Experiments in Fluids 33 (2002) 265–269
DOI 10.1007/s00348-002-0410-2

Quantitative three-dimensional imaging of soot volume fraction in turbulent non-premixed flames

J. Hult, A. Omrane, J. Nygren, C. F. Kaminski, B. Axelsson, R. Collin, P.-E. Bengtsson, M. Aldén

Abstract A three-dimensional (3-D) imaging system for studies of reactive and non-reactive flows is described. It can be used to reveal the topology of turbulent structures and to extract 3-D quantities, such as concentration gradients. Measurements are performed using a high repetition rate laser and detector system in combination with a scanning mirror. In this study, the system is used for laser-induced incandescence measurements to obtain quantitative 3-D soot volume fraction distributions in both laminar and turbulent non-premixed flames. From the acquired data, iso-concentration surfaces are visualised and concentration gradients calculated.

1 Introduction

In almost all practical combustion applications, chemical reactions take place in a turbulent flow field. As turbulence is an intrinsically three-dimensional (3-D) phenomenon, 3-D measurements of relevant flow and flame quantities are highly desirable. Such information is necessary to reveal the topology of turbulent flames or mixing layers, from which data such as surface-to-volume ratios, connectedness and curvature can be extracted. 3-D measurements are also needed to determine all three components of relevant scalar gradients or to calculate scalar dissipation rates.

Laser-based diagnostic techniques have proved to be powerful tools for the study of turbulent and combustion-related flows (Taylor 1993). They can provide spatially resolved information on parameters such as species concentration but are usually limited to one- or two-dimensional (2-D) measurements. 2-D imaging techniques can be applied to obtain 3-D information by rapidly recording a stack of closely spaced planar images. This is feasible by sweeping the laser beam through the measurement volume using a rapidly rotating mirror. The signals generated must then be imaged at repetition rates higher than the characteristic time scales of the flow studied. Fast 3-D measurements based on this principle have been demonstrated using various laser techniques, for example Mie scattering (Yip et al. 1987; Patrie et al. 1994), Rayleigh scattering (Yip et al. 1988) and laser-induced fluorescence (LIF) from O_2 (Kychakoff et al. 1987), acetone (Patrie et al. 1994) and biacetyl (Kychakoff et al. 1987; Yip et al. 1988).

In this paper, we present a new versatile system for 3-D imaging of reactive and non-reactive flows. The system consists of a high repetition rate laser/detector system (Kaminski et al. 1999) and a rapidly scanning mirror. Previously reported 3-D imaging systems in the present context have been based on either flashlamp pumped dye lasers or high repetition rate excimer lasers. The long pulse length associated with the former approach makes frequency doubling difficult to achieve and limits the energy available per exposure. In the latter case, repetition rates were limited to 250 Hz. In practice, this prohibited the measurement of flame species under practically relevant conditions. The present technique is not limited in these respects, and here we used it to quantitatively image the soot volume fraction, f_v, in laminar and turbulent non-premixed flames using 3-D laser-induced incandescence (LII).

LII has been used in numerous studies for soot volume fraction measurements (Ni et al. 1995; Mewes et al. 1997; Dec 1997; Vander Wal and Jensen 1998). In LII, laser radiation from a pulsed laser heats soot particles to temperatures where partial vaporisation occurs. The resulting increase in particle thermal radiation by three to four orders of magnitude constitutes the signal, and is found to be proportional to the soot volume fraction (Melton 1984; Bengtsson and Aldén 1995). Typically, 532-nm or 1064-nm radiation from a pulsed Nd:YAG laser is used in LII measurements. By forming a laser sheet and using an intensified CCD camera, 2-D images of soot volume fraction distributions can be obtained. For quantitative imaging, the LII signal intensity has to be calibrated, which can be done in a flame with well-characterised soot properties.

Received: 19 October 2000 / Accepted: 23 October 2001
Published online: 9 April 2002

J. Hult (✉), A. Omrane, J. Nygren, C. F. Kaminski, B. Axelsson, R. Collin, P.-E. Bengtsson, M. Aldén
Department of Combustion Physics,
Lund Institute of Technology, PO Box 118,
221 00 Lund, Sweden
E-mail: johan.hult@forbrf.lth.se
Tel.: +46-46-2223733
Fax: +46-46-2224542

C. F. Kaminski
Department of Chemical Engineering,
University of Cambridge,
Cambridge CB2 3RA, UK

This work was financially supported by the Foundation of Strategic Research (SSF) through the Centre for Combustion Science and Technology (CECOST), the Swedish National Energy Administration (STEM), and the Swedish Research Council for Engineering Sciences (TFR).

2 Experimental

The experimental set-up is illustrated in Fig. 1. The laser source was a Nd:YAG laser cluster (BMI/CSF-Thomson, France), consisting of four individual laser heads. Special beam combination optics were used to combine the beams from the four lasers into a single beam with minimum associated energy losses. By firing the individual lasers in series and operating them in double-pulse mode, a short burst of eight laser pulses could be obtained, with a separation of 6.25–145 μs between pulses. In this study, the time separation between consecutive pulses was set to 12.5 μs. The Nd:YAG laser output was frequency doubled to 532 nm, with a resulting output energy of 150 mJ/pulse.

A scanning galvanometric mirror (GSI Lumonics) reflected the collinear beams at right angles. The mirror speed was adjusted to give a sheet displacement of either 0.9 mm or 0.4 mm between adjacent measurement planes. For all measurements reported, the depth of field of the imaging optics exceeded the dimensions of the measurement volume. A telescope using cylindrical and spherical lenses was used to form parallel light sheets of cross section $15\times0.3\text{-mm}^2$ in the interaction region. The laser fluence was approximately 0.3 J/cm^2, well inside the plateau region of the LII response curve (Axelsson et al. 2000).

The LII signal was detected using a high-speed framing camera based on eight individual CCD cameras (Imacon 468, DRS Hadland, UK). Each camera consists of an intensified 8-bit CCD, featuring 576×385 pixels. By using short exposure times and by exposing the cameras in series, a temporal resolution of 10 ns can be achieved. To increase the light sensitivity, an optional, sequentially gated, image intensifier was used at the camera's optical input, with an associated minimum time separation of 1 μs between consecutive images. A low-pass transmission filter (λ<450 nm) was used to discriminate against flame radiation and scattered laser light. The laser and detector were triggered from a photodiode signal monitoring a continuous wave (cw) laser beam reflected from the scanning mirror. The variation in mirror speed at the measurement position was a few per cent from scan-to-scan, which

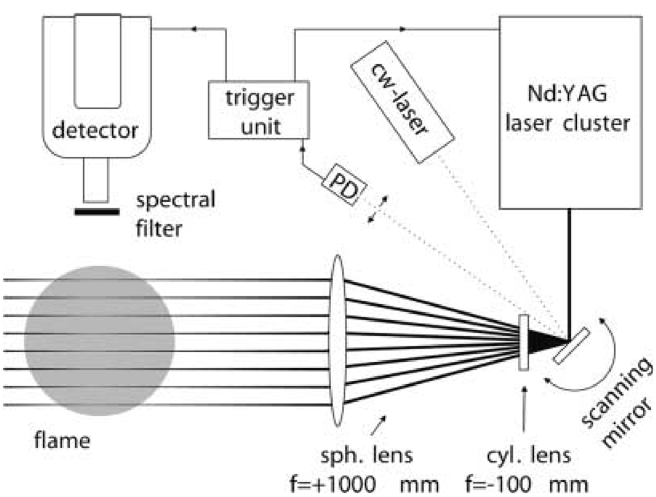

Fig. 1. Schematic overview of experimental set-up: *PD*, photodiode

resulted in good sheet distance reproducibility. By fixing the mirror position, it was verified that the accumulative 3-D image acquisition time, 87.5 μs, was sufficiently short on the flow time scales to freeze the motions of the low Reynolds number flow, as no change could be detected at the detector's spatial resolution between the first and last images of such a sequence.

To obtain absolute values of soot volume fraction, the incandescence signal was calibrated against a well-characterised premixed flat C_2H_4-air flame with Φ=2.3 (Axelsson et al. 2000). The flame, burning on a porous plug burner, was introduced into the measurement region and made it possible for the signal from each of the eight laser pulses to be calibrated individually. The width of the porous plug was 60 mm, and the flame was stabilised by means of a metal cylinder positioned 21 mm above the burner surface. Air pressure can affect the soot volume fraction, and soot build-up on the stabiliser also introduces a slight variation over time, particularly close to the stabiliser, but a variation of more than 5% is not expected. After calibration, the flat flame burner was replaced with the turbulent non-premixed flame to be investigated.

Slight misalignments between the individual CCD cameras made it necessary to correct the raw LII images using the geometrical transformation procedure outlined in Dreizler et al. (2000). This geometrical transform maps the images from the different CCDs to a common reference image coordinate system, which is established by imaging a common grid pattern with all eight CCDs. The transform is a vector function, approximated by a polynomial equation that maps each pixel to a new position. The coefficients of the first-order polynomial equations are determined by identifying corresponding points in the eight images of the grid pattern. The residual misalignment between the individual images after this transformation is on the order of 1 pixel. Distortions are also caused by the change in magnification with distance to the detector, which in the present set-up was found to be 0.4%/mm. As the resulting displacements of the imaged objects were smaller than the sheet spacing, no attempt to compensate for these was made. Intensities in each image were scaled to absolute soot volume fractions using the calibration factors determined in the reference flame. Finally, 3-D iso-concentration surfaces were reconstructed based on the eight sequential 2-D images.

3 Results

Results from a small laminar C_2H_4 (ethylene) non-premixed flame are shown in Fig. 2. The flame was stabilised on a conical burner with an exit diameter of 1.7 mm. The absolute soot volume fractions in the eight imaged planes are shown in the sequence to the left in Fig. 2. The imaged region corresponds to 9×16 mm, with a laser sheet separation of 0.9 mm. As expected, the soot distribution is symmetrical in all three directions, which demonstrates the capability of the experimental set-up to quantitatively measure the 3-D soot volume fraction. To the right, the corresponding 3-D iso-concentration surface for a soot volume fraction of 1 ppm is plotted, image 1 corresponds to the back and image 8 to the front planes of this

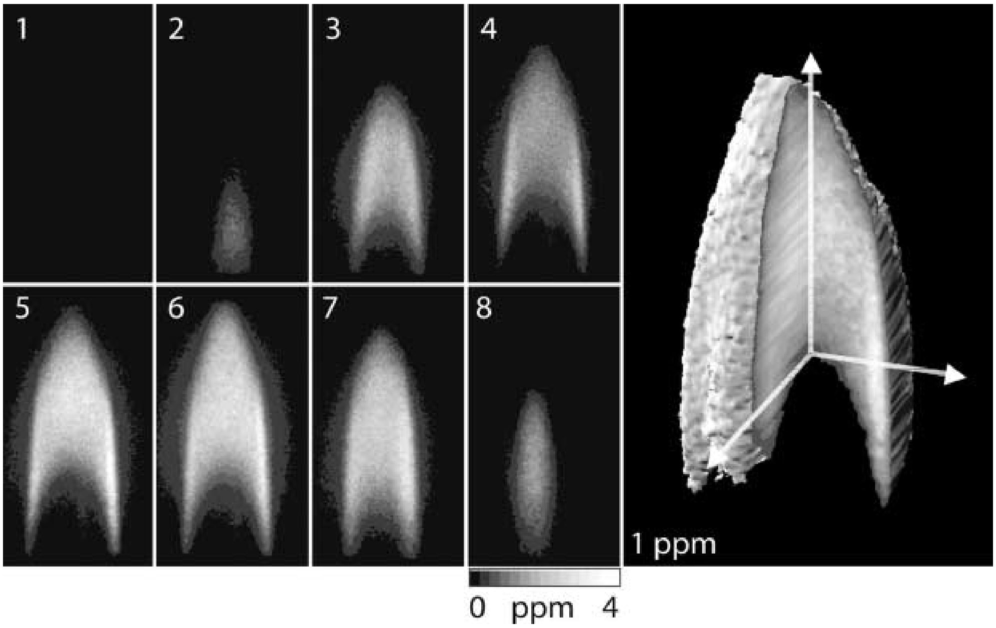

Fig. 2. *Left*: Soot volume fraction distributions acquired in eight equidistant planes in a laminar C_2H_4 non-premixed flame. The entire sequence was recorded in 87.5 μs. The imaged region corresponds to 9×16 mm, with a relative image displacement of 0.9 mm. *Right*: 3-D iso-concentration surface corresponding to a soot volume fraction of 1 ppm. A *corner* has been cut out of the reconstruction to reveal the internal structure of the flame, where regions with f_v>1 ppm are shown

reconstruction. For both the calibration and the actual measurement, the same fuel was used; however, differences in refractive index can be considered an uncertainty, since both temperature and chemical composition affect this property. Several different values are found in literature, and the relative error in refractive index will result in a comparable relative error in the evaluated soot volume fraction. The LII signal response to the laser fluence is weak if a fluence in the plateau region is chosen, and therefore the shot-to-shot variations are small – smaller than the laser-pulse energy variation. However, considering inherent sources of uncertainty, of which the refractive index is the largest in an LII measurement, the difference between the measured value of the soot volume fraction can differ by as much as 20% from the true value.

In Fig. 3, the results from a turbulent non-premixed flame are shown, stabilised on the same burner as the laminar flame above. A mixture of C_2H_4 (64% by volume) and N_2 (36%) was used as fuel, at an exit velocity of 15 m/s, corresponding to a Reynolds number of $Re \approx 2{,}200$. Eight soot volume fraction images representing cuts through the centre of the flame at a height of 110 mm above the burner nozzle are presented. The imaged regions correspond to 21×15 mm, with a laser sheet separation of 0.4 mm. Since the soot is primarily formed towards the fuel-rich side near the stoichiometric air/fuel boundary in a non-premixed flame, the large-scale soot structures seen in the image are due to wrinkling of this boundary by the turbulent flow. In Fig. 4, the 3-D iso-concentration surfaces corresponding to 1 ppm, 2 ppm and 3 ppm soot volume fraction are

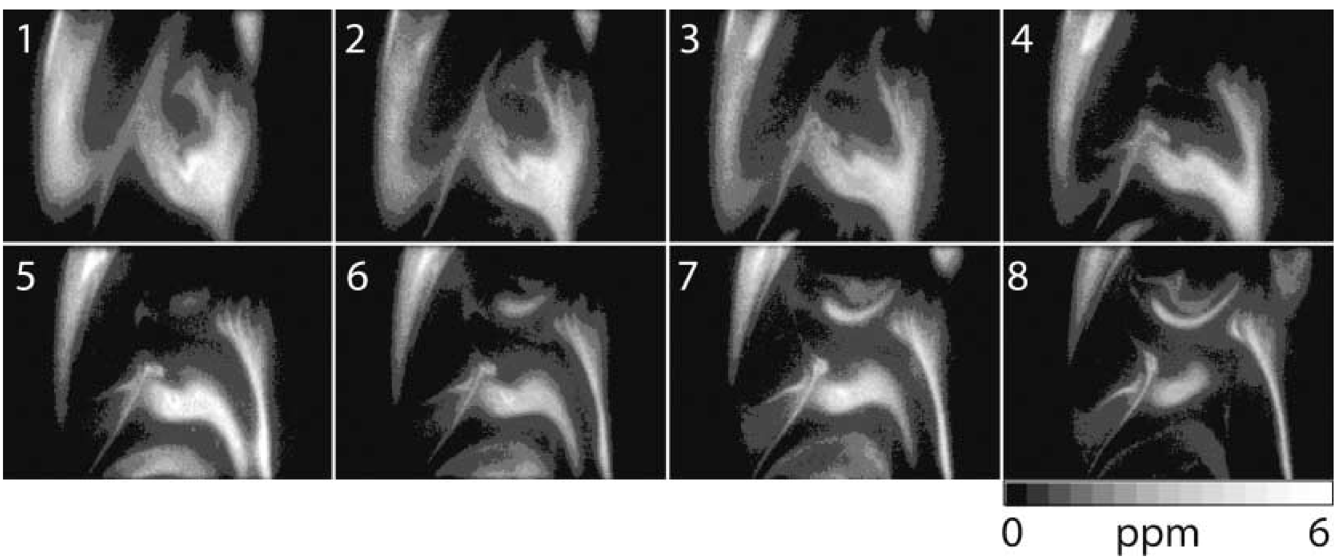

Fig. 3. Soot volume fraction distributions acquired in eight equidistant planes in a turbulent non-premixed flame ($Re \approx 2200$). The fuel mixture was 64% C_2H_4 and 36% N_2. The imaged region corresponds to 21×15 mm, with a relative image displacement of 0.4 mm

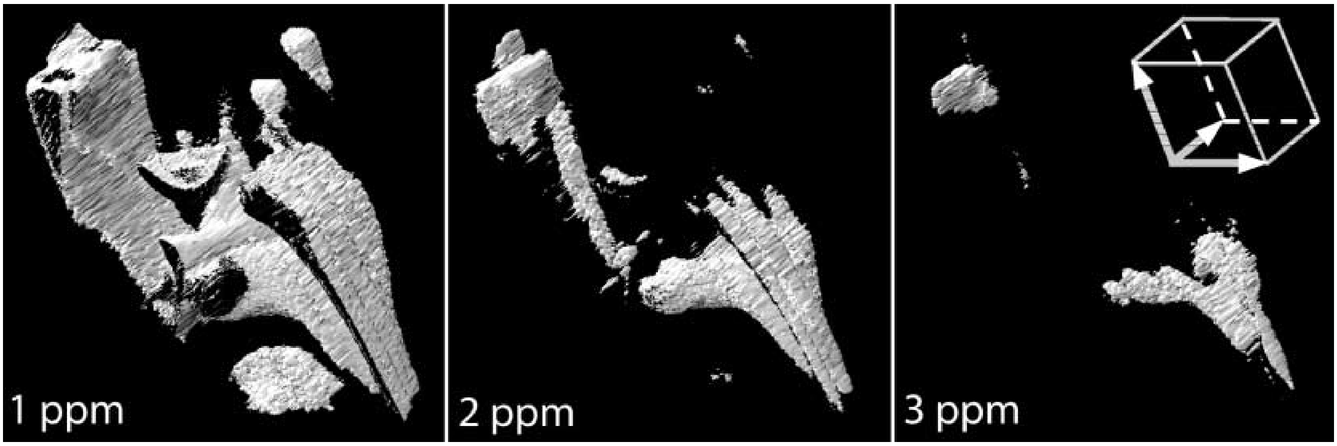

Fig. 4. 3-D iso-concentration surfaces corresponding to a soot volume fraction of 1 ppm, 2 ppm and 3 ppm, respectively. Surfaces are based on data presented in Fig. 3

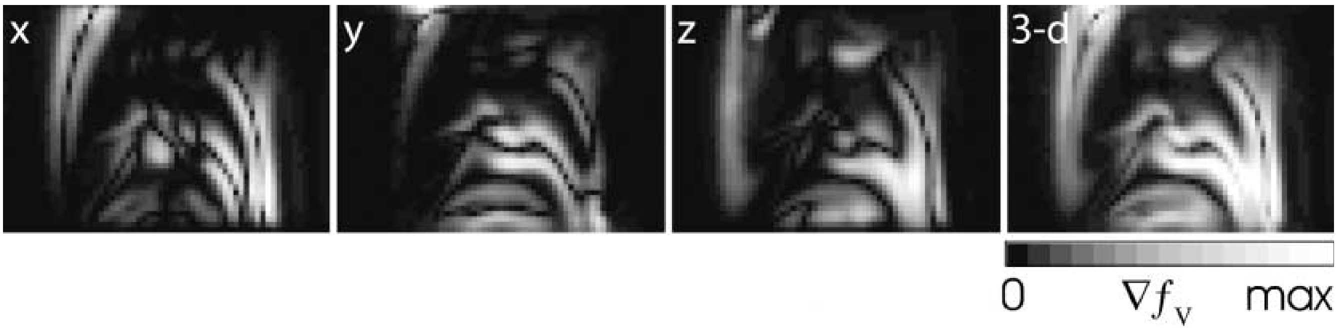

Fig. 5. Magnitude of x-, y- and z-components of the soot volume fraction gradient and corresponding 3-D gradient. The intensity greyscale is the same on all images shown. Gradients are plotted in the plane corresponding to *image 5* in Fig. 4

visualised. The type of information available in Fig. 4 can be used to study the topology of complex turbulent flames.

For the measurement of scalar dissipation rates in turbulent flows, the local mixture fraction χ has to be determined in three dimensions (Cruyningen et al. 1990; Warnatz et al. 1996). That such information, in principle, is available by use of the current technique is demonstrated in Fig. 5, where we show the magnitude of the true 3-D gradient, ∇f_v, of the soot volume fraction based on images 4, 5 and 6 of the sequence in Fig. 4. The x, y and z components of the gradient are also shown. As the separation between the laser sheets is larger than the resolution in the eight images, the data were processed to match the image resolution with the sheet spacing before the gradients were calculated. The images were first smoothed by convolution with a Gaussian function of the same width as the laser sheets, and were then resampled with the spacing which was used between the laser sheets. The resulting uniform resolution in all directions is needed to correctly estimate the gradients; however, the resolution of the processed data determines the smallest scale at which the gradients can be calculated. The present technique can be extended to measure local mixture fractions (by use of suitable tracer species or by direct fuel excitation) and can even be performed sequentially to provide a time history of the scalar dissipation.

4
Summary

In summary, a 3-D imaging system for turbulent reacting and non-reacting flows has been presented and demonstrated for 3-D imaging of absolute soot volume fractions in laminar and turbulent non-premixed flames. The system is unique in terms of its flexibility to extend various planar laser spectroscopic techniques into three dimensions. In combination with a dye laser and suitable non-linear frequency conversion techniques, 3-D LIF imaging of native species will be possible. The technique described is also applicable in combustion devices, e.g. engines, with higher Reynolds number flows, since it is possible to use shorter 3-D acquisition times. For eight planes, the minimum total acquisition time is 44 μs, and for a four-image stack it is 3 μs, which should be short enough to freeze most flows of interest.

References

Axelsson B, Collin R, Bengtsson P-E (2000) Laser-induced incandescence (LII) for soot particle size measurements in premixed flames. Appl Opt 39:3683–3690

Bengtsson P-E, Aldén M (1995) Soot-visualization strategies using laser techniques: laser-induced fluorescence in C2 from laser-vaporized soot and laser-induced soot incandescence. Appl Phys B 60:51–59

Cruyningen IV, Lozano A, Hanson RK (1990) Quantitative imaging of concentration by planar laser-induced fluorescence. Exp Fluids 10:41–49

Dec JE (1997) A conceptual model of DI diesel combustion based on laser-sheet imaging. SAE Paper 970873

Dreizler A, Lindenmaier S, Maas U, Hult J, Aldén M, Kaminski CF (2000) Characterisation of a spark ignition system by planar laser-induced fluorescence of OH at high repetition rates and comparison with chemical kinetic calculations. Appl Phys B 70:287–294

Kaminski CF, Hult J, Aldén M (1999) High repetition rate planar laser induced fluorescence of OH in a turbulent non-premixed flame. Appl Phys B 68:757–760

Kychakoff G, Paul PH, Cruyningen IV, Hanson RK (1987) Movies and 3-D images of flowfields using planar laser-induced fluorescence. Appl Opt 26:2498–2500

Melton LA (1984) Soot diagnostics based on laser heating. Appl Opt 23:2201–2208

Mewes B, Seitzman JM (1997) Soot volume fraction and particle size measurements with laser-induced incandescence. Appl Opt 36:709–717

Ni T, Pinson JA, Gupta S, Santoro RJ (1995) Two-dimensional imaging of soot volume fraction by the use of laser-induced incandescence. Appl Opt 43:7083–7091

Patrie BJ, Seizman JM, Hanson RK (1994) Instantaneous three-dimensional flow visualization by rapid acquisition of multiple planar flow images. Opt Eng 33:975–980

Taylor AMKP (1993) Instrumentation for flows with combustion. Academic Press, London

Vander Wal RL, Jensen KA (1998) Laser-induced incandescence applied to droplet combustion. Appl Opt 37:1607–1616

Warnatz J, Maas U, Dibble RW (1996) Combustion, physical and chemical fundamentals, modeling and simulation, experiments and pollutant formation. Springer, Berlin Heidelberg New York

Yip B, Lam JK, Winter M, Long MB (1987) Time resolved 3D concentration measurements in a gas jet. Science 235:1209–1211

Yip B, Schmitt RL, Long MB (1988) Instantaneous three-dimensional concentration measurements in turbulent jets and flames. Opt Lett 13:96–98