Improving Our Understanding of Turbulent Combustion by Imaging Eddy / Flame Interactions

James F. Driscoll

Department of Aerospace Engineering
University of Michigan, Ann Arbor MI 48109-2140

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In the area of nonpremixed turbulent combustion, it has been well-established that an important parameter is the mean scalar dissipation rate ($\overline{\chi}$) that is conditionally averaged at the location of the instantaneous reaction zone layer. Also of importance are the pdf and the variance (σ_χ) of this conditioned scalar dissipation rate. However, a fundamental weakness of present models is that there is incomplete understanding of how the velocity field parameters (including the vorticity and strain rate, which depend on velocity derivatives) control the scalar gradients. Assumptions are based on little experimental verification; for example, one assumption is that $\overline{\chi}$ is proportional to ε, which is the dissipation rate of the turbulent kinetic energy. Another assumption is that $\overline{\chi}$ is proportional to a mean strain rate, which is true for a steady counterflow flame, but is not true if the strain field oscillates at a high frequency. Corresponding oscillations in the scalar gradients do not occur due to the limited time response of the diffusion-limited processes.

Therefore it is important to improve our understanding of two processes:

(a) the mechanism by which turbulent eddies exert unsteady strain on reaction zone, and

(b) the mechanism by which this unsteady strain affects the scalar gradients, which control the diffusion of fuel and oxidizer to the reaction zone and determines the values of $\overline{\chi}$ and σ_χ. The experimental challenge is to:

IDENTIFY STOICHIOMETRIC CONTOUR (CH-OH PLIF)

MEASURE STRAIN RATE ON STOICHIOMETRIC CONTOUR (PIV)

MEASURE SCALAR DISSIPATION RATE ON STOICHIOMETRIC CONTOUR (NO PLIF)

IMPROVED MODEL RELATING SCALAR DISSIPATION RATE TO STRAIN RATE

Fortunately, new CH-OH-NO PLIF and PIV laser diagnostics [1-4] make it possible to identify the stoichiometric contour (as the boundary between simultaneous CH/OH layers). The in-plane components of the strain rate can be determined using PIV with adequate resolution that is equal to the Taylor scale. New ways to image the scalar dissipation rate employ NO PLIF and Rayleigh scattering diagnostics [5]. The time history of the eddies has been visualized using Cinema-PIV [6] to show how eddies interact with the reaction zone. Some new advances in each of these areas are discussed.

A related issue is how to assess if new models, such as LES, realistically simulate the effects of turbulent eddies on the reaction zone. Parameters that are currently used for assessment, such as profiles of mean quantities, are not sufficient. Instead, "flame-structure" parameters should be identified, measured, and added to existing databases. Suggested parameters include: the flame surface density (Σ), the subgrid flame surface density, the thickness of CH layers, the mean strain rate and the variance of the strain rate exerted on the CH layers. The flame surface density (Σ) is determined directly from the images of CH reaction layers. Also important is the degree of flamelet extinction, as determined from CH-OH PLIF images.

Figure 1 shows some simultaneous CH PLIV/PIV results [1] in a turbulent jet flame at Re = 18,700. The CH layer remains thin (less than 1 mm thick), which confirms the flamelet concept. Severe wrinkling of the CH reaction layers are seen. The strain rate along the CH reaction layers is plotted in Fig. 1 and it exceeds the extinction strain rate, yet nowhere is extinction observed. Also, the thickness of the CH layers does not increase and decrease where the strain is positive and negative. Both of these findings indicate that the large strain rates are applied for such a short time that the scalar properties do not respond to the unsteady strain field. The images show that strain varies over a length scale of a few mm; using Taylor's Hypothesis, this corresponds to a frequency of oscillation of 10 kHz, which is too large to allow the diffusion processes to respond.

Figure 2 indicates that when the turbulence intensity is greatly increased, the flamelets do not broaden, but instead they extinguish [4]. Apparently the Karlovitz number associated with extinction is reached before the corresponding Ka required to broaden the flamelets into distributed reaction zones. The CH reaction zones remain less than 1 mm thick in these gas-turbine-like turbulence conditions.

Figures 3 and 4 show eddies that interact with a fully turbulent premixed flame. The eddies are regions where the vorticity is measured using PIV to exceed 2000 s^{-1} and the black region is the CH reaction layer. In Fig. 4 one observes a pair of eddies exerting positive strain, which causes a thinning of the reaction layer, as expected. Another pair of eddies is seen to exert negative strain, which forces the flame to move toward and between the eddies, causing positive flame curvature. This is one physical reason why strain and flame curvature are correlated.

Figure 5 shows a time-history of eddies moving upward in turbulent jet at Re = 4300 and interacting with a lifted methane-air nonpremixed jet flame. Images were taken at 8,000 PIV images/s using a Cinema-PIV system [6]. The time-history was used to determine that the local propagation speed of the flame base does not correlate with the passage of large eddies, or with the turbulence level at the base, which changes in time. This finding casts doubt on two models of flame liftoff that are based on large eddy recirculation of hot gases, and the turbulent burning velocity of the base. Instead, the findings can be best explained by the edge-flame theory. Gas expansion causes a divergence of velocity vectors from the lifted reaction zone, thus the flame base acts as a bluff body around which the streamlines must diverge. This streamline divergence lowers the local gas velocity, allowing a laminar-like flame base to stabilize.

Another issue is the relative roles of molecular diffusion and turbulent diffusion. Unsteady flamelet models assume that molecular diffusion dominates in thin reaction zones where the high temperatures increase the molecular diffusivity and the viscous and gas expansion processes limit any diffusion due to small eddies. Other models instead assume that small eddies play a more important role in the reaction zone. Images of the CH layers indicate that the layers extinguish before they broaden, as the turbulence intensity is increased. As Karlovitz number (based on u') increases it is observed that the flamelets extinguish, forming short flamelets in the "shredded flame" regime, but the CH reaction layers remain as thin as those in laminar flames. Results show that for the experiments considered, thickened reaction zones do not occur.

A new method to measure the scalar dissipation rate is discussed. Sutton and Driscoll showed that nitric oxide (NO) can be added in large quantities to a fuel jet consisting of carbon monoxide (CO) fuel. Precautions were taken to remove all hydrogen-containing compounds, especially water vapor, and it is shown that the NO is a conserved scalar that has the same molecular diffusivity as the CO fuel and the surrounding air. Using the NO-doped CO fuel, $\overline{\chi}$ is measured with exceptionally large signal-to-noise ratio using NO PLIF diagnostics. This method also avoids a problem associated with Raman and other PLIF diagnostics; those diagnostics typically employ a hydrogen-based conserved scalar, so the numerous radicals containing H must be measured simultaneously near the reaction layer.

References

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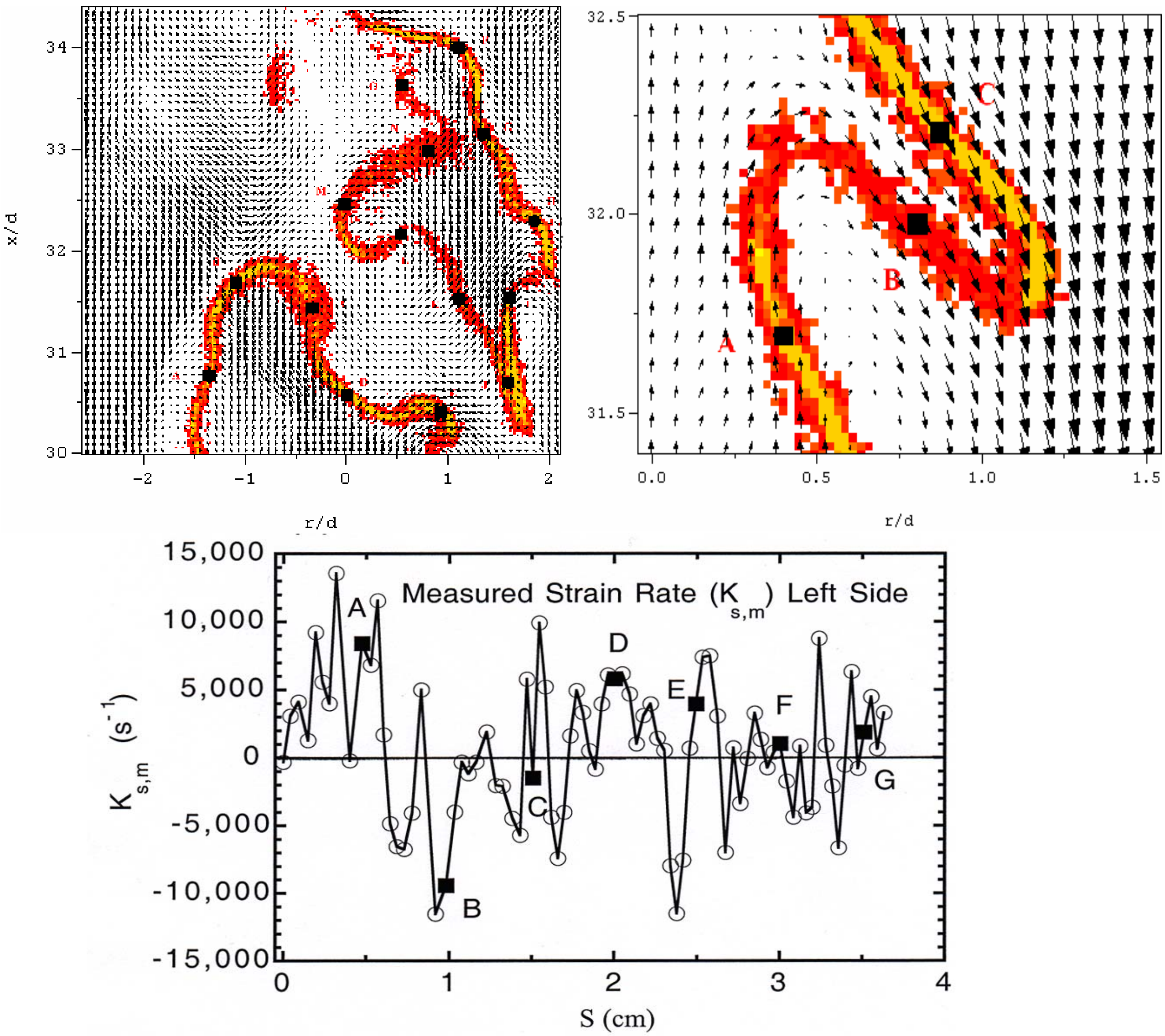

Figure 1. Images of CH Reaction Layers and the Surrounding Velocity Field in a Methane-Air Nonpremixed Turbulent Jet Flame at Re = 18,700. Also shown are the Strain Rates Measured Using PIV Along the Stoichiometric Contour Identified by the CH Layers Shown Above. Donbar et al. [1].

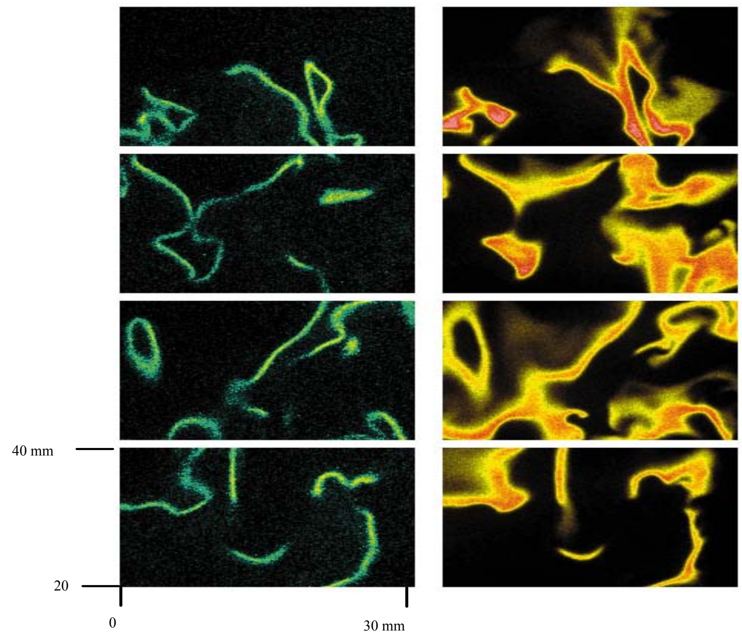

Figure 2. . Intensely-Wrinkled Flame Showing that CH Reaction Layers (Left) Extinguish Before They Broaden. CH Layers on left remain less than 1 mm thick. Simultaneous OH layers are shown on right. Each image is 23 mm by 30 mm. Ratner et al. [4].

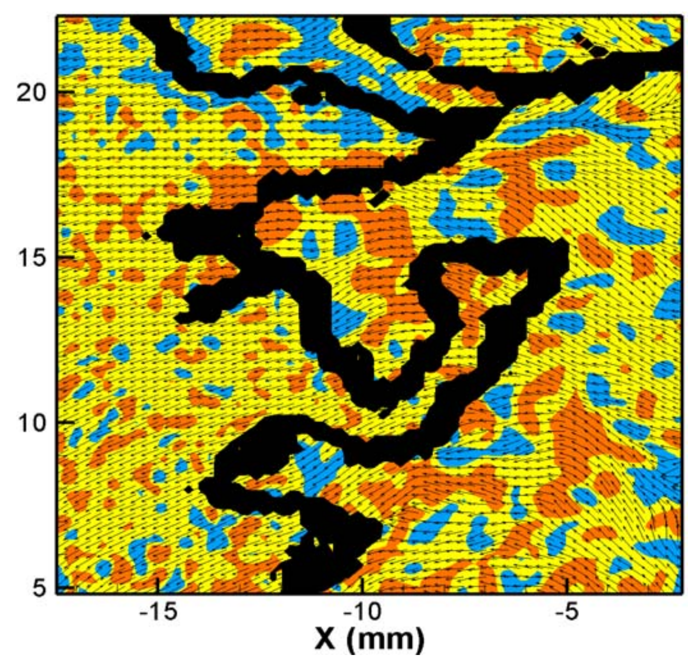

Figure 3. Image of Eddies and the CH Reaction Layer (black) in a Premixed Turbulent Flame. Reactants on right, products on left, flow is upward in the Bunsen flame. Filatyev, Driscoll, Carter and Donbar, submitted for publication.

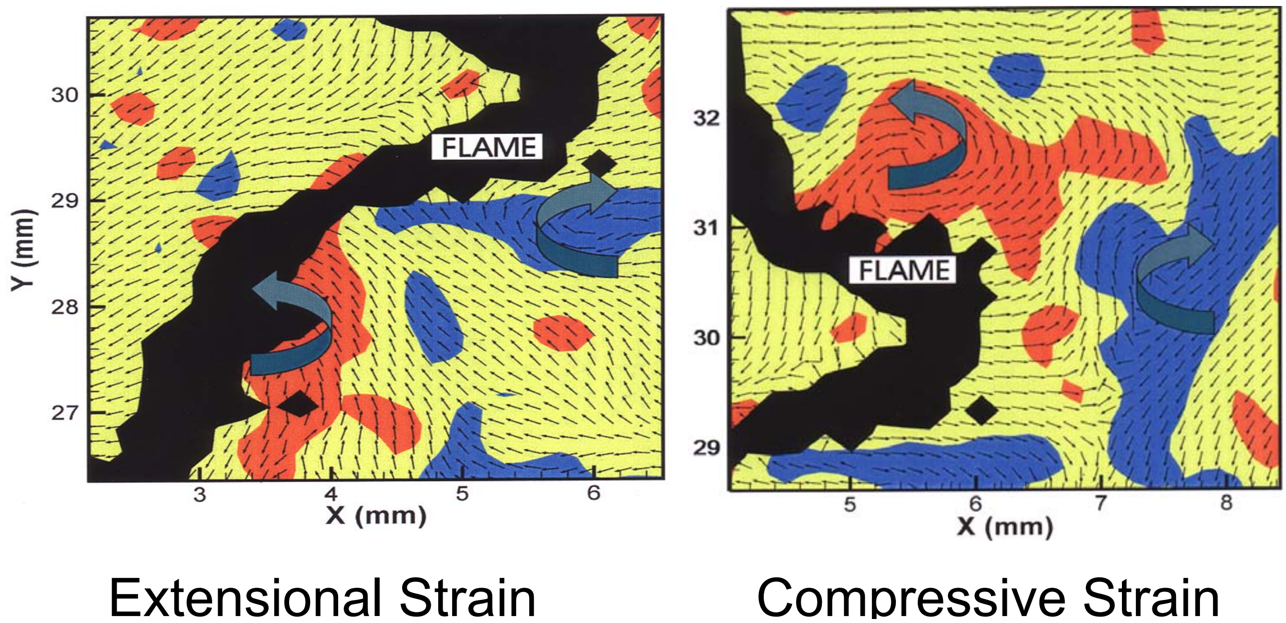

Figure 4. Magnified Images of a Small (4 mm by 4 mm) Region of the CH Reaction Zone (black) in the Turbulent Premixed Flame. (a) A pair of eddies exert extensional (positive) strain, as in a counterflow flame; (b) a pair of eddies exert compressive strain.

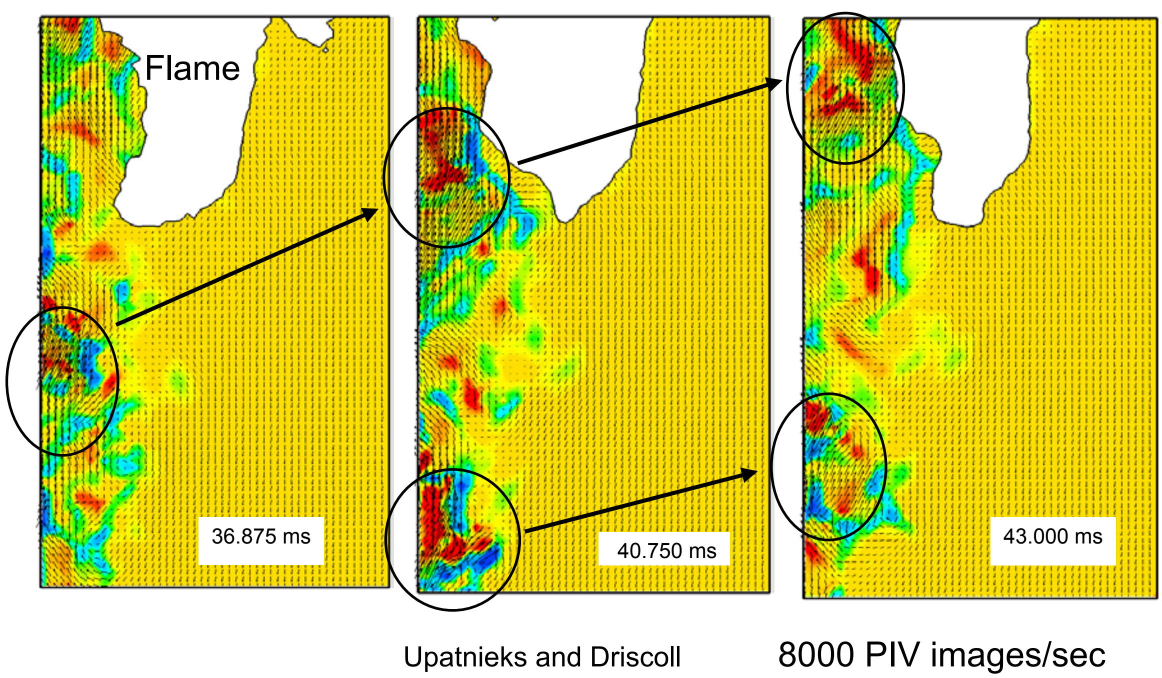

Figure 5. A Time History of Eddies Passing By a Lifted Flame Base in a Nonpremixed Turbulent Jet Flame. Upatnieks et al. [6].