High-Speed Tomographic PIV Measurements of Strain Rate Intermittency and Clustering in Turbulent Partially-Premixed Jet Flames

Bruno Coriton and Jonathan H. Frank*

Combustion Research Facility, Sandia National Laboratories

Livermore, California 94551, USA

The effects of combustion on the strain rate field in turbulent jets were studied using 10 kHz tomographic particle image velocimetry (TPIV). Measurements were performed in three turbulent jets: a well-studied, piloted partially-premixed methane/air jet flame, *Sandia Flame C*, with low probability of localized extinction; a second piloted jet flame, analogous to flame *C* but with a reduced pilot flow rate and a high probability of localized extinction; and a non-reacting air jet. Since the jet exit Reynolds number of approximately 13,000 was nearly identical in the three jets, differences in the strain rate fields were attributed to the effects of combustion. Spatiotemporal characteristics of the strain rate field were analyzed. Overall, the strain rate norm was larger in the flames than in the non-reacting jet with the most stable flame having the largest values. In all three jets, the compressive strain rate was on average the largest of the three principal strain rates. At high strain rates, the ratios of the compressive and extensive strain rate to the intermediate

strain rate were similar to those found in isotropic incompressible turbulent flows. The three-dimensional velocity measurements were used to analyze the spatial distribution of strain rate clusters, defined as singly-connected groups of voxels where the strain rate magnitude exceeded a threshold value. The presence of a stable flame significantly attenuated the number of clusters of intermediate strain rate. Strain rate bursts, corresponding to sudden increases in the number of clusters, were identified in the three jets. The largest bursts in the non-reacting jet and the unstable flame contained twice as many clusters as in the stable flame. The temporal intermittency of intense strain rate clusters was analyzed using the time-series measurements. Clusters with strain rates greater than five times the standard deviation of the strain rate norm were highly intermittent.

Keywords: tomographic PIV; turbulent flames; strain rate; intermittency.

1. Introduction

In turbulent flows, the dynamics of intermittent fine-scale dissipative structures and their interplay with flames are not well understood [1-2]. Experimental studies of turbulent flames have greatly contributed to our understanding of turbulent combustion, but they are frequently limited to single-shot line or planar measurements and therefore unable to capture the three-dimensional transient dynamics of turbulent flows. Ultimately, the development of high-speed, 3-D imaging capabilities is required to fully capture the dynamics of turbulent combustion. The ability to perform high-speed volumetric velocity field measurements is particularly valuable for studying the fluid dynamic strain field, which plays a central role in turbulent transport and turbulence-flame interactions.

On-going development of high-speed lasers and cameras opens new possibilities for experimental investigation of turbulent reacting flows. Tomographic particle image velocimetry (TPIV), introduced by Elsinga *et al.* [3], is an advanced PIV technique that provides instantaneous measurements of all three velocity components within a three-dimensional probe volume. TPIV has gained popularity within the fluid dynamics community and has been applied to studies ranging from fundamental turbulence to applied-engineering problems [4]. Recently, single-shot [5] and high-speed [6] TPIV measurements in flames were demonstrated with potential to unveil new insights into turbulent combustion.

In the present study, we use high-speed TPIV measurements to investigate the effects of combustion on three-dimensional structures of elevated strain rate in turbulent jet flames. TPIV provides measurements of all nine components of the velocity gradient tensor, from which the deviatoric strain rate tensor can be determined [6]. We analyze statistics of the strain rate tensor in terms of its Euclidean norm and eigenvalues, also known as the principal strain rates, denoted s_1 , s_2 and s_3 , which are defined such that $s_1 \geq s_2 \geq s_3$ and $s_1 + s_2 + s_3 = 0$. The maximum and minimum principal strain rates, s_1 and s_3 , correspond to the most extensive and compressive strain rate components, respectively. The ratio of the three principal strain rates along with the sign of s_2 provides insight into the structure of the strain field. High-speed TPIV measurements reveal the temporal evolution of the strain rate field structure.

High-speed TPIV measurements were performed on the *Sandia flame C* [7], a well-studied, piloted partially-premixed CH₄/air jet flame with low probability of localized extinction. To investigate the effects of combustion on turbulent strain, we compare results in flame *C* to measurements in a turbulent non-reacting air jet and a second jet flame with significantly greater probability of localized extinction and intermittent blowoff. The results are presented in the following three parts: 1) characteristics of the principal strain rates, 2) strain rate spatial clustering and 3) the temporal intermittency of high strain rate structures.

2. Experimental Methods

2.1. Flow Conditions

High-repetition rate tomographic PIV was used to study the three jet flow conditions that are summarized in Table 1. Measurements in *Sandia flame C*, a piloted partially-premixed CH₄/air jet flame with a jet exit Reynolds number Re_{jet} of 13,000 [7], were performed at a distance of $y/D = 15$ (viz. $y = 112$ mm) above the nozzle exit. The measurements in flame *C* were compared to two additional cases: 1) a turbulent jet of air (case *Air* in Table 1) with identical bulk jet exit velocity, V_{jet} , as in flame *C* and 2) a second turbulent flame (labelled flame C_{LP}) with identical jet composition and Reynolds number as in flame *C* but with the pilot reduced to 26% of the original flow rate in flame *C*. Whereas flame *C* is moderately turbulent with rare localized extinctions, flame C_{LP} exhibits frequent localized extinction and intermittent blowoff that is rapidly followed by flame re-ignition. For all these cases, the coflow of air was set with an exit velocity of 0.9 m/s.

2.2. Experimental Apparatus

The layout of the experimental setup is depicted in Fig. 1. The TPIV system is identical to that used in Ref. [6] and consisted of a high speed diode-pumped dual-head Nd:YAG laser and a set of four high speed CMOS cameras. Measurements were performed at a repetition rate of 10 kHz using a laser energy of 5 mJ/pulse across the probe volume. The pulse delay between laser heads was set to 10 μ s in the *Air* jet and 8 μ s in the flames. A pair of cameras was positioned on each side of the laser beam with two camera lenses positioned at 20 degrees with respect to the z -axis and the other two camera lenses at 30 degrees. The cameras were operated at 20 kHz in a frame straddling mode using a 896x800 px² region of the detector with a projected pixel size of approximately 15 μ m/px. Jet and coflow were both seeded with 0.3 μ m aluminum oxide particles. Light scattering from the alumina particles was imaged onto each

camera using identical camera lenses and Scheimpflug mounts to compensate for the displacement of the imaging plane. The camera lens apertures were set to f/16 and f/22 to obtain the necessary depth of field across the probe volume. Computation of the velocity vectors consisted of: 1) smoothing (3×3 px² Gaussian filter) and correcting the raw particle images for non-uniformity of particle scattering signals, 2) reconstructing the particle volume distribution using a Multiplicative Algebraic Reconstruction Tomography (MART) algorithm [3], 3) calculating the velocity vectors by iterative volume cross-correlation for a final volume interrogation size of $24 \times 24 \times 24 \text{ vx}^3$ ($393 \times 393 \times 393 \mu\text{m}^3$) with 75% overlap and 4) removing/replacing spurious vectors identified via an outlier detection method and reducing the measurement noise with a spatial filter based on a penalized least-square method [8] with a parametric smoothing strength of 2.0. The probe volume size was $16.5 \times 12.3 \times 2.5 \text{ mm}^3$ and contained $169 \times 126 \times 26$ vectors with $98.4 \mu\text{m}$ spacing.

2.3. Velocity Measurement Uncertainty

Uncertainty in the 10 kHz TPIV measurements was first evaluated using a steady laminar partially-premixed counterflow flame. A premixed stream of dimethyl-ether (DME) and air of equivalence ratio 3.6 was counterflowing against a second stream of air with a 16 mm nozzle separation. Volume-averaged velocities at the nozzle exits were 3.9 m/s. The 12.3 mm-high probe volume was centered between the nozzles. Laminar counterflows provide a well-characterized velocity field with a velocity gradient along the burner axis. The TPIV uncertainty was readily determined in a steady flow field such that any variations in the measured velocities or velocity gradients were attributed to measurement error. The TPIV setup was identical to that of the measurements in the turbulent jets and the laser head pulse delay was increased to $50 \mu\text{s}$ to account for the lower velocities of the laminar opposed jets. Figure 2a shows mean centerline profiles of all three velocity components from 500 single-shot measurements. The length of the error bars displayed every 12 data points along the curves in Fig. 2 corresponds to twice the

standard deviation at these points. Because of heat release in the flame, the axial velocity has an inflection point near the stagnation plane at $Y \sim 0$ mm. The standard deviations of all three velocity components ranged from 3 cm/s to 8 cm/s in the reactants and increased up to 12 cm/s in the flame. The velocity derivatives are more sensitive to noise degradation. In Fig. 2b, the mean divergence is nearly zero in the reactants and displays two peaks in the flame because of dilatation. The uncertainty of the divergence measurements was $\pm 150/\text{s}$ in the reactants and $\pm 230/\text{s}$ in the flame. The standard deviations of the principal strain rates in the reactants and flame were respectively 110/s and 150/s for s_1 and 160/s and 240/s for s_3 . The profiles in Fig. 2 are consistent with velocities in reactive counterflow jets and demonstrate the ability of TPIV to measure a 3D velocity field in a flame. The slightly larger errors in the flame zone may be attributed to thermophoretic diffusion and beam steering [5-6].

In turbulent flows, additional sources of errors emerge from flow acceleration and under-resolved turbulence lengthscales [6]. Distributions of divergence in incompressible flows are often used to evaluate the extent of measurements errors. In the incompressible *Air* jet of Table 1, measurement errors caused the local divergence to deviate from zero with an uncertainty of $\pm 900/\text{s}$. Principal strain rates in the presumably irrotational air coflow were as large as 1,000/s. These errors are however relatively small in comparison to the strain rates that are of greatest interest in this study.

3. Results and Discussion

The effect of combustion on turbulent strain was investigated by comparing 500ms time sequences of TPIV measurements acquired at 10kHz in the three flow conditions of Table 1. The measurement probe volume was centered in the jet shear layer at a radial position of $r/D = 1.15$ and included portions of the flame reaction zone as well as regions of unburnt fuel mixture (jet) and air (coflow). The velocity measurements therefore included characteristics of each region. In order to characterize the strain rate

field in the turbulent jet and shear layer, statistics were conditioned on flow regions of velocity magnitude exceeding 2m/s, thereby ignoring the low-velocity coflow region. Therefore, the following analysis mostly pertains to the turbulent jet region rather than the quasi-laminar coflow. The fluid dynamics properties of the three jets were nearly identical and, therefore, differences in the strain rate fields could be attributed to the presence or absence of a flame and its burning stability. Dynamics of the reaction zones in flames *C* and *C_{LP}* were qualitatively compared using 10 kHz planar laser induced fluorescence (PLIF) measurements of OH, available in supplemental material S1. The OH PLIF measurements were performed using the apparatus and methodology in Ref.[6]. The results show that flame *C* is a steadily-burning turbulent flame with rare occurrences of localized extinction, whereas flame *C_{LP}* exhibits fragmented reaction zones, frequent localized extinction, and intermittent blowoff followed by re-ignition.

3.1. Strain Rate Magnitude and Principal Strain Rates

To investigate the effects of combustion on the strain rate field, we first consider the distributions of the norm of the strain rate tensor: $|s| = |s_1^2 + s_2^2 + s_3^2|^{0.5}$, which provides a measure of the total strain rate and is related to the kinetic energy dissipation as $\varepsilon = 2\nu|s|^2$. Probability density functions (PDFs) of $|s|$ are plotted in Fig. 3 for the three flow conditions of Table 1. The PDFs of $|s|$ are skewed with long tails that extend toward large strain rate values, indicative of the intermittency of the largest strain rates. The strain rate magnitude is enhanced by combustion with the tail of the PDF of $|s|$ extending to the largest values in flame *C* and intermediate values in flame *C_{LP}*. Values of the strain rate standard deviation, $|s'| = \langle |s|^2 \rangle^{0.5}$, are given in Fig. 3. Extreme values of $|s|$ that exceed $5|s'|$ only occur in approximately 1% of the spatiotemporal measurements, for all the flow conditions. Nevertheless, because of their large magnitude, these rare events may have a disproportionate impact on the flame chemistry.

The effects of combustion on the structure of the strain rate tensor were investigated using an analysis of the principal strain rates. Figure 4 shows PDFs of the normalized intermediate principal strain

rate: $s_2^n = s_2/(|s|^2/6)^{0.5}$, where the factor $\sqrt{6}$ is introduced to bound the normalization within $[-1;1]$. The sign of s_2^n indicates whether the local strain rate has a single compressive axis and two extensive axes, for $s_2^n > 0$, or two compressive axes and a single extensive axis, for $s_2^n < 0$. To elucidate the structural differences in high strain rate regions, we compared PDFs of s_2^n conditioned on large strain rates, $|s| > 5|s|'$, with those that include all regions of non-zero strain rate, $|s| > 0$. The PDFs of s_2^n for $|s| > 5|s|'$ are significantly more skewed than for $|s| > 0$, such that s_2^n is predominantly positive in regions of high strain rate for all the flow conditions. This shift is slightly greater for the non-reactive case than for the flames. Similar shifts in the skewness of PDFs of s_2^n for large values of $|s|$ were observed in simulations of Ashurst *et al.* [9] and experiments of Tsinober *et al.* [10] in incompressible isotropic turbulence. Other numerical studies in non-reacting turbulence with shear [11-12] and pseudo-3D velocity measurements in the far-field of a low Reynolds number jet flame [13] indicated that the most probable value of s_2^n remains positive but tends to decrease in presence of mean shear. Our results indicate that the skewness in the distribution of the intermediate strain rate is a generic feature of non-reactive and reactive turbulent flows.

An investigation of the relative ratios between the three principal strain rates, $s_1/s_2:1:s_3/s_2$, provides further insight into the strain rate field. According to Refs. [9-10], the most probable ratios in isotropic turbulence are approximately 3:1:-4. In presence of shear, the strain rate ratios $|s_1/s_2|$ and $|s_3/s_2|$ tend to increase, indicating a strain field that is locally more two-dimensional in turbulent shear flows than in isotropic turbulence [11-13]. For the conditions of Table 1, the PDFs of s_2^n conditioned on $|s| > 0$ in Fig. 4 show that the most probable value of s_2^n is approximately 0.2, corresponding to strain rate ratios of approximately 8:1:-9. These ratios signify that the extensive and compressive strain rates dominate over the intermediate strain rate. However, regions of high strain rate exhibit a somewhat different structure. In Fig. 4, the PDFs of s_2^n conditioned on $|s| > 5|s|'$ show a shift in the most probable value of s_2^n toward 0.6, and, thus, strain rate ratios approaching 2.2:1:-3.2, which is comparable to values

in isotropic turbulence. Therefore, intense strain rates in the reacting and non-reacting turbulent jets are preferentially sheet-forming with a single axis of compressive strain and the other two axes of extensive strain.

3.2. Strain Rate Clustering

To further understand the effects of combustion on strain, we compare the topology of strain rate structures in the *Air* jet and flames C_{LP} and C . Three-dimensional rendering of strain rate isosurfaces in the turbulent *Air* jet and the turbulent flame C are presented in Figs. 5a and 5b, respectively. The volume renderings in Fig. 5 use a subset of the total probe volume that omits most of the coflow region. The examples in Figs. 5a and 5b illustrate the strain rate topology in the *Air* jet and flame C , respectively. For each case, a single-shot measurement is displayed using three different levels of strain rate isosurfaces, namely $|s| = 6,000/s$, $9,000/s$, and $12,000/s$. Figure 5 shows the qualitative differences between the *Air* jet and flame C as well as the effect of varying the isosurface threshold that is used to represent three-dimensional flow structures.

Strain rate structures exhibit a large variety of sizes and shapes in both the non-reacting and reacting flows. The shapes of these structures are more amorphous than the lamella-like structures of scalar dissipation layers in turbulent jet flames [14]. In the *Air* jet, the sudden accumulation of numerous structures such as those shown in Fig. 5a is repeatedly observed. These bursts are also observed in flame C but typically include fewer structures. In flame C , however, an elongated sheet-like structure spans the height of the probe volume (Fig. 5b) and is aligned along the shear layer. Structures of high strain rate and vorticity are known to align along the reaction zone in turbulent jet flames [6, 15].

As the strain rate isosurface level is increased, the number of visible structures and their size decrease. In Fig. 5b, the large sheet-like structure remains identifiable across the $6,000/s$ - $12,000/s$ range of strain rate isosurfaces. However, as the strain rate threshold is increased, many of the small structures

disappear. This dependence of the strain topology on the strain rate threshold indicates that using a single threshold value provides an incomplete representation of the strain rate field. As a result, the strain rate field topology must be analyzed as a function of the strain rate threshold, denoted $|s_{thrs}|$.

The number of structures and their volume are quantified as a function of $|s_{thrs}|$ using a clustering analysis. For a given value of $|s_{thrs}|$, a *cluster* is defined as a singly-connected group of voxels where $|s| > |s_{thrs}|$ [16]. The size and shape of the clusters vary greatly with $|s_{thrs}|$, as it can be inferred from Fig. 5. For a given snapshot, clustering is quantified in terms of the number of clusters, N_c , appearing in the probe volume and the fraction of the probe volume occupied by clusters, V_c . The ensemble-averages of N_c and V_c are plotted as function of $|s_{thrs}|$ in Fig. 6 for all three turbulent jet cases.

Figure 6a provides insight into the structure of the strain rate field, which consists of many local maxima and minima. For a very low value of $|s_{thrs}|$ such that it is below most of the minima, there is very little segmentation of the strain rate field, and the number of clusters is small. As $|s_{thrs}|$ is increased and exceeds the local minima, the field becomes segmented and $\langle N_c \rangle$ systematically increases. Once $|s_{thrs}|$ is sufficiently large with respect to the majority of local strain rate peaks, $\langle N_c \rangle$ reaches a maximum (e.g. at approximately $|s_{thrs}| = 5,000/s$ for the *Air* jet in Fig. 6a). Further increases in $|s_{thrs}|$ eliminate much of strain rate field, and the only remaining clusters are for the extreme maxima, as seen in Fig. 5. As a result, $\langle N_c \rangle$ decreases. A low profile of $\langle N_c \rangle$ in Fig. 6a is indicative of a well-connected strain rate field with few local maxima and minima, whereas a high profile of N_c corresponds to a scattered spatial distribution of intermediate-to-high strain rate clusters. Accordingly, Fig. 6a indicates that the strain rate field is better connected in the stable flame *C* than in the two other cases. In the *Air* jet and flame C_{LP} , $\langle N_c \rangle$ exceeds 100 clusters for $|s_{thrs}|$ between 4,000/s and 5,500/s. For $|s_{thrs}| \geq 6,000/s$, $\langle N_c \rangle$ decreases faster in the *Air* jet than in flame C_{LP} since local strain rate maxima are typically of higher magnitude in flame C_{LP} than in the *Air* jet. For elevated strain rate ($|s_{thrs}| \geq 8,000/s$), $\langle N_c \rangle$ becomes comparable in flames C_{LP} and *C*.

A more complete picture of the cluster characteristics emerges when the results of Fig. 6a are combined with the profiles of $\langle V_c \rangle$ in Fig. 6b. Figure 6b shows that clusters occupy a decreasing fraction of the probe volume as $|s_{thrs}|$ is increased. On average, strain rate clusters occupy a larger volume in the two flames than in the *Air* jet. For intermediate strain rates (3,000/s-6,000/s), flame *C* has the largest volume occupied by clusters and the fewest number of clusters (Fig. 6a). Therefore, individual clusters of intermediate strain rate are on average larger in flame *C* than in flame C_{LP} or the *Air* jet.

3.3. Strain Rate Bursts and Temporal Intermittency

The spatial intermittency of small-scale turbulence has been studied more extensively than its temporal intermittency [2]. Previous experimental studies of turbulent intermittency have focused on the spatial intermittency of the velocity components and their derivatives [17]. However, the temporal intermittency of the strain rate field may have significant implications in turbulent combustion. For example, turbulent flames can withstand transient strain rates that are an order of magnitude larger than the extinction strain rate of the corresponding steady laminar flame [6]. The level of localized extinction in turbulent flames may well depend on the intermittency and lifetime of these very high strain rates [18]. High-speed three-dimensional measurements of the velocity field are required to fully capture the intermittency of the strain rate field. The temporal intermittency of the intense strain rate clusters was investigated using 500 ms time series of TPIV measurements at 10 kHz. Images displayed in Fig. 7 show the number of clusters, N_c , parameterized on $|s_{thrs}|$ for 100 ms subsets of these time series. Each column in the images corresponds to a profile of N_c as a function of the strain rate threshold, $|s_{thrs}|$, at a single instant in time. Each image row is a time series of N_c for a single value of $|s_{thrs}|$. The rapid modulation of the time traces in Fig. 7 is indicative of intermittent bursts of large numbers of clusters appearing simultaneously in the probe volume. In the *Air* jet and flame C_{LP} , for intermediate strain rates (3,000/s-6,000/s), bursts of over 200 clusters can rapidly accumulate in the probe volume, whereas, in flame *C*, the bursts rarely exceed 100

clusters. Burst dynamics may be related to the growth of the shear layer hydrodynamic instability, which is attenuated in turbulent jet flames [19]. The vertical profiles of the tallest peaks in Fig. 7 indicate that large bursts of high strain rate clusters are generally coincident with bursts of intermediate strain rate clusters. An example of a burst of high strain rate clusters was shown for the *Air* jet in Fig. 5a, where structures of high strain rate ($|s_{thrs}| = 12,000/\text{s}$) were embedded within clusters of intermediate strain rate ($|s_{thrs}| = 6,000/\text{s}$).

To characterize the intermittency of strain rate clusters, we evaluated the probability, $P(N_c \geq 1)$, that at least one cluster with a strain rate exceeding $|s_{thrs}|/|s|'$ was contained in the probe volume. In Fig. 8a, $P(N_c \geq 1)$ is plotted as a function of $|s_{thrs}|/|s|'$, with the values of $|s|'$ for the three flow conditions indicated in Fig.3. Remarkably, the decrease of $P(N_c \geq 1)$ with increasing values of $|s_{thrs}|/|s|'$ is nearly identical in the *Air* jet and the flames. Clusters for $|s_{thrs}|/|s|' \leq 5$ are almost continuously present in the probe volume. The probability that structures of higher strain rate appear in the probe volume decreases rapidly with increasing $|s_{thrs}|$. For instance, according to Fig. 8a, the likelihood that clusters of strain rate magnitude exceeding $10|s|'$ appear in the probe volume is less than 2% for all flow conditions. Clusters of extremely large strain rate are statistically insignificant but their effects on combustion may not be negligible if the duration of their interaction with the flame is long enough to impact the chemistry [18].

The time-series measurements enable determination of the time intervals, t_i , between appearances of clusters with normalized strain rates greater than $|s_{thrs}|/|s|'$ and the duration, t_d , of these clusters in the probe volume. For the three turbulent jet conditions, the mean times $\langle t_i \rangle$ and $\langle t_d \rangle$ are plotted as a function of $|s_{thrs}|/|s|'$ in Fig. 8b. To distinguish real flow structures from apparent structures that could result from measurement noise, we only considered occurrences of clusters that persisted for a minimum duration of two frames, that is, for $t_d \geq 0.2$ ms. Clusters are convected in and out of the probe volume and can be produced or dissipated inside the probe volume. The mean time interval $\langle t_i \rangle$ scales identically as a function of $|s_{thrs}|/|s|'$ in all three cases, indicating that combustion has a negligible effect on the

temporal intermittency of strain rate structures in these turbulent jets. The decrease in $\langle t_d \rangle$ as a function of $|s_{thrs}|/|s|'$ is very similar for the two flames but is shifted towards higher normalized strain rates for the non-reacting jet. The continuous presence of clusters with $|s_{thrs}|/|s|' \leq 5$ results in $\langle t_i \rangle \sim 0$ ms for these clusters. However, as $|s_{thrs}|/|s|'$ increases above 5, $\langle t_i \rangle$ increases and $\langle t_d \rangle$ decreases rapidly. The mean flow residence times across the probe volume are approximately 1.3 ms in the *Air* jet, 0.8 ms in flame *C_{LP}* and 0.6 ms in flame *C*. For all flow conditions, values of $\langle t_d \rangle$ for high strain rate clusters exceeding $\sim 7|s|'$ are less than the mean flow residence time across the probe volume. Therefore, these structures tend to form or dissipate within the probe volume. In all three jet flows, clusters of intense strain rates exceeding $10|s|'$ appear in the probe volume approximately every 6 ms, which is a factor of 5 to 10 times greater than the mean flow residence times. The mean duration time of these structures is less than 0.3 ms. The interaction time between these structures of extreme strain rate and the flame reaction zone is critical for understanding localized extinction in turbulent flames.

4. Summary

The effects of combustion on strain rate properties, intermittency and clustering were investigated using 10 kHz tomographic PIV to measure the temporal evolution of the strain rate field in three dimensions. Measurements in stable and unstable partially-premixed jet flames of jet Reynolds number $\sim 13,000$ were compared to a turbulent non-reactive jet.

The findings are summarized as follows:

- The magnitude and fluctuations of the strain rate increase in turbulent reacting jets. In both non-reacting and reacting jets, the compressive strain rate is on average the largest of the principal strain rates, particularly in regions of high strain. The compressive and extensive strain rates tend to be significantly

larger than the intermediate principal strain rate, indicating a locally two-dimensional strain. At elevated strain rates, the principal strain rate ratios approach those found in isotropic incompressible turbulence.

- Clusters of intermediate strain rate tend to occupy a larger volume in the stable flame than in the other two cases. The number of clusters in the stable flame is also typically lower than in the other cases.
- Strain rate bursts, corresponding to sudden increases in the number of clusters, are observed in all three jet flows. Bursts in the non-reacting jet and the unstable flame could contain twice as many clusters as in the stable flame.
- Clusters of strain rate magnitude less than $5|s|'$ are continuously present in the probe volume. Structures of higher strain rates are highly temporally intermittent.

These results show the multi-faceted effects of combustion on the magnitude, structure, and intermittency of the strain rate field. The flame with localized extinction and blowoff has strain rate characteristics that are a mixture between those of the fully reacting flame and the air jet. These insights into the strain rate field are highly relevant to the development and validation of turbulent combustion models and LES sub-models.

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Tables

<i>Cases</i>	ϕ_{jet}	Re_{jet}	V_{jet}	V_{Pilot}
			(m/s)	(m/s)
<i>Air</i>	0.0	13,500	27.5	0.0
C_{LP}	6.0	13,000	27.5	1.8
C	6.0	13,000	27.5	6.8

Table 1 – Summary of flow conditions

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Figure 1 – Experimental Setup for high-repetition rate tomographic PIV.

Figure 2 – Centerline profiles of a) velocity components and b) divergence and extensive and compressive strain rates in a laminar counterflow flame.

Figure 3 – PDFs of the norm of the strain rate in the three turbulent jet conditions.

Figure 4 – PDFs of normalized intermediate principal strain rate, s_2^n , conditioned on $|s| > 0$ or $|s| > 5|s|'$.

Figure 5 – Rendering of strain rate isosurfaces for $|s|=6,000/s$ (left), $|s|=9,000/s$ (middle) and $|s|=12,000/s$ (right) in a) the turbulent *Air* jet and b) flame *C*. Box dimensions: $L \times H \times W = 10.7 \times 12.3 \times 2.5 \text{ mm}^3$ (subset of total probe volume).

Figure 6 – Clustering statistics in the three turbulent jet conditions of Table 1. a) Average number of clusters in the probe volume per snapshot. b) Average fraction of probe volume occupied by clusters (logarithmic y-axis).

Figure 7 – Time series of the number of clusters, N_c , as a function of strain rate threshold in the three flow conditions of Table 1.

Figure 8 – a) Probability of $N_c \geq 1$ (logarithmic y-axis). b) Mean time interval (black) between appearances of clusters of strain rate magnitude greater than $|s_{thrs}|/|s|'$ and mean duration (red) of these occurrences (logarithmic y-axis). Values of $|s|'$ are given in Fig. 3.