Acquisition and Representation of 2D and 3D Data from Turbulent Flows and Flames

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Although turbulence has been studied for over 100 years, prediction of many important quantities in turbulent flows is still not possible, leaving turbulence an unsolved problem of classical mechanics. From an engineering standpoint as well, turbulent flows and flames are extremely important. Most naturally occurring flows are turbulent, as are flames in industrial combustors, automobile engines, jet engines, and rockets. A better understanding of this phenomenon would directly impact a broad range of practical devices and aid in the design of more efficient engines, vehicles with reduced drag, and combustors with lower pollution levels.

Part of the difficulty of the turbulence problem lies in the vast amount of information that must be specified. For example, to fully characterize a turbulent flame would require measurements of temperature, pressure, density, concentrations of all species, and all three components of the velocity vector at each point within a volume. Because of the great diversity of length scales present in a turbulent flow, even a relatively simple turbulent flame could require measurements at more than 10^7 points. At each point, all of the quantities mentioned would have to be recorded as functions of time with characteristic time scales on the order of 10 microseconds.

Clearly, the problem is very complex, and the prospect of determining flow quantities with the measure of detail described above remains distant. Significant progress has been made, however, both theoretically and experimentally. We will present laser light-scattering techniques for making two- and three-dimensional measurements in turbulent flows and flames, along with examples of methods used to represent the large quantities of data obtained. While our work has focused on developing new diagnostic techniques, the methods of data representation and display are topics of immediate importance to scientists hoping to understand the tremendous amount of information their measurements provide. We hope this article will challenge those working in computer processing and graphics by making them more aware of the needs of today's flow and combustion diagnostics community.

Laser light-scattering techniques for making two- and three-dimensional measurements, and better methods for representing the large quantities of data obtained may help solve the "turbulence problem."

Laser diagnostic measurement techniques

In the last decade significant advances in lasers and detector technology, coupled with the advent of laboratory...
computers to record the data, have prompted development of techniques that have provided a wealth of new data. Rather than relying on disruptive physical probes to make measurements, researchers are making increasing use of the fact that light scattered from the molecules in a flow can reveal a great deal of information. The ability of laser techniques to make nonintrusive, in situ, time-resolved measurements of molecular species, temperatures, velocities, pressures, and densities has been demonstrated.

Figure 1 shows an experimental configuration typical of those used to make two-dimensional measurements in a turbulent flow or flame. The flow used in the examples presented here emerges from a simple round nozzle. Gas issues from the nozzle exit and mixes (and, in some cases, reacts) with the ambient air. To study the turbulent mixing of the gases, a laser beam is formed into a thin sheet that intersects the flow centerline slightly downstream of the nozzle exit. A very small fraction of the laser light is

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**Figure 1.** An experimental configuration for two-dimensional light-scattering measurements in turbulent flows and flames. A laser beam is formed into a thin sheet to illuminate the flow. Scattered light is collected and imaged onto a CCD (charge-coupled-device) array detector. The images stored in the computer contain information on temperature, density, or species, depending on the scattering mechanism used.

**Figure 2.** A two-dimensional image of a nonreacting Freon jet mixing with ambient air. The false-color map represents the different Freon concentrations. A discontinuous sequence of hues of varying saturation is used, as the dynamic range of the measurement exceeds the capabilities of easy reproduction by continuous-color variations.
scattered by the flow. This scattered light is collected normal to the illumination sheet by a lens, and an optical filter selects a specific range of wavelengths. The selected wavelength is imaged onto a computer-controlled digital camera, and the intensity distribution is recorded. The particular quantity deduced from the scattered light depends on the specific gases present, the laser power and wavelength, and the detected wavelength. A number of light-scattering mechanisms can be used in this way, including Rayleigh, Lorenz-Mie, Fluorescence, and Raman scattering. A recent review article summarized the specifics of these techniques.

Figure 2 shows an example of the data obtained from this type of experiment. In this case the flow is a nonreacting Freon jet mixing with the ambient air. The measurement shows the distribution of Freon within the thin illumination sheet. In the figure a false-color representation is used, with different colors representing different Freon concentrations (that is, mole fractions). Because the dynamic range of the measurement is too great to be easily reproduced by a continuous change in intensity or color, a discontinuous sequence of hues with varying degrees of saturation is used. The color bar shows the mapping of colors to gas concentrations.

As mentioned, many quantities are required to fully characterize a turbulent flame, and current experimental techniques cannot provide them all simultaneously. Some simultaneous measurements can be made, however, by using multiple detectors, with each detector measuring a different quantity by monitoring a different light-scattering mechanism. Figure 3 shows two pairs of concentration and temperature distributions from a turbulent premixed methane-hydrogen flame. The lower part of the figure shows the concentration of methane as determined from Raman scattering, and the upper part shows the corresponding temperature distributions as determined by Rayleigh scattering. The correspondence between the two quantities can be seen by noting that regions of high fuel-gas concentration (shown in yellow on the bottom part of the figure) correspond to areas of lower temperature (blue regions in the upper part of the figure). The information is also complementary, with the temperature distribution giving a better indication of the location of the hot flame zone.

![Figure 3](image3.png)

**Figure 3.** Two pairs of simultaneous temperature and concentration measurements in a turbulent methane-hydrogen flame. The lower part of the figure shows the methane concentration as determined from Raman scattering, while the upper portion shows the corresponding instantaneous temperature distributions as determined from Rayleigh scattering.

![Figure 4](image4.png)

**Figure 4.** Alternative ways of representing the same two-dimensional gas concentration measurement in a turbulent nonreacting flow. The nozzle gas concentration was measured by imaging Lorenz-Mie scattering in a plane oriented normal to the axis of an axisymmetric jet of Reynolds number 4160. The illumination sheet intersected the centerline six nozzle diameters downstream, where the flow has become three dimensional.

Turbulence by its nature is a three-dimensional phenomenon, so that with data in only two dimensions, some ambiguities remain. For example, Figure 4 shows another visualization of the gas concentration distribution from a turbulent jet. Now, however, the measurement sheet has been oriented normal to the jet.
axis, intersecting it six nozzle diameters downstream. It is clear from Figure 4 that even though the flow emerges from a round nozzle, it quickly loses its axial symmetry, thereby becoming three dimensional. Depending on the orientation of the sheet, very different features of the flow become evident, and thus a single slice through the flow cannot contain all of the information required to fully describe the structures.

Progress has been made in developing techniques capable of providing three-dimensional flow measurements. One way to obtain three-dimensional information from a flow is to simply record a large number of two-dimensional measurements from many closely spaced parallel sheets. The most stringent requirement for this measurement is that data from all of the two-dimensional sheets must be recorded before the flow changes significantly. The detection system must have a high framing rate (that is, the rate at which images can be acquired) to record as many two-dimensional sheets as possible during this time. In addition, a laser source is desired that can provide sufficient energy during the measurement time to enable molecular light-scattering processes to be detected.

Figure 5 shows an experimental arrangement that has been used for making essentially instantaneous three-dimensional measurements in nonreacting and reacting flows. A laser illumination sheet is swept rapidly through the flow, and the scattered light from the scanning sheet is recorded by a high-speed electronic framing camera capable of recording 10 to 20 images at framing rates up to $2 \times 10^7$ frames per second. The framing camera produces a series of images on a phosphor screen that correspond to different sheet locations. This intensity distribution can then be measured electronically with a CCD (charge-coupled device) detector. In recent work we showed that it is possible to get truly instantaneous (less than 1 microsecond) gas concentration measurements in turbulent jets and flames.

Figure 6 shows a false-color representation of a series of nozzle gas concentration distributions corresponding to different planes intersecting a flow. The contour characteristics are seen to change as the sheet intersected different locations in the flow. Although the concentration distributions shown in Figure 6 give a complete representation of the three-dimensional data, they do not pro-

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**Figure 5.** An experimental arrangement used for the time-resolved three-dimensional measurement of a scalar in a gas jet. A laser sheet is swept rapidly through the flow by a rotating mirror. Images of parallel vertical slices are produced on the phosphor screen of a high-speed electronic framing camera. The image is then recorded by a two-dimensional CCD (charge-coupled-device) array. The series of imaged planes constitutes a three-dimensional recording of the flow.

**Figure 6.** A series of flow planes in an acoustically forced jet, represented by false-color-mapped concentration contours. The concentration is determined from the intensity of Lorenz-Mie scattering. The region imaged is 1.8 centimeters in the streamwise direction and centered 2.4 cm downstream from a nozzle 0.3 cm in diameter. The frames correspond to planes spaced 0.8 millimeter apart.
Figure 7. Instantaneous constant fuel-gas concentration surface in a turbulent Bunsen-burner flame. The surface corresponds to a concentration of 64 percent of the maximum in this region and has been generated from experimental data. The flame was a stoichiometric methane-air mixture seeded with butane vapor as a fluorescent marker, with a jet velocity of 19.5 meters per second. The imaged region is $2 \times 1 \times 0.5$ nozzle diameters ($d=6$ millimeters) in size, centered five diameters downstream from the burner. The flow direction is from bottom to top.

Figure 8. Constant-concentration surfaces in a photoacoustically perturbed Freon-air jet measured by Rayleigh scattering. The left- and right-hand structures correspond to Freon concentrations of 27 percent and 18 percent, respectively. The three-dimensional effect is heightened by the shadows cast.

Figure 9. A three-dimensional iso-concentration surface reconstructed from a measurement of Mie scattering from a transitional aerosol-seeded jet of air. The surface corresponds to a region $6.8 \times 2.1 \times 0.7$ nozzle diameters ($d=2$ millimeters) in size, centered 10 diameters downstream from the orifice. The exit velocity of the jet was 8 meters per second. In this representation each point on the surface is color coded according to the magnitude of the concentration gradient vector.

provide much insight into the topology of the flow structures.

The approach we have used is to represent constant-concentration surfaces, which are analogous to lines of constant concentration in a two-dimensional plot. Figure 7 shows a constant gas concentration surface obtained from a set of slices similar to those shown in Figure 6. The data in the figure represent a constant fuel concentration surface in a turbulent premixed flame. Different concentration values would provide different surfaces, with higher concentration contours fitting inside lower ones. Figure 8 shows two different contours obtained from a single three-dimensional data set. Normally, these would lie one inside the other, but, for display, the higher contour value (left) has been removed from inside the lower (right) and light has been cast upon an imaginary plane to highlight the three-dimensional effect.

Figure 9 shows another means of relating more of the three-dimensional information recorded in a single measurement. The figure shows a constant-concentration surface again, but now the color at each point on the surface has been coded by the magnitude of the concentration gradient vector at that location. The representation of the species data obtained in these measurements as constant-concentration surfaces coincides quite well with one of the current models of turbulent combustion. According to the flame sheet model of combustion, chemical reactions in flames occur in thin sheets located in regions that have the proper mixture of fuel and oxidizer. In this model the data shown in Figure 9 correspond to the flame sheet in a turbulent flame. The availability of three-dimensional data allows the topology of the flame struc-
Figure 10. Three-dimensional time evolution of an acoustically forced jet. Shown are instantaneous three-dimensional surfaces obtained by delaying the phase of the measurement relative to the acoustic forcing. The phase is varied at 50-microsecond intervals to produce a "movie" sequence. The flow is from bottom to top at a velocity of 8 meters per second. The nozzle diameter is 3 millimeters.

structures to be investigated.

The most difficult aspect of obtaining instantaneous three-dimensional data is the need for the measurement to be made when the flow is essentially stationary. To relax this constraint, measurements can be performed in forced flows. By causing the flow to evolve in a repeatable fashion, the constraint of having to make very rapid measurements is replaced with the need to make the measurement at the right phase of the repeatable flow. Since the flow is repeatable, many instantaneous shots can be accumulated to integrate weak signals. Sequential measurements of several different quantities such as temperature, species, and velocity are also possible.

Another advantage of using forced flows is realized by varying the relative phase of the perturbation and the measurement. In this way the evolution of the three-dimensional structures can be recorded. It is then possible to construct an animated sequence to visualize the development of the three-dimensional surfaces of constant concentration. Figure 10 shows a sequence of surfaces obtained at different phase delays relative to an acoustic perturbation. The convection and evolution of the structures are evident.

Data representation issues

The preceding section gave a sampling of the type of experimental flow data currently available. For most quantitative research in this area, acquisition and display of single images are not sufficient. Ideally, many measurements are made for a given set of flow conditions, and statistical quantities of interest are calculated from the data. Therefore, the amount of data to be stored, analyzed, and displayed is large; effective and efficient means of displaying the data are needed.

The preceding figures showed several display approaches. However, none of these display techniques emerges as the single best approach for visualizing the data. In some cases the physics of the problem may dictate the type of display that most clearly illustrates the phenomenon under study. The data display techniques presented here by no means represent a complete survey of the methods proposed and used to examine flow data. Other possibilities include a flexible scheme that can represent the concentration data as semitransparent clouds. Another attractive approach, though computationally intensive and rather expensive, is to construct a hologram from this measured data.

The constant-property surfaces presented here were generated using a modified version of the commercially available Movie.DYU graphics program. The hidden-surface calculations were performed on a MicroVAX II, and data display was done on a Macintosh II. Because of the complexity of surface rendering and the modest computational power used, calculation of some images took several hours. The surfaces are represented by a polygon mesh, and because of their complexity, many polygons are needed to fully match the resolution of the measurement. With our current hardware-software configuration, the number of polygons that can be represented is limited to approximately 8,000, whereas more than 30,000 polygons would be needed to fully display the resolution of our best measurements.

Another practical issue in displaying the data is cost. Using color provides an important extra dimension in displaying the complex data set obtained. Currently, however, the cost of publishing two-color plates in some scientific journals represents more than half the cost of the laboratory computer that controls the experiment, stores the data, and displays the results. Therefore, the use of color figures (which can best present the results) might be hard to justify.

Even static color figures are far from the ultimate means of understanding the data. Because of the complexity of some constant-property surfaces, a good object hypothesis is difficult to obtain from a single view. Dynamic projection of three-dimensional data helps considerably. In our laboratory we calculate a sequence of single frames of different object orientations and subsequently animate the precalculated sequence. This animation capability is also extremely useful for time development data like that shown in Figure 10. Ideally, of course, these calculations and the display would be done in real time. Even with the rapid advances in computers, the cost of systems capable of such performance is significant.

Acquiring and displaying data from turbulent flows and flames presents a number of challenges for representing the information we can now obtain experimentally. While the
emphasis here has been on experimental data, nearly identical problems face those working in computational fluid dynamics and combustion. Storage, analysis, and display of data represent a significant bottleneck. With the wealth of new data available from both experimental and computational work, there is hope that a more satisfactory means of visualizing data may lead to a significant new understanding of these very complex systems.

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References


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