Scalar/velocity imaging of the fine scales in gas-phase turbulent jets

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ABSTRACT

Results are reported for an experimental study that is directed at investigating the fine scale structure of turbulent jet flows using the simultaneous imaging of the velocity and conserved scalar 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 fluid. The measurements resolve the classical Kolmogorov scale of the flow. These highly-resolved measurements are used to investigate the statistics of kinematic quantities such as vorticity, strain rate, and kinetic energy dissipation. They also permit the analysis of the relationships between strain, kinetic energy dissipation, and scalar dissipation. Worsening the resolution from 1 to 2 Kolmogorov scales appears to have a significant effect on the statistics of vorticity, strain, and kinetic energy dissipation, but this is believed to be due to differences in the noise present in the images rather than to a resolution effect. As further evidence for this, no significant difference is observed when the resolution is worsened from 2 to 4 Kolmogorov scales. Qualitatively, regions of high scalar dissipation tend to be correlated with regions of high principal compressive strain and high kinetic energy dissipation. The topology of the kinetic energy dissipation structures is also seen to be substantially more complex than the layer-like structures found in the scalar dissipation field.

I. INTRODUCTION

The topic of turbulent mixing at fine scales is important in many engineering applications, such as industrial chemical processing and gas-phase combustion. As a result, many investigations have been conducted to explore the phenomena that occur at these finest scales. This topic is of particular interest to the study of reacting flows, where the mixing process can have a profound impact on heat release and pollutant formation. It is well-known, for instance, that achieving an understanding of the structure of turbulent nonpremixed flames requires a knowledge of the interaction between the underlying velocity field, molecular diffusion, and flame chemistry (Bilger, 1976; Peters, 1984). Today, turbulent flows are being studied extensively with nonintrusive optical diagnostics such as particle image velocimetry (PIV) and planar laser-induced fluorescence (PLIF). An important issue that arises in these studies is the velocity resolution required for accurate computation of strain rates that influence the flame structure. Some controversy exists in the literature on this topic. For example, Bilger (1988) used scalar dissipation measurements in an isothermal turbulent jet to argue that, in a flame, the fine scale turbulence will tend to thicken reaction zones. He justifies this with his observation that the Kolmogorov scale is expected to be much smaller than the scalar dissipation structures he observed. However, Buch and Dahm (1996, 1998) argue that the strain-diffusion balance for Sc ≈ 1 fluids (i.e.,

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gases) precludes a substantially different scale for the kinetic energy and scalar dissipation structures. Direct numerical simulations of isotropic turbulence with passive scalar mixing (e.g., Kerr, 1985; Rogers & Moin, 1987; Ashurst et al., 1987) also do not indicate a substantial difference in the sizes of kinetic and scalar energy dissipation structures. Fundamental to this controversy is that much is still not known about the relationship between the conserved scalar and velocity fields in turbulent mixing and combustion.

As relevant background, consider the transport of a conserved scalar, $x(\boldsymbol{x},t)$,which is governed by the equation,

$$\left[\frac{\partial}{\partial t} + \mathbf{u}\cdot\nabla - D\nabla^2\right]\xi = 0 \qquad (1)$$

where D is the mass diffusivity. Equation (1) can be used to derive the transport equation for the so-called scalar energy,

$$\left[\frac{\partial}{\partial t} + \mathbf{u}\cdot\nabla - D\nabla^2\right]\frac{1}{2}\xi^2 = -\chi \qquad (2)$$

where $\frac{1}{2}\xi^2$ is the scalar energy and $\chi = D(\nabla\xi\cdot\nabla\xi)$ is the scalar energy dissipation rate. Similarly, the kinetic energy $\frac{1}{2}\mathbf{u}\cdot\mathbf{u}$ is governed by the transport equation,

$$\left[\frac{\partial}{\partial t} + \mathbf{u}\cdot\nabla - \nu\nabla^2\right]\frac{1}{2}\mathbf{u}\cdot\mathbf{u} = -\mathbf{u}\cdot\nabla p + \nu\nabla\mathbf{u}\cdot\nabla\mathbf{u}^{T} - 2\nu\mathbf{s}:\mathbf{s} \qquad (3)$$

where ν is the kinematic viscosity. The last term in Equation 3 is the kinetic energy dissipation rate ε, which is computed from the strain rate tensor,

$$\boldsymbol{s} = s_{ij} = \frac{1}{2}\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right) \qquad (4)$$

Classical turbulence theory holds that the kinetic energy is dissipated at the Kolmogorov scale, η, which is defined as

$$h \equiv \left(\frac{n^3}{e}\right)^{1/4} \qquad (5)$$

and represents the finest vorticity scale. The corresponding finest concentration scale is the Batchelor scale λ_B, given by

$$\lambda_B = \eta\, Sc^{-1/2} \qquad (6)$$

where Sc is the Schmidt number. Buch & Dahm (1996, 1998) suggest relations for the finest scales in terms of outer scale variables. The strain-limited vorticity diffusion scale, λ_ν, is defined as

$$\frac{l_n}{d} = \Lambda\cdot \mathrm{Re}_d^{-3/4} \qquad (7)$$

and the corresponding strain-limited mass diffusion scale, λ_D is given by

$$l_D = l_n \cdot Sc^{-1/2} \qquad (8)$$

where δ is the local 5% concentration full width, Re_δ is the local Reynolds number, and Λ is a constant. Buch & Dahm's measurements of l_D indicate that the constant Λ has a value of 11.2 based on $\delta_{0.05}$. The scales λ_ν and l_D characterize the smallest distance over which a gradient may be sustained in the velocity and scalar field, respectively.

A relationship between η and λ_ν can be found by considering how the dissipation ε scales for a given turbulent flow. For a round jet, using the dissipation data of Friehe et. al. (1971) and the velocity scaling laws given in Chen & Rodi (1980), one finds that $\lambda_\nu \approx 6\eta$. This suggests that the strain-limited vorticity scale is in fact substantially larger than the Kolmogorov scale. While hot-wire measurements in turbulent flows have confirmed that velocity fluctuations exist at scales of order η, there is no current consensus on whether η or λ_ν represents the best estimate of the finest scale.

The topology of the scalar dissipation field is now well-known to consist of sheet- or layer-like structures that are oriented orthogonal to the direction of the maximum principal compressive strain rate (e.g., Kerr, 1985; Ashurst et al., 1987; Buch & Dahm, 1996, 1998; Su & Dahm, 1996). Buch & Dahm (1996, 1998) measured the thickness of these sheet-like structures, and report that they have a mean thickness equal to l_D with Λ = 11.2. Measurements of dissipation layer thicknesses by Su & Clemens (1998) suggest a value of Λ that is approximately 20% larger than the Buch & Dahm value. Pitts et al. (1999) compare their data from a nonreacting jet to the data of Buch & Dahm, and suggest that the two studies propose different resolution requirements. The topology of the kinetic energy dissipation field is substantially more complex, containing sheet-, line-, and "blob"-like structures (e.g., She et al, 1990; Kerr, 1987; Yamamoto & Hosokawa, 1988; Siggia, 1981). This increased complexity is likely the reason for the lack of agreement on the precise magnitude of the smallest scale of turbulence.

The present investigation is part of a long-term research program aimed at resolving at least some of these issues. Preliminary results of this investigation were reported by Tsurikov et. al. (1999). Velocity and conserved scalar measurements are conducted in an axisymmetric turbulent flow, at a location where the finest scales are large enough to be fully resolved by the optical diagnostics. Velocity measurements are conducted using two-component PIV, and conserved scalar measurements are conducted using PLIF of acetone vapor seeded into a nitrogen jet. These measurements permit a statistical analysis of such quantities as vorticity, strain, and kinetic energy dissipation, as well as an analysis of the topology of the fine scale structures found in the flow. More importantly, the data can be used to determine the relationship between the kinematics of the flow (as found from the velocity field) and the conserved scalar field. Another topic that can be addressed using these results is the aforementioned resolution requirements for accurate computation of strain. These topics are addressed in the current work.

II. EXPERIMENTAL SETUP

The flow facility is designed to produce a turbulent flow in which the Kolmogorov scale, η, is large enough to be fully resolvable by our optical diagnostics. The facility was sized to balance the need to obtain a large Kolmogorov scale and to operate the facility at various flow conditions. A schematic of the facility is shown in Figure 1. The facility is 92 cm wide by 92 cm long by 1.89 m high, and is constructed of 0.25" aluminum structural members and 0.040" aluminum sheet for the walls. 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 jet air flow rate is monitored by differential pressure gauges (Omega PX181-200G5V). The jet is surrounded by a coflow, which is supplied by a 230 CFM industrial blower (Dayton model 4C444A). The coflow enters the jet facility through a network of PVC pipes, and is conditioned by sections of honeycomb and stilling screens prior to entering the test section. The top part of the facility has four windows that provide optical access for the laser beams and cameras. The jet and coflow velocity profiles were investigated at various locations in the test section using a hot film traverse system.

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/5.6 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 glycerine-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 using Linux-based cross-correlation PIV software developed in-house. This software also validates the vector fields and produces the derived quantities, such as vorticity and strain rate.

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 an acetone bubbler. This yields a jet fluid that is virtually saturated with acetone vapor (about 24% acetone by volume). Because acetone vapor (molecular weight = 58) is considerably heavier than air (molecular weight = 29), 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 was circumvented by heating the jet gas to a temperature at which the gas density is equal to that of ambient air. An inline gas heater with closed-loop control is used to achieve the required heating. 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 55 and 90 mJ. The blue acetone fluorescence is imaged with a slow-scan cooled CCD camera (PixelVision SV512V1). A Canon 58 mm f/1.2 lens is used with the camera, and is operated at full aperture. To ensure that 532 nm light scattered from particles in the flow would not interfere with the fluorescence signal, the camera lens was 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 to yield the scalar dissipation rate field.

The entire experimental arrangement is shown in Figure 2. The 532 nm and 266 nm beams were combined using a 266 nm mirror, which is transparent to the 532 nm beam. The combined beams were then passed through two cylindrical lenses, and emerged as collimated light sheets about 48 mm high. The cameras were placed on opposite sides of the test section, and aligned by imaging an optical target. The optical target imaged by both cameras was also used to match the fields of view for the two cameras during post-processing.

III. LIMITATIONS OF 2-D MEASUREMENTS

In this study, our aim is to investigate the relationships between vorticity, strain rate, kinetic energy dissipation rate, and scalar dissipation. A limitation of the present work is that our measurements provide information only in two dimensions. Such measurements allow us to compute only two components of velocity, one component of the vorticity vector (ω_z), 4 of 9 components of the strain rate tensor, and two components of the scalar gradient vector. This may seem to be an insurmountable limitation in studying a flow that is inherently highly three-dimensional. This issue is discussed in this section.

The kinetic energy dissipation rate ε is given by,

$$\varepsilon = 2\nu\left[\left(\frac{\partial u}{\partial x}\right)^2 + \left(\frac{\partial v}{\partial y}\right)^2 + \left(\frac{\partial w}{\partial z}\right)^2 + \frac{1}{2}\left(\frac{\partial u}{\partial y}+\frac{\partial v}{\partial x}\right)^2 + \frac{1}{2}\left(\frac{\partial u}{\partial z}+\frac{\partial w}{\partial x}\right)^2 + \frac{1}{2}\left(\frac{\partial v}{\partial z}+\frac{\partial w}{\partial y}\right)^2\right] \tag{9}$$

where our PIV measurements permit us to compute only the first, second, and fourth terms. We can use the incompressible continuity equation,

$$\nabla\cdot\mathbf{u} = \frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}+\frac{\partial w}{\partial z} = 0 \tag{10}$$

to solve for $\partial w/\partial z$. This allows us to compute what we define as the "2D kinetic energy dissipation", denoted as ε_{2D}, which is computed from the first four terms of Equation (9).

As discussed in the introduction, scalar dissipation sheets tend to align orthogonally to the direction of the maximum principal compressive strain. We are thus particularly interested in obtaining accurate estimates of the principal strains. Following the approach of Rehm & Clemens (1998), we argue that we can compute the correct principal strains under two conditions: *i)* when the flow is locally two-dimensional and *ii)* where the *z*-axis (the axis orthogonal to the laser sheet) is already a principal axis. The first condition is highly unlikely when considering the fine scale structure of a three-dimensional flow. We argue, however, that the second condition is likely to be true near very thin dissipation layers. This is because when we observe a thin dissipation layer, we can assume that it is oriented approximately normal to the laser sheet. In accordance with the sheet-like topology of the layer, the *z*-axis must thus be a principal axis. In this case, the *z*-direction shear components of the strain rate tensor are zero, and a simple transformation to principal coordinates from two-component velocity data gives the correct principal strains. Furthermore, the strain in the *z* direction must be extensive by the orientation of the dissipation layer (although the strain's magnitude is not known).

IV. RESULTS AND DISCUSSION

The data presented in this paper were acquired at a distance x = 112 cm (x/D = 45) downstream of the jet exit. Table 1 presents various relevant experimental parameters at this location. The local Reynolds numbers, $Re_{\delta,0.05}$ and $Re_{\delta,1/2}$, were computed using the local velocity difference, $U_c - U_\infty$, with U_c the absolute centerline speed and U_∞ the coflow speed.

A sample set of PIV and PLIF images is shown in Figure 3. To achieve a spatial resolution of 0.65 mm for both PIV and PLIF measurements, a fairly small field of view is required. In this experiment, the typical fields of view are 21x21 mm^2 for the PIV data and 100x100 mm^2 for the PLIF data. This field of view enables the PIV images to be processed with a 32x32 pixel interrogation window with no overlap, yielding a PIV spatial resolution of 0.6 mm. Based on the area 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 loss of contrast that occurs when imaging fine structures. This loss of contrast is generally described by the modulation transfer function (MTF) of the imaging system. The MTF is generally quite difficult to measure, and for this reason is generally overlooked. The MTF of the current PLIF image acquisition system was measured, and shows that contrast attenuation is less than 50% for scales larger than 0.6 mm. Based on this information, we believe that we can adequately resolve structures larger than 0.6 mm in size. Thus, both imaging techniques resolve the Kolmogorov scale. Since the PIV field of view is considerably smaller than the PLIF field of view, the PLIF image must be cropped to isolate the region of interest corresponding to the PIV image. The data consisted of approximately 2000 PIV images, 500 PLIF images, and 200 PIV / PLIF images acquired simultaneously. (The disparity in the dataset sizes is due to the fact that the PLIF camera acquires images much more slowly than the PIV camera.)

One of the goals of this study is to investigate the relationships between the velocity and scalar fields. Figures 4 and 5 show representative simultaneous PIV / PLIF data acquired at x/D = 45. All spatial coordinates shown in these figures are normalized by the Kolmogorov scale η = 0.65 mm. Figures 4a and 5a show the fluctuating velocity field that was obtained from the original vector field (such as that shown in Figure 3) by subtracting the mean velocity field computed from an ensemble of 2000 images. The velocity field is differentiated to yield other kinematic quantities, which are presented here as contour plots. Figures 4b and 5b show the *z*-component of vorticity ω_z. Figures 4c and 5c show the 2D minimum principal strain rate (i.e., the smallest strain, whether positive or negative), which is computed as discussed in the last section. Figures 4d and 5d show the 2D kinetic energy dissipation ε_{2D}, also defined in the last section. Figures 4e and 5e show the conserved scalar field obtained by PLIF, where light regions correspond to high concentrations of jet fluid. These images are processed to obtain the scalar dissipation rate field. This field is shown in Figures 4f and 5f, where light areas indicate regions of high dissipation.

Figures 4b and 5b show that vorticity is often concentrated in thick, somewhat circular regions, with regions of positive and negative vorticity often in close proximity to each other. These observations may indicate the presence of tube-like vortical structures such as those seen in direct numerical simulations (e.g., Kerr, 1985). Further, it is common for scalar dissipation layers to be "wrapped" around these regions of vorticity (as is particularly evident in Figure 5b and 5f). The data also show a good correlation between regions of high compressive strain and of high scalar dissipation. The kinetic energy dissipation rate field, shown in Figures 4d and 5d, consists of large regions of low dissipation and isolated regions of high dissipation. (The bright spot at the right of Figure 5d is an artifact caused by a misaligned velocity vector.) This indicates that kinetic energy dissipation occurs infrequently, and is consistent with prior work (e.g., Su & Dahm, 1996), which describes the appearance of kinetic energy dissipation as "spotty". An examination of the data shows that high kinetic energy dissipation is frequently found in regions of high scalar dissipation. This trend is consistent with prior experimental results reported by Tsurikov et al. (1999) and with numerical simulations of Ashurst et al. (1987). The complex topology of the kinetic energy dissipation field is readily evident in these images.

At this time, the observations made above are only qualitative, and several features were observed that depart from the aforementioned trends. For instance, as shown in Figure 6, regions of high kinetic energy dissipation and strain appear to be shifted to one side of a prominent scalar dissipation layer, instead of overlapping it. In other cases, prominent scalar dissipation structures and equally prominent kinetic energy dissipation structures do not overlap at all. This observed lack of correlation between kinetic and scalar energy dissipation structures is certainly not surprising considering that they are governed by different transport equations. In the future, a statistical analysis will be performed to quantify these observations.

As stated earlier, another goal of this study is to evaluate the effect of resolution on the accuracy of measured vorticity, strain, and dissipation. For the velocity data, the effect of worsening resolution can be achieved by increasing the size of the PIV interrogation window. The PIV images were thus processed with interrogation windows of 32x32, 64x64, and 128x128 pixels, always without overlap. This resulted in velocity grids of 32x32, 16x16, and 8x8 vectors. In turn, this corresponds to spatial resolutions of 0.6, 1.3, and 2.6 mm (1η, 2η, and 4η), respectively.

Probability density functions were computed for the kinematic quantities of interest. Figure 7 shows a probability density function of the *z*-component of vorticity. The three curves are for three interrogation window sizes (see the last paragraph). The mean vorticity is seen to be zero, which is physically consistent with an isotropic turbulent flow. The plots also show that, as resolution worsens, the range of vorticity values decreases (as seen from the narrowing of the PDF peaks). This, too, is physically consistent, for "worsening resolution" intrinsically implies an averaging over a larger area and a smoothing of gradients. Figure 8 shows a probability density function of the 2D minimum principal strain rate. As seen from the figure, the mean strain is slightly compressive, indicating the presence of compressive strain that is responsible for forming thin scalar dissipation layers. Figure 9 shows a probability density function of the 2D kinetic energy dissipation rate. The mean kinetic energy dissipation is zero, with the probability of finding higher dissipation dropping off quite sharply. (The scatter on the right side of the plots is due to noise in the velocity derivatives.)

An interesting feature seen in these probability density functions is that, while there is a noticeable difference in worsening resolution from 1η to 2η, there is virtually no difference in worsening it from 2η to 4η. This result appears to be due to the difference in the level of noise (random error) that is present in the images, rather than to an effect of resolution on the flow structures. In other words, because the error in the velocity tends to increase, as the interrogation window is made smaller, then the error in any derivative term of the form $\Delta u/\Delta x$ will tend to infinity as $\Delta x \rightarrow 0$. This shows that any improvement in resolution must be weighed against the penalty that may have to be paid in reduced accuracy of the measurements. Furthermore, some "stray" vectors, which clearly do not point in the direction of their neighbors, inevitably appear when the mean velocity is subtracted from the original validated velocity fields. An example of such a vector is seen in Figure 5, at coordinates (24,15). These vectors effectively introduce noise into the measurements. This noise manifests itself in small regions of artificially high vorticity, strain rate, and kinetic energy dissipation. The extent and significance of this noise has not been quantified yet. However, it is obvious that increasing the processing resolution decreases this noise. Figure 10 shows the kinetic energy dissipation of one PIV image processed with different resolutions. Figure 10a, processed at a resolution of 1η, shows a prominent structure surrounded by pockets of noise. Figure 10b, processed at a resolution of 2η, shows the noise dramatically reduced and the structure much clearer. This effect will be explored in greater detail in future work.

These data can also be used to examine the sizes of structures found in the kinetic energy dissipation and scalar dissipation fields. The scalar dissipation fields of 500 PLIF images taken at x/D = 45 were processed with a program that extracts the thickness of the scalar dissipation layers. To date we have measured the thicknesses of the layers that exhibit the highest levels of dissipation. We expect that such layers will be the thinnest because high strain both thins layers and increases the magnitude of the dissipation. The reason for restricting our analysis to only the highest dissipation layers is because the thicknesses can be measured with greater accuracy. Our preliminary analysis indicates that the highest dissipation layers have thicknesses that range from about 1.5 to 4 Kolmogorov scales, with a mean of 2.5. Solving for Λ in Equation (7), we obtain a value $\Lambda = 5$. This value is somewhat smaller than the value quoted by Buch & Dahm (1998) of $\Lambda = 5.6$ for the *minimum* dissipation layer thickness. In the future, all dissipation layers will be analyzed. The size of the structures in the kinetic energy dissipation field are a measure of λ_ν. Due to the more-complex topology of these structures, it is harder to define a characteristic size for them. However, as seen in all figures, the structures are all much larger than those seen in the scalar field; sizes of 8-10η are not uncommon. These large sizes indicate that all the data presented here are indeed fully resolved.

V. CONCLUSIONS AND FUTURE WORK

Fully-resolved PIV / PLIF measurements were conducted in a flow facility designed to produce large turbulent fine scales. Data were gathered in an axisymmetric coflowing jet in which the classical Kolmogorov scale η was resolved. A qualitative analysis of simultaneous PIV / PLIF measurements identify the same trends noted earlier by Tsurikov et al. (1999). In particular, good correlation exists between areas of high principal compressive strain, high kinetic energy dissipation, and high scalar dissipation. Statistics of vorticity, strain rate, and kinetic energy dissipation were computed for resolutions ranging from 1η to 4η. These statistics showed a noticeable difference when the resolution was worsened from 1η to 2η, but little difference when the resolution was worsened from 2η to 4η. The likely reason for this is the different level of noise that is associated with the images that were processed with different resolutions. Substantial additional work will be required before we understand the extent to which the noise effects our interpretation of the flow structures. Preliminary measurements of the thickness of scalar dissipation layer structures were also conducted. The thickness of the strongest (thinnest) layers was found to be 2.5η, which suggests that the constant in Equation (7) is $\Lambda = 5$. This is in agreement with the value reported by Buch & Dahm (1996, 1998). The size of the structures in the kinetic energy dissipation field is often considerably larger than the size of the scalar dissipation structures.

In the near future, more data will be acquired at different Reynolds numbers. This will be done to investigate the dependence of dissipative phenomena on Reynolds number. Another immediate goal is to determine a statistical correlation, if any, between scalar dissipation structures, strain, and vorticity. This will provide a quantitative description of the qualitative trends described above. A possible long-term project is the extension of our optical diagnostics to three dimensions. This would eliminate the limitations listed in Section III, and enable us to compute the full strain rate tensor and the true kinetic energy dissipation.

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VIII. REFERENCES

Ashurst, W.T., Kerstein, A.R., Kerr, R.M., and Gibson, C.H. (1987) "Alignment of vorticity and scalar gradient with strain rate in simulated Navier-Stokes turbulence." *Phys. Fluids* **30:** pp. 2343-2353.

Bilger, R.W. (1976) *Comb. Sci. Tech.* **13:** 155-170

Bilger, R.W. (1988) "The structure of turbulent nonpremixed flames." *Twenty-Second Symposium (Int.) on Combustion, Boulder, CO*

Buch, K.A. and Dahm, W.J.A. (1996) "Experimental study of the fine scale structure of conserved scalar mixing in turbulent shear flows. I. Sc » 1." *J. Fluid Mech.* **317:** 21-71

Buch, K.A. and Dahm, W.J.A. (1998) "Experimental study of the fine scale structure of conserved scalar mixing in turbulent shear flows. I. Sc ≈ 1." *J. Fluid Mech.* **364:** 1-29

Chen, C.J. and Rodi, W. (1980) *Vertical turbulent buoyant jets: a review of experimental data*. Oxford: Pergmon Press

Friehe, C.A., van Atta, C.W., and Gibson, C.H. (1971) "Jet turbulence: dissipation rate measurements and correlations." *AGARD Turbulent Shear Flows CP-93*, 18-1 - 18-7

Kerr, R.M. (1985) "Higher-order derivative correlations and the alignment of small-scale structures in isotropic numerical turbulence." *J. Fluid Mech.* **153**: pp. 31-58

Lozano, A., Yip, B. and Hanson, R.K. (1992) "Acetone: a tracer for concentration measurements in gaseous flows by planar laser-induced fluorescence," *Expts in Fluids.* **13**: 369-376

Peters, N. (1984) "Laminar diffusion flamelet models in nonpremixed turbulent combustion." *Prog. Energy Comb. Sci.* **10:** 319-339

Rehm, J.E. (1999) "The effect of heat release on planar jet diffusion flames." Ph.D. thesis. University of Texas at Austin, 1999.

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 NISTIR-6393*

Rogers, M.M. and Moin, P. (1987) "The structure of the vorticity field in homogeneous turbulent flows." *J. Fluid Mech.* **176:** 33-66

She, Z.-S., Jackson, E., and Orszag, S.A. (1990) "Intermittent vortex structures in homogeneous isotropic turbulence." *Nature* **344**: 226-228

Siggia, E.D. (1981) "Numerical study of small-scale intermittency in three-dimensional turbulence." *J. Fluid Mech.* **107:** 375-406

Su, L.K. and Clemens, N.T. (1998) " The structure of the 3-dimensional scalar gradient in gas-phase planar turbulent jets." *AIAA Paper 98-0429*

Su, L.K. and Dahm, W.J.A. (1996) "Scalar imaging velocimetry measurements of the velocity gradient tensor field in turbulent flows. II. Experimental results". *Phys. Fluids* **8:** 1883-1906

Yamamoto, K., and Hosokawa, I. (1988) "A decaying turbulence pursued by the spectral method." *J. of the Physical Soc. of Japan* **57/5**: 1532-1535