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SIMULTANEOUS MULTIPOINT MEASUREMENTS OF DENSITY GRADIENTS AND TEMPERATURE IN A FLAME

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Abstract

A summary is given of research directed toward the study of turbulent reacting and nonreacting flows by nonintrusive *in situ* optical techniques. During the funding period, new diagnostic techniques were developed for the instantaneous mapping of species concentration and temperature in turbulent flames in two and three dimensions. A number of different light scattering mechanisms were utilized including Rayleigh scattering, spontaneous Raman scattering, and fluorescence. Simultaneous measurements of multiple scalars were demonstrated and a method for determining all three components of the scalar gradient was developed. Using advances in high-speed imaging systems, two-dimensional measurements of gas-phase flows were performed at rates high enough to follow their temporal evolution. The data provided by these techniques will be useful for understanding the interaction of turbulence and chemistry in turbulent flames.

Introduction

The problem of predicting turbulent flows is one that remains unsolved despite nearly a century of study. In turbulent flames, the additional presence of chemical reactions and their interaction with the turbulent flow field adds another layer of complexity that makes the task even more difficult.[1] More work must be done both experimentally and theoretically before this extremely important practical problem can be solved.

A central theme in our DOE-funded work was to develop and apply new optical diagnostic techniques for studying turbulent reacting flows. The techniques developed take advantage of developments in computer-controlled low-light-level imaging systems and lasers in order to provide data at a large number of spatially and temporally resolved points (typically 10^4). In our initial work, techniques were developed for mapping out species concentrations in cold flows.[2,3] These techniques were then extended to allow their application to the mapping of species concentrations and temperatures in reacting flows.[4,5] By continuing to develop and extend our imaging techniques, we have now demonstrated the capability of obtaining quantitative, two-dimensional mappings of concentration, temperature, and/or indicators of the flame front position in turbulent flames at a single instant.

The two-dimensional data provided are useful for studying the spatial nature of large-scale structures in the flow, which are now widely accepted as being an important aspect of turbulent reacting and nonreacting flows. A more complete characterization of the role of these structures should aid in the understanding of the interaction between turbulence and chemistry. There are several ways in which the data can be used to give information that is not available from single-point measurements.[6] For example, the characteristics of the structures in the flow can be inferred from the calculation of the covariance of fluctuations in concentration. For this, the covariance is calculated in the streamwise direction relative to an arbitrary fixed location downstream. The positive and negative peaks in the resulting covariance indicate the average length scales in the flow and give an idea of the degree of coherence in the flow. Other calculations performed were concerned with the nature of contours of constant concentration. For example, the average arc length of these contours gives an indication of the degree of mixing that has taken place. The average number of times that a particular contour crosses a line perpendicular to the flow direction indicates the degree to which structures are "broken off" from the main jet.

Two-dimensional imaging techniques have now matured to the point that their use is becoming more widespread and they are being adopted by many investigators.[7-11] More developmental work remains to be done, however, to fully exploit this measurement approach. In the next section, a summary of progress during the funding period will be reviewed.

Time Development

One goal of the research has been to extend our capabilities in high-speed imaging of turbulent cold flows and flames. The data on the temporal evolution of structures is important for studying their formation and development and will add a key dimension to our understanding of the structures in these flows. The emphasis of the techniques developed was to ensure that the data remained quantitative. With quantitative data on the time development of a scalar field, quantities such as convection velocities of the structures, rates of change in area of the structures, and rates of change of contour length can be calculated. These quantities can give insight into mixing rates and will represent a new type of information that is not currently available. In addition to calculating quantities directly involving the temporal development, it will be possible to obtain all the same spatial quantities calculated for the existing two-dimensional data. If this high-speed approach can be fully developed, the entire time needed to take a statistically significant data set would be greatly reduced and it should be possible to study a larger class of flows.

To obtain two-dimensional images at a rate sufficient to follow the evolution in gas-phase flows, it is necessary to configure the experiment so that the detector, computer, and laser can be optimized for high-speed operation. Several different approaches were investigated, with each one providing unique capabilities.[12] In an initial experiment, a solid-state camera (Reticon 100 x 100 diode array camera) was synchronized with a pulsed Cu vapor laser to obtain a framing rate of 480 Hz for 120 sequential frames of a turbulent cold jet. Subsequently, the experiment was improved by utilizing an updated version of the previous camera that allows more rapid data readout. This detector also allows us to scan only a fraction of the total number of pixels, resulting in a higher effective framing rate. By reading out one quarter of the 128 x 128 diode array, a 1100 Hz framing rate over 320 continuous frames was achieved. This camera was initially used in conjunction with a continuous wave argon-ion laser to detect Lorenz-Mie scattering from aerosols. By using the Cu vapor laser with the data acquisition system and adding an image intensifier to the solid state detector, sufficient signal was obtained with Rayleigh scattering from a cold jet of Freon to record the mixing with the ambient air at the 1100 Hz rate.

Multi-Species Measurements

During the research period, some of our experiments were performed at the Combustion Research Facility at Sandia National Laboratories in Livermore, CA. The unique capabilities of the lasers available at the CRF have helped considerably in our efforts to develop and apply new diagnostic techniques. One of the facility lasers is a flashlamp-pumped dye laser which is ideally suited for use in our imaging experiments. By using this laser in conjunction with two camera systems, it has been possible to map out simultaneously the species concentration and temperature in turbulent premixed and nonpremixed flames.[13] The species concentration was obtained by monitoring the spontaneous Raman scattering with one detector and the temperature was obtained by measuring the Rayleigh-scattered intensity with the other camera.

Since both temperature and concentration distributions can now be obtained at the same instant, it is possible to investigate the spatial relationships between these quantities. One approach that takes advantage of the two-component information available is to locate areas in which the temperature and concentration fall within certain defined bounds. This type of comparison can give insight into the mechanisms of mixing that would not be possible if only one measurement were available. For example, if regions of relatively low temperature and concentration are found in the central region of the jet in a nonpremixed flame (i.e., with high temperature regions on either side), this indicates that the region is one in which unreacted fuel has been mixed with air through the turbulent motion. Investigation of the data obtained indicates that this situation does occur.

A more recent experiment that made use of this two-detector approach was the simultaneous, two-dimensional measurement of both temperature (with Rayleigh scattering) and flame front position. In collaboration with researchers at the CRF, we detected fluorescence from C_2 and CH in nonpremixed hydrocarbon flames.[14,15] Fluorescence from these two species is of particular interest because studies indicate that they are good markers for the position of the flame front. One advantage of C_2 or CH fluorescence as flame zone markers is that they are relatively short-lived species. Uncertainties as to the region in which the marker is created are therefore minimized. The fact that the temperature can also be mapped at the same time enables us to calculate correlations between temperatures and flame front location. In addition, the absence of C_2 or CH fluorescence has been shown to indicate that the flame is locally extinguished and allows the study of cases in which the turbulence levels are sufficient to cause extinction.

Scalar Gradient Measurement

A new technique was developed that allows simultaneous measurement of all three components of the gradient of a scalar at each point within a plane.[16] Using Rayleigh scattering, the concentration and concentration gradient vector were measured in a cross section of a turbulent Freon jet. The technique has the potential to be used in flames and with other scattering mechanisms for the measurement of different scalar gradients.

The basis of the method is to simultaneously and instantaneously illuminate the flow with two closely-spaced parallel light sheets and to use two cameras with each camera detecting the image from a single sheet. To ensure that each camera images the scattered light from only one sheet, lasers of different output wavelength are used and appropriate wavelength-selective optical filters are placed in front of each camera. After measuring the separation of the two illumination sheets and the spatial resolution of the images from each camera, the gradient vector can be calculated.

In the experiment, a frequency-doubled pulsed Nd:YAG laser produced one illumination sheet at a wavelength of 532 nm and also pumped a dye laser to produce another laser sheet of different wavelength (563 nm). The cameras were both silicon intensified target vidicon detectors operated in the pulsed mode. An ensemble of 7000 similar measurements was made to allow statistical analysis of the results, which should prove useful in evaluating theoretical models.

The measurement of the full scalar gradient represents a significant advance in the capability of diagnostic techniques. For the first time, it is possible to map out the distribution of concentration and its three-dimensional gradient at all points within a plane intersecting a turbulent flow. The joint pdf of a scalar and its gradient is a quantity that is of interest to both turbulence modelers and modelers of turbulent combustion. Thus, even though this technique has been applied only to non-reacting flows thus far, the results of these measurements are of interest to combustion modelers. By appropriate modification of the experimental configuration, this technique can also be directly applied to flames.

Three-Dimensional Measurements in Forced Flows

One of the basic characteristics of turbulent flow is its three-dimensional nature. A complete understanding of turbulence will therefore not be possible until information can be obtained in three dimensions. As described above, we have started to develop techniques which provide three-dimensional data in these flows. As a means of focusing on the three-dimensional nature of turbulent flows, an experiment was done in which the gas concentration in a photoacoustically forced gas jet was measured at all points within a three-dimensional volume.[17] A pulsed CO_2 laser focused onto a laminar gas flow was used to trigger a localized disturbance which evolved with time. After a fixed time delay, the gas concentration in a two-dimensional cross section of the jet was measured by recording Rayleigh scattering from a frequency- doubled Nd:YAG laser used to illuminate a thin sheet intersecting the flow. A series of these two-dimensional measurements was made at a fixed time delay but with the measurement planes intersecting the flow at different parallel positions, resulting in a full three-dimensional mapping of structures within the flow. Computer graphics enabled the subsequent reconstruction and visualization of the three-dimensional surfaces of constant concentration as well as the magnitude of the concentration gradient on such surfaces.

Three-Dimensional Measurements in General Flows

The work on multipoint gradient measurements and three-dimensional measurements in photoacoustically perturbed flows was part of a long range research effort aimed at instantaneously measuring the gas distribution throughout a flow volume. The final step was to measure the gas concentrations within planes of a more general aperiodic flow in real time. This was done by rapidly scanning a laser sheet through the flow volume, and using a fast data acquisition system to record a number of illuminated flow planes during the time taken scan the volume.[18]

In the first implementation of the technique, the illumination source was an argon-ion laser pulsed at a 30 kHz rate using a cavity dumper to produce 10 ns, 0.3 μJ pulses. Cylindrical lenses shaped the beam into a 260 μm thick sheet, which was swept through a jet by a rotating mirror. The air jet was seeded with submicron-sized sugar aerosols by an atomizing aerosol generator in order to enhance light scattering from illuminated flow planes. The sweep rate of the mirror (8 Hz), the distance between the mirror and the observed region of the jet (10 cm), and the laser pulse repetition rate (30 kHz) combined to produce a spacing between consecutive illuminated flow planes of 360 μm. Elastically scattered light from the aerosols was imaged onto a rectangular portion of a low-light-level camera system. An image intensifier was coupled to a gated silicon-intensified-target vidicon, which was interfaced to an LSI 11/23 computer. Since the detector could not be operated at a 30 kHz framing rate, a second rotating mirror was used to sweep six consecutive images onto different rectangular regions of the detector. Thus several slices of the flow were imaged during one sweep of the laser (i.e., one slice per cavity-dumped light pulse). The information was stored on the detector face as accumulated charge until all six pulses had occurred before it was digitized and stored on the computer, which required about 3 seconds.

A second experiment used a faster detector. Again a rotating mirror (5 Hz) swept a sheet of laser light through the jet volume, but instead of pulsing the laser to illuminate distinct slices of the flow and using a second rotating mirror to separate the images of the slices, these functions were performed electronically by a high-framing-rate camera. A Hadland Photonics Imacon 790 electronic framing camera was operated at a framing rate of 100 kHz with a 2 μs exposure time for each frame. The experimental arrangement was similar to that described above, except that the second rotating mirror was removed and the collection optics and camera were then placed in a line parallel to the initial laser beam. The argon-ion laser was operated without the cavity-dumper at 4.5 W in the all-lines output. With this arrangement up to sixteen consecutive planes of the flow could be recorded on film during one sweep of the laser sheet through the jet volume. Each plane was separated by 85 μm which corresponded to the thickness of the laser sheet. The imaged planes were later digitized and corrected. For a flow of Reynolds number of 1100 based on nozzle diameter, convective motion of flow structures during the 160 μs between the measurement of the first and last sheet corresponded to only 11 of 215 pixels in the streamwise direction.

The availability of instantaneous three-dimensional measurements that can be provided by the techniques developed during the funding period will allow new questions to be addressed. For the first time, direct investigation of surface connectivity, surface/volume ratios, curvatures, and fractal dimensionalities will be possible.

Summary

The emphasis of the work during the funding period has been on the development and application of new laser diagnostic techniques that can provide new information on the large-scale structure in turbulent flames. New techniques developed allow the measurement of multiple scalar quantities, complete scalar gradients, instantaneous three-dimensional scalar measurements, and the temporal evolution of structures. The data provided by these techniques will be useful for understanding the interaction of turbulence and chemistry in turbulent flames.

References

1. P. A. Libby and F. A. Williams, eds., *Turbulent Reacting Flows* (Springer-Verlag, New York, 1980).

2. M. B. Long, B.-T. Chu, and R. K. Chang, *AIAA Journal* **19**, 1151 (1981).

3. M. C. Escoda and M. B. Long, *AIAA Journal* **21**, 81 (1983).

4. M.B. Long, D.C. Fourguette, M.C.Escoda, and C.B. Layne, *Opt. Lett.* **8**, 244 (1983).

5. D.C. Fourguette, R.M. Zurn, and M.B. Long, *Combustion Sci. Tech.* **44**, 307 (1985).

6. M. B. Long and B. T. Chu, *AIAA Journal* **19**, 1158 (1981).

7. R.J. Cattolica and S.R. Vosen, *Twentieth Symposium (International) on Combustion* (The Combustion Institute, Pittsburgh, PA, 1984), p. 1273.

8. G. Kychakoff, R.D. Howe, R.K. Hanson, M. Drake, R.W. Pitz, M. Lapp and C.M. Penney, *Science* **224**, 382 (1984).

9. A.O. zur Loye, F.V. Bracco, and D.A. Santavicca, International Symposium on Diagnostics and Modeling of Combustion in Reciprocating Engines, Tokyo, 1985.

10. M.J. Dyer and D.R. Crosley, *Opt. Lett.* **7**, 382 (1982).

11. A. Vranos and D . Liscinsky, Presented at the AIAA/ASME/SAE 21st Joint Propulsion Conference, Monterey, CA, 1985, AIAA Paper No. 85-1444.

12. M. Winter, J.K. Lam, and M.B. Long, *Exp. Fluids* **5**, 177 (1987).

13 M.B. Long, P.S. Levin, and D.C. Fourguette, *Opt. Lett.* **10**, 267 (1985).

14. R.W. Dibble, M.B. Long, and A. Masri, in *Dynamics of Reactive Systems Part II: Modeling and Heterogeneous Combustion, Proceedings of the Tenth International Colloquium on Dynamics of Explosions and Reactive Systems*, J.R. Bowen, J.-C. Leyer, and R.I. Soloukhin, eds. (American Institute of Aeronautics and Astronautics, Inc., New York, 1986), p. 99.

15. M. Namazian, R.L. Schmitt, and M.B. Long, *Appl. Opt.* **27**, 3597 (1988).

16 B. Yip and M.B. Long, *Opt. Lett.* **11**, 64 (1986).

17. B. Yip, D.C. Fourguette, and M.B. Long, *Appl. Opt.* **25**, 3919 (1986).

18. B. Yip, J.K. Lam, M. Winter, and M.B. Long, *Science* **235**, 1209 (1987).

Publications

D.C. Fourguette, R.M. Zurn, and M.B. Long, "Two-Dimensional Rayleigh Thermometry in a Turbulent Nonpremixed Methane-Hydrogen Flame," *Combustion Sci. Tech.* **44**, 307 (1985).

M.B. Long, P.S. Levin, and D.C. Fourguette, "Simultaneous Two-Dimensional Mapping of Species Concentration and Temperature in Turbulent Flames," *Opt. Lett.* **10**, 267 (1985).

B. Yip and M.B. Long, "Instantaneous Planar Measurement of the Complete Three-Dimensional Scalar Gradient in a Turbulent Jet," *Opt. Lett.* **11**, 64 (1986).

R.W. Dibble, M.B. Long, and A. Masri, "Two-Dimensional Imaging of C_2 in Turbulent Nonpremixed Flames," in *Dynamics of Reactive Systems Part II: Modeling and Heterogeneous Combustion, Proceedings of the Tenth International Colloquium on Dynamics of Explosions and Reactive Systems*, J.R. Bowen, J.-C. Leyer, and R.I. Soloukhin, eds. (American Institute of Aeronautics and Astronautics, Inc., New York, 1986), p. 99.

B. Yip, D.C. Fourguette, and M.B. Long, "Three-Dimensional Gas Concentration and Gradient Measurements in a Photoacoustically Perturbed Jet," *Appl. Opt.* **25**, 3919 (1986).

M. Winter, J.K. Lam, and M.B. Long, "Techniques for High-Speed Digital Imaging of Gas Concentrations in Turbulent Flows," *Exp. Fluids* **5**, 177 (1987).

M. Namazian, R.L. Schmitt, and M.B. Long, "Two-Wavelength Single Laser CH and CH_4 Imaging in a Lifted Turbulent Diffusion Flame," *Appl. Opt.* **27**, 3597 (1988).

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Michael Winter, Ph.D., 1988, "Two-Dimensional Measurement of the Time Development of Gas Phase Flows."

Brandon Yip Ph.D., 1988, "Three-Dimensional Laser Diagnostics in Gas Flows."