
5	0.3	0.6	0.058	0.127
6	0.3	0.8	0.083	0.045