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Influence of combustion on principal strain-rate transport in turbulent premixed flames

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Abstract

The transport of principal strain-rates (s_i) was experimentally investigated using high-repetition-rate (10 kHz) tomographic particle image velocimetry (T-PIV) and OH planar laser induced fluorescence (PLIF) in a $\mathrm{Re_j} = 13,000$ turbulent premixed flame. These measurements allowed calculation of the source terms in the s_i transport equation associated with the strain-rate and vorticity fields. Furthermore, the Lagrangian derivatives of s_i could be calculated by tracking theoretical Lagrangian fluid particles through space and time using the T-PIV data. These Lagrangian derivatives and the resolved source terms allowed the combined effects of the unresolved source terms to be inferred, namely the pressure Hessian, viscous dissipation, density gradients, and viscosity gradients. Statistics conditioned on the location of the Lagrangian fluid particles relative to the flame showed slight reductions in the strain-rate and vorticity source terms in the flame, indicating that these aspects of the turbulence were attenuated by the flame. Comparing the difference between the inferred source terms in the vicinity of the flame to the non-reacting flow showed that attenuation of s_i arose due to the combined effects of density and pressure gradients in the flame. The effects of flame-induced dilatation were small relative to the turbulent strain-rate and no change was found in the relative alignment of vorticity and strain-rate in the flame.

Keywords: Turbulent premixed flames; Strain-rate; High-repetition-rate laser diagnostics; Tomographic PIV; PLIF

1. Introduction

The interaction between a premixed flame and the turbulent strain-rate field through which it propagates is a fundamental process in turbulent combustion. Such strain-rate/flame interactions alter the topology and scalar structure of the flame, as well as the magnitude and geometry of the turbulence [1–8]. As such, terms describing this interaction appear in various governing equations and must be modeled in simulations. These terms generally involve both the magnitude of the strain-rate field and its orientation relative to the flame surface, often taking the form $n_i n_j S_{ij}$, where $\hat{n}$ is the scalar gradient (flame surface) normal direction and $S_{ij} = 1/2\left(\partial u_i/\partial x_j + \partial u_j/\partial x_i\right)$ is the strain-rate tensor.

The strain-rate tensor can be expressed in its local eigenframe, wherein the strain-rates are

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represented by the three eigenvalues or principal strain-rates (s_i, ordered $s_1 > s_2 > s_3$) that act in the directions of the corresponding eigenvectors ($\hat{e}_i$). Strain-rate/flame interactions therefore typically are characterized by

$$n_i n_j S_{ij} = s_1|\hat{e}_1 \cdot \hat{n}|^2 + s_2|\hat{e}_2 \cdot \hat{n}|^2 + s_3|\hat{e}_3 \cdot \hat{n}|^2 \quad (1)$$

It therefore is necessary to understand how $\hat{e}_i \cdot \hat{n}$ and s_i evolve through a flame.

Recent computational studies have elucidated several aspects of strain-rate/flame alignment. For example, Chakraborty et al. studied such alignment using 3D DNS of statistically planar flames with one-step chemistry at Reynolds numbers of about $\mathrm{Re}_t = u'_r l/\nu \approx 50$ and over a range of Damköhler numbers ($\mathrm{Da} = (l/\delta_l)/(u'_r/s_l) = 0.3-6.8$), and Karlovitz numbers ($\mathrm{Ka} = \delta_l^2/\lambda_k^2 = 9.8-34.3$) [5]. Here, l, λ_k, and u'_r are the turbulence integral length scale, Kolmogorov length scale, and root-mean-squared velocity fluctuations in the reactants; δ_l and s_l are the laminar flame (thermal) thickness and speed. Additionally, Hamlington et al. studied numerous aspects of turbulence-flame interaction using simulations of highly turbulent H_2-air flames at $\mathrm{Da} = 0.03-0.39$ and corresponding $\mathrm{Ka} = 174.2-3.45$ [3]. At lower turbulence intensities, both studies found that dilatation-related extensive strain-rate within the flame could dominate over the turbulent strain-rate. Hence, scalar gradients preferentially aligned with the eigenvector of the most extensive strain-rate, $\hat{e}_1$, within the flame. At higher turbulence intensities, turbulence dominated over dilatation and the strain-rate/flame alignment resembled that found in passive scalar fields; scalar gradients aligned perpendicular to the most extensive strain-rate direction.

Regarding the principal strain-rate magnitudes, the relevant transport equations in a reacting flow can be written as

$$\underbrace{\frac{\mathrm{D}s_i}{\mathrm{D}t}}_{L_i} = \underbrace{-s_i^2}_{\tilde{T}_{1i}} + \underbrace{\frac{1}{4}\left(\tilde{\omega}_k\tilde{\omega}_k - \tilde{\omega}_i^2\right)}_{\tilde{T}_{2i}} + \underbrace{\nu\frac{\partial^2 s_i}{\partial x_k \partial x_k}}_{\tilde{T}_{3i}} - \frac{1}{\rho}\tilde{\Pi}_i + \tilde{T}_{4i} + \tilde{T}_{5i} \quad (2)$$

where $\mathrm{D}/\mathrm{D}t = \partial/\partial t + u_j\partial/\partial x_j$ is the Lagrangian derivative, $\tilde{\omega}_j$ is the vorticity vector in the local strain-rate eigenframe ($\tilde{\omega}_i = E_{ij}^T\omega_j, E_{ij}^T$ is the transpose (and hence inverse) of the orthogonal matrix $E = [\hat{e}_1\hat{e}_2\hat{e}_3]$), and $\tilde{\Pi}_i$ is the i^{th} diagonal element of the pressure Hessian ($\Pi_{ij} = \partial^2 p/\partial x_i \partial x_j$) expressed in the strain eigenframe ($\tilde{\Pi} = E^T \Pi E$). $\tilde{T}_1 - \tilde{T}_3$ and $\tilde{\Pi}_i$ take the same form in the non-reacting (constant density) transport equation, but are influenced by reaction through changes in the velocity, density, viscosity, and pressure fields. Furthermore, dilatation and the influence of heat release on the vorticity field also affect strain-rate transport. The $\tilde{T}_4$ and $\tilde{T}_5$ terms in Eq. (2) arise due to density and viscosity gradients associated with combustion and take the form

$$\tilde{T}_4 = E^T\left[\frac{1}{2\rho^2}\left(\frac{\partial p}{\partial x_i}\frac{\partial \rho}{\partial x_j} + \frac{\partial p}{\partial x_j}\frac{\partial \rho}{\partial x_i}\right)\right]E \quad (3)$$

$$\tilde{T}_5 = E^T\left[\frac{1}{2}\left(\frac{\partial \nu}{\partial x_j}\frac{\partial^2 u_i}{\partial x_k \partial x_k} + \frac{\partial \nu}{\partial x_i}\frac{\partial^2 u_j}{\partial x_k \partial x_k}\right)\right]E \quad (4)$$

For non-reacting flows, Nomura and Post studied the mean contribution of the principal strain-rate source terms using DNS of decaying isotropic turbulence [9]. They classified these terms into local effects (*i.e.* $\tilde{T}_1, \tilde{T}_2$, and the locally induced portion of $\tilde{\Pi}$), non-local effects of $\tilde{\Pi}$, and viscous dissipation ($\tilde{T}_3$). Local generation of the principal strain-rates typically was balanced by dissipation, with non-local effects being the smallest contribution.

In a reacting flow, Hamlington et al. studied the evolution of the vorticity across the flame [3]. They calculated budgets of the various source terms in the reacting vorticity transport equation and showed that those associated with the combustion (*viz.* dilatation and baroclinic torque) were significant at low turbulence intensities, but were dominated by turbulent production at higher intensities.

The insight gained from such computational studies can be enhanced and validated by experimental studies employing high-repetition-rate laser diagnostics. Such experiments allow investigation of more practically-relevant flames without the need for modeling, albeit with lower resolution, fewer detectable quantities, and potentially greater uncertainty. In this work, the evolution of the principal strain-rates are experimentally investigated using high-repetition-rate tomographic particle image velocimetry (T-PIV) and OH planar laser induced fluorescence (PLIF). These experiments allow explicit determination of the 3D principal strain-rates, their Lagrangian derivative, and several of the source terms in Eq. (2).

2. Experiment and diagnostics

The burner geometry was similar to that of the Sandia Piloted Jet Flame series and is shown in Fig. 1 [10]. Premixed dimethyl-ether (DME) and air at $\phi = 1.1$ ($s_l \approx 0.4$ m/s, $\delta_l \approx 0.6$ mm) were provided to a central jet nozzle with diameter $D_j = 7.45$ mm. This was surrounded by a pilot flame annulus ($CO_2/N_2/C_2H_2/H_2$ with air at $\phi = 0.6$) and air co-flow with diameters of 18.2 mm and 254 mm, respectively. All mass flow rates ($\dot{m}$) were metered using calibrated electromechanical flow controllers (MKS). The center of the measurement region was located at $(x/d, y/d, z/d) = (0, 10, 0)$, with the coordinate axes as shown in Fig. 1. Properties of the jet