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On flame–turbulence interaction in constant-pressure expanding flames

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Abstract

In this paper we present one of the first high-speed particle image velocimetry measurements to quantify flame–turbulence interaction in centrally-ignited constant-pressure premixed flames expanding in near-isotropic turbulence. Measurements of mean flow velocity and *rms* of fluctuating flow velocity are provided over a range of conditions both in the presence and absence of the flame. The distributions of stretch rate contributions from different terms such as tangential straining, normal straining and curvature are also provided. It is found that the normal straining displays non-Gaussian *pdf* tails whereas the tangential straining shows near Gaussian behavior. We have further tracked the motion of the edge points that reside and co-move with the edge of the flame kernel during its evolution in time, and found that within the measurement conditions, on average the persistence time scales of stretch due to pure curvature exceed that due to tangential straining by at least a factor of two.

Keywords: Turbulent premixed flame; Stretch rate; High-speed PIV

1. Introduction

An expanding flame is one of the most canonical flame configurations that finds applications spanning from engineering devices like spark-ignition engines to astrophysical events like supernova explosions. Laminar expanding flames have been routinely adopted for experimentally determining laminar flame speeds which is used to (partially) validate chemical reaction mechanisms [1]. All practical flames of this configuration are however turbulent in nature; hence extensive studies have been conducted recently on expanding flames interacting with near-isotropic turbulence [2–13]. The fundamental parameters that quantify the state of turbulence, if it is nearly isotropic, are the turbulence intensity u_{rms} and the integral length scale L_I. The quantities that characterize the local flame structure are the local laminar flame speed $\tilde{S}_L$ and flame thickness δ_L. According to the hydrodynamic theory of premixed flames the stretched laminar flame speed $\tilde{S}_L$ is given by:

$$\tilde{S}_L = S_L - \delta_M \mathbf{K} \quad (1)$$

where S_L and δ_M are the planar laminar flame speed and Markstein length, respectively [14,15],

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K is the total stretch rate which can be further decomposed as [16,17]:

$$\mathbf{K} = \overbrace{\underbrace{S_L \kappa}_{\text{stretch rate by pure curvature: } K_c} - \underbrace{(\mathbf{v}\cdot\mathbf{n})\kappa}_{\text{normal strain: } K_n}}^{\text{stretch rate by curvature: } K_\kappa} + \underbrace{\nabla_t \cdot \mathbf{v}_t}_{\text{tangential strain: } K_t}, \quad (2)$$

in which $K_t = (\delta_{ij} - n_i n_j)S_{ij}$, and $\delta_{ij} = 1$ for $i = j; 0$ for $i \neq j$; with S_{ij} being the strain rate tensor. The second and third terms on the RHS of Eq. (2) together is the stretch rate contribution by the strain rate, K_s. Stretch rates originating from the tangential strain rate K_t, normal strain K_n and stretch due to pure curvature K_c can be considered to be parameters that quantify the turbulence–flame interaction as well [18]. In general, turbulence causes multi-scale wrinkling of the flame surface, affecting the aerodynamics of the flame which in turn affects the nearby flow field by heat release and gas expansion. Since the burned products in the expanding flame should be statistically stationary, the flame could induce a mean outward flow that might affect the turbulence parameters like u_{rms} and L_I in the otherwise cold non-reacting flow. It appears that in most experimental efforts on turbulent expanding flames, only cold flow turbulence parameters like u_{rms} and L_I measured in the absence of flame have been reported [7–12] with the exception of Lawes [13] who performed one point Laser Anemometry in the fresh mixture ahead of the turbulent flame. It is thus critical to investigate with detailed field measurements, to what degree these fundamental quantities are affected, if at all, by the flame as these modified parameters are what distort the flame instead of the quantities measured in its absence.

In view of such a need, we shall attempt to provide experimental high-speed particle image velocimetry data that quantifies flame–turbulence interaction dynamics well resolved in two dimensional space and time, as the flame evolves from a wrinkled flame kernel to a well-developed expanding turbulent flame. The high-speed Mie scattering which is a necessary precursor to HS-PIV allows us to extract the flame edges from the maximum seed density gradients. This enables tracking the evolution of the stretch rates, curvature statistics. The flow velocity and strain rate tensor components from the HS-PIV could be superposed on these flame edges, allowing investigation of the evolution of stretch rate statistics due to both local strain rate and curvature.

2. Experimental method

The experiment uses a constant-pressure, dual-chamber, fan-stirred vessel that enables investigation of spherically expanding flames (Fig. 1a) with the help of high speed imaging. The chamber has been widely used for both laminar and turbulent expanding flames and is detailed in previous articles [1,9,19] and in the Supplementary material [S1].

To detect the flame edge during the combustion process the fuel/air mixture was seeded using DEHS droplets (nominal diameter 1–2 μm) using a high-pressure nebulizer. A high-speed Nd-YLF laser (527 nm) synchronized with a high-speed camera (Phantom v7.3) is used for Mie-scattering imaging and subsequent PIV processing. Using beam expanding optics the 2 mm diameter laser beam is expanded to a 750 μm thick laser sheet inside the inner chamber as shown in Fig. 1a. The camera placed at 90° from the laser plane recorded images with a pixel resolution of 608 × 600 to achieve a spatial resolution of ~50 μm/pixel. For high quality, high-speed 2D particle image velocimetry (PIV) the camera was triggered at a framing rate of 8000 frames/s with corresponding laser synchronization, such that the correlated image pairs could be recorded with a time interval of 30 μs. Before the ignition, the entire chamber remains filled with droplet mist showing a uniform distribution of seed density. Following ignition, as the flame propagates the seeding droplets vaporizes at the flame edge, hence limiting the high seeding density only outside of the flame.

Post processing was performed in two stages. First, from the high-speed Mie-scattering images the instantaneous 2D flame (on the laser plane) edge was detected using Canny edge detection technique through Matlab. Second, vector computation was performed using commercially available software DaVis multi-pass strategy with interrogation window size reducing from 16 × 16 to 8 × 8 pixel^2 having 50% overlap. Image area close to the electrodes was excluded from the vector calculation to minimize error. The consistency and accuracy of the vector computation was reflected in very high Q value (~0.95), which is the ratio of two most probable displacement values in each interrogation window. PIV was performed both in cold flow (before ignition) and with flame (after ignition). The information of instantaneous flame edge and velocity field was then combined onto a common grid to obtain the relevant flame–turbulence interaction statistics.

In the following we clarify the limitations and uncertainties of the technique used. The flame edge detected using Mie scattering images approximately represents an isotherm that corresponds to the boiling/saturation temperature of DEHS which is the composition of the seeding droplets. The resolution of the current high speed Mie scattering images is approximately 50 μm, which restricts us from completely resolving the finest structures for the very high pressure flames (Flame thickness and Kolmogorov length scales are tabulated in Table 1). Moreover, for PIV, the smallest interrogation window was 8x8 pixels