The structure of dissipative scales in axisymmetric turbulent gas-phase jets  

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ABSTRACT

Results are reported for an experimental study directed at investigating the fine scale structure of turbulent jet flows using the simultaneous imaging of the concentration and velocity fields. The measurements are obtained in an axisymmetric coflowing jet using particle image velocimetry (PIV) and planar laser-induced fluorescence (PLIF) imaging of acetone vapor seeded into the jet gas. The measurements resolve the Kolmogorov scale, \( \eta \), of the flow. These measurements are used to investigate the relationships among the vorticity, strain rate, kinetic energy dissipation, and scalar dissipation fields. The data are also used to analyze the physical size of the structures in the scalar and kinetic energy dissipation fields. The results show good correlation between regions of high compressive principal strain, scalar dissipation, and kinetic energy dissipation. Structures in the scalar dissipation field are seen to be sheet-like with thicknesses ranging between 1\( \eta \) and 6\( \eta \), while those in the kinetic energy dissipation field are more topologically complex and range in scale from 1\( \eta \) to 10\( \eta \). The mean sizes of scalar and kinetic energy dissipative structures are 3\( \eta \) and 4\( \eta \), respectively. The constant \( \Lambda \) relating mean scalar dissipative structure size to outer scale variables (\( \lambda = \Lambda \delta Re_s^{-1/4} Sc^{-1/2} \)) is measured to be 7.8. These results indicate that scalar dissipative structures are approximately a factor of two smaller than has been suggested in previous studies.

I. Introduction

The rapid molecular mixing associated with turbulent flows is of great importance to many chemical and combustion processes. This process, which occurs at the finest (smallest) scales of turbulence, can have a profound impact on heat release and pollutant formation. For example, a flame front may be quenched by the high strain rates and dissipation that occur at the fine scales. The dynamics of the fine scales are also important to turbulence theory and to the development and validation of subscale models used in large-eddy simulations. For these reasons and many others, numerous experiments and simulations of fine scale turbulence have been conducted. This research has yielded much insight into the fine scales of turbulence; however, as will be discussed below, much more remains to be done.

As relevant background, consider the transport equation for the kinetic energy in a turbulent flow,

\[
\frac{\partial q}{\partial t} + u \cdot \nabla q + \nu \nabla^2 q = -u \cdot \nabla p + \nu (u \cdot \nabla u^T) - \varepsilon
\]  

where \( u \) is the velocity vector, \( q = \frac{1}{2} u \cdot u \) is the kinetic energy, \( p \) is the pressure, \( \nu \) is the...
The kinematic viscosity of the fluid, and $\varepsilon$ is the rate of kinetic energy dissipation. The quantity $\varepsilon$ can be expressed as

$$\varepsilon = 2\nu s : s$$  \hspace{1cm} (2)$$

where $s$ is the strain rate tensor, expressed in index notation as

$$s = \frac{1}{2} \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right)$$

Any scalar quantity that is neither created nor destroyed in a flow, such as concentration, is called a conserved scalar. The transport of a conserved scalar is governed by the equation

$$\frac{\partial \xi}{\partial t} + \mathbf{u} \cdot \nabla \xi = -\nabla \cdot \mathbf{D}$$  \hspace{1cm} (3)$$

where $\xi$ is the conserved scalar and $\mathbf{D}$ is the mass diffusivity. Analogous to the kinetic energy, the scalar energy $\vartheta$ can be defined as

$$\vartheta = \frac{1}{2} \xi^2$$

and is governed by the equation

$$\frac{\partial \vartheta}{\partial t} + \mathbf{u} \cdot \nabla \vartheta + \nabla \cdot \mathbf{D} \vartheta = -\chi$$

where $\chi$ is the dissipation rate of scalar energy

$$\chi = \mathbf{D} (\nabla \xi \cdot \nabla \xi)$$

According to classical turbulence theory, kinetic energy is dissipated at the Kolmogorov scale, $\eta$, which is defined as

$$\eta \equiv \left( \frac{\nu^3}{\varepsilon} \right)^{1/4}$$  \hspace{1cm} (4)$$

Physically, $\eta$ is the finest scale in the velocity field over which a gradient may be sustained. The corresponding finest scale in the concentration field is the Batchelor scale, which is related to the Kolmogorov scale by

$$\eta_B = \eta \text{Sc}^{-1/2}$$

where Sc is the Schmidt number of the flow

$$\text{Sc} = \frac{\nu}{\mathbf{D}}$$

The Kolmogorov scale and the large scale of a flow can be related by

$$\frac{\eta}{\ell} = \text{Re}_\ell^{-3/4}$$

where $\ell$ is the integral length scale of the flow and $\text{Re}_\ell$ is a "fluctuation Reynolds number" defined by

$$\text{Re}_\ell = \frac{u_{\text{rms}} \ell}{\nu}$$

where $u_{\text{rms}}$ is the RMS fluctuation of the velocity.

These scalings were used by Buch & Dahm (1996, 1998) to define the strain-limited diffusion scales, which are expressed in terms of outer-scale variables:

$$\lambda_\nu = \Lambda \delta \text{Re}_\delta^{-3/4}$$  \hspace{1cm} (5)$$

$$\lambda_D = \lambda_\nu \text{Sc}^{-1/2}$$  \hspace{1cm} (6)$$

In these equations, $\lambda_\nu$ is the strain-limited vorticity diffusion scale and $\lambda_D$ is the strain-limited mass diffusion scale. These represent the sizes of dissipative structures in the velocity and conserved scalar fields, respectively, and are thus analogous to the Kolmogorov and Batchelor scales. In Equation (5), $\delta$ is a characteristic flow outer scale, $\text{Re}_\delta$ is the Reynolds number based on this scale, and $\Lambda$ is a constant of proportionality to be determined empirically. Buch & Dahm (1996, 1998) analyzed the size of dissipative structures in an axisymmetric jet, and concluded that $\Lambda = 11.2$ when $\delta$ is the 5% velocity width of the jet. Su & Clemens (1999) performed a similar analysis, but arrived at a higher value for $\Lambda$ ($\Lambda = 14.9$). The relationship between $\lambda_\nu$ and $\eta$ (or $\lambda_D$ and $\eta_B$) can be found by considering how the flow parameters vary for a given turbulent flow. For a round jet, for example, using the kinetic energy dissipation data of Friese et al. (1971) and the velocity scaling laws of Chen & Rodi (1980), one finds that $\lambda_\nu$ is approximately 6$\eta$. This suggests that the strain-limited vorticity diffusion scale may be substantially larger than the Kolmogorov scale.

Fine scale turbulence has been investigated with a variety of techniques, such as hot
wire/film anemometry, nonintrusive optical diagnostics, and numerical simulations. Several studies (cf. Sreenivasan and Antonia, 1997) determined that dissipation is a highly intermittent phenomenon, with high dissipation occurring infrequently. Other experiments sought to investigate the spatial structure of the dissipative scales directly. Based on an analysis of Equations (1) and (3), Buch & Dahm (1991) argue that only sheet-like structures should be observed in the scalar dissipation field. These findings were confirmed by several experiments which used laser-induced fluorescence (LIF) of a conserved scalar to extract the scalar dissipation field (Buch & Dahm, 1996, 1998; Pitts et al., 1999; Su & Clemens, 1999). These confirmed that the scalar dissipation field consists of thin sheet-like structures in both liquid-phase (Sc \(\approx 1\)) and gas-phase (Sc \(\approx 1\)) jets. However, these experiments showed that in liquid-phase jets these sheets are thin and highly convoluted, while in gas-phase jets they are somewhat thicker and far less convoluted. In these studies, the dissipation was observed to be virtually isotropic, as is expected for the fine scales (e.g., Hinze, 1975). Direct numerical simulations (DNS) of isotropic turbulence have been used to examine the spatial relationship between vorticity, strain rate, and scalar gradient (Kerr, 1985; Ashurst et al., 1987; She et al., 1990). The results indicate that the vorticity field consists of both sheet- and line-like structures, and that scalar dissipation structures frequently wrap around the vortical structures. In addition, the scalar gradient appears to align with the axis of the principal compressive strain. This is consistent with the aforementioned strain-diffusion model of the formation of the dissipative structures. The topology of the kinetic energy dissipation field is substantially more complex, containing sheet-, line-, and blob-like structures (Siggia, 1981; Yamamoto & Hosokawa, 1988). This complexity may be one reason for why the kinetic energy dissipation field has not been investigated as extensively as the scalar dissipation field. Some of the trends observed in the DNS studies have been verified experimentally by Tsinober et al. (1992) using a specially-built 12-element hot wire probe. Additional confirmation was provided by Su & Dahm (1996), who used scalar imaging velocimetry (SIV) to investigate the fine scale turbulence in a Sc \(\approx 1\) water jet. The SIV technique inverts Equation (3) to extract the velocity field from spatio-temporally resolved conserved scalar images. The results showed that the vorticity vector tends to align with the axis of the intermediate (extensive) principal strain, while the scalar dissipation surface normal vectors tend to align with the axis of the compressive principal strain. The latter is consistent with the experiments and simulations mentioned above. The probability density functions of the kinetic energy dissipation were also found to be log-normal.

An important issue that arises in experimental studies of the dynamics of fine scales is the resolution required to capture these scales. Some disagreement exists in the literature over the true finest dissipative length scale, however. For example, Antonia and Mi (1993) conducted dissipation measurements using cold wires separated by a known distance, and concluded that a resolution of \(3\eta\) is apparently sufficient to compute dissipation accurately. (Indeed, finer resolutions yielded erroneous results due to probe interference and electronic noise.) Buch & Dahm (1998) compute a PDF of scalar dissipative structure thickness, and observe that the width of the thinnest scalar dissipation layers in gas-phase jets is approximately \(3\eta\). The thicknesses reported by Su & Clemens (1999) are approximately 30 percent higher than Buch & Dahm’s. On the other hand, Pitts et al. (1999) report dissipative scale sizes that are significantly smaller than these studies found.

The objective of the current study is to investigate the structure of the dissipative scales in a gas-phase turbulent jet and to determine requirements for full resolution of the true finest scales. The study is an experimental investigation of a turbulent gas-phase flow using particle image velocimetry and planar laser-induced fluorescence (PLIF). The experiments are conducted in a flow facility in which the finest turbulent scales can be fully resolved by the optical diagnostics. The fully-resolved measurements permit the statistical analysis of
such quantities as vorticity, strain, and kinetic energy dissipation, and an examination of the topology of the dissipative structures in the scalar and kinetic energy fields. These data can be used to determine the relationship between the kinematics of the flow (as found from the velocity field) and the concentration field.

II. Experimental considerations

The experimental setup is shown in Figure 1. The flow facility is designed to produce a turbulent flow in which the Kolmogorov scale is large enough to be fully resolvable by our optical diagnostics. The facility is 92 cm wide by 92 cm long by 117 cm high, and is constructed of 0.25" aluminum structural members and 0.040" aluminum sheet for the walls. The facility consists of an axisymmetric turbulent jet exhausting into a coflow of air. The jet issues upward from a circular pipe, 26 mm in diameter, located at the center of the facility; the jet exit is 45 cm above the bottom of the facility. Industrial-grade nitrogen is used for the jet gas. The gas flow rate is controlled by a manually-operated valve and monitored by an electronic mass flowmeter (McMillan 50D-15). The coflow is supplied by an industrial blower (Grainger/Dayton model 5C508) which runs at a fixed speed. The coflow enters the jet facility through a network of PVC pipes, and is conditioned by sections of honeycomb and fine-mesh screens prior to entering the test section. Measurements are taken just above the top of the test section walls (about 30 diameters downstream) on the jet centerline.

A jet exhausting into a stagnant environment is known as a pure jet. A pure axisymmetric jet is self-similar, and hence can be described by simple scaling laws (Wygnanski & Fielder, 1969; Friese et al., 1971; Chen & Rodi, 1980). When the jet is surrounded by a coflow, its behavior begins to deviate from that of a pure jet. The degree to which a jet is pure or coflowing is characterized in terms of the momentum radius $\theta$, given by (e.g., Biringen, 1975)

$$\theta = \sqrt{\frac{J_o}{\pi \rho \omega U_{\infty}^2}}$$
where $J_0$ is the source momentum flux given by

$$J_0 = \frac{\pi D^2}{4} \rho_o U_o^2$$

Based on the data of Biringen (1975), Dahm and Dibble (1988) propose that, for a pure jet,

$$\frac{x}{\theta} \leq 2$$

where $x$ is the distance downstream from the jet virtual origin (approximately 3 diameters upstream of the exit). For the data described below, the quantity $x/\theta$ is approximately 4, indicating that the jet is mildly coflowing. For this reason, detailed jet/coflow velocity profiles were conducted to determine such quantities as jet centerline speed, coflow speed, and jet width. The velocity data can also be used to estimate the mean kinetic energy dissipation rate $\varepsilon$, using the approximation (Hinze, 1975)

$$\varepsilon \approx A \frac{u_{rms}^3}{l}$$  \hspace{1cm} (7)

where $A$ is a constant that is approximately equal to 0.33 (Antonia et al., 1980). The integral length scale $l$ is defined in terms of the autocorrelation of the velocity fluctuations. This was done for an axisymmetric jet by Wygnanski & Fielder (1969), who report that on the jet centerline

$$l = 0.226 \delta_{1/2}$$

where $\delta_{1/2}$ is the full width of the jet as determined by the points where the mean velocity has dropped to half its centerline value. This allows us to calculate the Kolmogorov scale directly using Equation (4).

Velocity field measurements are obtained with two-component PIV. A dual oscillator Nd:YAG laser (Spectra-Physics PIV400), which produces 10 ns pulses of 532 nm light at 10 Hz, is used as the light source. The double-pulsed images are acquired with a double-exposure CCD camera (Kodak MegaPlus ES1.0), which captures the image from each laser pulse on a separate frame. Since each pulse is in a different frame, there is no directional ambiguity for the velocity vectors. A Nikon 200 mm lens operated at f/4 is used with the camera. The particles used in the PIV imaging are generated by a theatrical fog machine (Rosco Model 1600) that uses a glycerin-based fluid to generate fine particles of nominal diameter 1 - 2 µm. The particles are seeded into the coflow, and are subsequently entrained by the jet as it develops. This ensures an adequate seed density at the measurement location. Images are stored on a personal computer (Pentium II, 300 MHz class), and processed on a Linux workstation using Matlab-based PIV software (developed at Stanford University) which utilizes adaptive window offset for greater accuracy.

The conserved scalar field is obtained by planar laser-induced fluorescence of acetone vapor, which acts as a conserved scalar marker (Lozano et al., 1992). The jet gas is seeded with acetone vapor by passing the flow through a three-stage acetone bubbler. This yields a jet fluid that is saturated with acetone vapor (about 26% acetone by volume), and hence guarantees the highest possible fluorescence signal level. (Saturation was confirmed by an absorption measurement using a dynamic cell.) Because acetone vapor is considerably heavier than air, the density of the fluid at the jet exit is higher than that of the coflow when the flow is at room temperature. The resulting jet is negatively buoyant, and severe “fountaining” occurs at the Reynolds numbers used in this study. This problem is circumvented by heating the jet gas to a temperature at which the gas density is equal to that of ambient air. (This occurs when the temperature is approximately 90 ºC.) An inline gas heater with closed-loop control is used to achieve the required heating. The high temperatures within the heater would create a fire hazard in an air-acetone mixture. Nitrogen gas is used to avoid this hazard. The acetone fluorescence is excited by ultraviolet light produced by an Nd:YAG laser operating at the fourth harmonic (266 nm); pulse energies are between 70 and 90 mJ. The blue acetone fluorescence is imaged with a slow-scan cooled CCD camera (Cryocam S5) fitted with a Nikon 105 mm lens operated at f/2.8. To ensure that 532 nm light scattered from particles in the flow
does not interfere with the fluorescence signal, the camera lens is fitted with two short wavelength pass filters (Schott BG-37) which transmit the fluorescence light but block the 532 nm light. The scalar field images are then processed on a Linux Pentium workstation using Matlab-based software developed in-house.

The 532 nm and 266 nm laser beams are combined using a 266 nm mirror, which is transparent to the 532 nm beam. The combined beams are then passed through two cylindrical lenses, and emerge as collimated light sheets 37 mm high. The cameras are placed on opposite sides of the test section, and aligned by imaging an optical target. The optical target imaged by both cameras is also used to match the fields of view for the two cameras during post-processing.

One of the goals of this study is to investigate the relationships between vorticity, strain rate, kinetic energy dissipation rate, and scalar dissipation rate. Since an axisymmetric jet is three-dimensional, these quantities are expected to vary in three dimensions as well. However, the planar measurements discussed above provide information only in two dimensions. Such measurements can yield only two components of velocity, one component of the vorticity vector, 4 of 9 components of the strain rate tensor, and two components of the scalar gradient vector. Expanding Equation (2) yields

\[
\varepsilon_{2D} = 2\nu \left( \left( \frac{\partial u}{\partial x} \right)^2 + \left( \frac{\partial v}{\partial y} \right)^2 + \left( \frac{\partial w}{\partial z} \right)^2 \right) + \frac{1}{2} \left( \frac{\partial u}{\partial y} + \frac{\partial v}{\partial x} \right)^2 + \frac{1}{2} \left( \frac{\partial u}{\partial z} + \frac{\partial w}{\partial x} \right)^2 + \frac{1}{2} \left( \frac{\partial v}{\partial z} + \frac{\partial w}{\partial y} \right)^2
\]

(8)

With 2-D PIV measurements, only the first, second, and fourth terms in Equation (8) may be computed. The incompressible continuity equation can be used to solve for the third term in Equation (8). These terms are used below to define the "2-D kinetic energy dissipation", \( \varepsilon_{2D} \).

III. Results and discussion

This section presents the experimental results acquired to date for one flow condition. The relevant parameters and their symbols are specified in Table 1. The data were acquired at a distance \( x = 83 \text{ cm} \) \((x/D = 32)\) downstream of the jet virtual origin. The width \( \delta_{1/2} \) is the distance between the points where the velocity has fallen to \( \frac{1}{2} (U_c - U_\infty) \). The width \( \delta_{0.05} \) is the distance between the points where the velocity has fallen to 0.05 \((U_c - U_\infty)\). The local Reynolds numbers were calculated from

\[
Re_{8,1/2} = \frac{(U_c - U_x)\delta_{1/2}}{\nu}
\]

and

\[
Re_{8,0.05} = \frac{(U_c - U_x)\delta_{0.05}}{\nu}
\]

The dataset consists of 3000 PIV image pairs, 3000 PLIF images, and 1000 simultaneous PIV/PLIF images. The rationale behind acquiring PIV-only and PLIF-only data was to yield data of much higher quality for each measurement than would be possible with simultaneous measurements. (For example, if the green PIV beam is not present, the BG-37 filters can be removed from the PLIF camera, resulting in a threefold increase in signal.) The PIV images were processed with a 32x32 interrogation window with no overlap, yielding a spatial resolution of 0.6 mm. Based on the area...
**Downstream distance, x** | 83 cm
---|---
**x / D** | 32
**Velocity full width at half max, δ₁/₂** | 12.2 cm
**Velocity 5% full width, δ₀.₀₅** | 25.5 cm
**Mean centerline speed, Uᵌ** | 0.71 m/s
**RMS centerline speed, Uᵌᵣ₉₅** | 0.17 m/s
**Mean coflow speed, Uᵌ∞** | 0.18 m/s
**Reδ₀.₀₅** | 8700
**Reδ₁/₂** | 4100
**Schmidt number, Sc** | 1.5
**Kolmogorov scale η** | 0.6 mm
**PIV / PLIF spatial resolution** | 0.6 mm

Table 1. Experimental parameters.

Figure 2 shows a typical result obtained from the independent PIV imaging. Figure 2a shows the fluctuating velocity field, which is differentiated to obtain the derived quantities mentioned above. These are presented as contour plots in Figures 2b, 2c, and 2d. The axes are normalized by the Kolmogorov scale. As seen in Figure 2b, vorticity is frequently concentrated in large, somewhat circular regions, with regions of positive and negative vorticity often located close together. These structures may be 2-D cross-sections of tube-like vortical structures. Figure 2c shows the minimum principal strain rate (whether compressive or extensive), and the data show that this strain rate is primarily compressive in nature. It is essential to remember, however, that these data are derived from a 2-D measurement, and hence may not be indicative of the true 3-D principal strain rates. The kinetic energy dissipation rate field typically consists of large regions of low dissipation and isolated regions of high dissipation. As seen in Figure 2d, prominent structures in this field are usually quite large; structures as small as 1η are rarely observed and thicknesses of 5η-8η are typical.

Figure 3 shows typical results obtained from the independent PLIF imaging. Figure 3a shows three PLIF images, where brighter regions indicate higher concentrations of jet fluid. These images are differentiated to obtain the scalar dissipation fields. These fields are shown in Figure 3b, where bright areas indicate high levels of scalar dissipation. Figure 3c shows the logarithm of the scalar dissipation. The scalar dissipation field is seen to consist of long, thin structures with large radii of curvature. This is consistent with the findings of other experiments in Sc ≈ 1 fluids (e.g., Buch & Dahm, 1998) and the expectation that 3-D scalar dissipative structures are sheet-like. Visual inspection of the dissipative structures indicates that the thickness of the highest dissipation structures seen in Figure 3b is 2 to 4 Kolmogorov scales. The structures appear thicker when plotted on a logarithmic scale (Figure 3c), because this highlights the low values of dissipation.

Imaged per pixel, the PLIF spatial resolution is 0.2 mm. However, this approach to computing resolution is deceptive because it does not take into account the blurring of the image due to the optical system. The resolution of an imaging system is generally described by its modulation transfer function (MTF), which is a measurement of the system's ability to transfer contrast information from the object to the image plane (e.g., Smith, 1990). The MTF for the current PLIF camera/lens system was measured using the scanning knife edge technique described in Clemens (2002). The results showed that at a spatial resolution of 0.6 mm, almost 90% of the contrast information is retained, indicating that there is virtually no blurring by the optical system at scales equal to η and larger. This excellent spatial resolution was made possible by the use of a high-quality macro lens (Nikon 105 mm) operated at a relatively small aperture (f/2.8). The Kolmogorov scale, calculated from Equation (7), is 0.6 mm. Thus, both the PIV and PLIF measurements resolve the Kolmogorov scale.
Figure 2. Sample data from one independent PIV image: (a) fluctuating velocity field; (b) vorticity; (c) strain rate; (d) kinetic energy dissipation. The Kolmogorov scale, $\eta$, is 0.6 mm.

Figure 4 shows typical results from the simultaneous PIV/PLIF imaging. Figures 4a-4d show the results derived from the PIV data, and Figures 4e-4f show the corresponding results derived from the PLIF data. As mentioned earlier, the simultaneous PLIF images are of lower quality than the PLIF-only images because of the threefold attenuation in signal due to the optical filters. Nonetheless, the aforementioned trends are readily noticed in these images as well. The simultaneous data also show that scalar dissipative structures are sometimes wrapped around vortical structures or "sandwiched" between areas of positive & negative vorticity (as seen in Figures 4b and 4f). These trends are consistent with those seen in direct numerical simulations (e.g., Kerr, 1985).

Figures 4c and 4f show that high compressive principal strain is frequently seen in the vicinity of scalar dissipative structures, consistent with the observation that scalar dissipation sheets tend to orient orthogonal to the direction of the maximum principal compressive strain. As seen in Figure 4d and 4f, the structures found in the kinetic energy dissipation field are usually much larger than those in the scalar field, and regions of high scalar dissipation frequently overlap regions of high kinetic energy dissipation.

Several statistical studies were performed to quantify these observations. Figure 5 shows probability density functions (PDFs) of vorticity, minimum principal strain rate, and kinetic energy dissipation. To obtain these plots, the
Figure 3. Sample PLIF-only data: (a) PLIF image; (b) scalar dissipation; (c) logarithm of scalar dissipation. The Kolmogorov scale, $\eta$, is 0.6 mm.

PIV-only data were processed with three different interrogation window sizes, corresponding to resolutions of $1\eta$, $2\eta$, and $4\eta$. (The amount of vectors in the images was kept constant by interpolating as needed to avoid problems with the finite-differencing algorithms used to calculate the derived quantities.) This was done to explore the effect of resolution on the inferred kinematic quantities. Figure 5a shows that the mean vorticity is zero, which is physically consistent with an isotropic turbulent flow. Figure 5b shows that the mean strain is compressive, indicating the presence of compressive strain that is responsible for forming thin scalar dissipation layers. The PDF of kinetic energy dissipation (Figure 5c) has been plotted with a logarithmic abscissa. With
Figure 4. Representative results: (a) fluctuating velocity field; (b) vorticity; (c) minimum 2-D principal strain rate; (d) 2-D kinetic energy dissipation; (e) PLIF image; (f) scalar dissipation field. The coordinate axes are normalized by the Kolmogorov scale ($\eta = 0.6$ mm).
these axes, the PDF is seen to be Gaussian, indicating a lognormal distribution. Such a distribution was initially postulated by Kolmogorov to account for the internal intermittency of turbulence, and has been observed experimentally elsewhere (Tsinober et al, 1992, Su & Dahm, 1996). This PDF also shows that high values of kinetic energy dissipation occur very infrequently. This is consistent with the aforementioned "spotty" nature of kinetic energy dissipation. As seen in figure 5a, the vorticity statistics do not change as

![Out-of-plane vorticity](image1)

![Min 2-D principal strain rate](image2)

![2-D kinetic energy dissipation](image3)

**Figure 5.** Probability density functions computed for three processing resolutions: (a) vorticity; (b) strain rate; (c) kinetic energy dissipation.

![2-D kinetic energy dissipation](image4)

**Figure 6.** Sample kinetic energy dissipation field from one PIV image processed at three different resolutions: (a) 1\(\eta\); (b) 2\(\eta\); (c) 4\(\eta\).
the resolution is worsened from $1\eta$ to $4\eta$. The strain statistics, as shown in Figure 5b, are virtually identical for all three resolutions. However, as resolution is worsened, the highest values of strain are underpredicted. A similar trend is noted in the kinetic energy dissipation statistics, shown in Figure 5c. The $2\eta$ and $4\eta$ resolutions underestimate the actual value of kinetic energy dissipation slightly. This effect can be seen visually in Figure 6, which shows the kinetic energy dissipation field from the same image processed at $1\eta$, $2\eta$, and $4\eta$. The contour levels are the same for all three images. As resolution is worsened, the general shape of the structures is preserved, but the peak values of dissipation are reduced (as evidenced by the diminishing red areas).

The simultaneous PIV/PLIF data were used to investigate the relationships of vorticity, strain rate, kinetic energy dissipation, and scalar dissipation. Each point in the velocity field was labeled as falling inside or outside a scalar dissipation layer, and statistics were computed for both cases. The results are presented in Figure 7. No significant difference is found in the vorticity field inside and outside scalar dissipation layers. In contrast, as seen in Figure 7b, the strain inside scalar dissipation layers is clearly more compressive than outside these layers. These observations are consistent with the preferential alignment of the scalar gradient perpendicular to the axis of compressive principal strain and of the vorticity with the intermediate extensive strain. Figure 7c shows higher values of kinetic energy dissipation inside scalar dissipation layers, confirming the visual observations introduced above. It should be noted, however, that structures in the kinetic energy and scalar dissipation fields do not

![Out-of-plane vorticity](image-a)

![Min 2D principal strain rate](image-b)

![2D kinetic energy dissipation](image-c)

Figure 7. Probability density functions computed inside and outside of scalar dissipation layers: (a) vorticity; (b) strain rate; (c) kinetic energy dissipation.

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always overlap; many cases were observed of prominent structures in one field without a corresponding structure in the other. This is to be expected, considering the different transport equations for the scalar and kinetic energy dissipation.

To yield further insight into the issue of resolution requirements, the PIV-only and PLIF-only data were analyzed to determine the physical size of the dissipative structures seen in the scalar and kinetic energy dissipation fields. The results are shown in Figure 8. Figure 8a is a PDF of the dissipative structure width. Following the approach of Buch & Dahm (1996, 1998), the thickness of scalar dissipation layers is determined by the points where the dissipation has fallen to 20% of maximum. The sheet-like topology of these layers make it easy to identify a thickness at each point in the layer. Because the topology of kinetic energy dissipative structures is more complicated, it is more difficult to define a thickness. The thicknesses reported below for these structures are defined as follows. First, each structure is isolated based on the points where the dissipation has fallen to 20% of maximum, thus defining a perimeter. Next, normal cuts are made at every point in the perimeter; each is treated as a width. Finally, a histogram of these widths is assembled, and the most frequently-occurring width is chosen as the characteristic structure width. The process is illustrated in Figure 8b. The PDFs in Figure 8a show that the scalar dissipation layers have a range of thicknesses from approximately 1$\eta$ to 6$\eta$, with the mean thickness being about 3$\eta$. Using this as the value for $\lambda_D$ in Equations (5) and (6), and solving for $\Lambda$, we obtain $\Lambda = 7.8$. This indicates that scalar dissipative structures

![Figure 8. Thicknesses of scalar and kinetic energy dissipation structures: (a) probability density functions; (b) illustration of how thicknesses were determined; (c) morphometric shape factor. The Kolmogorov scale, $\eta$, is 0.6 mm.](https://example.com/figure8.png)
are significantly thinner than reported by Buch & Dahm (1996, 1998; $\Lambda = 11.2$) and by Su & Clemens (1996, 1998; $\Lambda = 14.9$). In the current study, great effort was taken to make measurements that were not compromised by resolution limitations of the optical systems, and therefore it is possible that the aforementioned discrepancy exists because the previous studies suffered from finite resolution effects. The mean thickness of the kinetic energy dissipative structures is approximately $4\eta$, slightly larger than that of the scalar structures. However, it is clear that kinetic energy dissipative structures have a greater range of thicknesses, and can be as thick as 10 Kolmogorov scales.

The topology of a structure can be roughly quantified by the morphometric shape factor, defined as (e.g., Banner, 1985)

$$S = \frac{4\pi A}{P^2}$$

where $S$ is the shape factor, $A$ is the structure area, and $P$ is the structure perimeter. The values of $S$ range from 0 to 1, with 0 corresponding to an infinitely thin line and 1 corresponding to a circle. (A square has $S = 0.7$.) In general, smaller values of $S$ indicate thinner structures. Figure 8c shows PDFs of the shape factor for scalar and kinetic energy dissipation structures. The plots show that structures in the kinetic energy dissipation field do indeed have a wide range of topologies, from thin line-like ($S < 0.3$) to almost-circular ($S > 0.8$), with the most probable topology being a somewhat fat ellipse. In contrast, the PDF for scalar dissipative structures clearly illustrates their predominantly line-like shape when projected onto the 2-D measurement plane, confirming their 3-D sheet-like topology. These results can be seen qualitatively in the data shown in Figures 2, 3, and 4. For instance, the prominent horizontally-oriented scalar dissipation layer in Figure 4f is approximately $3\eta$ thick along its length, while the associated kinetic energy dissipation structure is more than twice as thick.

**IV. Conclusions and future work**

The structure and dynamics of the dissipative scales were investigated using PIV and PLIF of a conserved scalar in an axisymmetric turbulent jet. The measurements resolve the classical Kolmogorov scale in the flow. Statistics of vorticity, strain rate, and kinetic energy dissipation were computed, and show trends previously identified in experimental and numerical studies. In particular, good correlation exists between areas of high compressive strain, scalar dissipation, and kinetic energy dissipation. An analysis of the topology of the structures in the scalar and kinetic energy dissipation field was performed. This analysis showed that scalar dissipation layers tend to be sheet-like, and that kinetic energy dissipative structures have more varied topologies. Scalar dissipation layers have thicknesses ranging from approximately $1\eta$ to $6\eta$, with a mean thickness of $3\eta$. Kinetic energy dissipative structures are thicker, with thicknesses ranging from approximately $1\eta$ to $10\eta$ and a mean thickness of $4\eta$. Using these values to solve for $\Lambda$ in Equations (5) and (6), we obtain $\Lambda = 7.8$, indicating that scalar dissipation layers are about a factor of two smaller than was previously reported. The effect of resolution on statistics of vorticity, principal strain, and kinetic energy dissipation was explored by processing the PIV data at four resolutions ($1\eta$, $2\eta$, and $4\eta$). No difference in statistics is observed for the vorticity field; however, the coarser resolutions slightly underpredict high magnitudes of principal compressive strain and kinetic energy dissipation.

In the near future, additional data acquisition and processing will be performed to explore these resolution effects further. One of the short-term goals is to perform a similar resolution study on the scalar dissipation field. Another is to examine the kinetic energy dissipation field and determine the correlation between structure size and dissipation. Long-term goals are to investigate Reynolds number effects (by varying the jet speed) and to examine
the relationship between principal strain and the other quantities in more detail.

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VI. References


Biringen, S. (1975) "An experimental study of a turbulent axisymmetric jet issuing into a coflowing airstream." Von Karman Institute Technical Note 110


Pitts, W. M., Richards, C. D., and Levenson, M. S. (1999) "Large- and small-scale structures
and their interactions in an axisymmetric jet." *NIST Report 6393*


